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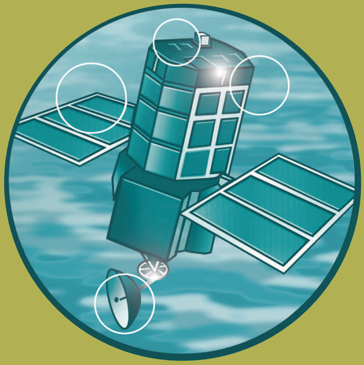
Joint Probability: Dependence between extreme sea surge, river flow and precipitation:

A study in South and West Britain

R&D Technical Report FD2308/TR3



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Joint Probability: Dependence between extreme sea surge, river flow and precipitation: A study in South and West Britain

R&D Technical Report FD2308/TR3

March 2005

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This document provides information for Defra and Environment Agency Staff about dependence between variables causing flooding in estuaries, and constitutes an R&D output from the Joint Defra / Environment Agency Flood and Coastal Defence R&D Programme.

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This work was funded by the Department for the Environment, Food and Rural Affairs, under project code FD2308 (Joint probability: dependence mapping and best practice). This technical report describes the findings of the CEH Wallingford study, which was carried out as a sub-contract to the overall coordinator of the project, HR Wallingford. The Project Manager for HR Wallingford was Dr Peter Hawkes. The Project Manager for CEH Wallingford was Dr Cecilia Svensson, assisted by colleague Dr David Jones. The Client Project Manager was Dr Suresh Surendran of the Environment Agency's Environmental Policy Centre for Risk and Forecasting at Reading. The project was undertaken under the joint Defra / Agency research theme Risk Evaluation and Understanding of Uncertainty, headed by Ian Meadowcroft.

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The tide and surge data were made available by the Proudman Oceanographic Laboratory under licence for use by CEH Wallingford and HR Wallingford during this project. The daily precipitation data were made available by the UK Met Office under a licence not specific to this project for use by CEH Wallingford. Daily mean river flow data were collected by the UK environment agencies, and provided by the National River Flow Archive for use by CEH Wallingford. The daily precipitation data from the HadRM3 regional climate model and the hourly sea surge data from the shelf-seas model were supplied by the UK Met Office for use by CEH Wallingford under a project specific licence.

EXECUTIVE SUMMARY

In 2000, Centre for Ecology and Hydrology, Wallingford, (CEH Wallingford) participated in MAFF (now Defra) research regarding extreme water levels in estuaries. Areas that may be at heightened risk of flooding because of the simultaneous occurrence of extreme sea surge and river flow in estuaries along the British east coast were identified. The purpose of the present study was to extend the analysis to encompass the south, west and north coasts of Great Britain. The heightened risk of flooding was investigated by estimating the dependence between extreme river flow and sea surge. To assist in the interpretation of why flow-surge dependence occurs in some areas and not in others, the dependence between precipitation and surge and between precipitation and river flow was also studied. Seasonal and lagged analyses were carried out to further explore the details of the dependence. Where dependence between sea surge and river flow was found, the meteorological situations causing combined high flows and surges were identified. A small climate change impact study and a study of the sensitivity of dependence to storm track was also carried out.

Sea surge observations for 19 stations, daily mean river flows for 72 stations and daily precipitation for 27 stations in catchments draining to the south, west and north coasts of Great Britain, were used for the period 1963-2001. A dependence measure, χ, especially suited for extremes, was employed to estimate dependence between the variables.

Statistically significant dependence between river flow and daily maximum sea surge may be found at catchments spread along most of the south, west and north coastline. However, higher dependence is generally found in catchments in hilly areas with a southerly to westerly aspect. Here, precipitation in southwesterly airflow, which is generally the quadrant of prevailing winds, will be orographically enhanced as the first higher ground is encountered. The sloping catchments may respond quickly to the abundant rainfall (of cyclonic origin), and the flow peak may arrive in the estuary on the same day as a large sea surge is produced by the depression.

There are three regions where surge-flow dependence is strong: the western part of the English south coast, southern Wales, and around the Solway Firth. The generally low dependence on the eastern part of the south coast of England may be related to these being generally permeable, predominantly chalk, catchments which respond slowly to rainfall. In order to reduce the influence of tide-surge interaction on the dependence analysis, the dependence between river flow and daily maximum surge occurring at high tide was estimated. The general pattern of areas with higher dependence is similar to that using the daily maximum surge.

A large part of the west coast experience a moderate strengthening of the flow-surge dependence in winters with a high North Atlantic Oscillation Index (NAOI) compared to winters with a low NAOI. The NAOI, which is an indicator of the main storm track location, is generally expected to shift towards its positive phase in future climate change scenarios. Using the UKCIP02 Medium-High climate change emission scenario (SRES A2), dependence between modelled sea surge and precipitation (used as a proxy for river flow) is expected to increase around most of the British coast, except the south part of the east coast, towards the end of the 21st century.

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1. INTRODUCTION

1.1 Background

In 2000, Centre for Ecology and Hydrology, Wallingford, (CEH Wallingford) participated in MAFF (now Defra) research regarding extreme water levels in estuaries, through a subcontract to HR Wallingford. Flooding in estuaries may be caused by river flooding or coastal flooding, or a combination of the two, and the CEH work involved the estimation of the dependence between river flow and sea surges on the British east coast. Understanding of the risks posed by combinations of extreme events is crucial for the successful management of these hazards.

The Department for Environment, Food and Rural Affairs (Defra) is funding best practice guidance on joint probability methods and mapping of dependence for several variable-pairs relevant to flood and coastal defence, carried out by HR Wallingford (project leader: Peter Hawkes). CEH Wallingford was invited to contribute to the HR Wallingford study through a sub-contract, by investigating the dependence between river flow, precipitation and sea surge. The present study extends the earlier east coast study (Svensson and Jones, 2000), to include the remaining coasts of Great Britain. The overall joint probability guidance and dependence mapping covering all coasts of Great Britain are presented in Defra/Environment Agency (2005a, 2005b).

1.2 Purpose

The purpose of the study was to identify areas that may be at heightened risk of flooding because of the simultaneous occurrence of extreme sea surge and river flow in estuaries along the south, west and north coasts of Great Britain. This was investigated by estimating the dependence between extreme river flow and sea surge. To assist in the interpretation of why flow-surge dependence occurs in some areas and not in others, the dependence between precipitation and surge and between precipitation and river flow was also studied. Seasonal and lagged analyses were carried out to further explore the details of the dependence. Where dependence between sea surge and river flow was found, the meteorological situations causing combined high flows and surges were identified. The present study expands on the scope of the previous east coast study by incorporating an estimate of the sensitivity of the dependence to a climate change proxy. Results of this new analysis for the east coast, together with a revisit of the original flow-surge analysis using a densified network of river flow stations, are presented in Appendix A.

The behaviour of surges (the difference between the observed sea level and the predicted astronomical tide) on the west and south coasts is altogether less well understood than the behaviour of surges in the North Sea. Considering the importance of orographic enhancement of precipitation to dependence on the east coast, it was hypothesised that the predominantly windward catchments on the south and west coasts would be similarly at risk.

While the project was underway, an extension to the study was commissioned, to assess the climate change impact on dependence. These results are presented in Appendix C.

1.3 Brief literature review

1.3.1 Sea surge

A sea surge may be described as the change in sea level due to meteorological effects. These include the tractive force of the wind and the effect of atmospheric pressure differences on the water surface. When a depression moves into a sea area the atmospheric pressure acting normal to the sea surface falls and the sea level rises. A reduction in pressure of 1 mb corresponds to a rise in the water level of about 1 cm, and vice versa. The effect of the wind, which is the more important in shallow waters, results in the water being dragged in a similar direction to the wind, but deflected to the right (in the northern hemisphere) because of the Coriolis effect (Hunt, 1972).

Meteorological disturbances are strongest in winter, and have the greatest effect where they act on shallow seas (Pugh, 1987). On the west coast, surges tend to be locally generated by the low atmospheric pressure and southerly to westerly winds associated with a depression approaching Britain from the west or southwest (Lennon, 1963; Heaps, 1967). The depression tracks associated with west coast surges are generally more to the south, crossing Ireland, than those resulting in surges in the North Sea (Pugh, 1987). Further, the depressions are often of a secondary nature, moving anti-clockwise around the parent depression to its north (Lennon, 1963). Positive surge events on the west coast tend to be of a shorter duration than on the east coast, often lasting between about 9 and 15 hours (Heaps, 1967).

There is a near-resonant response of the Irish Sea and the Bristol Channel to tidal forcing from the Atlantic. These resonant modes are probably also responsive to meteorological forcing at similar frequencies, resulting in short-lived intense surges that are quickly generated and decay during a single semidiurnal tidal cycle (Pugh, 1987).

In shallow water, wave characteristics such as speed and amplitude are influenced by water depth. When the increase in water depth due to tide and surge waves is not negligible compared to the total water depth, non-linear interaction between tide and surge will occur. The interaction is complex and best calculated by numerical models (Pugh, 1987). Heaps (1983) and Defra/Environment Agency (2005a) suggest that non-linear interaction between surge and tide occurs in the Bristol Channel as well as in the Irish Sea. Tides and surges travelling up features like the Bristol Channel will also be affected by “funnelling”: the gradual narrowing of an estuary tends to increase the wave amplitude as the width of the wave front is reduced (Pugh, 1987).

Storm surges in the English Channel are smaller than those encountered on the British east and west coasts, with large Channel surges of about 1m. They may be generated locally in the Channel, or enter it from the west or from the North Sea (Heaps, 1983).

1.3.2 Precipitation

Mid-latitude cyclonic activity affecting the British Isles is more vigorous during autumn and winter than during the rest of the year (e.g. Wallén, 1970). Consequently, frontal precipitation is more abundant in this season (Manley, 1970). Orographic enhancement, which is more prominent in winter, increases the precipitation on windward slopes (e.g. Harrison, 1997). Because of the predominantly westerly winds, this is particularly pronounced in the western parts of the country (Mayes and Wheeler, 1997). Towards the east, precipitation associated with thunderstorms results in the average monthly totals having a primary or secondary maximum during the summer (Manley, 1970). In a study on heavy 1-day falls, Dales and Reed (1989) noticed that summer events outnumbered the winter events at higher quantiles regardless of location in England or Wales.

The majority of cyclones travel from west to east, in latitudes north of Scotland, or from south-west to north-east past the Hebrides (Manley, 1970). When studying mid-season months, this or similar patterns emerge for most of the year (October, January and April). However, during the summer (July) the main storm track is typically further to the south, crossing Scotland from west to east (Whittaker and Horn, 1984).

1.3.3 River flow

In general, the month with the highest frequency of floods occurs in late autumn and winter in large areas of the north and west of Britain (Bayliss and Jones, 1993), similar to the seasonality of intense cyclones and associated precipitation. For most rivers in north Britain at least 78% of events occur in the October-March half-year (Black and Werritty, 1997). However, catchments to the south and east show more of a late winter and early spring seasonality. This is because the soil moisture content in these catchments generally returns to near field capacity later in the year. The result is a later onset and a shorter flood season (Bayliss and Jones, 1993).

Bayliss and Jones (1993) analysed over 800 peaks-over-threshold flood records. Their results indicate that for large catchments the occurrence of floods is highest in either December or January, presumably because a large percentage of the catchment needs to be at or near field capacity before flooding can take place. Conversely, small, urbanised and quickly responding catchments in south and central England are shown to have their highest number of peak-over-threshold events in June, July or August, presumably in response to convective rainfall.

1.3.4 Dependence studies of sea surge and river flow

Samuels and Burt (2002) investigated the dependence between river flow on the Taff at Pontypridd and sea levels at Cardiff in south Wales. They extracted the 20 highest peak river flows and paired them with the corresponding nearest high water levels. They concluded that there was no correlation between the series, and that the corresponding water levels were not unusually high (which would have suggested that there might be dependence). Weston (1979) quantified the magnitudes of freshwater flow and tide that combine to certain observed water levels of the tidal Dee in north Wales, but does not include a frequency estimate or study of the dependence between the variables.

Different methods used in other countries to establish whether there is dependence between the variables or not are described in e.g. van der Made (1969) and Loganathan *et al*., (1987). van der Made (1969) investigated the dependence between river flow in the river Rhine in the Netherlands and water levels in the North Sea. The dependence problem is approached by comparing the frequency of river flows occurring simultaneously to extreme storm surges, with the frequency of river flows occurring regardless of the size of surge. The frequencies are found to not be significantly different from each other, and thus there is no dependence.

Loganathan *et al.* (1987) concludes that there is dependence between flow in the Rappahannock River and water levels in the Chesapeake Bay on the east coast of the United States. In this case, iso-lines of empirical exceedance probability are plotted in a diagram of water level versus streamflow, and show that high flows tend to occur simultaneously to high water levels.

2. DATA

2.1 Sea surge

Hourly sea surge and total sea level data covering the period 1963-2001 for 19 stations on the British south, west and north coasts were used. The stations are Dover, Newhaven, Portsmouth, Weymouth, Newlyn, Ilfracombe, Avonmouth, Milford Haven, Fishguard, Holyhead, Liverpool Princes Pier, Liverpool Gladstone Dock, Heysham, Portpatrick, Millport, Tobermory, Ullapool, Lerwick and Wick (Figure 1, Table 1). The surge residuals were calculated as the difference between the observed total sea level and the predicted astronomical tide. Daily series of maximum surge, and of maximum surge occurring at high tide, were derived for the water day, 9.00-9.00 GMT. The daily maximum surge was thought to have the strongest connection with precipitation and river flow because of the relatively short duration of very high surges. However, because of tide-surge interaction in shallow waters, daily maximum surge occurring at high tide was also extracted from the hourly data.

As a brief quality check of the extremes, daily maximum surges exceeding the station mean daily maximum surge plus two standard deviations were plotted for all the stations using a shared time axis (not shown). The figure revealed an unusual amount of high surges for some stations, and these were investigated by plotting the hourly data and comparing with neighbouring stations. As a result, sea level data were set to missing on 1/1-4/2 and 25/2-25/3 1965 for Milford Haven, 13/10-22/10 1970, 16/8-31/8 1973, 15/6-12/7 1975, 12/10-23/10 1979 for Liverpool Princes Pier, 18/9-25/9

Table 1 General information about the 19 sea level stations. The easting and northing coordinates are in the Great Britain national grid coordinate system. Missing data refer to the extracted daily maximum surge series.

Station	Easting (km)	Northing (km)	Mean daily maximum surge (mm)	Missing data (%)
Wick	336.7	950.8	66	19.1
Lerwick	447.8	1141.4	67	14.3
Ullapool	212.9	893.9	99	32.1
Tobermory	150.8	755.3	107	74.4
Millport	217.7	654.5	150	51.3
Portpatrick	199.8	554.2	102	18.9
Heysham	340.3	460.1	198	16.9
Liverpool Princes Pier	333.6	390.6	316	48.0
Liverpool Gladstone Dock	332.5	395.3	205	78.3
Holyhead	225.5	382.9	101	35.5
Fishguard	195.1	238.8	108	11.2
Milford Haven	189.2	205.3	130	18.2
Avonmouth	350.6	179.0	381	61.8
Ilfracombe	252.6	147.9	153	51.3
Newlyn	146.8	28.6	82	2.9
Waymouth	368.4	78.9	104	73.4
Portsmouth	462.7	100.5	132	75.0
Newhaven	545.1	100.1	154	66.5
Dover	632.7	140.3	160	16.5

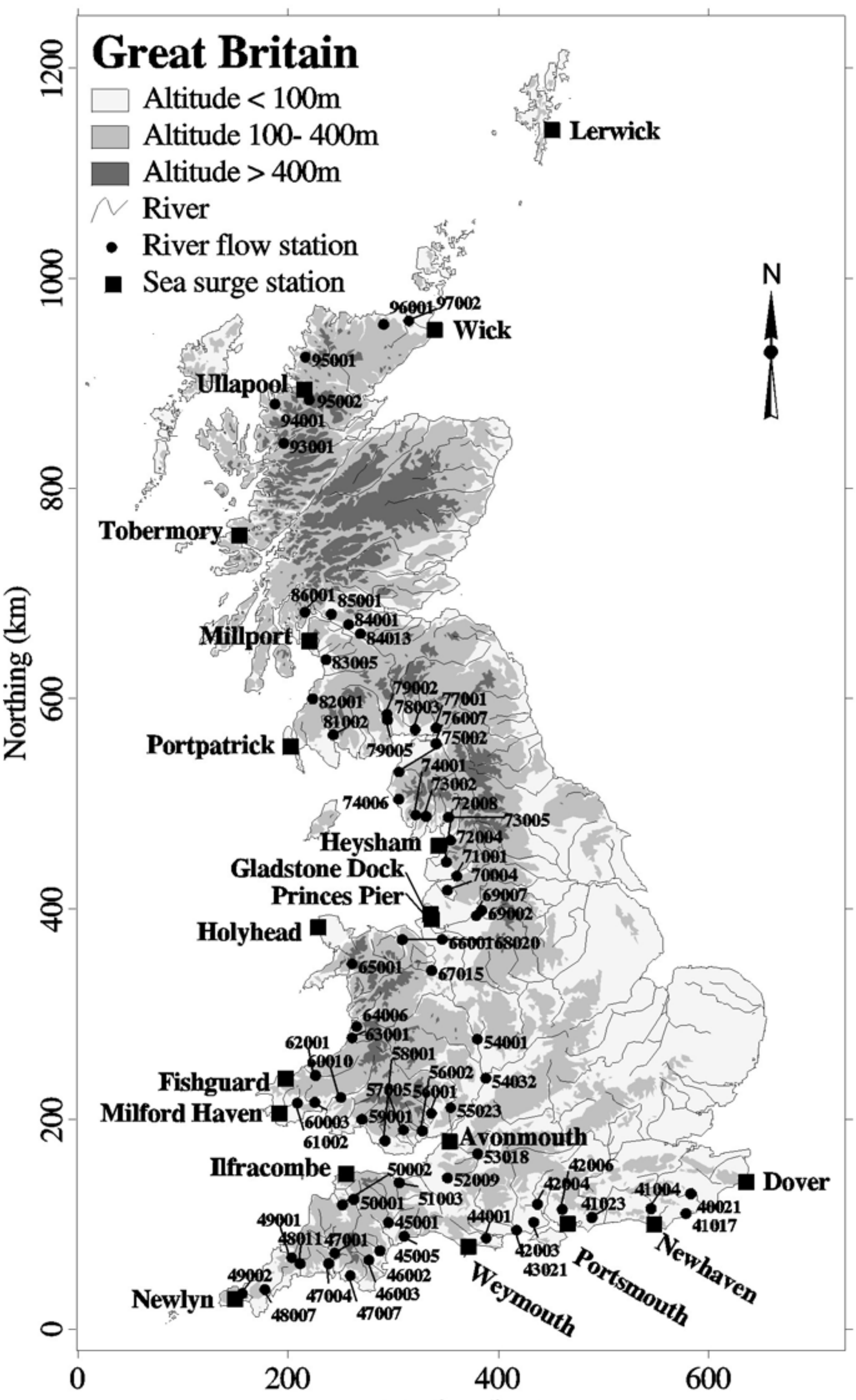

Figure 1 Location of sea level stations and river flow stations.

and 4/10-9/10 1978, 20/9-16/11 and 23/11-12/12 1979, 4/9-24/11 1980 for Ullapool, and 3/9-9/12 1968, 16/9-17/12 1980, 3/3-21/4 1981 for Ilfracombe.

There are two records for Liverpool. The means of daily maximum surge for Liverpool Princes Pier (1963-1986) and Liverpool Gladstone Dock (1993-2001) are rather different (316 and 205 mm), and the change between the time periods differ in sign to that at three of four surrounding stations (Portpatrick, Holyhead and Fishguard increase, whereas Heysham decreases) for the same time periods. Therefore, the two Liverpool sites were treated as two separate records rather than being aggregated into one long record.

The amount of missing data in the daily maximum surge series varies between 2.9% for Newlyn to 78.3% for Liverpool Gladstone Dock.

More information on extreme surges can be found in Department of Energy (1977 and 1984). These offshore design guidelines cover the whole of the British Isles.

Table 2 General information about the 72 river flow stations. The easting and northing coordinates are in the Great Britain national grid coordinate system. Missing data: 0 denotes a complete record, and 0.0 denotes that less than 0.05% is missing.

Station	River	Location	Easting (km)	Northing (km)	Altitude (m)	Area (km^2)	Mean river flow (m^3/s)	Missing data (%)
40021	Hexden Channel	Hopemill Br Sandhurst	581.3	129.0	5.2	32	0.3	48.2
41004	Ouse	Barcombe Mills	543.3	114.8	5.2	396	3.6	19.7
41017	Combe Haven	Crowhurst	576.5	110.2	1.9	31	0.3	18.0
41023	Lavant	Graylingwell	487.1	106.4	20.7	87	0.3	21.1
42003	Lymington	Brockenhurst	431.8	101.9	6.1	99	1.0	0.8
42004	Test	Broadlands	435.4	118.9	10.1	1040	10.8	0.2
42006	Meon	Mislingford	458.9	114.1	29.3	73	1.0	0.0
43021	Avon	Knapp Mill	415.6	94.3	0.9	1706	19.9	33.1
44001	Frome	East Stoke Total	386.6	86.7	~9	414	6.4	12.0
45001	Exe	Thorverton	293.6	101.6	25.9	601	16.0	0
45005	Otter	Dotton	308.7	88.5	14.5	203	3.2	0
46002	Teign	Preston	285.6	74.6	3.8	381	9.2	2.6
46003	Dart	Austins Bridge	275.1	65.9	22.4	248	11.0	2.6
47001	Tamar	Gunnislake	242.6	72.5	8.2	917	22.4	0
47004	Lynher	Pillaton Mill	236.9	62.6	8.5	136	4.6	2.0
47007	Yealm	Puslinch	257.4	51.1	5.5	55	1.7	2.8
48007	Kennal	Ponsanooth	176.2	37.7	13.6	27	0.5	14.7
48011	Fowey	Restormel	209.8	62.4	9.2	169	4.9	0.0
49001	Camel	Denby	201.7	68.2	4.6	209	6.1	4.3
49002	Hayle	St Erth	154.9	34.1	7.0	48	1.0	13.2
50001	Taw	Umberleigh	260.8	123.7	14.1	826	18.5	0
50002	Torridge	Torrington	250.0	118.5	13.9	663	16.0	0.0
51003	Washford	Beggearn Huish	304.0	139.5	67.1	36	0.8	18.2
52009	Sheppey	Fenny Castle	349.8	143.9	5.8	60	1.1	3.8
53018	Avon	Bathford	378.5	167.0	18.0	1552	18.0	17.7
54001	Severn	Bewdley	378.2	276.2	17.0	4325	60.6	0
54032	Severn	Saxons Lode	386.3	239.0	7.5	6850	87.2	19.9
55023	Wye	Redbrook	352.8	211.0	9.2	4010	76.0	0
56001	Usk	Chain Bridge	334.5	205.6	22.6	912	27.9	0
56002	Ebbw	Rhiwderyn	325.9	188.9	30.6	217	7.6	7.4
57005	Taff	Pontypridd	307.9	189.7	45.1	455	19.7	20.5
58001	Ogmore	Bridgend	290.4	179.4	13.8	158	6.7	2.2
59001	Tawe	Ynystanglws	268.5	199.8	9.3	228	12.1	1.1
60003	Taf	Clog-y-Fran	223.8	216.0	7.0	217	7.5	7.3
60010	Tywi	Nantgaredig	248.5	220.6	7.8	1090	39.2	0.1
61002	Eastern Cleddau	Canaston Bridge	207.2	215.3	5.0	183	6.0	0.2

Table 2 Continued.

Station	River	Location	Easting (km)	Northing (km)	Altitude (m)	Area (km^2)	Mean river flow (m^3/s)	Missing data (%)
62001	Teifi	Glan Teifi	224.4	241.6	5.2	894	28.7	0
63001	Ystwyth	Pont Llolwyn	259.1	277.4	12.0	170	6.0	2.1
64006	Leri	Dolybont	263.5	288.2	14.6	47	1.3	0
65001	Glaslyn	Beddgelert	259.2	347.8	32.9	69	5.8	0.4
66001	Clwyd	Pont-y-Cambwll	306.9	370.9	15.3	404	6.3	0
67015	Dee	Manley Hall	334.8	341.5	25.4	1019	30.9	0
68020	Gowy	Bridge Trafford	344.8	371.1	4.1	156	1.1	42.7
69002	Irwell	Adelphi Weir	382.4	398.7	24.1	559	17.5	3.3
69007	Mersey	Ashton Weir	377.2	393.6	14.9	660	12.4	34.4
70004	Yarrow	Croston Mill	349.8	418.0	6.9	74	1.9	35.6
71001	Ribble	Samlesbury	358.7	431.4	6.0	1145	32.9	1.3
72004	Lune	Caton	352.9	465.3	10.7	983	35.3	5.1
72008	Wyre	Garstang	348.8	444.7	10.9	114	3.3	14.9
73002	Crake	Low Nibthwaite	329.4	488.2	38.6	73	4.0	2.0
73005	Kent	Sedgwick	350.9	487.4	18.9	209	8.9	15.0
74001	Duddon	Duddon Hall	319.6	489.6	14.8	86	4.8	17.9
74006	Calder	Calder Hall	303.5	504.5	26.4	45	1.8	9.3
75002	Derwent	Camerton	303.8	530.5	16.7	663	25.8	0
76007	Eden	Sheepmount	339.0	557.1	7.0	2287	51.9	12.2
77001	Esk	Netherby	339.0	571.8	14.3	842	26.1	7.5
78003	Annan	Brydekirk	319.1	570.4	10.0	925	29.5	12.2
79002	Nith	Friars Carse	292.3	585.1	19.8	799	27.5	0
79005	Cluden Water	Fiddlers Ford	292.8	579.5	22.9	238	7.9	1.9
81002	Cree	Newton Stewart	241.2	565.3	4.8	368	15.7	1.9
82001	Girvan	Robstone	221.7	599.7	9.1	246	6.6	2.0
83005	Irvine	Shewalton	234.5	636.9	4.8	381	9.6	23.3
84001	Kelvin	Killermont	255.8	670.5	27.0	335	8.6	0.1
84013	Clyde	Daldowie	267.2	661.6	7.5	1903	48.8	2.0
85001	Leven	Linnbrane	239.4	680.3	5.3	784	43.5	1.6
86001	Little Eachaig	Dalinlongart	214.3	682.1	10.1	31	1.8	15.0
93001	Carron	New Kelso	194.2	842.9	5.6	138	10.9	41.0
94001	Ewe	Poolewe	185.9	880.3	4.6	441	29.7	20.0
95001	Inver	Little Assynt	214.7	925.0	60.3	138	8.5	37.4
95002	Broom	Inverbroom	218.4	884.2	4.6	141	7.3	56.5
96001	Halladale	Halladale	289.1	956.1	23.2	205	5.1	33.3
97002	Thurso	Halkirk	313.1	959.5	30.2	413	8.8	23.1

2.2 River flow

Daily mean river flows, generally for 9.00-9.00 GMT, for 72 stations in catchments draining to the south, west and north coasts of Great Britain, were extracted for the period 1963-2001 (Figure 1, Table 2) from the National River Flow Archive at CEH Wallingford. The stations were chosen to be as far downstream as possible without being tidally influenced and to have as few missing data as possible. For the Severn, two nested catchments were used because the downstream station 54032 (Severn at Saxons Lode), commonly used for general analysis, is tidally influenced at high tides.

Daily mean river flows were used rather than flows of a higher resolution as the latter were not available in digitised form for many stations. Daily mean flows are indicative of the magnitude of the peak flow during the day, especially for more slowly responding catchments. However, it may not necessarily be the case that instantaneous peak flows would be more appropriate to use than mean flows, as water levels in the estuary are influenced by the possibly rather slow change in storage in the estuary.

Thirteen river flow records are complete, and station 95002 (Broom at Inverbroom) has the most missing data at 56.5%.

More information about extreme UK river flows can be found in Volume 3 of the Flood Estimation Handbook (Robson and Reed, 1999).

2.3 Precipitation

Daily precipitation totals from 9.00 to 9.00 GMT were obtained from the UK Met Office. Precipitation data were extracted for the period 1963-2001 for 27 stations in catchments draining to the south, west and north coasts of Great Britain (Figure 2, Table 3).

Eleven out of the 27 gauges have complete records. Station 741962 (Knockanrock) has the poorest record, with 27.4% missing data.

Table 3 General information about the 27 precipitation stations. The easting and northing coordinates are in the Great Britain national grid coordinate system. Missing data: 0 denotes a complete record, and 0.0 denotes that less than 0.05% is missing.

Station	Location	Easting (km)	Northing (km)	Altitude (m)	Mean annual precipitation (mm)	Missing (%)
302179	Wye	605.8	146.9	56	744	0
320345	Bognor Regis	493.3	98.8	7	733	0
328989	Leckford	439.3	136.2	117	811	0
361850	Chudleigh	286.6	79.2	70	1012	0
381210	Penzance	146.8	30.2	19	1156	4.1
386255	Bude	220.8	106.3	15	906	0
404124	Ashcott, Bradley Cottage	343.9	136.5	35	733	5.8
412297	Lacock	392.1	170.2	49	716	0
444643	Kyre	363.8	262.0	99	736	8.3
489170	Neuadd Resr No.11A	303.3	218.4	463	2198	3.2
511627	Dale Fort	182.3	205.1	33	869	0.0
519357	Cwmystwyth	277.3	274.9	301	1805	1.3
541918	Llanuwchllyn	287.8	329.9	173	1676	0.8
547250	Loggerheads	320.0	362.2	215	931	0
565260	Knutsford	375.6	378.3	65	836	2.6
576634	Preston, Moor Park	353.7	431.1	33	997	2.8
588005	Coniston, Holywath	329.9	497.8	76	2473	0
627478	Pullaugh Burn	254.4	574.1	183	2260	1.5
652672	Carnwath	297.4	646.4	208	849	0
666484	Younger Botanic Garden	214.1	685.7	12	2338	0
691637	Onich	202.8	763.3	15	2115	16.2
708615	Plockton	180.2	833.2	12	1430	0.5
717685	ULVA: Ulva House	144.2	739.1	15	1678	1.3
741962	Knockanrock	218.7	908.7	244	2047	27.4
757883	Hoy P.Sta.	313.7	960.7	23	961	0
763886	SHETLAND: Lerwick Observatory No.2	445.3	1139.7	82	1219	12.8
792393	Fairburn House	245.5	852.8	152	1009	0.9

More information about extreme UK precipitation can be found in Volume 2 of the Flood Estimation Handbook (Faulkner, 1999).

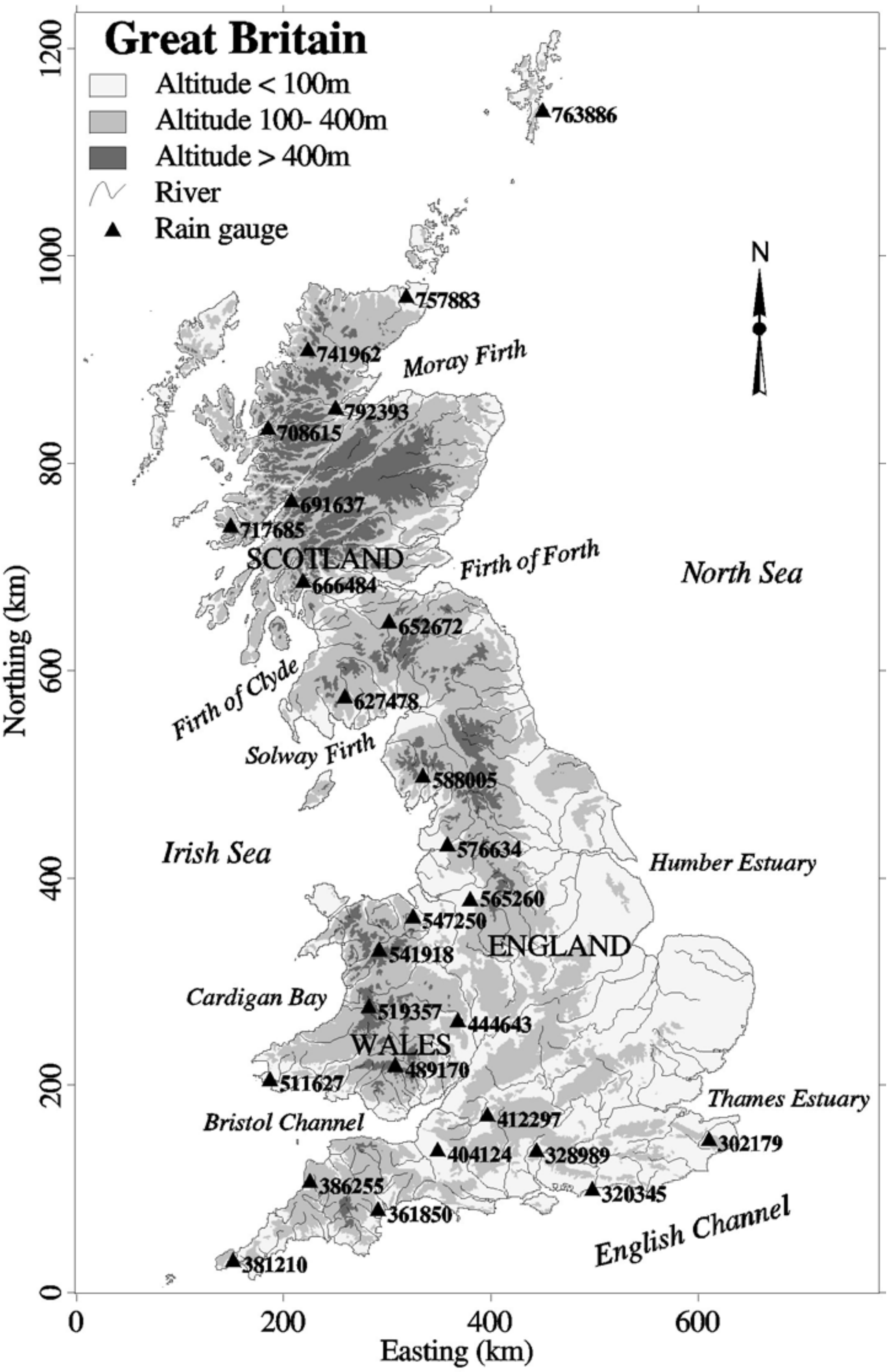

Figure 2 Location of precipitation gauges and geographical features.

2.4 Meteorological maps

Meteorological information was gathered for a selection of flood and surge events. For events prior to 1981 this was obtained from the Daily Weather Report of the British Meteorological Office, and for 1981 onwards from the Daily Weather Summary compiled by the London Weather Centre. Prior to 1998 maps are drawn four times per day and show the surface conditions over Britain and, at 12.00 GMT, also for part of the northern hemisphere. From 1998 and onwards only two maps per day are available.

2.5 North Atlantic Oscillation Index

The North Atlantic Oscillation Index (NAOI) is a measure of the (oscillating) difference in sea level pressure between the subtropical high pressure in the north Atlantic and the Icelandic low (Hurrell, 1995). Monthly pressure data at the Azores and southwest Iceland, 1963-2000, were down-loaded from the Climatic Research Unit's web page at http://www.cru.uea.ac.uk/cru/data/.

The monthly pressure values at each location were standardised through subtraction of the mean and division by the standard deviation. Monthly NAOI were then calculated by subtracting the standardised Iceland pressure from the standardised Azores pressure. These values were subsequently aggregated into seasonal values, by averaging over the six winter months (October-March), thus obtaining a time series of winter NAOI.

3. METHODS

3.1 Dependence measure χ

A dependence measure specially suited for estimating dependence as the variables reach their extremes was used. The measure, χ, has been described in detail by Buishand (1984) and Coles *et al.* (2000). Buishand employed it to assess the inter-station dependence in precipitation data, whereas Coles *et al.* applied it to several different variables, among them precipitation and sea surge data. The following description of the method is based on Coles *et al*. (2000).

When used for bivariate random variables (X, Y) with identical marginal distributions, the measure χ provides an estimate of the probability of one variable being extreme provided that the other one is extreme:

$$\chi = \lim_{z \to z^*} \Pr(Y > z \mid X > z), \tag{1}$$

where z^* is the upper limit of the observations of the common marginal distribution.

In our case the marginal distributions are not likely to be identical, and are therefore transformed to become so. Further, the marginals are unknown and must be estimated using their empirical distributions. Thus, one approach to obtaining an estimate of identical marginal distributions is to simply rank each set of observations separately, and divide each rank with the total number of observations in each set. This corresponds to a transformation of the data to Uniform [0,1] margins.

Rather than estimating χ as the limit in Equation 1, it is convenient to approach the problem in a different way. Consider the bivariate cumulative distribution function $F(x, y) = \Pr(X \leq x,\ Y \leq y)$. It describes the dependence between X and Y completely. The influence of different marginal distributions can be removed by observing that there is a function C in the domain $[0,1] \times [0,1]$ such that

$$F(x, y) = C\{F_X(x),\ F_Y(y)\},$$

where F_X and F_Y are (any) marginal distributions. The function C is called the copula, and contains complete information about the joint distribution of X and Y, apart from the marginal distribution. This means that C is invariant to marginal transformation. The copula can be described as the joint distribution function of X and Y after transformation to variables U and V with Uniform [0, 1] margins, via $(U, V) = \{F_X(X), F_Y(Y)\}$.

We define the dependence measure $\chi(u)$ for a given threshold u as

$$\chi(u) = 2 - \frac{\ln \Pr(U \leq u,\ V \leq u)}{\ln \Pr(U \leq u)} \quad \text{for } 0 \leq u \leq 1. \tag{2}$$

This is related to χ of Equation 1 by

$$\chi = \lim_{u \to 1} \chi(u) = \lim_{u \to 1} \Pr(V > u \mid U > u).$$

The choice of the particular form in Equation 2 is justified by Coles *et al.* (2000), for $u \rightarrow 1$, using the relation

$$\Pr(V > u \mid U > u) = \frac{\Pr(U > u, V > u)}{\Pr(U > u)} = \frac{1 - 2u + C(u,u)}{1-u} = 2 - \frac{1 - C(u,u)}{1-u}$$
$$\approx 2 - \frac{\ln C(u,u)}{\ln u}.$$

As the variables approach their extremes, $\chi = 1$ signifies total dependence and $\chi = 0$ signifies independence or negative dependence. The value of χ can be interpreted as the risk that one variable is extreme, given that the other is. Suppose that one variable exceeds the threshold corresponding to a certain (small) exceedance probability. Then, if the dependence between the variables is estimated to $\chi = 0.1$, it means that there is a 10% risk of the other variable exceeding the threshold corresponding to the same probability.

Equation 2 is the measure of dependence used in the present study. It can be evaluated at different quantile levels u. This will be discussed further below. For the moment, suppose that we have selected a particular level u, which corresponds to threshold levels (x^*, y^*) for the observed series. In practice, Equation 2 is applied by counting the number of observation-pairs, (X, Y), so that

$$\Pr(U \le u, V \le u) = \frac{\text{Number of } (X,Y) \text{ such that } X \le x^* \text{ and } Y \le y^*}{\text{Total number of } (X,Y)} \qquad (3)$$

and

$$\ln \Pr(U \le u) = \frac{1}{2} \ln\left(\frac{\text{Number of } X \le x^*}{\text{Total number of } X} \cdot \frac{\text{Number of } Y \le y^*}{\text{Total number of } Y}\right). \qquad (4)$$

For much of the rest of this report, χ will be used as a short-hand symbol for $\chi(u)$ for a given way of choosing u, rather than denoting the limit as expressed by Equation 1.

3.2 Selection of threshold level

Rather than using the Uniform distribution for the margins, we have chosen to transform the data onto an annual maximum non-exceedance probability scale. This only affects the selection of the thresholds, and χ is calculated as outlined in Equations 2 to 4. The transformation enables us to interpret the dependence between the variables in a familiar context: that of different return periods. The annual maximum non-exceedance probability, a, is

$$a = \Pr(\mathit{Annual\ maximum} \le x), \qquad (5)$$

where x is the magnitude of the variable. It relates to the return period, T_a, as $T_a = 1/(1-a)$. The transformation is achieved through a peaks-over-threshold (POT) approach, which is considered to give a more accurate estimate of the probability distribution than using only the annual maximum series (e.g. Stedinger *et al.*, 1993).

The non-exceedance probability, p, of the POT series with a rate of λ events per year, is related to that of the annual maximum as

$$a = \exp(-\lambda(1-p)), \tag{6}$$

where 1-p is the exceedance probability of the POT series which can be estimated using a plotting position. Hazen's plotting position is a traditional choice, and leads to the estimate

$$\lambda(1-p) = \frac{N_e}{N} \cdot \frac{i-0.5}{N_e} = \frac{i-0.5}{N}, \tag{7}$$

where i is the rank of the independent POT events, N_e is the total number of POT events, and N is the number of years of observations. The highest observation is given rank 1, the second highest rank 2, etc. The independence criterion used in this study was that two POTs must not occur on consecutive days, but be separated by at least three days. Thus, substituting Equation 7 into Equation 6 results in the following transformation to the annual maximum scale:

$$a = \exp(-\frac{i-0.5}{N}). \tag{8}$$

The magnitude of x in Equation 5 corresponds to the magnitude of the POT with rank i in Equation 8 for the same annual maximum non-exceedance probability, a.

The dependence measure χ can be estimated for any threshold. Initial trials showed a fairly constant, slightly decreasing, value of χ for annual maximum non-exceedance probabilities between about 0.1 and 0.5. For higher probabilities, χ tended to become 0 as no observation-pairs exceeded both thresholds (Appendix B of Svensson and Jones, 2000). The threshold was selected to be a = 0.1. This corresponds to selecting a threshold for the data-values that about 2.3 events per year will exceed. The annual maximum will exceed this threshold in 9 out of 10 years. The use of a threshold in this sort of range is dictated by two requirements: to have enough data-points above the threshold in order to be able to estimate dependence reliably, and for the threshold to be high enough to regard the data-points as extreme.

3.3 Missing data

Only observation-pairs where both observations in the pair were available were included in the count in Equations 2 to 4. A minimum of 1825 observation-pairs, equivalent to 5 complete years of simultaneous data, was set as a requirement for χ to be estimated reasonably reliably. For the seasonal analysis this was reduced to 912 observation-pairs.

However, when estimating the threshold levels (x*, y*) for the margins, each margin was treated separately so that as much information as possible was used. The number of years, N, in Equations 7 and 8 was thus calculated for each series as

$$N = \frac{N_c}{N_t} N_{orig}$$

where N_c is the number of days with complete observations, N_t is the total number of days, and N_{orig} is the total number of years in the study period. Note that N is treated as a non-integer.

3.4 Significance

The values of χ corresponding to the 5% significance level were estimated using a permutation method (e.g. Good, 1994). This type of method is used to generate data-sets in which independence would hold. A large number of data-sets are generated and a test statistic, in our case χ, is calculated for each of these new data-sets. This provides a sample of χ for independently occurring data. If the χ calculated for the original data-set is rather different to most of the χ calculated from the generated values, then this suggests that the two original records are not independent. Dependence occurring because both records show similar seasonal characteristics can be accounted for by generating data that show the same seasonal characteristics.

Two slightly different permutation methods were used for the previous east coast study and for the present west, south and re-run east coast studies, prompted by the larger amount of missing sea level data for the south and west coasts. In the east coast study (Svensson and Jones, 2000), one of the records for each station-pair was permuted while the other was kept unchanged. This removes the dependence structure between the two series. The permutation of the data was performed by randomly reshuffling intact blocks of one year, in order to preserve the seasonality. Using all the years in the series works well for almost complete data records. However, for the west and south coasts only years with observations were used for the reshuffling. Thus, a random resample of years (with observations) was drawn from each of the two series, so that the number of years in each resample equalled the number of years with any concurrent data in the original two series. Each year could be represented only once in each resample, to resemble a true permutation. For both methods no year was allowed to be paired up with itself, and leap years were permuted separately to non-leap years.

In total, 199 permutations of the data were made for each station-pair and a new χ was calculated each time. The 199 χ values were subsequently ranked in descending order and the 10th largest value was accepted as corresponding to the 5% significance level, or the 95% point of the null distribution (the distribution of values that would occur if data-pairs were independent). If the χ calculated for the original series exceeded this value, then the data provides reasonably strong evidence that the dependence between the variables can be considered genuine. A stronger significance level was not used because this would have required a greater number of permutations. These were very time-consuming, and, considering the high number of station combinations, it was not deemed practical.

3.5 Confidence intervals

Confidence intervals give an indication of the range of values in which the “true” dependence χ can be expected to lie. In the absence of infinitely long records, this true value is unknown. A bootstrapping method (e.g. Efron, 1979) was used to estimate the confidence intervals. Similar to the permutation method used for estimating significance, bootstrapping can be used where the underlying statistical population is unknown or where an analytical solution is impractical.

Bootstrapping is based on the generation of many new data-sets, resamples. In contrast to when significance levels were estimated and independence between the two series was sought, each observation-pair is here kept intact and treated as one value.

The original sample of observation-pairs is used as the distribution from which the resamples are chosen randomly with replacement, i.e. with each observation-pair being returned to the original sample after it has been chosen, so that it may be chosen again. A large number of data-sets are generated and a test statistic, in our case χ, is calculated for each of these new data-sets. This provides a sample of χ that would occur for a range of situations, as χ is calculated from some resamples including many data-pairs consistent with dependence, and from some resamples including many data-pairs consistent with independence. Seasonality is kept intact by sampling in blocks of one year, rather than using individual observation-pairs.

In this study balanced resampling (e.g. Fisher, 1993) was used, which is a more efficient method. It ensures that each year occurs equally often overall among the total number of bootstrap samples. It is implemented by creating a vector of length BN consisting of the N years of record repeated B times. This array is then randomly reshuffled, and divided into slices of length N, to obtain B bootstrap samples.

In total, $B = 199$ bootstrap samples of the data were made for each station-pair and a new χ was calculated each time. The 199 χ values were subsequently ranked in descending order and the 10th and 190th largest values were accepted as delimiting the 90% confidence interval.

Because the resampling was very computationally demanding, confidence intervals were only estimated for the primary variable-pair, surge and flow (precipitation being used only to aid in the interpretation of why dependence occurs).

3.6 Division into seasons

For some of the studies the data were divided into a summer season, April-September, and a winter season, October-March. In these cases the threshold levels (x^*, y^*) corresponding to $a = 0.1$ would change, since the same number of POTs (on average 2.3 POTs per season) would be extracted using data from only part of the year, instead of from the whole year. Rather than representing the number of complete years of observations, N in Equations 7 and 8 then corresponds to the number of complete seasons.

4. RESULTS AND INTERPRETATION

The dependence measure χ was used to estimate the dependence between extreme sea surge, river flow and precipitation. River flow and sea surge both influence the water levels in the estuary, whereas precipitation is used to assist in the interpretation of why surge-flow dependence occurs in particular places and not in others.

Because the variables are used at a daily resolution, results are only indicative of where extreme river flow and sea surge *may* occur simultaneously. Modelling of how sea levels and river flow affect the water levels in the estuary needs to be done at a higher resolution to assess actual estuary water levels. However, if there is no dependence on a daily basis, such as presented in this study, it is highly unlikely that there will be dependence at a higher temporal resolution.

This chapter is divided into six parts. The first two parts deal with dependence between events occurring on the same day. Part one discusses the inter-station dependence for each variable separately, and part two examines the cross-variable dependence. The third part of the chapter concerns differences in the dependence between summer and winter, and the fourth involves a lagged dependence analysis. The fifth part is a study of meteorological situations resulting in high river flow or high sea surge, or both. The last part discusses possible impacts of climate change.

4.1 Inter-station dependence

Two main types of figures are used to display the results of the same-variable dependence analysis. The first comprises a scatter plot of the dependence against the distance between the stations, and the second shows the geographical distribution of the dependence on a map.

Figure 3 shows the estimated inter-station dependence plotted against distance for daily maximum sea surge, daily mean river flow and daily precipitation totals. Values of χ that are significant at the 5% level (exceed the 95% point of the null distribution) are shown as filled circles, whereas non-significant values are shown as empty circles. Although the measure χ is not appropriate for measuring negative dependence, a few flow station-pairs had an estimated χ less than the 5% point of the null distribution. This can be indicative of independence as well as negative dependence. These values are shown as stars on the plot.

Of the three variables, surge shows the strongest spatial dependence and precipitation the weakest. For flow and precipitation, the strength of dependence is reasonably similar to that found in eastern Britain (not shown), with some dependence in river flow being stronger in the west than in the east. However, the scatter of the points for the surge (Figure 3a) is much greater in the west than in the east (not shown, see Svensson and Jones (2000, 2002) for a related plot, of χ v difference in northing), with the top envelope being of similar magnitude. On the east coast, surges are often generated north of Scotland, and travel down the east coast (Pugh, 1987), resulting in a well structured dependence behaviour of the surge. Dependence is much more variable on the west coast, presumably because of the complex coastline and the obstruction of the Irish landmass to wind-induced water movement from the west.

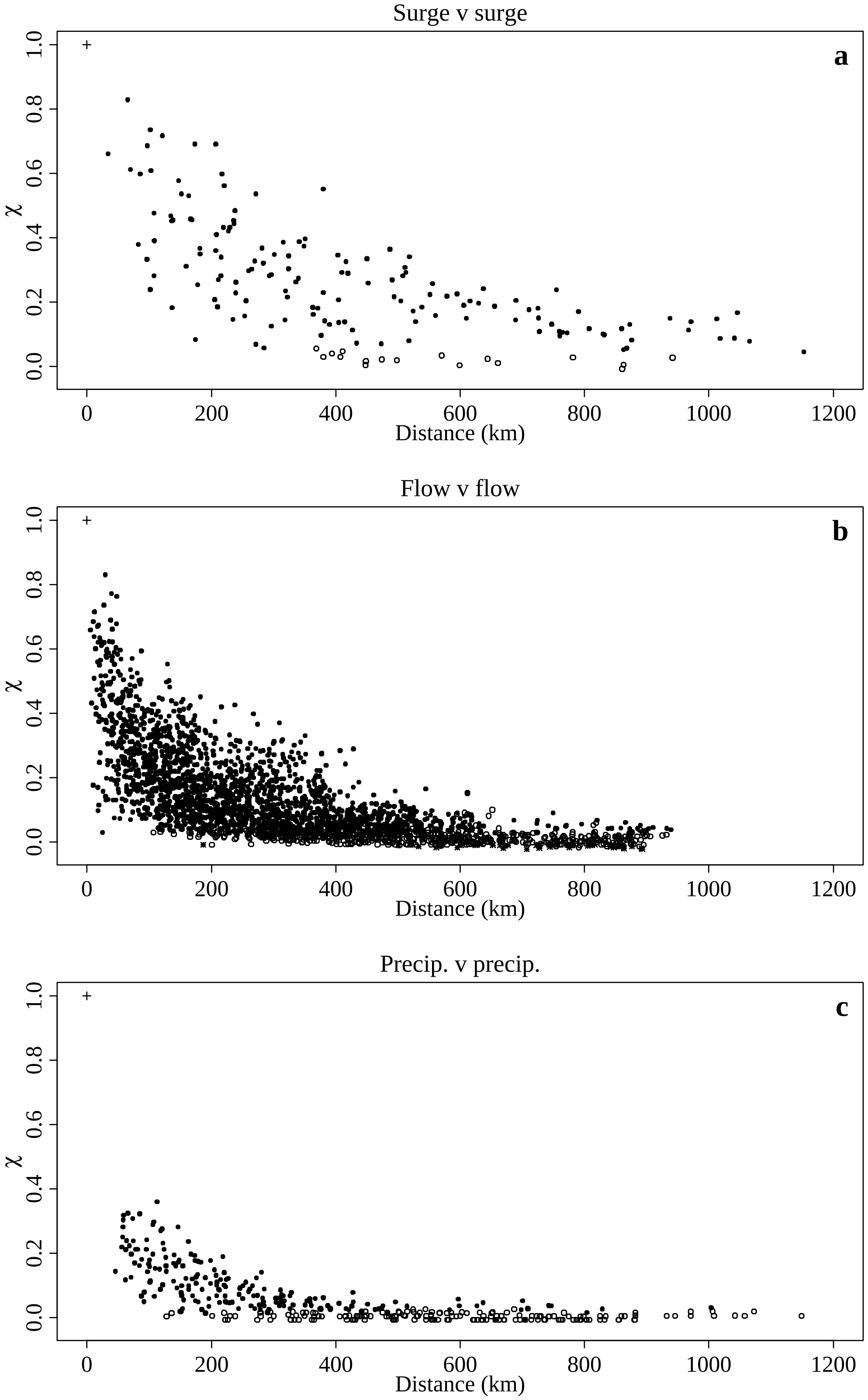

Figure 3 **Inter-station dependence versus distance in a) daily maximum sea surge, b) river flow, and c) precipitation. Values of χ significant at the 5% level are shown as filled circles and non-significant values as empty circles. Stars indicate independent or negatively dependent values.**

The dependence in surge is stronger on the west coast than on the south coast (Figure 4), and dependence is weaker in the eastern part of the south coast than in the western. From west to east similarly distanced station-pairs show decreasing dependence: $\chi = 0.42$ for Newlyn and Weymouth, $\chi = 0.25$ for Weymouth and Newhaven, and $\chi = 0.08$ for Portsmouth and Dover. This may be related to the incursion of North Sea surges into the English Channel from the east. There are seven station-pairs for which dependence was not estimated because of too few data observations. All the pairs include Liverpool Princes Pier, whose record ended in 1986. Dependences between Liverpool and the other halves of the missing station-pairs were successfully estimated using the later Liverpool record, Gladstone Dock.

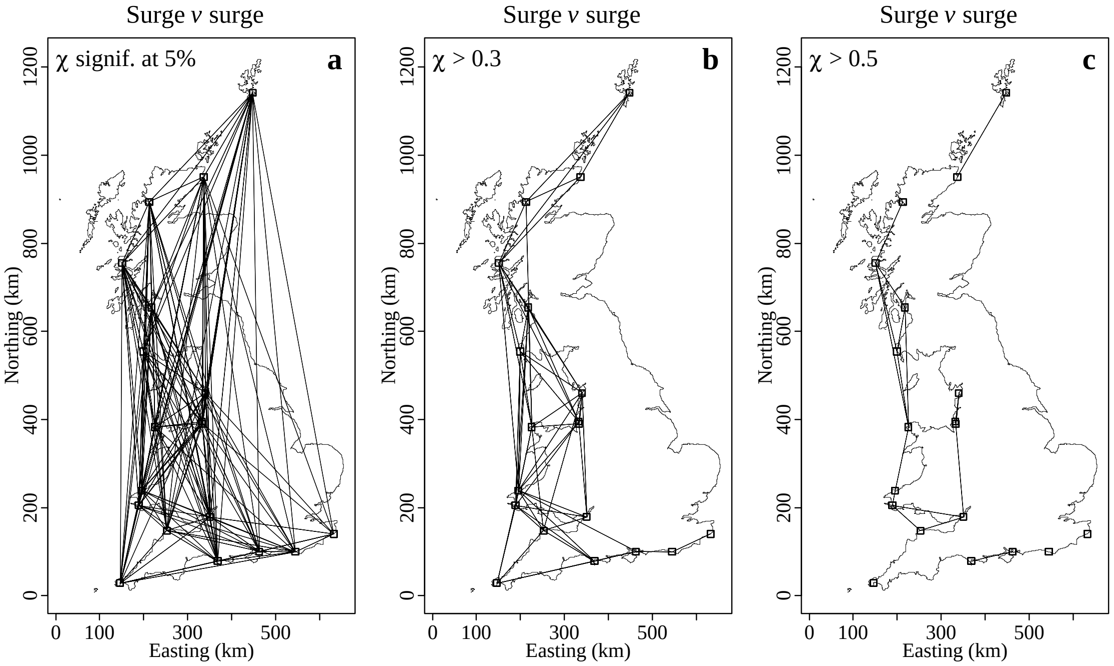

Figure 4 **Inter-station dependence in daily maximum surge. Lines connect station-pairs with χ exceeding a) the 95% point (significant dependence), b) 0.3, and c) 0.5.**

For river flow, two large groups of gauges with stronger dependence emerge (Figure 5). River flows in the Solway area and the west coast of northern England would appear to be more strongly dependent with each other than they are to river flows in Wales and the south of England (Figure 5b). The few stations in northern Scotland may belong in a third group. As the threshold increases to $\chi = 0.5$ (Figure 5c) river flow stations in Wales separate out from the group(s) of stations in southern England. The division into two groups may be related to that precipitation in the Solway/north England area may be associated with rain-bearing systems (such as fronts or low pressures) centred further to the north than systems resulting in heavy precipitation in south Wales and south England. Northern Wales may act as a natural break between the two main groups, as this area will be in rainshadow in the prevailing southwesterly airflow. There is weak support for a break in the dependence between Wales and south England on the one hand and northern England and Scotland on the other, in the precipitation analysis, but dependence is fairly evenly distributed along the British south and west coasts (Figure 6).

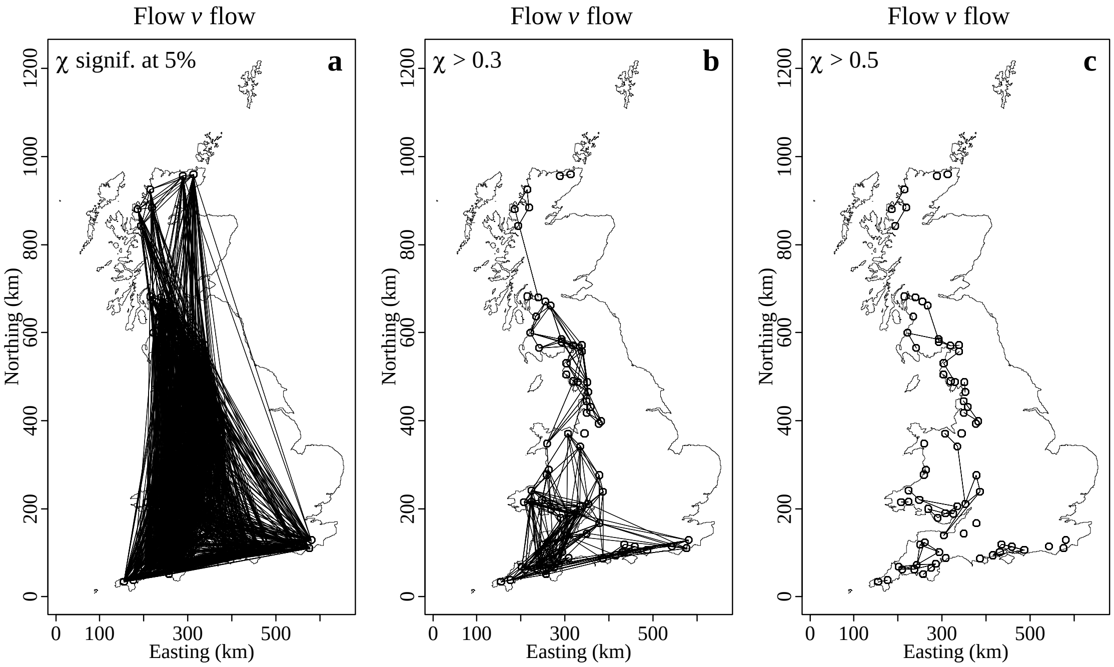

Figure 5 Inter-station dependence in river flow. Lines connect station-pairs with χ exceeding a) the 95% point (significant dependence), b) 0.3, and c) 0.5.

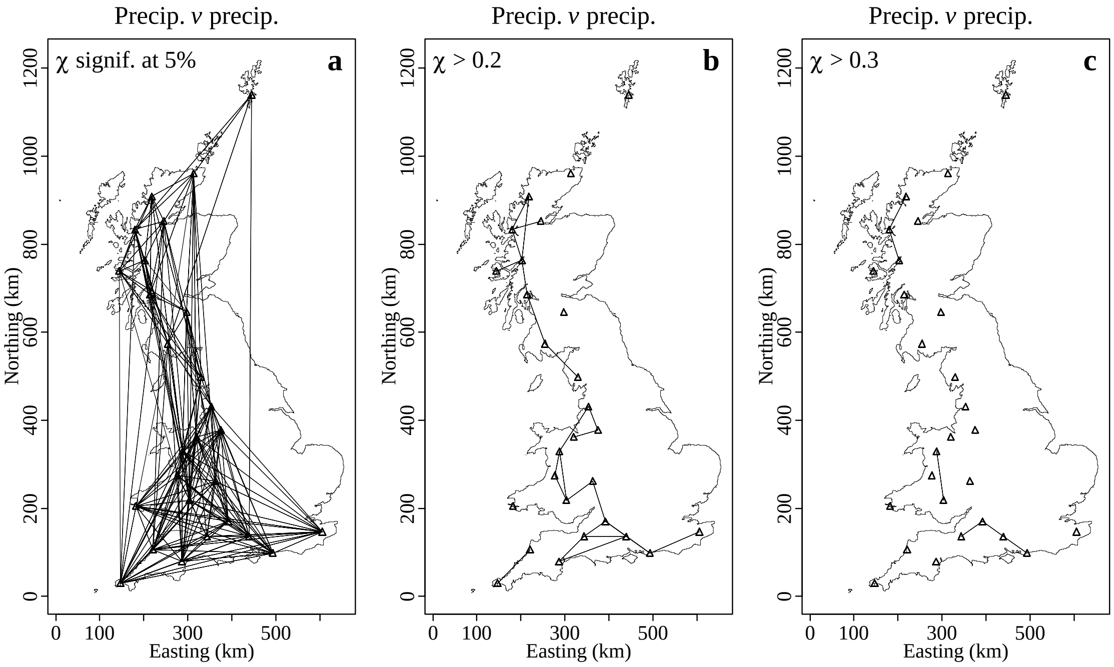

Figure 6 Inter-station dependence in precipitation. Lines connect station-pairs with χ exceeding a) the 95% point (significant dependence), b) 0.2, and c) 0.3.

4.2 Cross-variable dependence

Similar to the same-variable inter-station analysis, results are shown as scatter plots of the dependence against the distance between the stations, and as maps showing the geographical distribution of the dependence. Results of the flow-surge analyses are also presented in tables (Appendix B).

Figure 7 shows the cross-variable dependence versus distance between the stations. Dependence between flow and daily maximum surge is reasonably strong also for long distances (Figure 7a). This presumably reflects the large scale of depressions and their associated fronts, and that most of the catchments on the south and west coasts face the prevailing wind direction (i.e. large parts of the study area are not in rain shadow and therefore behaving differently). This is supported by the precipitation versus surge analysis (Figure 7b), for which dependence also tapers off slowly with distance. However, dependence between precipitation and river flow is much stronger locally than a distance away, and for many station-pairs the short-distance dependence is stronger for precipitation-flow than for the other variable combinations (Figure 7c).

4.2.1 Flow and surge

For the flow-surge variable-pair, confidence intervals around the dependence measures are estimated. Because the bootstrap routine for these was computationally expensive, values of χ with confidence intervals are only estimated for neighbouring stations (Appendix B). That is, one surge station on either side of the river estuary is paired with the river flow station, unless the surge station is located in, or very near, the estuary in which case only that surge station is used. Because of the very short surge records for Portsmouth and Weymouth, the river flow stations between these surge stations have also been paired with the long surge record at Newlyn. The two river flow gauges on the north coast, 96001 and 97002, have been paired with surges at Ullapool, Lerwick and Wick. Note that Liverpool has two surge records, Princes Pier and Gladstone Dock. River flow stations between Heysham and Holyhead have therefore also been paired with (up to) three surge stations. One station-pair (Liverpool Princes Pier and 68020) has too few simultaneous observations for χ to have been estimated. However, the record for Liverpool Gladstone Dock sufficiently overlaps that of 68020.

Dependence between river flow and sea surge can vary over short distances as each river responds differently depending on its catchment characteristics, such as area and geology. Small and impervious catchments generate faster runoff with a shorter time to peak flow than larger and more permeable catchments. The site-specific nature of the river flow characteristics means that a dense network of gauges is needed, and results may be difficult to generalise to a larger area. However, some regional patterns emerge.

Figure 8 shows dependence between river flow and daily maximum surge at neighbouring stations. The map shows dependence for neighbouring stations, rather than using all the station-pairs (as in Figure 7a), because regions where local dependence is strong are easier to distinguish (see Figure 21c for all station combi-

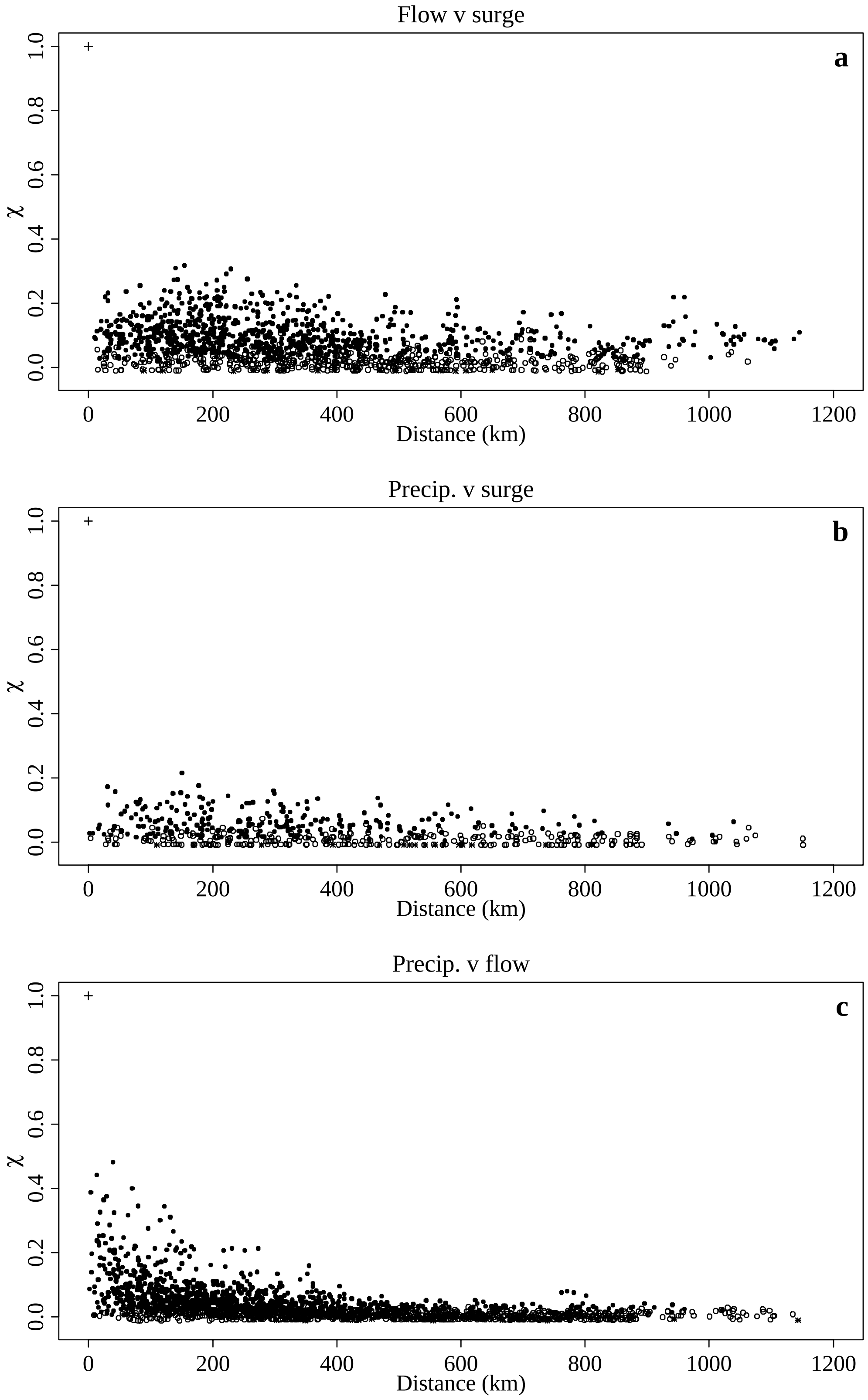

Figure 7 **Dependence versus distance for a) river flow and daily maximum sea surge, b) precipitation and daily maximum sea surge, and c) precipitation and river flow. Values of χ significant at the 5% level are shown as filled circles and non-significant values as empty circles.**

nations). Although dependence significant at the 5% level may be found at catchments spread along most of the coastline, higher dependence (χ>0.1) is generally found in catchments in hilly areas with a southerly to westerly aspect. Here, precipitation in southwesterly airflow, which is generally the quadrant of prevailing winds (e.g. Barrow and Hulme, 1997), will be orographically enhanced as the first higher ground is encountered. The sloping catchments may respond quickly to the abundant rainfall, and the flow peak may arrive in the estuary on the same day as a large sea surge occurs.

It is important to point out that because the variables are used at a daily resolution, results are indicative only of where extreme river flow and surge *may* occur simultaneously. Modelling of how sea levels and river flow affect the water levels in the estuary needs to be done at a higher resolution to assess actual estuary water levels. However, if there were no dependence on a daily basis, such as presented in this study, it is highly unlikely that there would be dependence at a higher temporal resolution.

The effect of different resolutions may be a contributing factor to the different results in the present study and those in Samuels and Burt (2002). Whereas the present study finds significant dependence between daily mean river flow at 57005 (Taff at Pontypridd) and surge at Avonmouth, Samuels and Burt using peak flow data for the same station and total water levels at Cardiff (the highest water level nearest in time to the flow peak) do not. However, perhaps the most important reason for the different results may be the use of total sea level data rather than surge residuals. The surge is more directly related to the weather causing both river flow (via precipitation) and surge, whereas the variation in total sea level arises mainly from the variation in astronomical tide, which is unrelated to the weather driving extreme events. The different results will also be influenced by the different sea level/surge locations and the different methods to estimate dependence.

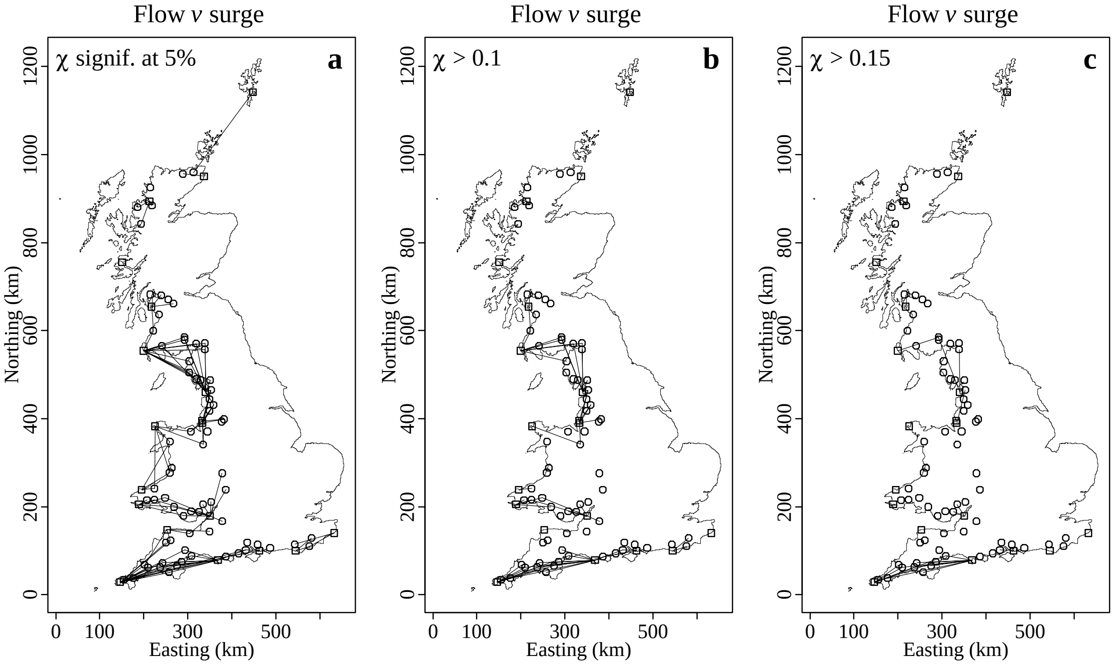

Figure 8 **Dependence between river flow and daily maximum sea surge. Lines connect neighbouring station-pairs with χ exceeding a) the 95% point (significant dependence), b) 0.1, and c) 0.15.**

The present study indicates three regions where surge-flow dependence generally exceeds $\chi>0.1$: the western part of the English south coast, southern Wales, and around the Solway Firth. Table B1 in Appendix B shows the estimated dependence, χ, and the associated 5% significance level and limits of the 90% confidence interval.

The generally low dependence on the eastern part of the south coast of England (Figure 8) may be related to these being generally permeable, predominantly chalk, catchments which respond slowly to rainfall. Runoff may therefore not form on the same day as the surge occurs.

In shallow water, wave characteristics such as speed and amplitude are influenced by water depth. When the increase in water depth due to tide and surge is not negligible compared to the total water depth, complex non-linear interaction between tide and surge will occur. In order to reduce the influence of this problem on the dependence analysis, the dependence between river flow and daily maximum surge occurring at high tide was estimated (Figure 9, Table B2 in Appendix B). The general pattern of areas with higher dependence is similar to that using the daily maximum surge.

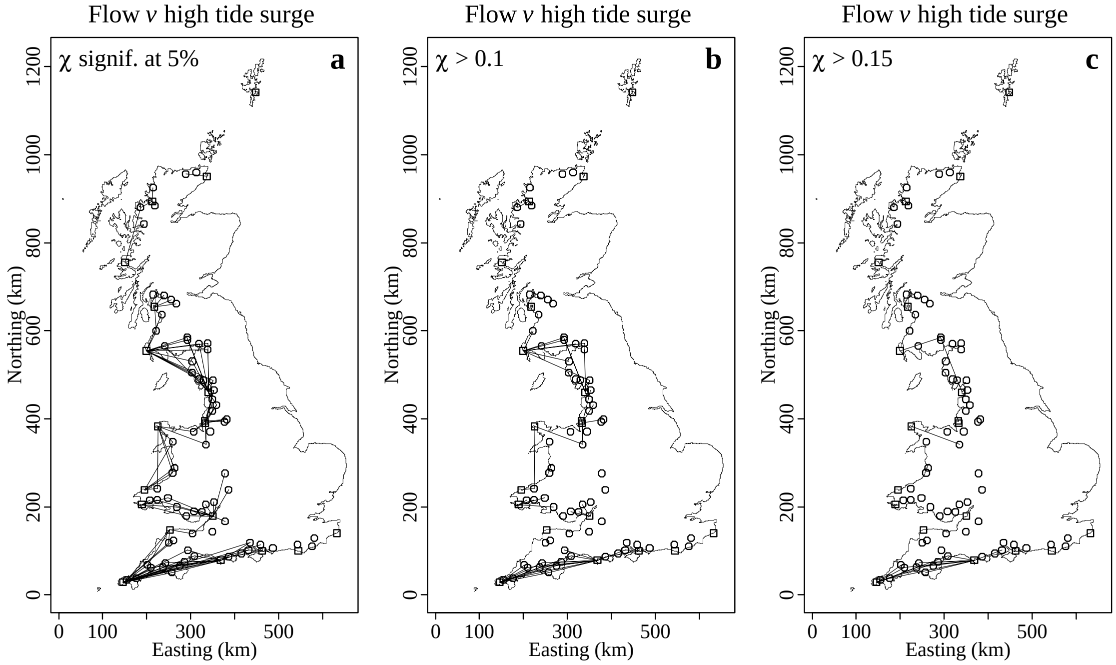

Figure 9 **Dependence between river flow and daily maximum sea surge occurring at high tide. Lines connect neighbouring station-pairs with χ exceeding a) the 95% point (significant dependence), b) 0.1, and c) 0.15.**

4.2.2 Precipitation and surge

On the south and west coasts dependence between precipitation and surge is very widespread, and is reasonably strong also for the eastern part of the south coast where flow-surge dependence is generally not significant (Figure 10). This suggests that flow-surge dependence breaks down for some other reason, presumably because of the slowly responding chalk catchments in this area, as discussed above. Dependence between precipitation and sea surge is much stronger on the south and west coasts than on the east coast (not shown, see Svensson and Jones (2000, 2002)).

The dependence was not estimated for five station-pairs because of too few observations (Figure 10d). The inter-station distance for all of these station-pairs is large, so this is of limited practical importance.

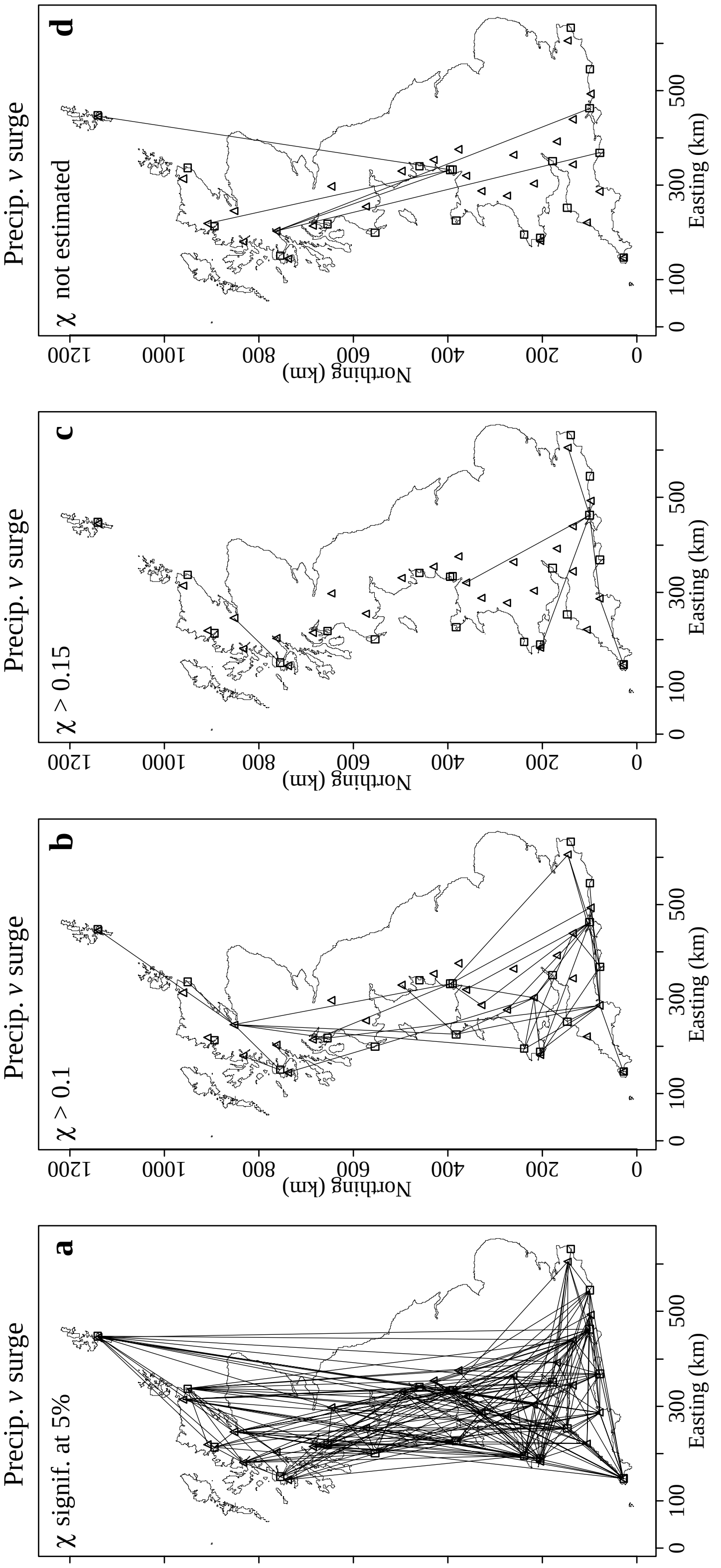

Figure 10 **Dependence between precipitation and daily maximum sea surge. Lines connect station-pairs with χ exceeding a) the 95% point (significant dependence), b) 0.1, and c) 0.15. Figure d) shows lines connecting station-pairs with too few simultaneous observations for χ to have been estimated.**

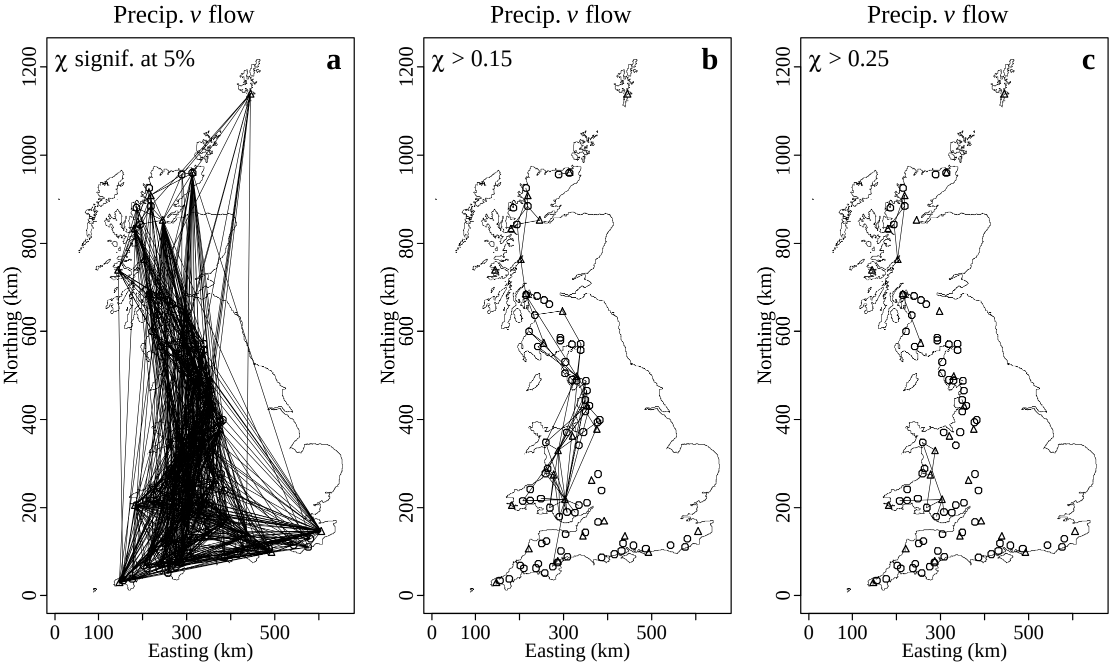

Figure 11 **Dependence between precipitation and river flow. Lines connect station-pairs with χ exceeding a) the 95% point (significant dependence), b) 0.15, and c) 0.25.**

4.2.3 Precipitation and flow

Dependence between precipitation and river flow is stronger in Wales and northward, than in the south of England (Figure 11). This may reflect smaller soil moisture deficits for a longer part of the year in the north, resulting in a more direct relationship between precipitation and runoff, making the extremes occur on the same day. Catchments in the west are also generally more hilly than in the south, promoting a faster runoff response. Further, in the eastern part of the south coast, the predominantly permeable chalk catchments there respond slowly to rainfall. The slower response of these catchments, and of very large catchments such as the Severn (54001 and 54032) and the Wye (55023), is also suggested by the lagged analysis (Figure 19).

4.3 Seasonal analysis

The same-variable and cross-variable dependence between daily maximum sea surge, river flow and precipitation was estimated for the winter (October-March) and summer (April-September) half-years. The results are shown on maps as the difference between the estimated dependence in winter and summer (winter minus summer).

The results are not unambiguous for the same-variable dependence. There are both positive and negative differences ($|\chi_{diff}| > 0.05$) between the seasons occurring in the same regions. However, there is generally a larger number of differences in one direction or the other. Inter-station dependence in daily maximum sea surge (Figure 12) is generally stronger in winter than in summer in Wales and northward. Stations on the south coast show stronger dependence in winter with stations to the north, but not with each other. On the contrary, dependence is stronger in summer for several station-pairs

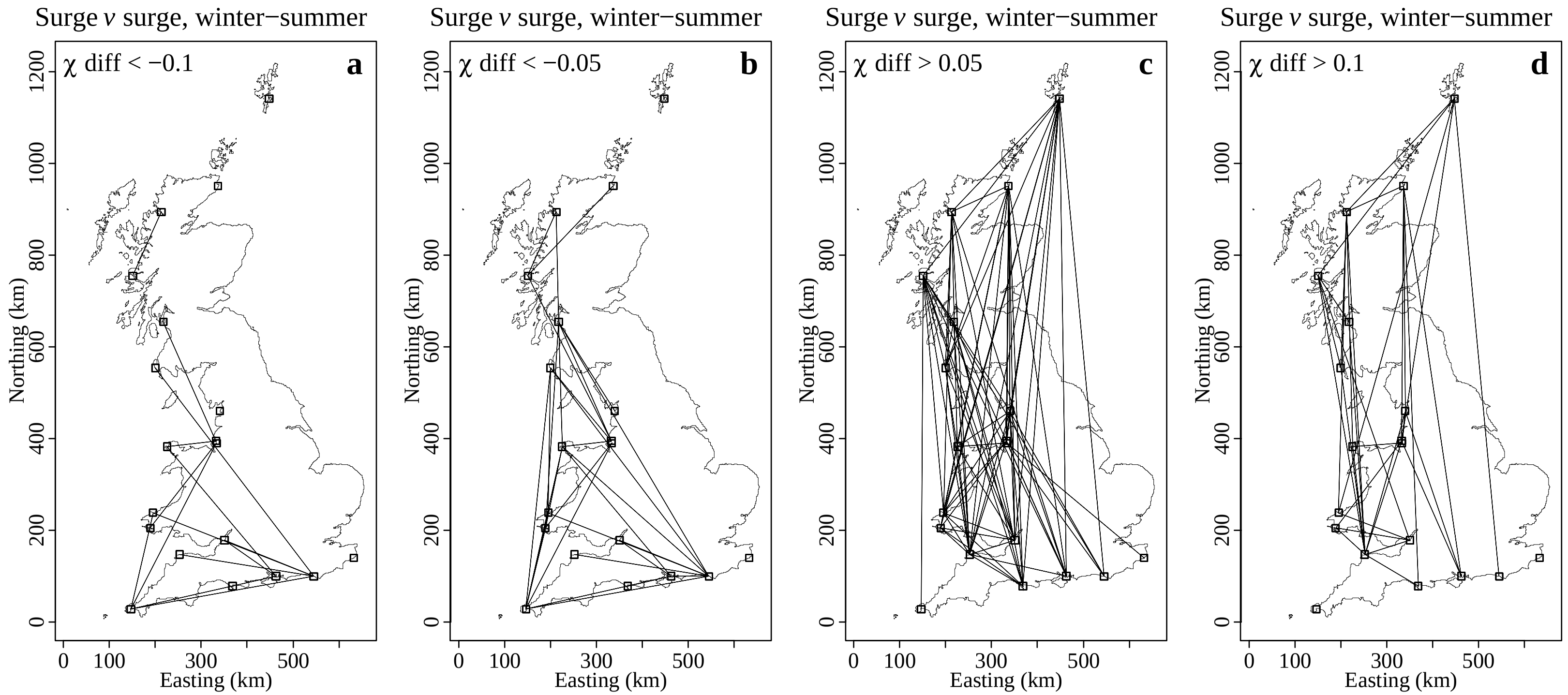

Figure 12 **Seasonal difference in inter-station dependence (χ for winter minus χ for summer) in daily maximum sea surge. Lines connect station-pairs with a difference in χ a) <–0.1, b) <-0.05, c) >0.05, and d) >0.1.**

in the southwest (Figure 12a). The generally stronger dependence in winter may be related to the generally more vigorous cyclones in this season, with the area of influence of the low pressure and strong winds being widespread. In winter, cyclones tend to track eastward to the north of Scotland (Whittaker and Horn, 1984). The dependence between Lerwick and Wick on the one hand, and south coast stations on the other, may be caused by externally generated (northwest of Scotland) North Sea surges travelling down the east coast and into the English Channel. In summer, storm tracks are more southerly, tracking across Great Britain (Whittaker and Horn, 1984), which may account for the stronger dependence in the southwest in this season. For river flow, and to some extent precipitation, dependence is generally stronger in summer than in winter, particularly in the southwest (Figures 13 and 14). This is probably also related to the more southerly storm tracks in summer.

The results of the cross-variable dependence analyses are also ambiguous (Figures 15-17). There are not many station-pairs with a seasonal difference in dependence between daily maximum sea surge and river flow exceeding 0.1 (Figure 15). However, several station-pairs on the western part of the south coast show somewhat stronger dependence ($|\chi_{\text{diff}}| > 0.05$) in winter than in summer, whereas the west coast of Wales and northward mainly show higher flow-surge dependence in summer than in winter. Higher soil moisture deficits in summer, inhibiting direct runoff, may be the reason why flow-surge dependence in the very south is higher in winter than in summer. The upland areas in Wales and northward may be less affected by soil moisture deficits, and more influenced by the effects of the more southerly storm tracks in summer, resulting in higher flow-surge dependence in these areas in summer than in winter. Flow-surge dependence in winter is similar to that for the whole year. For the majority of the station combinations, the absolute difference in χ is less than 0.02.

Dependence between precipitation and river flow is also stronger in winter than in summer in the south of the country, probably as an effect of higher soil moisture deficits in summer (Figure 17). Similar to the flow-surge analysis, soil moisture effects may be less strong further north, where dependence between precipitation and river flow is stronger in summer than in winter. Dependence between precipitation and daily maximum sea surge appears to be about as strong in winter as in summer, possibly with a slight bias towards stronger dependence in winter (Figure 16). This may be a reflection of the more vigorous cyclones in winter.

The stronger flow-surge dependence in summer suggests that both river flow and sea surge are generated by cyclones moving eastwards across Great Britain, as this is the main storm track in summer (Whittaker and Horn, 1984). It suggests that the sea surge develops locally by the low pressure and winds associated with the depression, rather than being formed elsewhere and propagating into the region. River flow presumably results from precipitation mainly at the fronts or at the depression centre. The meteorological situations associated with a few events of extreme river flow and sea surge are investigated in Section 4.5.

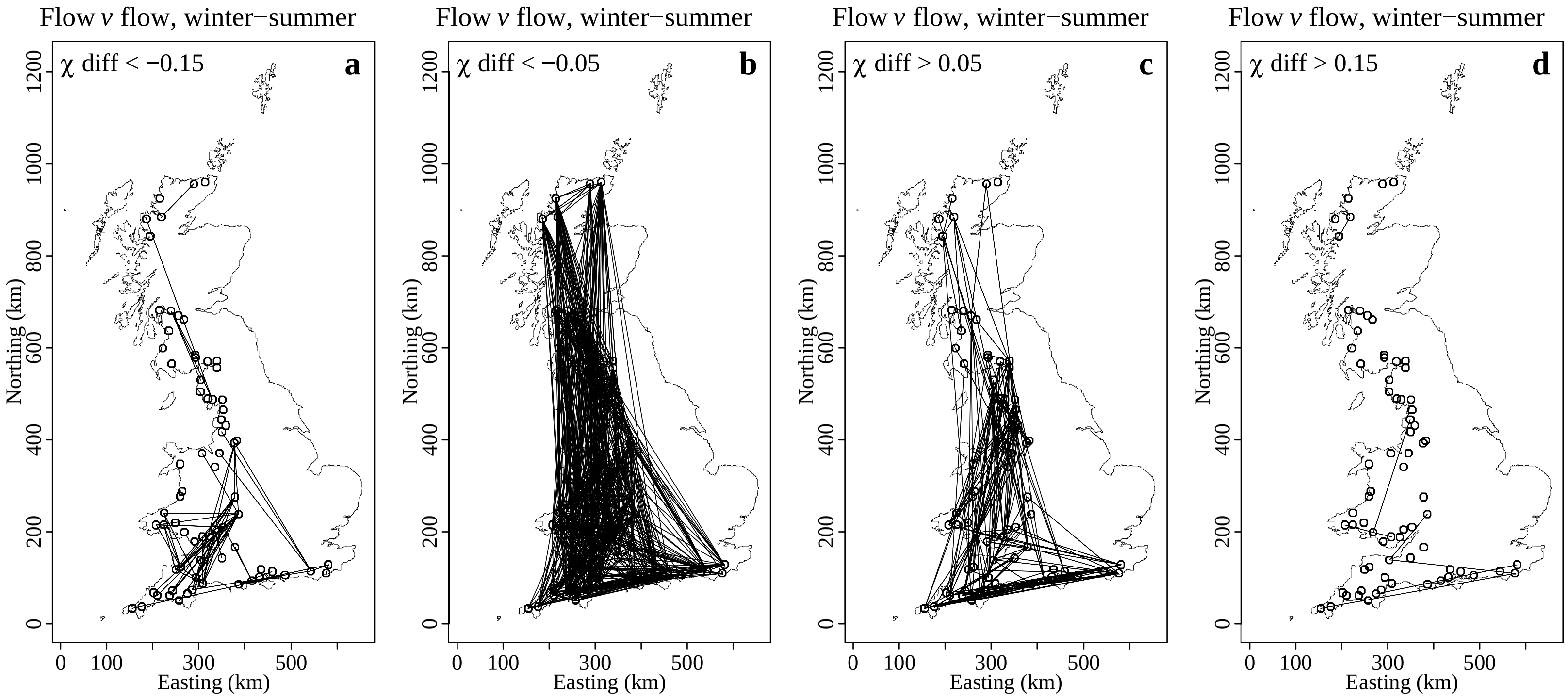

Figure 13 Seasonal difference in inter-station dependence (χ for winter minus χ for summer) in river flow. Lines connect station-pairs with a difference in χ a) <–0.15, b) <-0.05, c) >0.05, and d) >0.15.

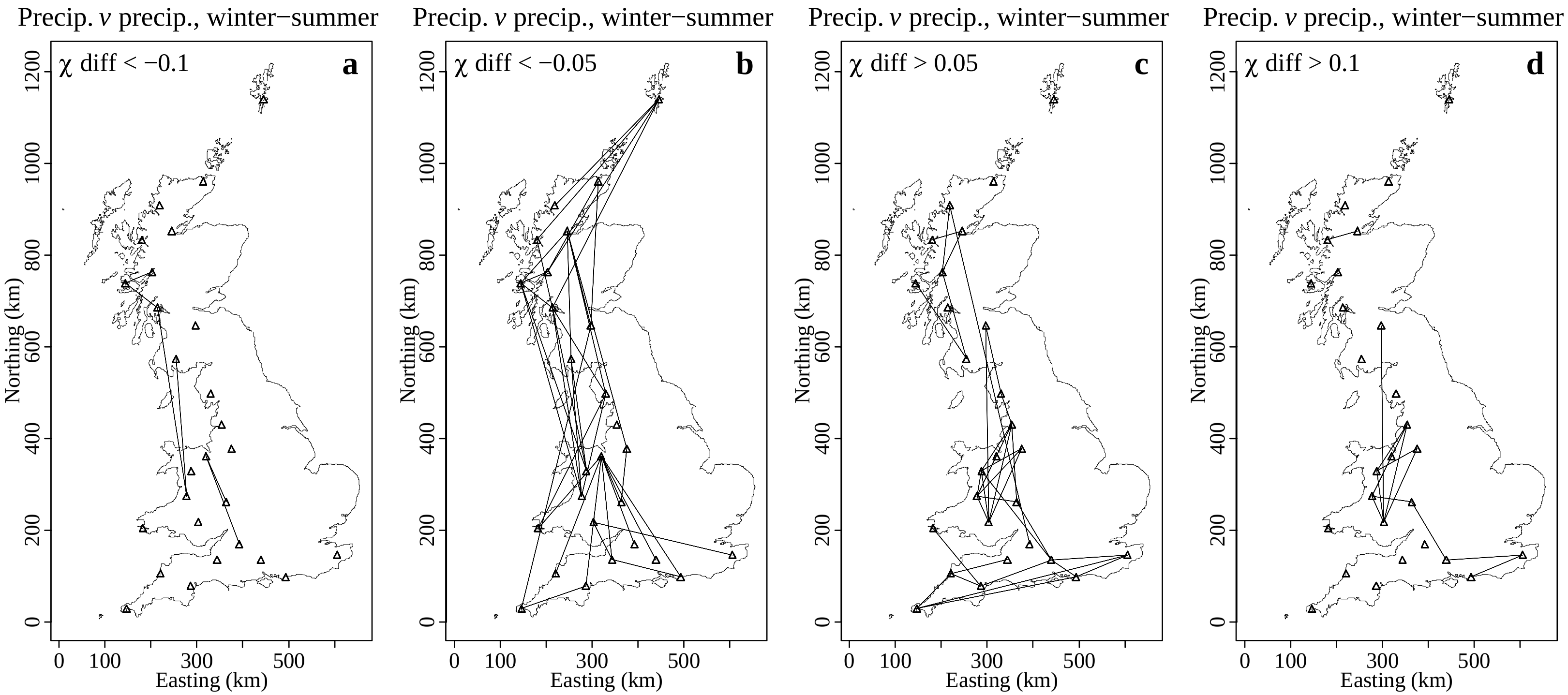

Figure 14 Seasonal difference in inter-station dependence (χ for winter minus χ for summer) in precipitation. Lines connect station-pairs with a difference in χ a) <–0.1, b) <-0.05, c) >0.05, and d) >0.1.

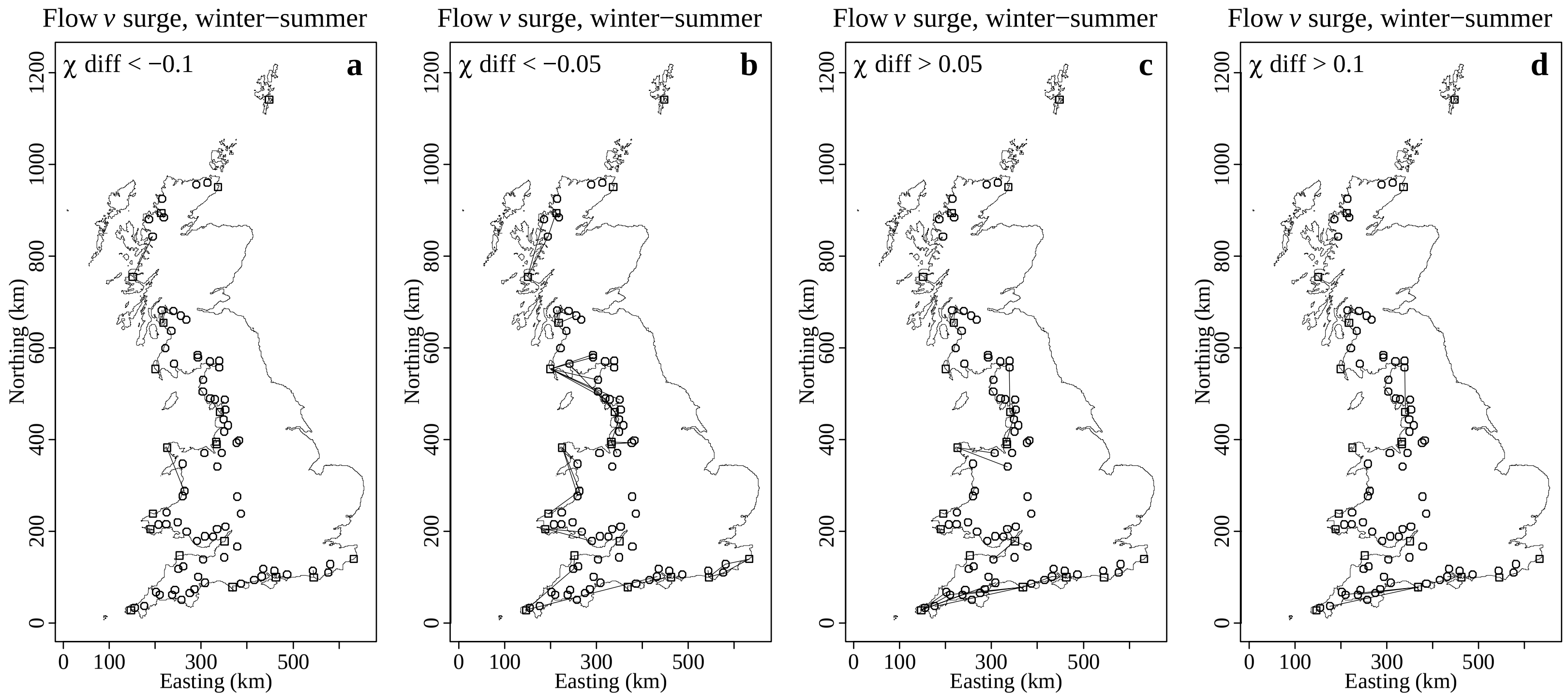

Figure 15 Seasonal difference in dependence (χ for winter minus χ for summer) between river flow and daily maximum sea surge, for neighbouring stations only. Lines connect station-pairs with a difference in χ a) <–0.1, b) <-0.05, c) >0.05, and d) >0.1.

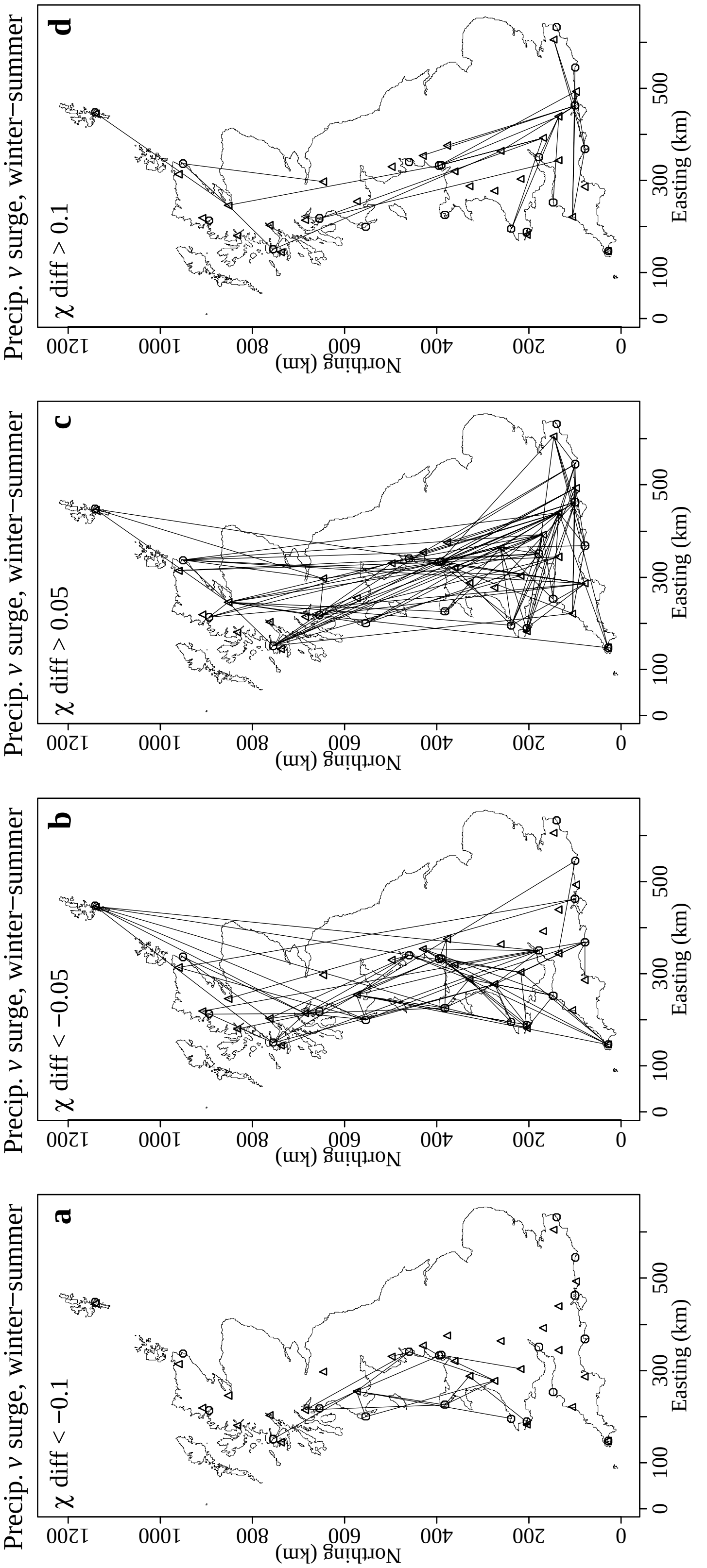

Figure 16 Seasonal difference in dependence (χ for winter minus χ for summer) between precipitation and daily maximum sea surge. Lines connect station-pairs with a difference in χ a) <–0.1, b) <-0.05, c) >0.05, and d) >0.1.

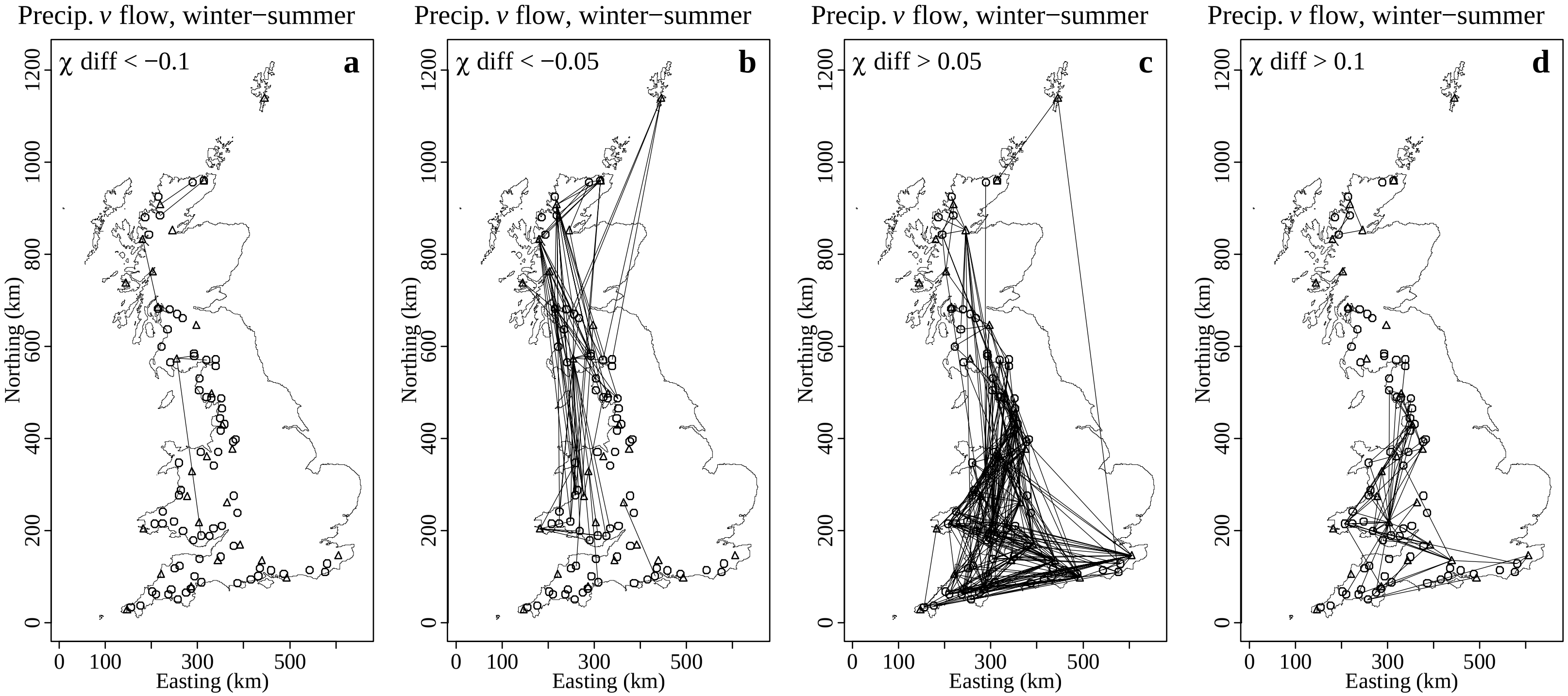

Figure 17 Seasonal difference in dependence (χ for winter minus χ for summer) between precipitation and river flow. Lines connect station-pairs with a difference in χ a) <–0.1, b) <-0.05, c) >0.05, and d) >0.1.

4.4 Lagged analysis

A lagged analysis was undertaken in order to better understand the timing of the occurrence of sea surge, river flow and precipitation. Figure 18 shows the lagged "auto-dependence" for daily maximum sea surge for lags up to 8 days. All the stations have significant dependence for a 1-day lag, with the highest dependence occurring at Lerwick (χ = 0.39). Lerwick and Ullapool show a slight peak for a 5-day lag, but there is not much support for that at any of the other stations.

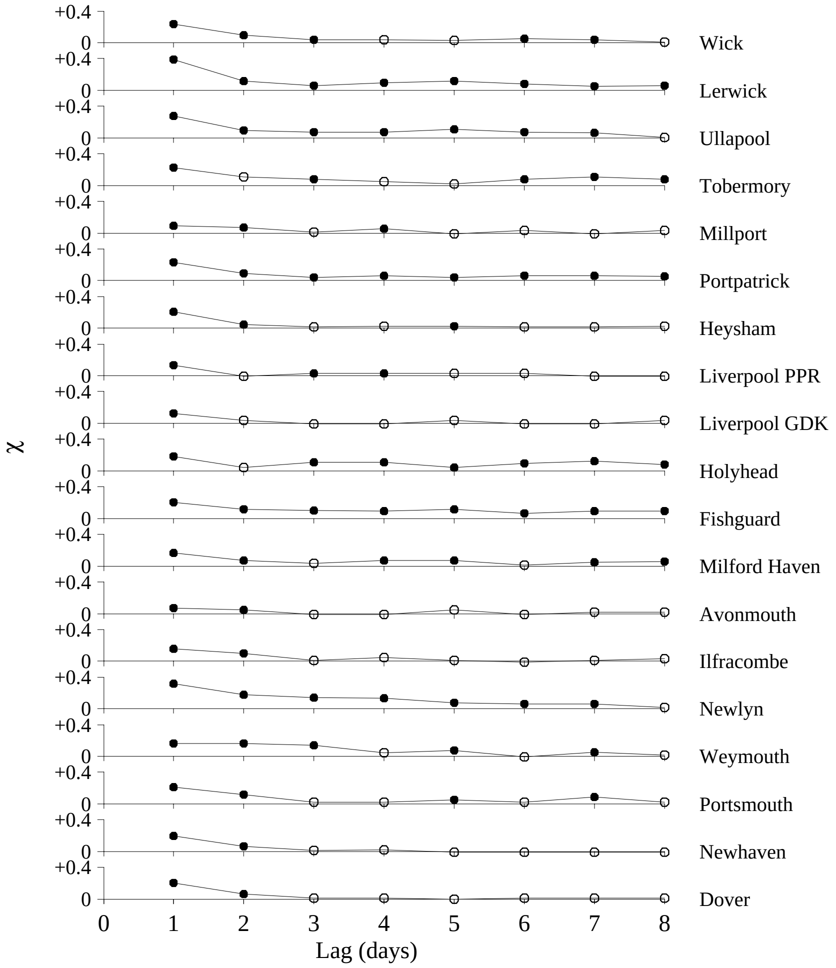

Figure 18 **Lagged dependence for daily maximum sea surge. Values of χ significant at the 5% level are shown as filled circles and non-significant values as empty circles.**

Temporal dependence in river flow is stronger than in surge (Figure 19), with 41023 (Lavant at Graylingwell) having the highest lag 1-day dependence at χ = 0.97. Other permeable catchments in the eastern part of the south coast, such as 42006 and 43021, also have very high lag 1-day dependences. Dependence in these catchments tapers off slowly with time. In contrast, the catchments in the north (Figure 19c) generally have a low temporal dependence that may become non-significant already for a lag of 2 days.

a

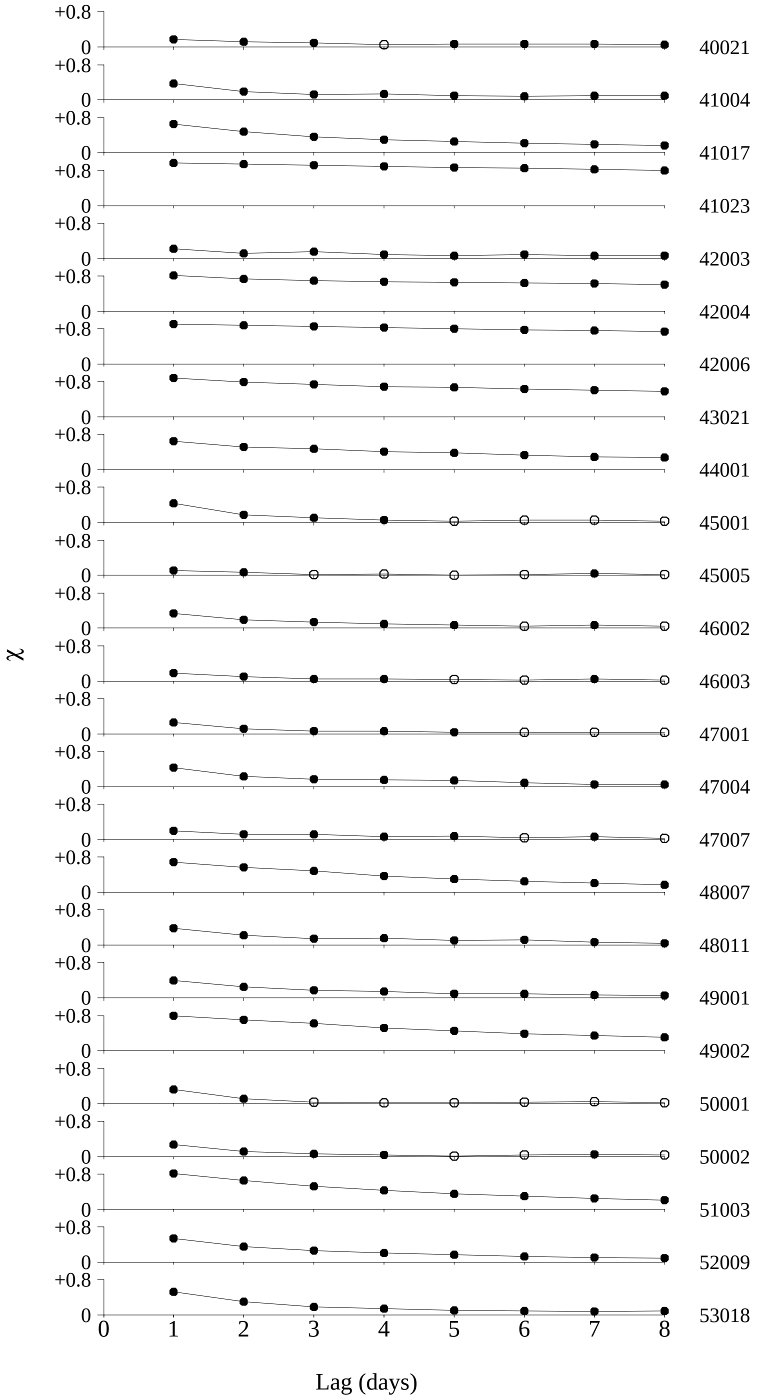

Figure 19 **Lagged dependence for river flow. Values of χ significant at the 5% level are shown as filled circles and non-significant values as empty circles.**

b

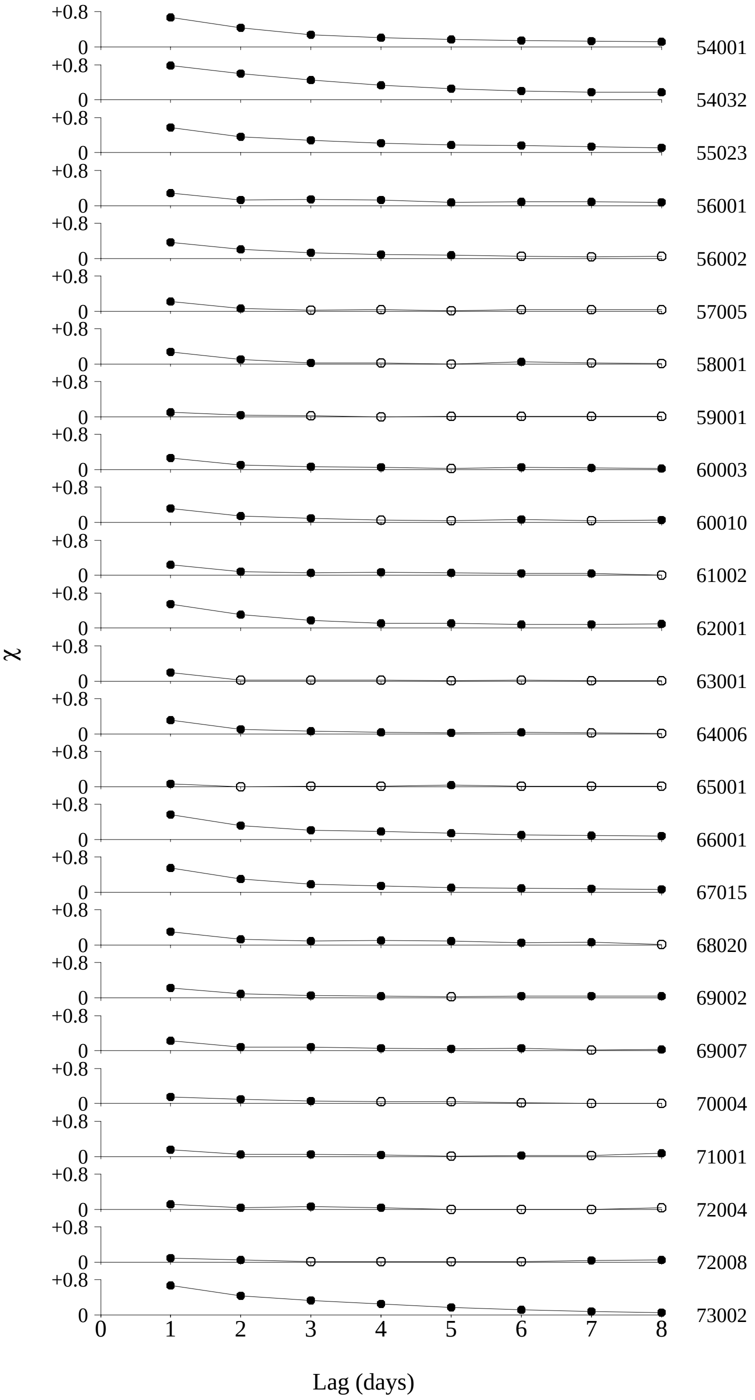

Figure 19 Continued.

c

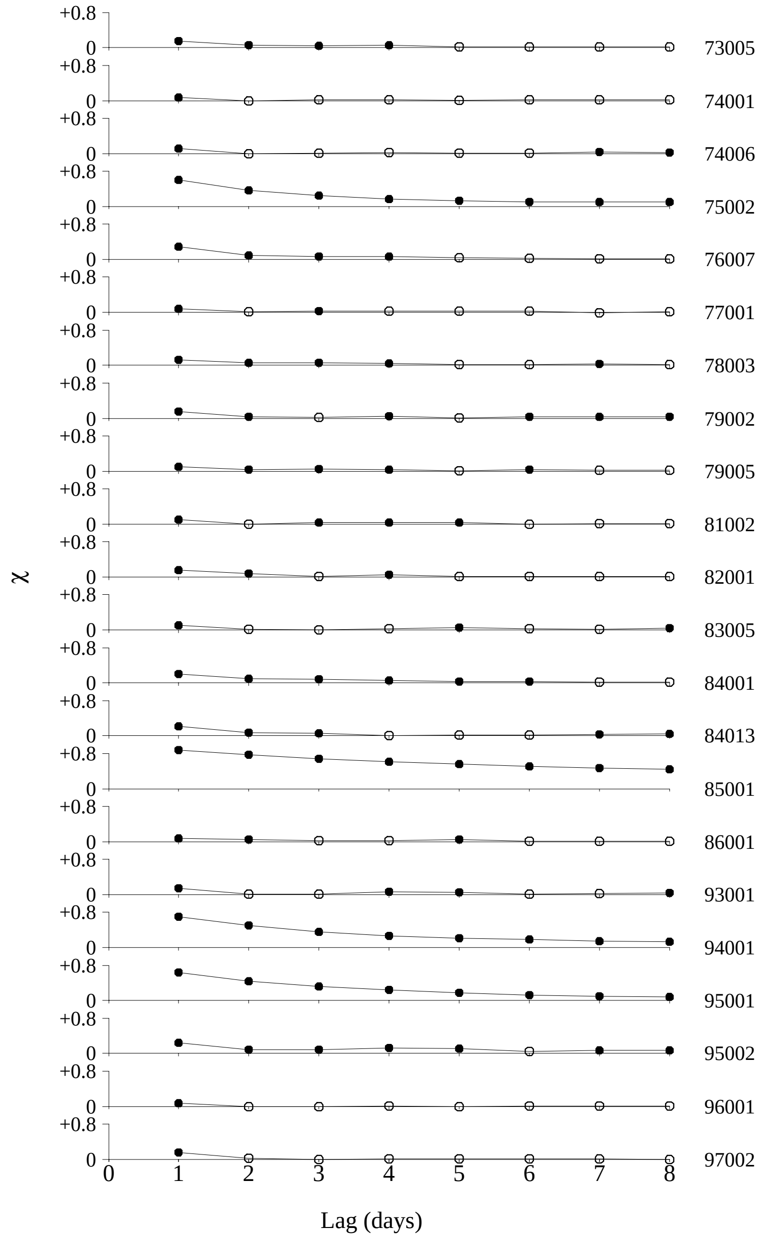

Figure 19 Continued.

Precipitation has the lowest temporal dependence, with lag 1-day dependence frequently being non-significant (Figure 20).

Figures 21-23 show maps of lagged cross-variable dependence. The dependence between river flow and daily maximum sea surge is often strongest when surge and flow occur on the same day. In general, dependence is strong also for flows lagged one day after the surge. Slowly responding catchments may reach their peak dependence for larger lags. For example, the Severn (54001, 54032), reaches its peak when the flow is lagged two days after the surge at Avonmouth (Appendix D of Svensson and Jones, 2000).

The dependence between precipitation and daily maximum surge is strongest when they occur on the same day, and not particularly strong for any lag (Figure 22). There are no station-pairs with $\chi > 0.1$ when precipitation is lagged after the surge. The same-day peak in dependence suggests that mainly quickly responding catchments will be at risk from simultaneous occurrence of extreme sea surge and river flow. Dependence between precipitation and river flow is strongest when they occur on the same day, and when precipitation precedes the flow by one day (Figure 23).

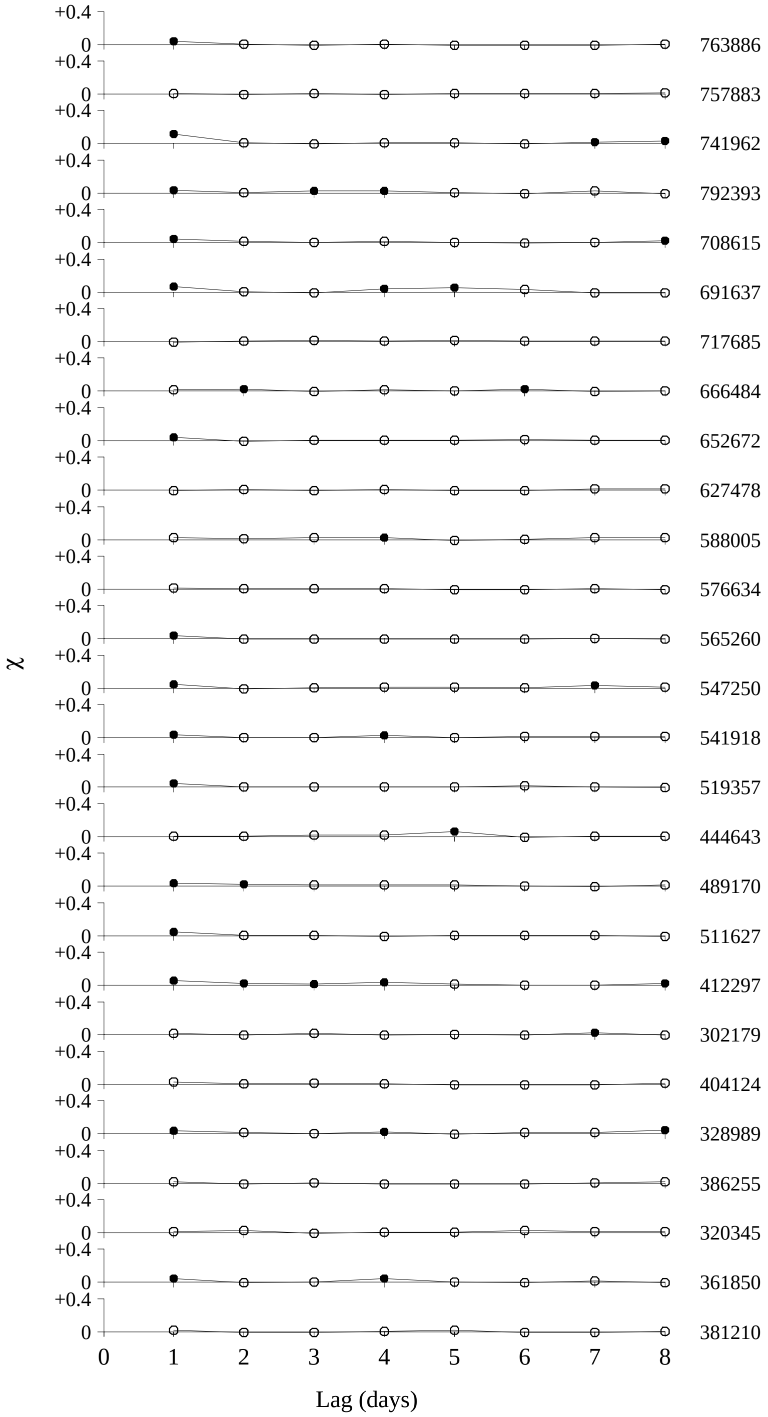

Figure 20 **Lagged dependence for precipitation. Values of χ significant at the 5% level are shown as filled circles and non-significant values as empty circles.**

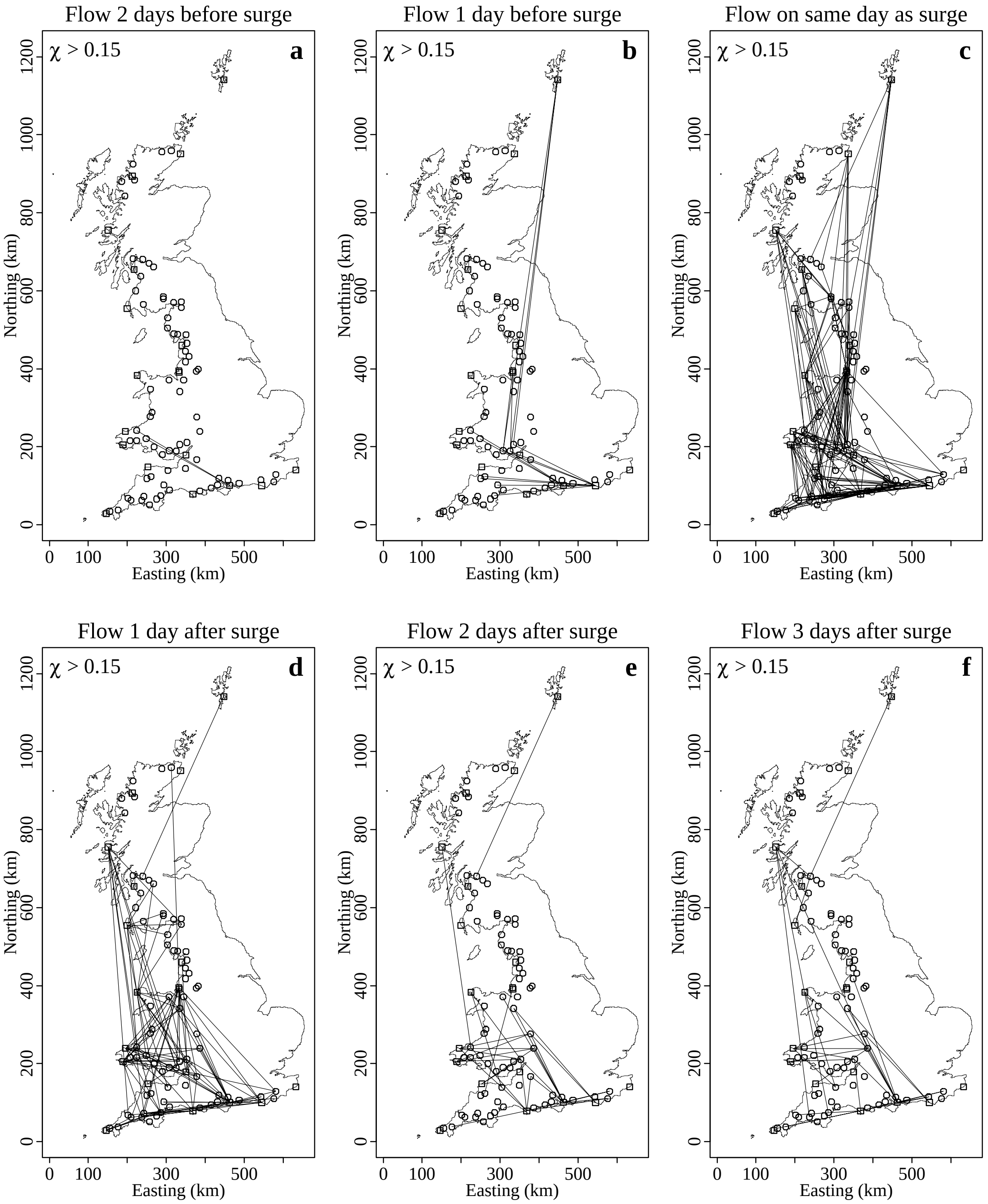

Figure 21 Dependence between river flow and daily maximum sea surge for different time lags. Lines connect station-pairs with χ exceeding 0.15.

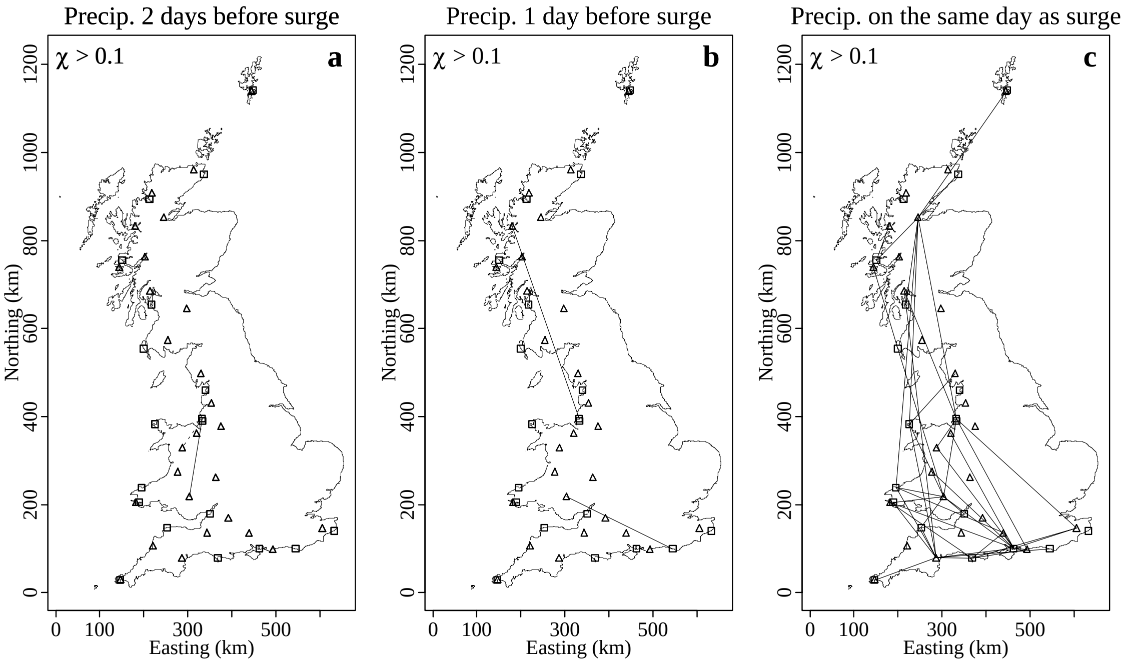

Figure 22 **Dependence between precipitation and daily maximum sea surge for different time lags. Lines connect station-pairs with χ exceeding 0.1.**

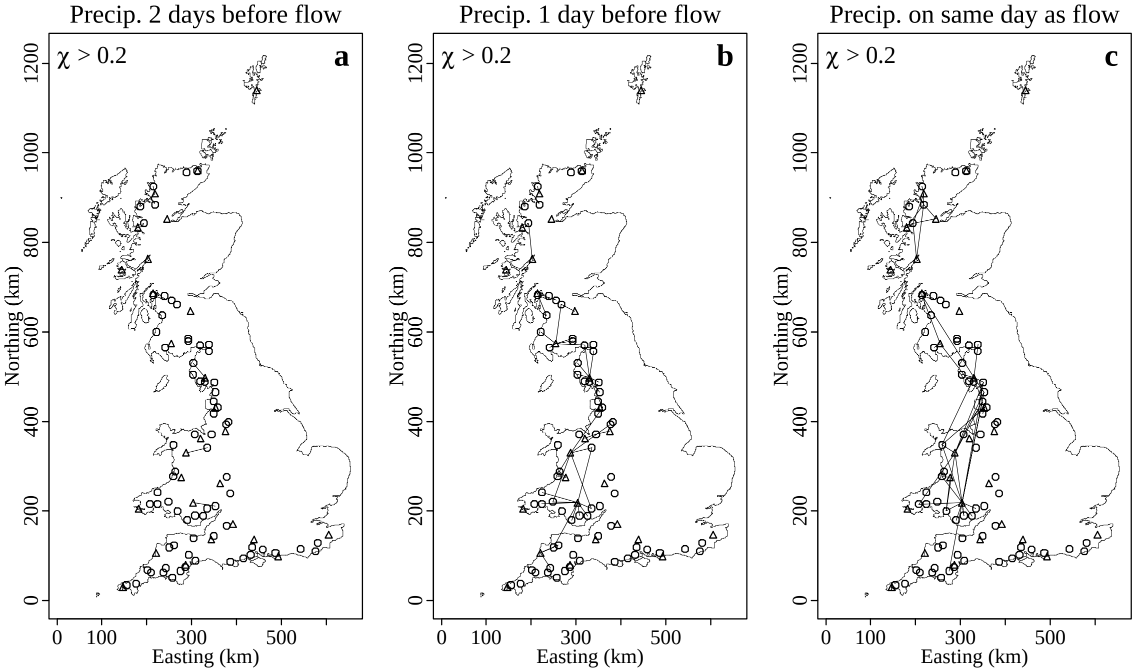

Figure 23 **Dependence between precipitation and river flow for different time lags. Lines connect station-pairs with χ exceeding 0.2.**

4.5 Meteorological analysis

Reasonably high dependence (χ>0.1) between river flow and sea surge occurs in three regions on the south and west coasts of Great Britain: the western part of the English south coast, southern Wales, and around the Solway Firth (Figure 8). Meteorological analyses of a set of extreme surge and/or flow events were therefore undertaken for these three areas. The regions were treated separately because Lennon (1963) identified different storm tracks associated with extreme surge events at Avonmouth and Liverpool.

Three types of situations were investigated: high surge with moderate or low river flow, both high surge and flow, and high flow and moderate or low surge. Five events of each type, for each region, means that in total 45 events were investigated. Information from Daily Weather Reports (until 1980) and Daily Weather Summaries (from 1981) were used. From 1998 onwards the maps only have a resolution of 12 hours, but prior to 1998 the maps are shown every 6 hours.

The daily mean river flow and daily maximum sea surge series were normalised by subtracting the series mean and dividing with the series standard deviation. For each variable separately, these normalised daily series were then averaged in space over all the gauges in each region. Region 1 (western English south coast) comprises 12 flow stations, 44001-49002 (see Appendix B and Figure 1 for individual station numbers), and the surge stations Weymouth and Newlyn. Region 2 (south Wales) comprises 10 flow stations, 55023-62001, and surge stations Avonmouth, Milford Haven and Fishguard. Region 3 (Solway Firth area) comprises 15 flow stations, 71001-82001, and the surge stations Heysham and Portpatrick.

The normalised flow and surge series were ranked and the nine sets (three regions by three types of events) of five events each were selected. The criterion for a small or moderate event was that the normalised flow or surge should be less than zero. It was reasonably easy to find events where both variables were large; the five events were found in about the top 50 of the ranked events for all regions. However, it was more difficult to pair up an extreme event with a moderate or low event. The extreme variable in the pair could generally be found in about the top 100, but for high flow/low surge events in regions 2 and 3, the smallest of the five flow extremes were found at rank 166 and rank 229, respectively. This reflects the tendency for large river flow to be associated with the occurrence of a reasonably large surge event, whereas a large surge may more easily occur without an associated large river flow.

It should be borne in mind that only five events were analysed in each category, and that the results therefore are only indicative. Contrary to the analysis for the east coast (Svensson and Jones, 2000; 2003), where the behaviour within each group was very similar, the west and south coast events are less homogeneous. However, some common features occur within each group, and also between the regions.

4.5.1 High sea surge and moderate river flow

Figures 24-26 show the tracks associated with the centre of depressions causing high surge and moderate or low river flow in Regions 1 to 3. Where possible, the tracks were plotted every 6 hours, during a 48 hour period, marking the 6-h position with a dot on the line. When only a 12-hourly resolution was available, or when the depression was outside the map (the maps cover different sized areas at different times of day), the intermediate position was estimated through linear interpolation. Towards the beginning or end of the tracks, interpolation was not possible, and the tracks are therefore sometimes shorter than 48 hours. Tracks start approximately 36 hours prior to the surge maximum at Newlyn, Fishguard and Portpatrick, respectively for the three study areas. These surge stations were selected because they had complete records for all the investigated events. The nearest 6-h location of the depression at surge maximum is encircled on the maps. The storms are denoted on the map with the date (water day, 9.00-9.00 GMT) on which the high sea surge and moderate river flow occurred.

The storms move in a general easterly direction, and are often located just west of Great Britain as the maximum surge occurs. The storms track progressively to the south with decreasing latitude of the study area. They are generally tracking south of the storms which result in large surges and moderate river flow in northeast Britain (Svensson and Jones, 2000; 2002), the latter moving northeastwards between Scotland and Iceland.

Storm tracks for Region 2 (Figure 25) bear some semblance to seven storm tracks causing large surges (regardless of river flow magnitude) at Avonmouth, reported by Lennon (1963). However, they include one far more northerly track (21/3/83) and one far more southerly track (3/1/79) than would have been expected from Lennon's results.

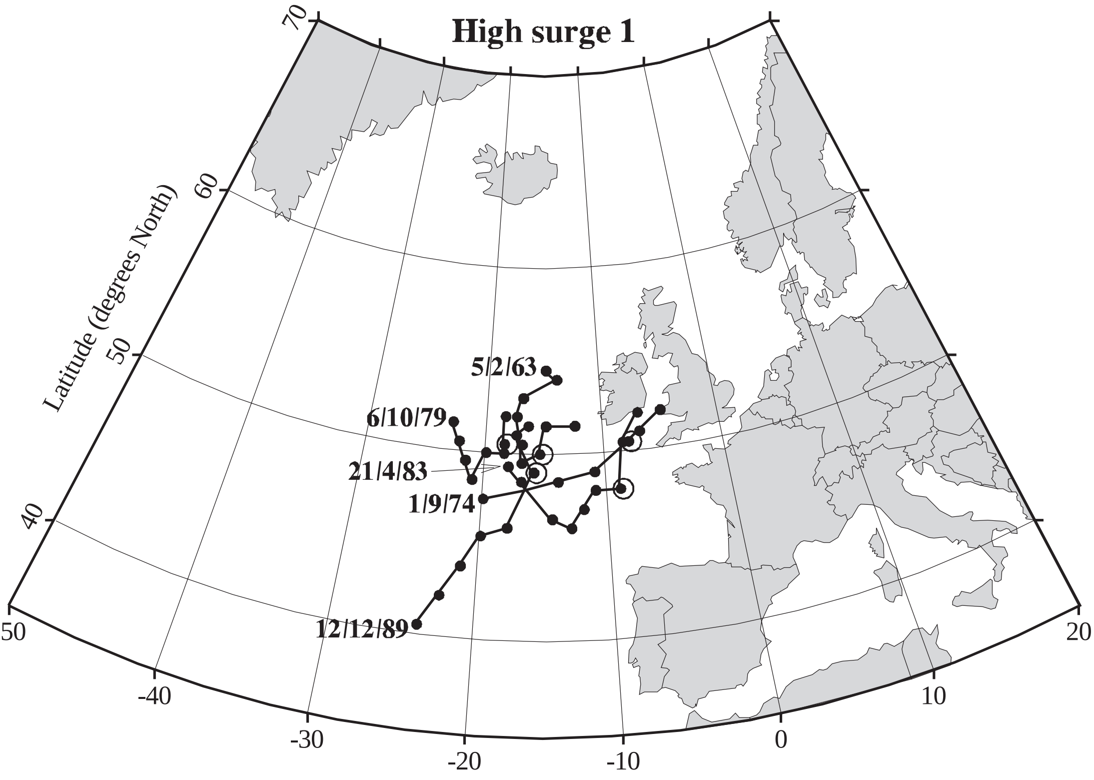

Figure 24 **Tracks of five depressions resulting in high sea surge and moderate river flow on the western part of the English south coast (Region 1).**

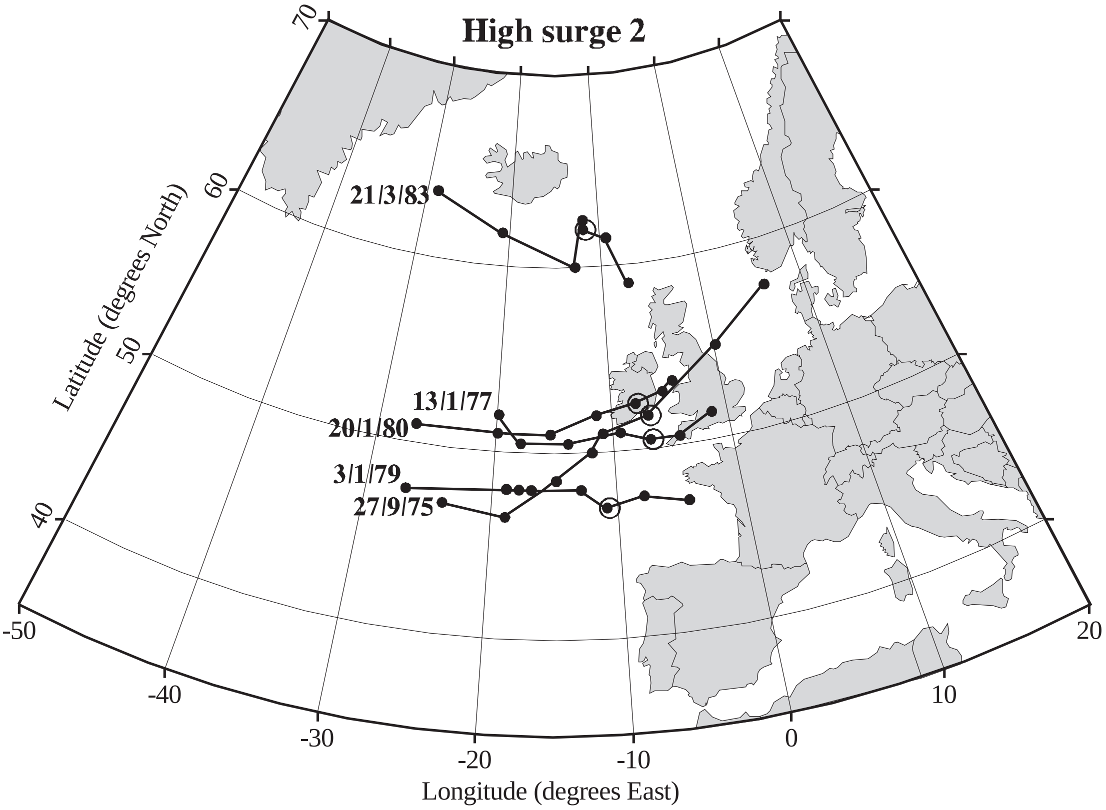

Figure 25 Tracks of five depressions resulting in high sea surge and moderate river flow in southern Wales (Region 2).

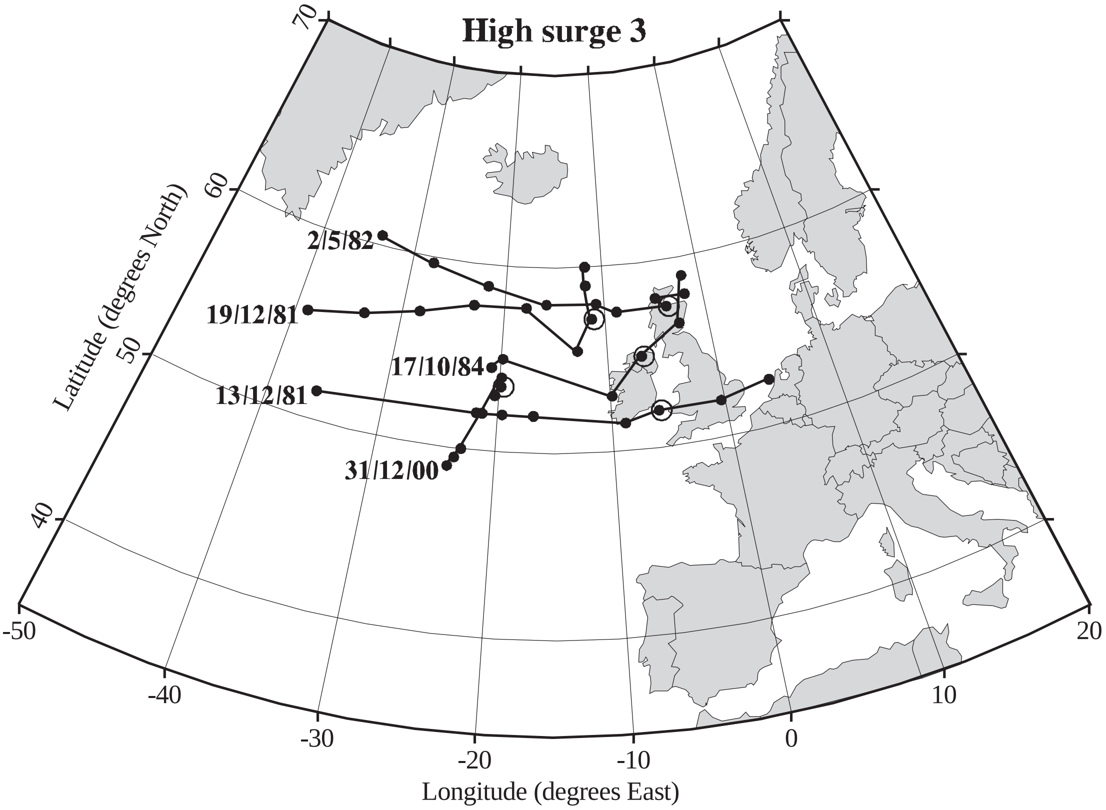

Figure 26 Tracks of five depressions resulting in high sea surge and moderate river flow in the Solway area (Region 3).

The minimum central pressures that the cyclones reach during their passage range from about 960 to 980 hPa for Regions 1 and 2, and from 950 to 970 hPa for Region 3 (keeping in mind that pressures are unknown when the depression is outside the map). For Region 2 it occurs within ±3h of the surge maximum at Fishguard, and for Region 3 within ±8h of the surge maximum at Portpatrick (keeping in mind the 6-h resolution of the maps). The location is more variable for Region 1, but for both Region 1 and 3 the pressure is low also at the occurrence of the surge maximum. The rather low central pressures would ensure a lifting of the sea level and the generation of strong winds that drive the water towards the coast.

For all three study areas there is often no precipitation in the first 24 hours (because the fronts associated with the cyclone are often located elsewhere), and sometimes not throughout the entire 48-hour period. During the last 24 hours precipitation is generally slight rather than moderate or heavy, and sometimes falls as snow or hail, especially in Region 3. This would delay runoff until the precipitation has melted. The storm season is similar for the three regions, starting in September-October and ending in March-May.

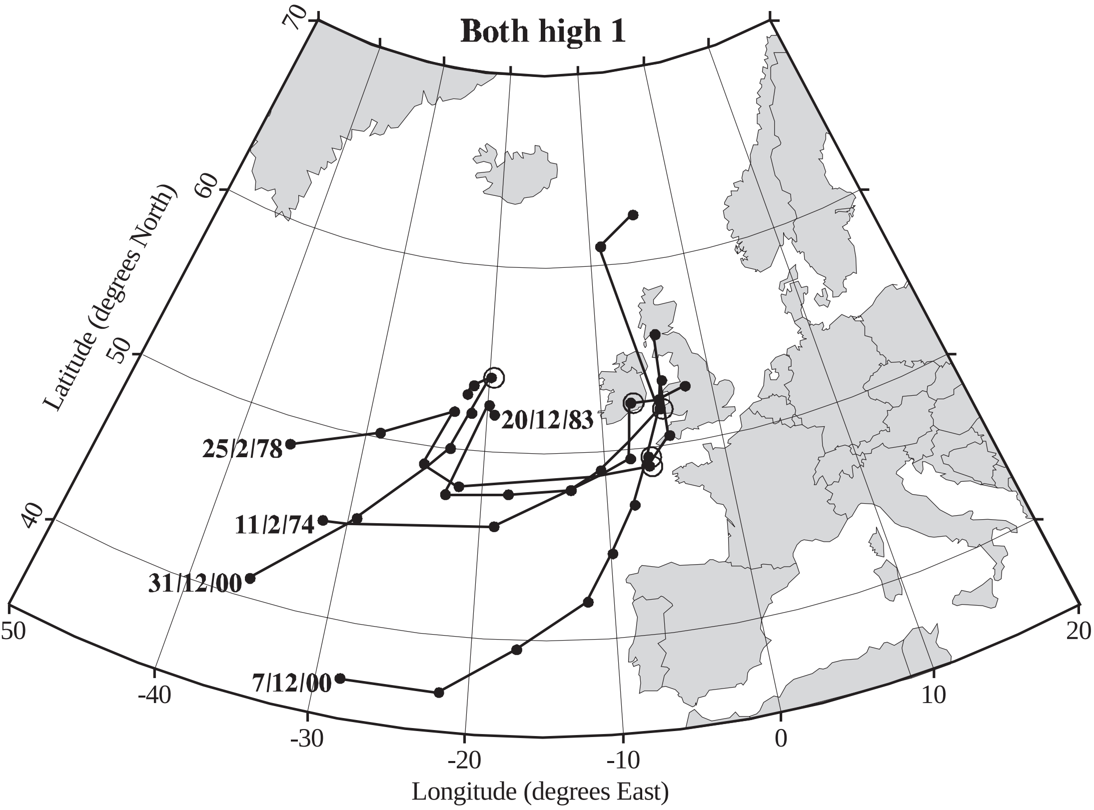

Figure 27 **Tracks of five depressions resulting in both high sea surge and river flow on the western part of the English south coast (Region 1).**

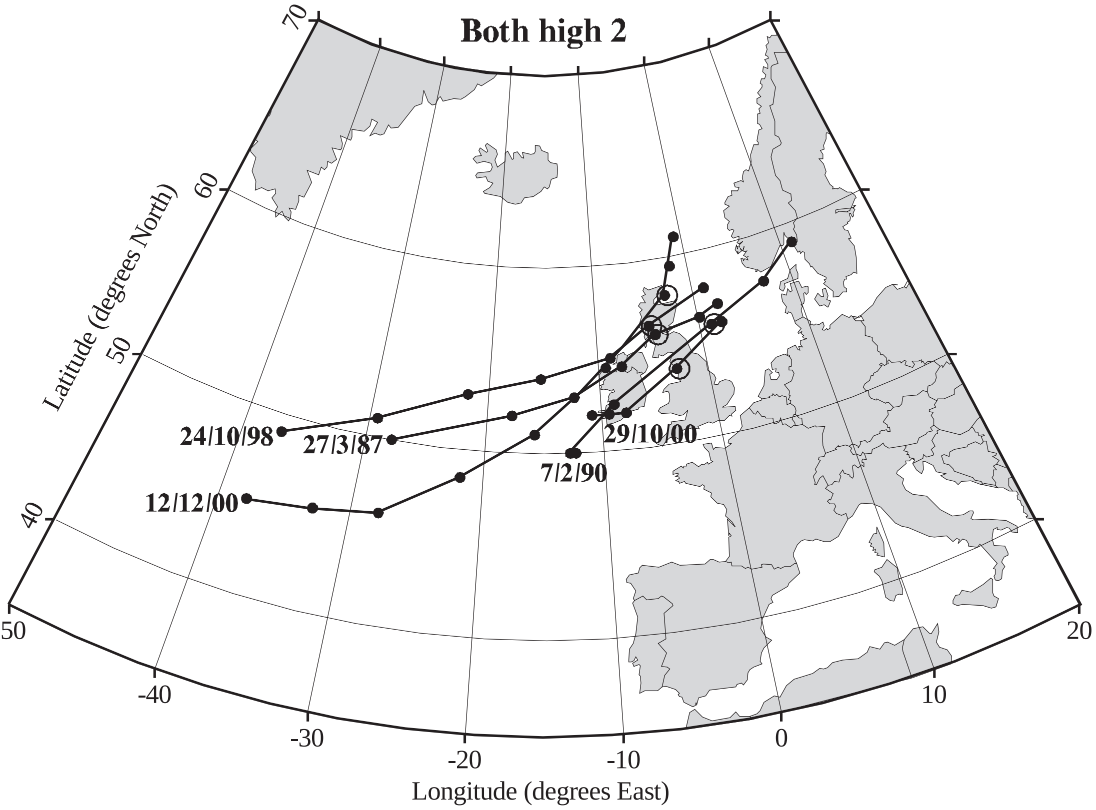

Figure 28 Tracks of five depressions resulting in both high sea surge and river flow in southern Wales (Region 2).

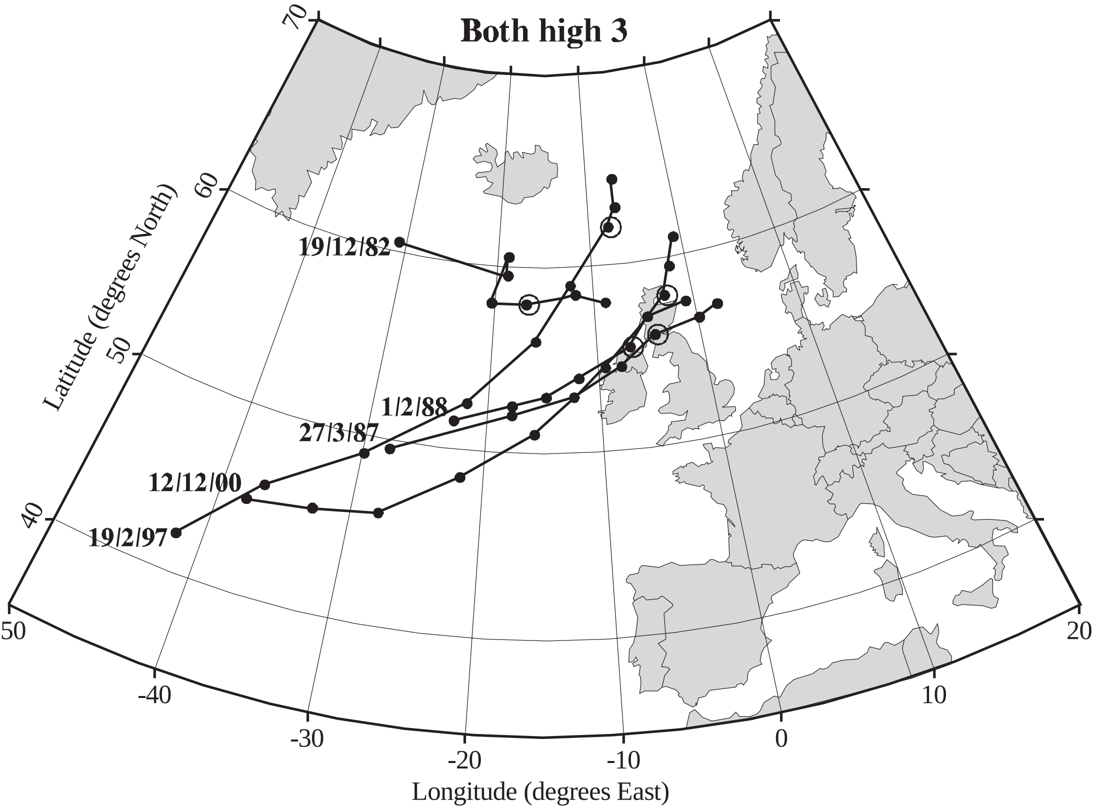

Figure 29 Tracks of five depressions resulting in both high sea surge and river flow in the Solway area (Region 3).

4.5.2 Both high sea surge and river flow

Figures 27-29 show the storm tracks associated with cyclones generating both high sea surge and high river flow. The tracks have more of a northeasterly, rather than easterly, direction and the surge maxima generally occur when they are located over or near the British Isles. The tracks are most homogeneous for Region 2, closely resembling those found by Lennon (1963) to cause high surges at Avonmouth. The storms resulting in both high surge and flow tend to move more swiftly than do storms causing only a high surge, especially in Region 1 (Figures 24 and 27). The northeastward passage of depressions across the Celtic Sea (between Ireland and southwest Britain) in Figure 27 is consistent with the track in the case study of the "Morning Cloud" storm surge in the English Channel (George and Thomas, 1978).

The minimum central pressure is similar to those of the cyclones causing only a high surge, varying between about 950 and 972 hPa for Regions 1 and 2, and between 932 and 967 hPa for Region 3. The timing of the minimum pressure is variable, but generally occurs between 4 hours before and 14 hours after the surge maximum.

There is generally slight rain or showers in the first 12-24 hours, followed by a 12-24-hour period where rainfall may reach moderate or heavy intensity. During the last 12 hours precipitation generally abates, coinciding with the fall in surge magnitude. This suggests that it is mainly reasonably quickly responding catchments that are at risk from river flow and surge peaks occurring simultaneously in the estuaries. The storm seasons are similar for the three regions, starting between October and December, and ending in February or March.

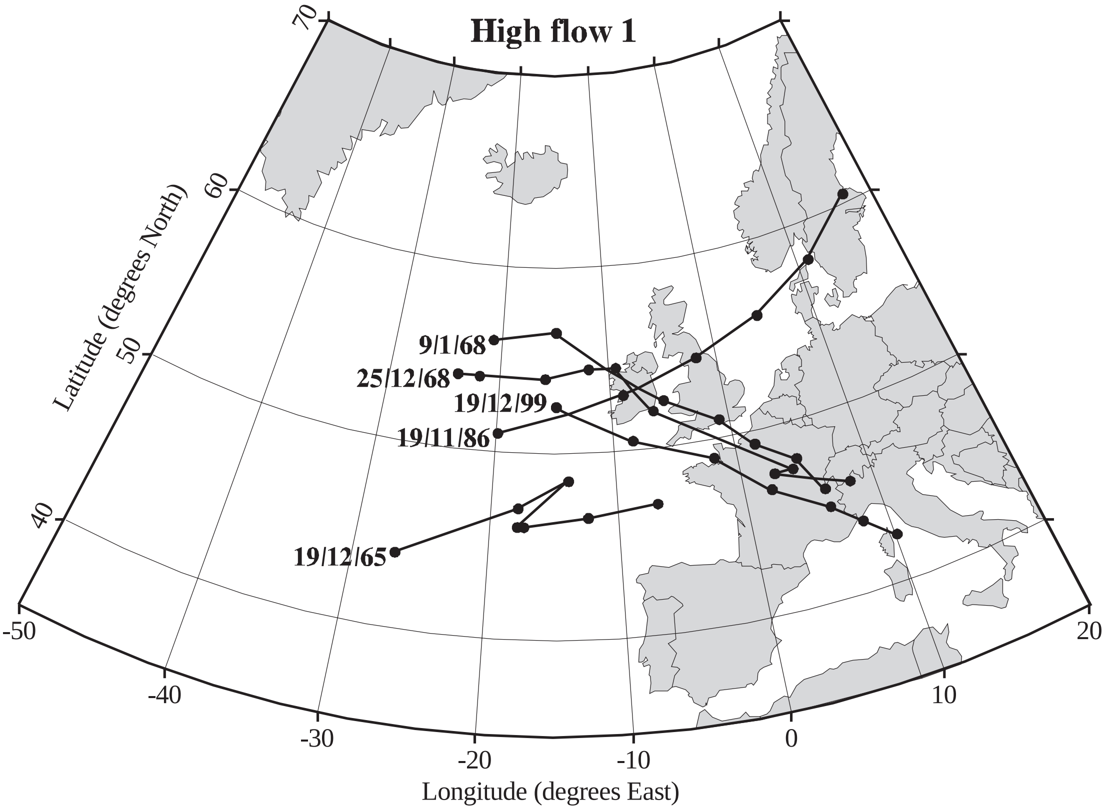

Figure 30 **Tracks of five depressions resulting in high river flow and moderate sea surge on the western part of the English south coast (Region 1).**

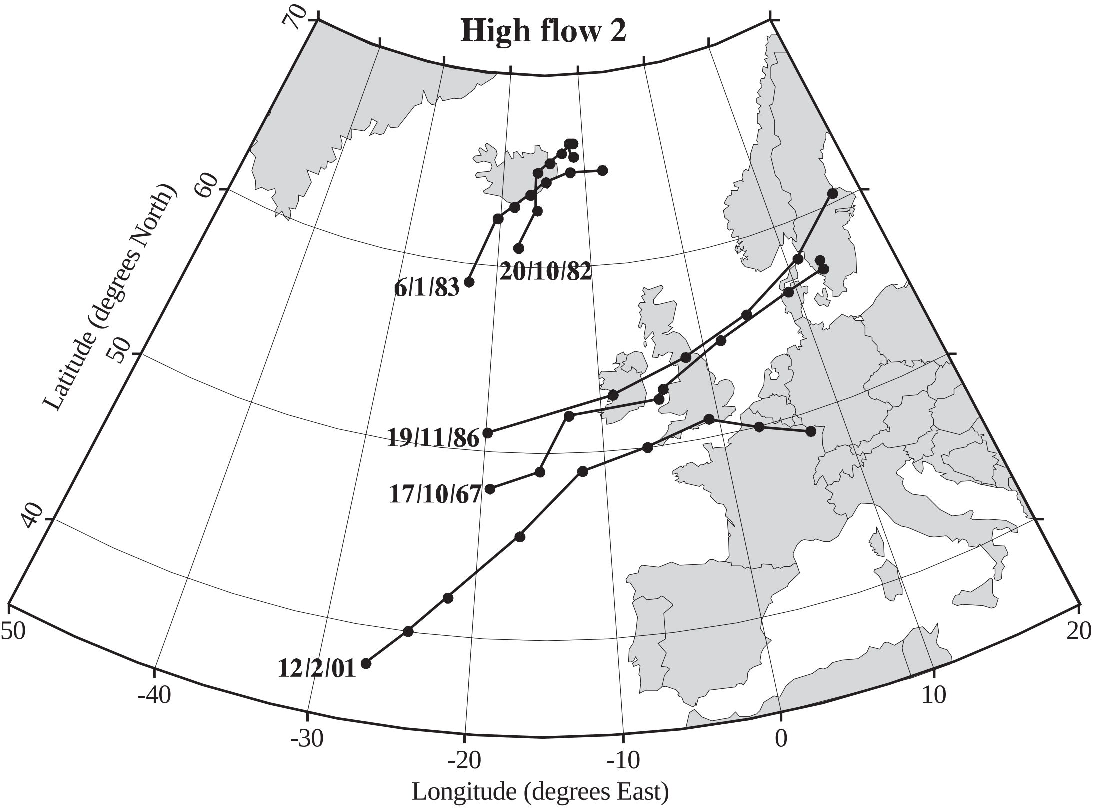

Figure 31 Tracks of five depressions resulting in high river flow and moderate sea surge in southern Wales (Region 2).

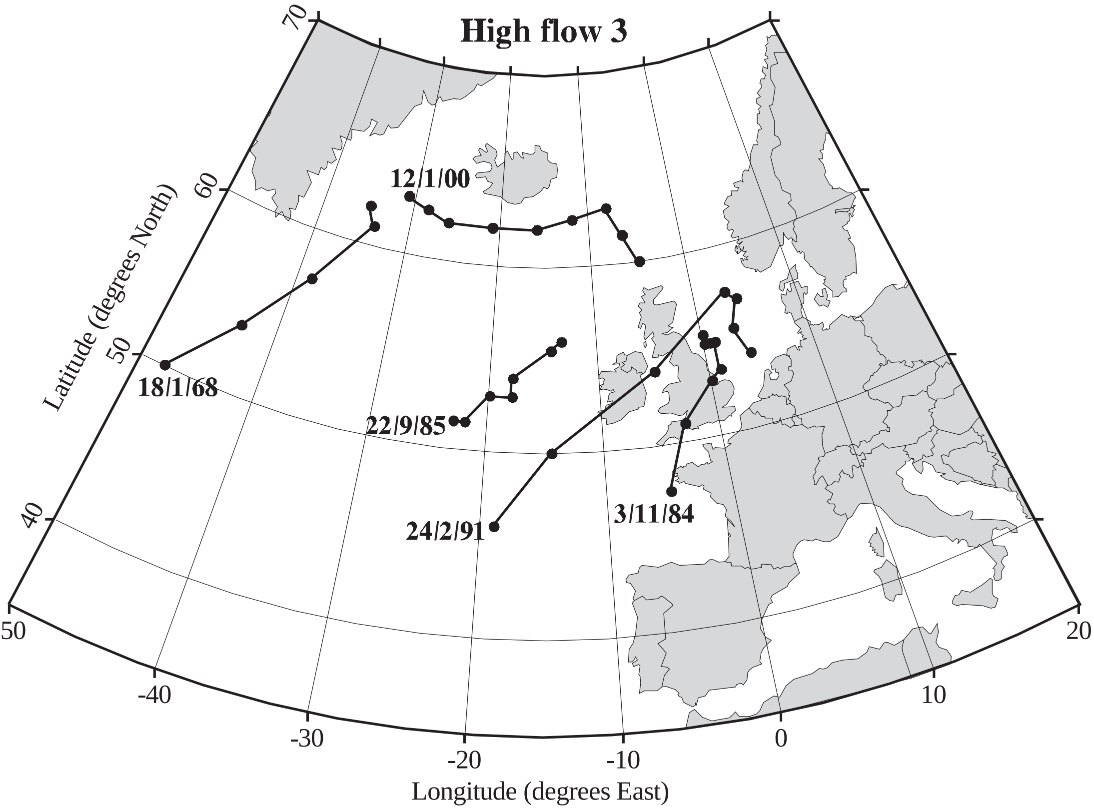

Figure 32 Tracks of five depressions resulting in high river flow and moderate sea surge in the Solway area (Region 3).

4.5.3 High river flow and moderate sea surge

The cyclones in this category were tracked during 48 hours starting at 00.00 GMT on the day before the water day (9.00-9.00 GMT) of extreme river flow. The storm tracks are rather diverse (Figures 30-32), sometimes being far away from Great Britain. Some distant storms (20/10/82 and 6/1/83 in Region 2, and 18/1/68 and 12/1/00 in Region 3) reach low minimum central pressures (930-974 hPa), all occurring when the depression is located in the vicinity of Iceland. The storm 17/10/67 in Region 2 crosses Great Britain, but does not reach its minimum pressure (968 hPa) until it is over southern Sweden (13°E, 57°N). The remainder of the depressions have higher minimum central pressures ranging from 984 to 1010 hPa.

These weak and/or distant depressions are not able to cause much of a surge, but rainfall at the associated fronts may be both continuous and, at times, heavy. In Region 3 there is generally rainfall throughout the 48-hour period, sometimes with dry spells. In Region 2 there is sometimes no rain in the first and last 6 hours, whereas in Region 1 there is sometimes no or only slight rain in the last 6-12 hours. Further northwards the start date of the events is earlier and the storm season longer, possibly in response to the shorter season of high soil moisture deficits in the north. The seasons are November-January in Region 1, October-January in Region 2, and September-February in Region 3.

4.6 Sensitivity to storm track

The flow-surge dependence is largely influenced by the main storm track of the depressions. To assess the sensitivity of the flow-surge dependence to inter-annual shifts in preferred storm track, the dependence was estimated for different phases of the North Atlantic Oscillation. The North Atlantic Oscillation Index (NAOI) is a measure of the (oscillating) pressure difference between the Azores and southwest Iceland. When the NAOI is in its positive phase storms tend to track in a northeasterly direction to the north of Scotland. However, when it is in its negative phase, storms tend to move eastwards along a more southerly track, at about 45°N (Rogers, 1990), i.e. level with southern France.

Most global climate models suggest a shift towards the positive phase of the NAOI under future scenarios of climate change (Gillett et al., 2002). This type of analysis therefore also gives a qualitative indication of whether dependence will increase or decrease in a future, greenhouse gas-induced warmer climate.

The analysis here was restricted to October to March because the NAOI is most pronounced during the winter. Twelve winters each of high and low NAOI were selected. High NAOI years encompassed 1972, 1973, 1983, 1987, 1989, 1990, 1992, 1993, 1994, 1995, 1999 and 2000, whereas low NAOI years included 1964, 1965, 1966, 1969, 1970, 1971, 1977, 1979, 1981, 1986, 1996 and 1998.

Figure 33 shows the difference in dependence between high and low NAOI winters. The results for the south and west coasts are ambiguous, and the differences are moderate. In total 18 of 74 station-pairs have absolute differences in χ exceeding 0.1. The results should be treated with caution as there are many station-pairs for which

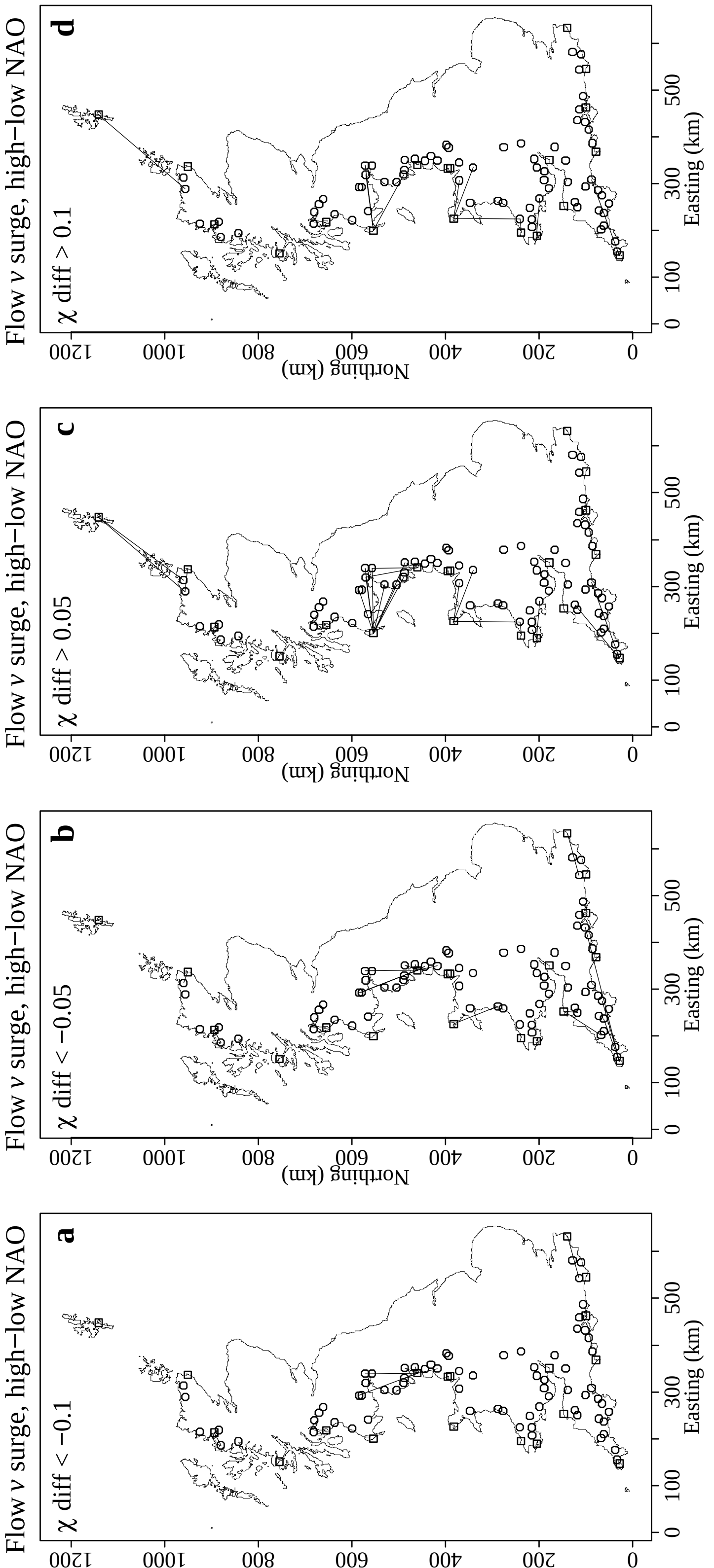

Figure 33 Difference in dependence between high and low NAOI winters (χ for high NAOI winters minus χ for low NAOI winters), for neighbouring stations of river flow and daily maximum sea surge. Lines connect station-pairs with a difference in χ a) <–0.1, b) <-0.05, c) >0.05, and d) >0.1.

dependence was not estimated because of too few data. However, more station-pairs show a strengthening than a weakening of the dependence in high NAOI years on the west coast from Wales up to the Solway Firth area, and possibly further north. The dependence in low NAOI years could not be estimated for most of Scotland.

Apart from storm tracks, other factors influencing the dependence between river flow and sea surge include soil moisture deficits. High deficits would delay precipitation reaching the rivers, as the soil moisture store recharges. Soil moisture deficits are large mainly in summer due to increased evapotranspiration at higher temperatures, and its effects in winter are more limited. Both river flow and sea surge tend to be at their most extreme during the winter, making winter rather than summer dependence more relevant to the joint probability problem of water levels in estuaries.

5. FURTHER DISCUSSION

5.1 Interpretation of χ

As mentioned earlier, the dependence measure χ can be interpreted as being the probability that one of a pair of variables will be extreme given that the other one is. This interpretation is clarified in this Section, and a brief examination is made of the adequacy of this approximate result. Section 5.2 looks at the possible implications of having a non-zero value of χ when calculations are made assuming that two series are independent.

Equation 2 may be rearranged to obtain

$$\Pr(U \le u, V \le u) = \Pr(U \le u)^{2-\chi(u)},$$

with notations as in Section 3.1. Here U and V represent transformations of the original variables to have a common (uniform) distribution. Thus $\Pr(U \le u) = \Pr(V \le u)$. In the context of the present study U and V relate to quantities defined on a daily basis. Thus, if the threshold u is defined in terms of return period T, via the expression

$$\Pr(U \le u) = 1 - \frac{1}{T} \tag{9}$$

then T is measured in units of days.

Given that u is defined via Equation 9,

$$\Pr(U > u) = \frac{1}{T}$$

$$\begin{aligned}\Pr(U > u, V > u) &= 1 - 2\ \Pr(U \le u) + \Pr(U \le u, V \le u) \\ &= 1 - 2(1 - \frac{1}{T}) + (1 - \frac{1}{T})^{2-\chi(u)} = (1 - \frac{1}{T})^{2-\chi(u)} + \frac{2}{T} - 1.\end{aligned} \tag{10}$$

It then follows that

$$\Pr(V > u \mid U > u) = \frac{\Pr(U > u,\ V > u)}{\Pr(U > u)} = T\left[(1 - \frac{1}{T})^{2-\chi(u)} + \frac{2}{T} - 1\right]. \tag{11}$$

An approximation derived from Equation 11 is as follows

$$\Pr(V > u \mid U > u) \approx \chi + \frac{(1-\chi)(2-\chi)}{2T},$$

which shows that the conditional probability is essentially equal to χ, once the return period is large enough. Table 4 shows a brief tabulation for the exact expression given in Equation 11 on the basis that χ does not vary with u (and hence T). The values in the table indicate that the approximation is very good when applied to events that occur less frequently than 1 in 50 samples (i.e. with a return period of greater than 50 days for the present study).

Table 4 Conditional probability that one variable exceeds a certain return period, given that the second variable does. The conditional probability (shaded area) is shown for different return periods of the margins (left column) and for different strengths of dependence between the two variables (top two rows). The value of χ equals zero for independent variables.

Return period for each variable (days)	χ										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
2	0.50	0.54	0.57	0.62	0.66	0.71	0.76	0.81	0.87	0.93	1.00
5	0.20	0.27	0.35	0.42	0.50	0.58	0.66	0.74	0.83	0.91	1.00
10	0.10	0.19	0.27	0.36	0.45	0.54	0.63	0.72	0.81	0.91	1.00
50	0.02	0.12	0.21	0.31	0.41	0.51	0.61	0.70	0.80	0.90	1.00
100	0.01	0.11	0.21	0.31	0.40	0.50	0.60	0.70	0.80	0.90	1.00
500	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
1000	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00

Hence, given the proviso that at least moderately extreme events are being considered, the dependence measure χ has the interpretation that it is equal to the probability that one variable will exceed a threshold of a given return period, given that the second variable exceeds the threshold of the same rarity for that variable.

5.2 Implication of non-zero χ

In practice, joint probability studies determine whether to count a possible sample data point pair as being an "extreme event" in ways which depend strongly on the characteristics of the problem being studied. For the present purpose of illustrating the effects of different levels of dependence, as measured by χ, it seems reasonable to count a sample defined by two values as being extreme if both values exceed given thresholds. In addition, the thresholds for the individual values are determined via Equation 9 to have the same return period when the variables are considered separately. Then it follows directly from Equation 10 that the return period for an event where both thresholds are exceeded, T_b, is given by

$$T_b = \frac{1}{(1-\frac{1}{T})^{2-\chi(u)} + \frac{2}{T} - 1}. \qquad (12)$$

As before, the return period here is measured in terms of "samples": for the present study T_b is measured in days. An approximation for the above expression is given by

$$T_b \approx \frac{T^2}{\chi T + \frac{1}{2}(1-\chi)(2-\chi)}.$$

Table 5 shows the return periods for events where both thresholds are exceeded for different strengths of dependence, as given by Equation 12. Here the results are presented for return periods expressed in terms of days. Table 6 shows the same results but re-expressed in the more common units for return periods of "years" on the basis that a years has 365 days. It can be seen that if the variables are independent and if the thresholds for the individual variables are set at a moderate number of years, the return periods for the joint event is several thousand times as long. In fact the exact result in this case is the square of the number of days in the return period which is divided by the number of days in a year to convert the result to have units of "years".

Table 5 **Return periods (in days) for combinations of events where both variables exceed a certain return period. The return period for the combined events (shaded area) is shown for different return periods of the margins (left column) and for different strengths of dependence between the two variables (top two rows). The value of χ equals zero for independent variables.**

Return period for each variable (days)	χ										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
2	4	3.73	3.48	3.25	3.03	2.83	2.64	2.46	2.30	2.14	2.00
5	25	18.4	14.4	11.9	10.0	8.65	7.59	6.75	6.06	5.48	5.00
10	100	53.8	36.7	27.8	22.3	18.6	15.9	13.9	12.3	11.0	10.0
50	2500	427	233	160	122	98.5	82.6	71.0	62.3	55.5	50.0
100	10000	921	483	327	247	199	166	142	125	111	100
500	250000	4916	2482	1660	1247	998	833	714	625	555	500
1000	1000000	9915	4982	3327	2497	1998	1666	1428	1250	1111	1000

Table 6 **Return periods (in years) for combinations of events where both variables exceed a certain return period. The return period for the combined events (shaded area) is shown for different return periods of the margins (left column) and for different strengths of dependence between the two variables (top two rows). The value of χ equals zero for independent variables.**

Return period for each variable (years)	χ										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1.5	821	14.8	7.45	4.98	3.74	3.00	2.50	2.14	1.87	1.67	1.50
2	1460	19.8	9.95	6.65	4.99	4.00	3.33	2.86	2.50	2.22	2.00
5	9125	49.8	25.0	16.6	12.5	10.0	8.33	7.14	6.25	5.56	5.00
10	36500	99.8	50.0	33.3	25.0	20.0	16.7	14.3	12.5	11.1	10.0
50	912500	500	250	167	125	100	83.3	71.4	62.5	55.6	50.0
100	3650000	1000	500	333	250	200	167	143	125	111	100

Tables 5 and 6 show that there is a substantial difference between the results for return periods of joint events for independence compared with those for dependence, even when the dependence measure χ is as low as 0.1.

There are three points to remember when using the results shown in Tables 5 and 6 in conjunction with the values of χ derived in the present study.

(i) The values of χ presented in earlier Sections have been calculated for thresholds u which correspond to a return period of about 160 days, which is chosen so that at least moderately large events are being studied while ensuring that there are enough event-occurrences to form a stable estimate of dependence. In the underlying theory, χ is treated as a function of u, $\chi(u)$, where the possible variation with u reflects the notion that there may be either more or less dependence as the events considered become more extreme. Using the tables with the values of χ derived from this study is broadly equivalent to assuming that these values will apply for all thresholds. For example, if Table 6 is used to see the effect of χ on the return period of joint exceedances when each variable is required to exceed a 100-year return period this is effectively assuming that the value of χ will apply at that threshold. The limited study of the variation of $\chi(u)$ with u possible in this study can not be counted as conclusive. However, while a decrease in dependence with return period was suggested in many cases, the opposite tendency was apparent in some, before the measure dropped to zero at the highest return periods (Appendix B). Data availability obviously precludes study of this relationship for return periods greater than about 5 years. Similar results have been reported for other environmental variables by Coles et al. (2000).

(ii) The results in Tables 5 and 6 correspond to a certain underlying model and it is important to understand what that model is. Starting with Table 5, where results are expressed in terms of days, one can think of randomly selecting days from within the record and counting how many selections need to be made until one finds a day on which both variables exceed their respective thresholds. In the case of Table 6, where results are expressed in terms of years, the same model applies, but it is more natural to think in terms of a continuous record of days formed in blocks of years. The calculation of return period does not assume that adjacent days are statistically independent, but it does assume that all values are identically distributed. This means, in particular, that the calculations are based on a model where there are no seasonal effects. This is clearly unrealistic but the results should still be useful in illustrating the relative effects of different levels of dependence. The interconnection between the notions of seasonality and dependence has not been fully explored. It is possible for similar seasonal effects in two variables to given rise to an apparent dependence between the variables even if they are statistically independent once the seasonality is taken into account. Note that the tests of significance of χ used in this study do take the seasonality into account. They are based on permutations of years, keeping days fixed as a block within the year. Therefore, they are essentially tests of whether the observed value of χ is so large that it cannot be explained by the seasonal effects present if, after seasonality is accounted for, the two variates are assumed to be independent. There is clearly further room for complicating the study of dependence even more by allowing for the possibility that dependence might vary seasonally.

(iii) By choosing to look at the case where a joint event is counted as extreme only if both variates exceed given thresholds we have perhaps over-dramatised the difference in results between independence and a small level of dependence. Nevertheless, one of the commonest calculations made in joint probability studies must be to simply take the product of the exceedance probabilities for two variates to estimate the chance that both variates will exceed their thresholds simultaneously.

The effect of neglecting dependence is likely to be to underestimate maximum water levels of a given frequency. However, the extent of the error made will be influenced both by the importance of the dependence effect being neglected and on the otherwise soundness of the solution method used. Different parts of the river estuary will be influenced to different degrees by river flooding and sea surges, respectively. Thus, the return period of the combined events as described above does not indicate the return period of the resulting water levels in the estuary. However, a so called structure function contains a detailed description of how two input variables, such as river flow and sea surge, combine to influence the critical output variable, such as water level, at a particular location. Methods to estimate water levels in the fluvial-tidal reach of rivers have been described by e.g. Ibidapo-Obe and Beran (1988) and Reed (1999).

6. CONCLUSIONS

The dependence measure χ was used to estimate the dependence between extreme sea surge, river flow and precipitation, at a daily resolution. For same-variable dependence, surge shows the strongest spatial dependence and precipitation the weakest.

Dependence between river flow and daily maximum sea surge, significant at the 5% level, may be found at catchments spread along most of the south, west and north coastline. However, higher dependence (χ>0.1) is generally found in catchments in hilly areas with a southerly to westerly aspect. Here, precipitation in southwesterly airflow, which is generally the quadrant of prevailing winds, will be orographically enhanced as the first higher ground is encountered. The sloping catchments may respond quickly to the abundant rainfall, and the flow peak may arrive in the estuary on the same day as a large sea surge occurs.

There are three regions where surge-flow dependence generally exceeds χ>0.1: the western part of the English south coast, southern Wales, and around the Solway Firth. The generally low dependence on the eastern part of the south coast of England may be related to these being generally permeable, predominantly chalk, catchments which respond slowly to rainfall. Runoff may therefore not form on the same day as the surge occurs. The precipitation-surge analysis confirms that the breakdown in flow-surge dependence is related to catchment processes, as the precipitation-surge dependence is significant also for the eastern part of the south coast.

In order to reduce the influence of tide-surge interaction on the dependence analysis, the dependence between river flow and daily maximum surge occurring at high tide was estimated. The general pattern of areas with higher dependence is similar to that using the daily maximum surge.

Dependence between precipitation and river flow is stronger in Wales and northward, than in the south of England. This may reflect smaller soil moisture deficits for a longer part of the year in the north, resulting in a more direct relationship between precipitation and runoff, making the extremes occur on the same day.

Higher soil moisture deficits in summer, inhibiting direct runoff, may be the reason why flow-surge dependence in the very south is higher in winter than in summer. The upland areas in Wales and northward may be less affected by soil moisture deficits, and more influenced by the effects of the more southerly storm tracks in summer (crossing Great Britain), resulting in higher flow-surge dependence in these areas in summer than in winter. Flow-surge dependence in winter is similar to that for the whole year.

The dependence between river flow and daily maximum sea surge is often strongest when surge and flow occur on the same day. In general, dependence is strong also for flows lagged one day after the surge. The dependence between precipitation and daily maximum surge is strongest when they occur on the same day, and not particularly strong for any lag.

Cyclones resulting in only a high sea surge tend to move in a general easterly direction, and are often located just west of Great Britain when the maximum surge occurs. The storms track progressively to the south with decreasing latitude of the study area. They tend to have similar, low, central pressures to the storms resulting in both high river flow and sea surge. The deep depressions ensure a lifting of the sea level and the generation of strong winds that drive the water towards the coast. However, whereas precipitation tends to be slight and sometimes in frozen form when only a surge is produced, rainfall associated with events resulting in both high flow and surge tends to be continuous and sometimes heavy. The storms resulting in both high surge and flow tend to move more swiftly and in a more northeasterly direction than do storms causing only a high surge.

Cyclones resulting in only high river flow tend to be associated with weak and/or distantly located depressions. They are not able to cause much of a surge in the study areas, but rainfall at the fronts may be both continuous and, at times, heavy.

Indications are that the west coast from Wales up to the Solway Firth area, and possibly further north, experience a moderate strengthening of the flow-surge dependence in winters with a high North Atlantic Oscillation Index (NAOI) compared to winters with a low NAOI. The NAOI, which is an indicator of the main storm track location, is generally expected to shift towards its positive phase in future climate change scenarios. This finding supports the climate change impact study reported in Appendix C, assuming the UKCIP02 Medium-High emission scenario (SRES A2). Dependence between modelled sea surge and precipitation (used as a proxy for river flow) show significant increases at several locations around the British coast, except the southern east coast, in a warmer climate towards the end of the 21st century.

GLOSSARY OF TERMS

Atmosphere The gaseous portion of a planet; the planet's envelope of air (Lutgens and Tarbuck, 1992)

Atmospheric (air) pressure The force excerted by the weight of a column of air above a given point (Lutgens and Tarbuck, 1992).

Cold front The discontinuity at the forward edge of an advancing cold air mass that is displacing warmer air in its path (Lutgens and Tarbuck, 1992).

Coriolis effect The deflective effect of the earth's rotation on all free-moving objects, including the atmosphere and oceans. Deflection is to the right in the northern hemisphere and to the left in the southern hemisphere (Lutgens and Tarbuck, 1992).

Cyclone An area of low atmospheric pressure characterised by rotating and converging winds and ascending air (Lutgens and Tarbuck, 1992).

Front A boundary (discontinuity) separating air masses of different densities, one warmer and often higher in moisture content than the other (Lutgens and Tarbuck, 1992).

High tide The maximum tidal level reached during a tidal cycle. Ocean tides and most shelf sea tides are dominated by semidiurnal oscillations (Pugh, 1987).

Mid-latitude (or wave) cyclone A cyclone that forms and moves along a front. The circulation around the cyclone tends to produce a wavelike deformation of the front (Lutgens and Tarbuck, 1992).

Occluded front A front formed when a cold front overtakes a warm front (Lutgens and Tarbuck, 1992).

Orographic enhancement Orographic enhancement of precipitation refers to the generally higher precipitation associated with mountainous regions compared with surrounding lowlands. Processes involved include orographic lifting, the seeder/feeder mechanism, and triggering of convection (Gray and Seed, 2000). It is mainly on the windward side of the mountain that precipitation is enhanced. By the time the air reaches the leeward side, much of the moisture has been lost and precipitation is reduced. This is known as the rain shadow effect (Lutgens and Tarbuck, 1992).

Surge The difference between the total observed sea level and the predicted astronomical tide. It is also referred to as the "weather effect" or "meteorological residual", as it is influenced by winds and atmospheric pressure (Pugh, 1987).

Tide (or astronomical tide) The periodic movements of the sea level which are directly related in amplitude and phase to some periodic geophysical force. The dominant forcing is the variation of the gravitational field on the surface of the earth, caused by the regular movements of the moon-earth and earth-sun systems (Pugh, 1987).

Warm front The discontinuity at the forward edge of an advancing warm air mass that is displacing cooler air in its path (Lutgens and Tarbuck, 1992).

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APPENDIX A

EAST COAST STUDY REVISITED

Svensson and Jones (2000) carried out a dependence study between extreme sea surge, river flow and precipitation on the British east coast. The river flow and sea surge analysis of the study is revisited in this appendix, using a denser network of river flow stations, longer records and new analyses incorporating confidence intervals and sensitivity to changes in storm track.

A.1 DATA AND METHODS

The network of sea level stations is the same as used in the previous study (Table A1, Figure A1), using records 1963-1999. The network of 40 river flow gauges draining to the east coast used earlier was densified to comprise 58 gauges, with records in the period 1963-1999 (Table A2, Figure A1). A few of the catchments are nested because the more downstream stations have shorter records than the upstream ones. The same method for estimating the dependence measure χ was used as in the previous study, described also in Chapter 3 of this report.

Table A1 General information about the 8 sea level stations. The Easting and Northing coordinates are in the Great Britain national grid coordinate system. Missing data refer to the extracted daily maximum surge series.

Station	Easting (km)	Northing (km)	Mean daily maximum surge (mm)	Missing data (%)
Lerwick	447.8	1141.4	67	9.2
Wick	336.7	950.8	66	14.0
Aberdeen	395.2	805.9	89	21.6
North Shields	435.9	568.2	123	20.8
Immingham	519.9	416.7	177	3.9
Lowestoft	654.8	292.7	140	5.4
Sheerness	590.7	175.4	253	22.7
Dover	632.7	140.2	160	11.4

Table A2 General information about the 58 river flow stations. The Easting and Northing coordinates are in the Great Britain national grid coordinate system. Missing data: 0 denotes a complete record, and 0.0 denotes that less than 0.05% is missing.

Station	River	Location	Easting (km)	Northing (km)	Altitude (m)	Catchment area (km^2)	Mean river flow (m^3/s)	Missing data (%)
2001	Helmsdale	Kilphedir	299.7	918.1	17.0	551	12.9	32.4
4001	Conon	Moy Bridge	248.2	854.7	10.0	962	51.7	14.2
7002	Findhorn	Forres	301.8	858.3	6.8	782	19.3	0
7004	Nairn	Firhall	288.2	855.1	7.2	313	5.6	43.2
8006	Spey	Boat o Brig	331.8	851.8	43.1	2861	64.0	0
9002	Deveron	Muiresk	370.5	849.8	25.3	955	16.2	2.7
10003	Ythan	Ellon	394.7	830.3	3.8	523	7.6	55.1
11001	Don	Parkhill	388.7	814.1	32.4	1273	20.0	18.7
12001	Dee	Woodend	363.5	795.6	70.5	1370	36.8	0
12002	Dee	Park	379.8	798.3	22.6	1844	46.4	26.6
13007	North Esk	Logie Mill	369.9	764.0	10.6	732	19.0	35.1
14001	Eden	Kemback	341.5	715.8	6.2	307	3.9	12.8
14002	Dighty Water	Balmossie Mill	347.7	732.4	16.1	127	1.5	18.2
15006	Tay	Ballathie	314.7	736.7	26.2	4587	169.2	0
15013	Almond	Almondbank	306.8	725.8	20.4	175	5.0	0
16004	Earn	Forteviot Bridge	304.4	718.3	8.0	782	28.6	26.4
17002	Leven	Leven	336.9	700.6	8.7	424	6.4	17.8
18002	Devon	Glenochil	285.8	696.0	5.5	181	4.5	0
18003	Teith	Bridge of Teith	272.5	701.1	14.8	518	23.8	0.2
18011	Forth	Craigforth	277.5	695.5	3.7	1036	48.8	49.8
19001	Almond	Craigiehall	316.5	675.2	22.8	369	6.1	0
19006	Water of Leith	Murrayfield	322.8	673.2	37.5	107	1.5	0
19007	Esk	Musselburgh	333.9	672.3	3.3	330	4.1	0.0
20001	Tyne	East Linton	359.1	676.8	16.5	307	2.8	0.4
21009	Tweed	Norham	389.8	647.7	4.3	4390	78.2	0
22001	Coquet	Morwick	423.4	604.4	5.2	570	8.4	2.3
22006	Blyth	Hartford Bridge	424.3	580.0	24.6	269	2.1	11.0
23001	Tyne	Bywell	403.8	561.7	14.0	2176	45.2	0.8
24009	Wear	Chester le Street	428.3	551.2	5.5	1008	14.3	39.9
25001	Tees	Broken Scar	425.9	513.7	37.2	818	16.7	0.0
26002	Hull	Hempholme Lock	508.0	449.8	2.8	378	3.4	12.9
27002	Wharfe	Flint Mill Weir	442.2	447.3	13.7	759	17.2	0
27003	Aire	Beal Weir	453.5	425.5	5.5	1932	35.9	2.4
27021	Don	Doncaster	457.0	404.0	4.4	1256	16.1	4.6
28009	Trent	Colwick	462.0	339.9	16.0	7486	83.7	0
28022	Trent	North Muskham	480.1	360.1	5.0	8231	88.6	15.5
29001	Waithe Beck	Brigsley	525.3	401.6	15.7	108	0.3	0.3
29002	Great Eau	Claythorpe Mill	541.6	379.3	6.6	77	0.7	0.1
31002	Glen	Kates Br and King St Br	510.6	314.9	6.1	342	1.1	0.7
32001	Nene	Orton	516.6	297.2	3.4	1634	10.1	21.7
33006	Wissey	Northwold	577.1	296.5	5.3	275	1.7	10.4
33007	Nar	Marham	572.3	311.9	4.6	153	1.1	0.0
33024	Cam	Dernford	546.6	250.6	14.7	198	0.9	0.6
33039	Bedford Ouse	Roxton	516.0	253.5	15.7	1660	11.1	26.5
34003	Bure	Ingworth	619.2	329.6	12.2	165	1.1	0.1
34006	Waveney	Needham Mill	622.9	281.1	16.5	370	1.7	2.6
34013	Waveney	Ellingham Mill	636.4	291.7	1.6	670	0.6	49.5
34019	Bure	Horstead Mill	626.7	319.4	1.3	313	2.1	31.2
35004	Ore	Beversham Bridge	635.9	258.3	2.4	55	0.3	7.6

Station	River	Location	Easting (km)	Northing (km)	Altitude (m)	Catchment area (km^2)	Mean river flow (m^3/s)	Missing data (%)
35013	Blyth	Holton	640.6	276.9	12.3	93	0.4	20.4
36006	Stour	Langham	602.0	234.4	6.4	578	2.9	0
37001	Roding	Redbridge	541.5	188.4	5.7	303	1.9	0
37005	Colne	Lexden	596.2	226.1	8.2	238	1.0	0.1
37009	Brain	Guithavon Valley	581.8	214.7	16.2	61	0.4	0.1
37010	Blackwater	Appleford Bridge	584.5	215.8	14.6	247	1.3	0.0
39001	Thames	Kingston	517.7	169.8	4.7	9948	60.9	0
40011	Great Stour	Horton	611.6	155.4	12.5	345	3.1	5.0
40012	Darent	Hawley	555.1	171.8	11.2	191	0.6	2.5

A.2 RESULTS

Results are presented in tables, and graphically on maps where pairs of stations with dependence exceeding a particular value are connected by lines. Dependence is only estimated for neighbouring stations, see Appendix B for station-pairs.

A.2.1 Dependence between river flow and sea surge

Figure A2 shows dependence between river flow and daily maximum surge on the east coast of Great Britain. The overall pattern is similar to that found in the previous study, showing that the strongest dependence is found to the north of the Firth of Forth. Although located in the east of the country, these catchments comprise the first higher ground that precipitation in southwesterly airflow encounters, and precipitation is orographically enhanced. The sloping catchments may respond quickly to the abundant rainfall, and the flow peak may arrive in the estuary on the same day as a large sea surge occurs.

However, the denser network reveals that there are a few station-pairs with weak but significant dependence (at the 5% level) also in the south, to the north of the Thames estuary. In the previous study, this region only showed dependence for daily maximum sea surge occurring at high tide.

Figure A3 shows the dependence between river flow and daily maximum surge occurring at high tide. Dependence is significant for even more station-pairs in the south, the region where tide-surge interaction is prominent.

The estimated dependence, χ, and the associated 5% significance level and limits of the 90% confidence interval, for dependence between river flow and sea surge are shown in Tables B1 and B2 in Appendix B.

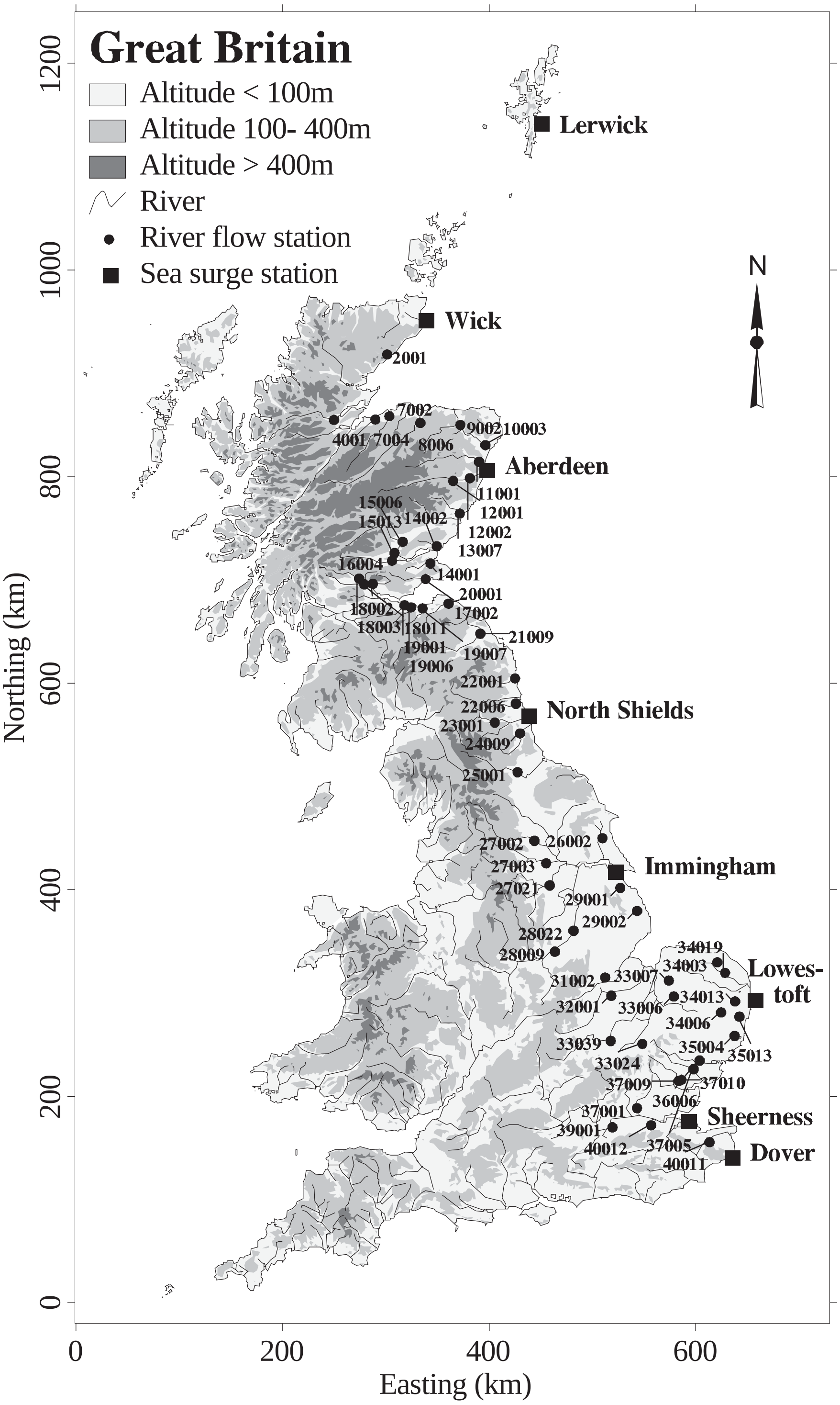

Figure A1 Location of sea level stations and river flow stations.

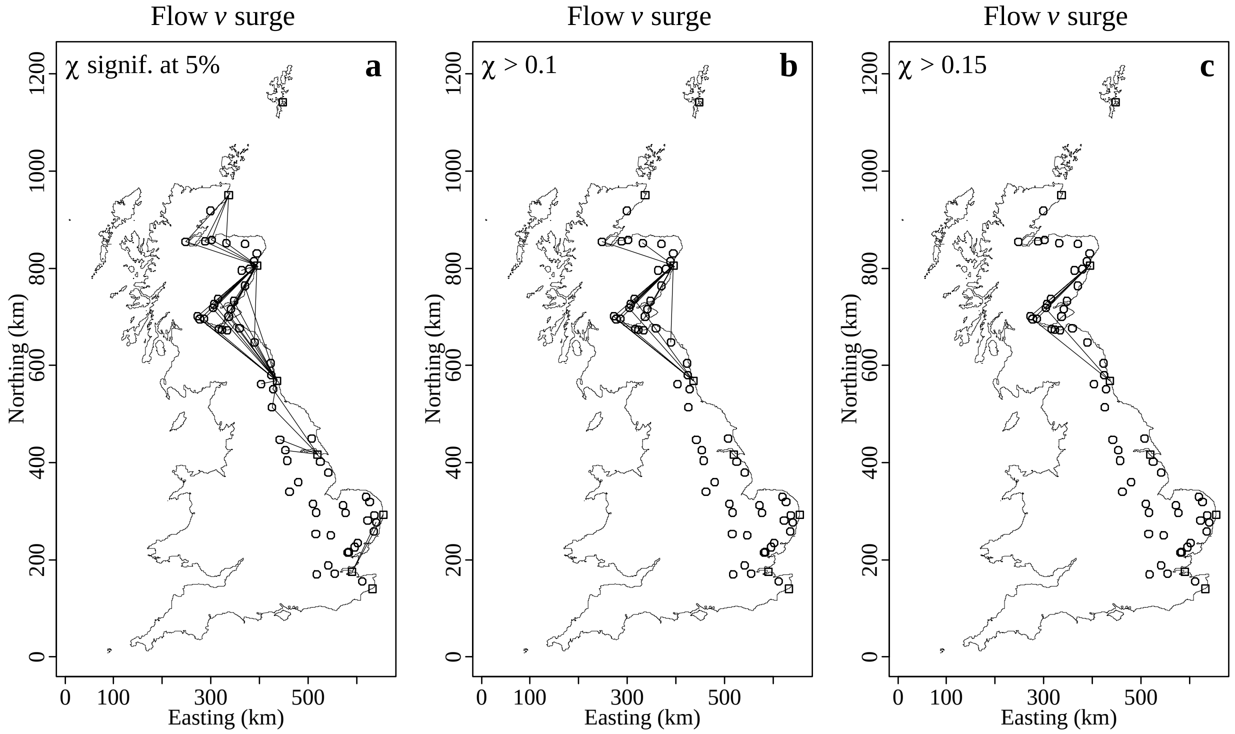

Figure A2 **Dependence between river flow and daily maximum sea surge. Lines connect neighbouring station-pairs with χ exceeding a) the 95% point (significant dependence), b) 0.1, and c) 0.15.**

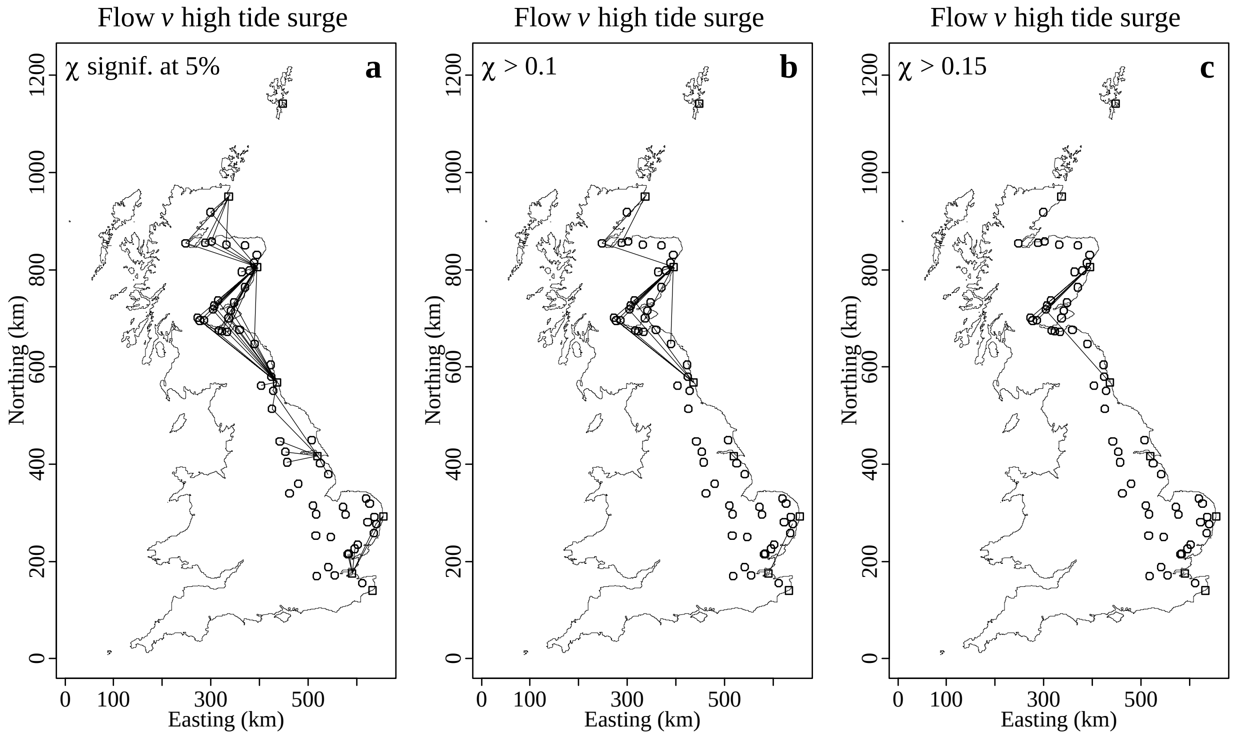

Figure A3 **Dependence between river flow and daily maximum sea surge occurring at high tide. Lines connect neighbouring station-pairs with χ exceeding a) the 95% point (significant dependence), b) 0.1, and c) 0.15.**

A.2.2 Sensitivity to storm track

The flow-surge dependence is largely influenced by the storm track of the depressions. The same study as for the south and west coast was applied to the new network of east coast stations, i.e. the sensitivity of the dependence measure χ to changes in storm track was investigated. Most global climate models suggest a shift towards the positive phase of the North Atlantic Oscillation Index (NAOI) in a future, warmer, climate (Gillett et al., 2002), and the difference in χ for twelve winters each of high and low NAOI was studied.

The differences in χ between high and low NAOI years are relatively modest, with 8 of 85 station-pairs having $|\chi_{diff}|$ exceeding 0.1. The results should be treated with some caution as there were 17 station-pairs for which dependence was not estimated because of too few data observations. However, when looking at the geographical spread of $|\chi_{diff}| > 0.05$ a pattern emerges. North of the Firth of Forth, the dependence between river flow and daily maximum surge tends to be higher in positive NAOI winters than in negative NAOI winters, whereas it is lower south of the Firth of Forth down to the Thames estuary.

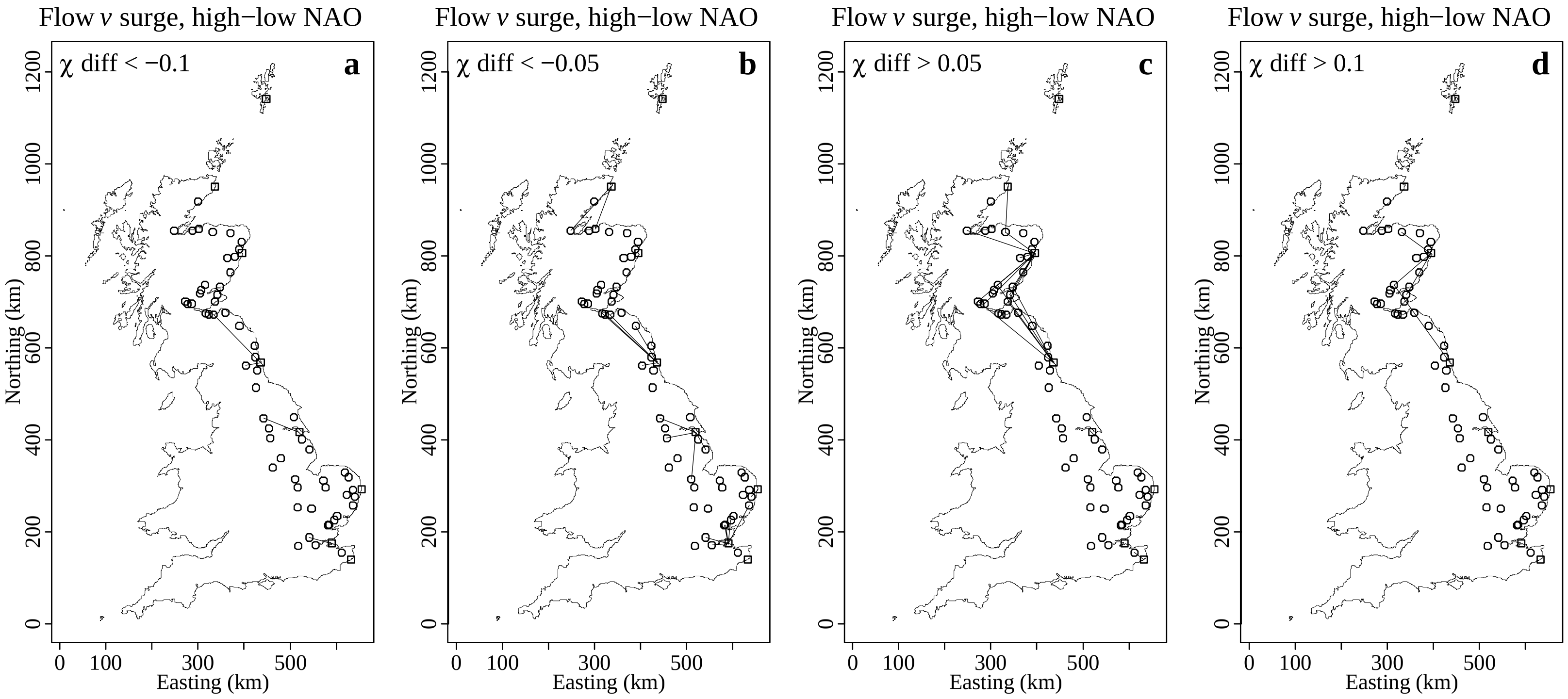

Figure A4 **Difference in dependence between high and low NAOI winters (χ for high NAOI winters minus χ for low NAOI winters), for neighbouring stations of river flow and daily maximum sea surge. Lines connect station-pairs with a difference in χ a) <–0.1, b) <-0.05, c) >0.05, and d) >0.1.**

APPENDIX B

TABLES OF DEPENDENCE BETWEEN EXTREME RIVER FLOW AND SEA SURGE AROUND THE COAST OF GREAT BRITAIN

This appendix contains tables of the dependence measure χ, values of χ corresponding to the 5% significance level and to the upper and lower limits of the 90% confidence interval, for dependence between observed extreme river flow and sea surge around the coast of Great Britain. The significance levels and confidence limits were derived using resampling techniques, keeping the data in intact blocks of one year. The independence criterion for setting the threshold for calculating χ was that peaks-over-threshold should be separated by at least 3 days.

Table B1 shows the dependence between daily mean river flow and daily maximum sea surge, and Table B2 shows the dependence between daily mean river flow and daily maximum sea surge occurring at high tide.

The tables list dependence between neighbouring stations only. That is, one surge station on either side of the river estuary is paired with the river flow station, unless the surge station is located in, or very near, the estuary in which case only that surge station is used. Because of the very short surge records for Portsmouth and Weymouth, the river flow stations between these surge stations have also been paired with the long surge record at Newlyn. The two river flow gauges on the north coast, 96001 and 97002, have been paired with surges at Ullapool, Lerwick and Wick. Note that Liverpool has two surge records, Princes Pier and Gladstone Dock. River flow stations between Heysham and Holyhead have therefore also been paired with (up to) three surge stations.

The general characteristics of the river flow and sea surge stations used are listed in Tables 1 and 2 in the main report (south, west and north coasts) and Tables A1 and A2 in Appendix A (east coast). Locations of the stations are shown in Figures 1 and A1, in the main report and Appendix A, respectively.

Table B1 **Dependence measure χ, values of χ corresponding to the 5% significance level and to the upper and lower limits of the 90% confidence interval, for dependence between extreme daily mean river flow and daily maximum sea surge.**

Flow station	Surge station	χ	5% signif. level	90% conf. interval, lower limit	90% conf. interval, upper limit	Flow station	Surge station	χ	5% signif. level	90% conf. interval, lower limit	90% conf. interval, upper limit
2001	Wick	0.03	0.04	-0.01	0.06	19007	Aberdeen	0.02	0.03	-0.01	0.06
2001	Aberdeen	0.02	0.03	-0.01	0.11	19007	North Shields	0.00	0.04	-0.01	0.04
4001	Wick	0.10	0.04	0.03	0.14	20001	Aberdeen	0.00	0.03	-0.01	0.04
4001	Aberdeen	0.11	0.04	0.06	0.17	20001	North Shields	0.00	0.02	-0.01	0.03
7002	Wick	0.03	0.02	0.01	0.08	21009	Aberdeen	0.12	0.03	0.06	0.21
7002	Aberdeen	0.03	0.02	-0.01	0.08	21009	North Shields	0.09	0.03	0.03	0.18
7004	Wick	0.10	0.05	0.04	0.15	22001	Aberdeen	0.00	0.02	-0.01	0.05
7004	Aberdeen	0.09	0.05	0.03	0.19	22001	North Shields	0.00	0.03	-0.01	0.04
8006	Wick	0.09	0.03	0.03	0.13	22006	Aberdeen	-0.01	0.03	-0.01	-0.01
8006	Aberdeen	0.11	0.03	0.04	0.16	22006	North Shields	-0.01	0.02	-0.01	-0.01
9002	Wick	0.00	0.02	-0.01	0.02	23001	North Shields	0.04	0.03	0.01	0.12
9002	Aberdeen	0.00	0.02	-0.01	0.03	24009	North Shields	0.04	0.03	-0.01	0.10
10003	Wick	0.01	0.04	-0.01	0.05	24009	Immingham	0.06	0.03	-0.01	0.12
10003	Aberdeen	0.01	0.04	-0.01	0.04	25001	North Shields	0.05	0.03	0.02	0.10
11001	Aberdeen	0.00	0.03	-0.01	0.02	25001	Immingham	0.03	0.02	0.00	0.08
12001	Aberdeen	0.10	0.03	0.05	0.17	26002	Immingham	0.01	0.03	-0.01	0.04
12002	Aberdeen	0.08	0.03	0.04	0.17	27002	Immingham	0.08	0.02	0.02	0.13
13007	Aberdeen	0.04	0.03	-0.01	0.12	27003	Immingham	0.05	0.03	0.01	0.07
13007	North Shields	0.03	0.02	-0.01	0.09	27021	Immingham	0.01	0.03	-0.01	0.03
14001	Aberdeen	0.12	0.04	0.05	0.20	28009	Immingham	0.00	0.04	-0.01	0.01
14001	North Shields	0.09	0.03	0.00	0.20	28022	Immingham	-0.01	0.03	-0.01	-0.01
14002	Aberdeen	0.06	0.04	-0.01	0.16	29001	Immingham	-0.01	0.03	-0.01	0.01
14002	North Shields	0.06	0.03	-0.01	0.16	29002	Immingham	0.00	0.04	-0.01	0.02
15006	Aberdeen	0.18	0.04	0.12	0.24	29002	Lowestoft	0.02	0.03	0.00	0.05
15006	North Shields	0.15	0.03	0.08	0.23	31002	Immingham	0.00	0.02	-0.01	0.02
15013	Aberdeen	0.14	0.03	0.06	0.23	31002	Lowestoft	0.01	0.03	-0.01	0.04
15013	North Shields	0.09	0.03	0.02	0.17	32001	Immingham	-0.01	0.03	-0.01	0.01
16004	Aberdeen	0.28	0.04	0.15	0.36	32001	Lowestoft	-0.01	0.03	-0.01	0.01
16004	North Shields	0.16	0.04	0.07	0.28	33006	Immingham	-0.01	0.03	-0.01	0.00
17002	Aberdeen	0.13	0.05	0.05	0.20	33006	Lowestoft	-0.01	0.03	-0.01	0.02
17002	North Shields	0.07	0.04	0.00	0.16	33007	Immingham	0.00	0.03	-0.01	0.01
18002	Aberdeen	0.20	0.04	0.11	0.26	33007	Lowestoft	0.01	0.03	-0.01	0.03
18002	North Shields	0.11	0.03	0.04	0.20	33024	Immingham	-0.01	0.03	-0.01	-0.01
18003	Aberdeen	0.20	0.04	0.11	0.28	33024	Lowestoft	0.01	0.03	-0.01	0.04
18003	North Shields	0.13	0.03	0.05	0.24	33039	Immingham	-0.01	0.03	-0.01	-0.01
18011	Aberdeen	0.22	0.06	0.09	0.30	33039	Lowestoft	-0.01	0.03	-0.01	-0.01
18011	North Shields	0.16	0.06	0.05	0.28	34003	Immingham	0.01	0.03	-0.01	0.03
19001	Aberdeen	0.06	0.03	0.02	0.10	34003	Lowestoft	0.01	0.03	-0.01	0.05
19001	North Shields	0.02	0.03	-0.01	0.05	34006	Immingham	0.00	0.03	-0.01	0.01
19006	Aberdeen	0.05	0.03	0.00	0.09	34006	Lowestoft	0.01	0.03	0.00	0.04
19006	North Shields	0.00	0.03	-0.01	0.04	34013	Immingham	0.01	0.08	-0.01	0.03

Table B1 Continued.

Flow station	Surge station	χ	5% signif. level	90% conf. inter-val, lower limit	90% conf. inter-val, upper limit	Flow station	Surge station	χ	5% signif. level	90% conf. inter-val, lower limit	90% conf. inter-val, upper limit
34013	Lowestoft	-0.01	0.05	-0.01	-0.01	44001	Newlyn	0.07	0.07	0.02	0.13
34019	Immingham	-0.01	0.03	-0.01	0.01	45001	Weymouth	0.13	0.06	-0.01	0.26
34019	Lowestoft	0.00	0.04	-0.01	0.03	45001	Newlyn	0.07	0.05	0.03	0.12
35004	Lowestoft	0.03	0.03	0.00	0.08	45005	Weymouth	0.24	0.05	0.07	0.38
35004	Sheerness	0.06	0.04	0.01	0.10	45005	Newlyn	0.19	0.04	0.12	0.25
35013	Lowestoft	0.01	0.03	-0.01	0.06	46002	Weymouth	0.25	0.07	0.14	0.39
35013	Sheerness	0.05	0.04	0.00	0.09	46002	Newlyn	0.23	0.05	0.17	0.28
36006	Lowestoft	0.00	0.03	-0.01	0.01	46003	Weymouth	0.16	0.06	-0.01	0.30
36006	Sheerness	0.00	0.04	-0.01	0.02	46003	Newlyn	0.14	0.05	0.09	0.19
37001	Sheerness	0.01	0.04	0.00	0.04	47001	Weymouth	0.20	0.05	0.07	0.32
37005	Lowestoft	0.02	0.03	0.00	0.04	47001	Newlyn	0.11	0.04	0.05	0.17
37005	Sheerness	0.03	0.04	0.00	0.07	47004	Weymouth	0.24	0.06	0.08	0.42
37009	Lowestoft	0.01	0.03	-0.01	0.04	47004	Newlyn	0.16	0.05	0.09	0.22
37009	Sheerness	0.02	0.03	0.00	0.06	47007	Weymouth	0.18	0.06	0.05	0.35
37010	Lowestoft	0.02	0.03	0.00	0.04	47007	Newlyn	0.08	0.04	0.05	0.14
37010	Sheerness	0.04	0.04	0.00	0.07	48007	Weymouth	0.20	0.08	0.07	0.28
39001	Sheerness	0.00	0.04	-0.01	0.02	48007	Newlyn	0.10	0.06	0.06	0.15
40011	Sheerness	0.00	0.03	-0.01	0.03	48011	Weymouth	0.25	0.05	0.10	0.35
40011	Dover	0.01	0.04	0.00	0.05	48011	Newlyn	0.17	0.05	0.09	0.24
40012	Sheerness	0.00	0.04	-0.01	0.02	49001	Newlyn	0.16	0.04	0.09	0.23
40021	Dover	-0.01	0.04	-0.01	0.03	49001	Ilfracombe	0.06	0.04	0.01	0.13
40021	Newhaven	0.15	0.07	0.05	0.29	49002	Newlyn	0.09	0.05	0.06	0.15
41004	Dover	0.06	0.05	0.00	0.10	49002	Ilfracombe	0.03	0.05	-0.01	0.08
41004	Newhaven	-0.01	0.05	-0.01	0.15	50001	Newlyn	0.07	0.05	0.04	0.11
41017	Dover	0.03	0.03	0.00	0.06	50001	Ilfracombe	0.05	0.03	0.01	0.12
41017	Newhaven	0.13	0.05	0.05	0.23	50002	Newlyn	0.06	0.05	0.01	0.10
41023	Newhaven	0.01	0.04	-0.01	0.05	50002	Ilfracombe	0.03	0.03	-0.01	0.09
41023	Portsmouth	0.04	0.06	0.01	0.10	51003	Ilfracombe	0.09	0.04	0.02	0.13
42003	Portsmouth	0.23	0.07	0.08	0.34	51003	Avonmouth	0.08	0.06	0.02	0.15
42003	Weymouth	0.14	0.07	-0.01	0.25	52009	Ilfracombe	0.04	0.03	-0.01	0.08
42003	Newlyn	0.06	0.03	0.04	0.13	52009	Avonmouth	0.01	0.04	-0.01	0.13
42004	Portsmouth	0.06	0.07	-0.01	0.15	53018	Avonmouth	0.11	0.03	0.04	0.18
42004	Weymouth	0.07	0.07	-0.01	0.15	54001	Avonmouth	0.05	0.04	0.02	0.11
42004	Newlyn	0.03	0.05	0.00	0.06	54032	Avonmouth	0.06	0.04	0.01	0.11
42006	Portsmouth	0.06	0.06	0.03	0.10	55023	Avonmouth	0.10	0.03	0.04	0.18
42006	Newlyn	0.03	0.06	0.00	0.05	56001	Avonmouth	0.21	0.04	0.13	0.30
43021	Portsmouth	0.03	0.06	-0.01	0.11	56002	Avonmouth	0.22	0.06	0.10	0.30
43021	Weymouth	0.07	0.08	-0.01	0.12	57005	Avonmouth	0.14	0.05	0.05	0.20
43021	Newlyn	0.01	0.07	-0.01	0.05	58001	Avonmouth	0.05	0.04	-0.01	0.11
44001	Portsmouth	0.13	0.10	0.03	0.24	58001	Milford Haven	0.06	0.04	0.00	0.09
44001	Weymouth	0.12	0.11	0.01	0.20	59001	Avonmouth	0.08	0.04	0.01	0.14

Table B1 Continued.

Flow station	Surge station	χ	5% signif. level	90% conf. inter-val, lower limit	90% conf. inter-val, upper limit	Flow station	Surge station	χ	5% signif. level	90% conf. inter-val, lower limit	90% conf. inter-val, upper limit
59001	Milford Haven	0.13	0.03	0.06	0.18	73005	Portpatrick	0.08	0.04	0.04	0.14
60003	Avonmouth	0.11	0.04	0.02	0.21	74001	Heysham	0.09	0.02	0.03	0.13
60003	Milford Haven	0.13	0.04	0.06	0.20	74001	Portpatrick	0.08	0.03	0.04	0.14
60010	Avonmouth	0.13	0.04	0.05	0.20	74006	Heysham	0.03	0.02	0.00	0.07
60010	Milford Haven	0.15	0.03	0.06	0.19	74006	Portpatrick	0.03	0.02	-0.01	0.07
61002	Milford Haven	0.14	0.03	0.06	0.19	75002	Heysham	0.07	0.04	0.04	0.11
62001	Fishguard	0.14	0.03	0.08	0.20	75002	Portpatrick	0.13	0.03	0.06	0.15
62001	Holyhead	0.09	0.04	0.03	0.18	76007	Heysham	0.15	0.05	0.09	0.20
63001	Fishguard	0.04	0.03	0.01	0.07	76007	Portpatrick	0.09	0.04	0.05	0.14
63001	Holyhead	0.03	0.02	-0.01	0.07	77001	Heysham	0.12	0.04	0.06	0.18
64006	Fishguard	0.02	0.02	-0.01	0.06	77001	Portpatrick	0.13	0.03	0.08	0.20
64006	Holyhead	-0.01	0.02	-0.01	0.04	78003	Heysham	0.11	0.03	0.06	0.20
65001	Fishguard	0.04	0.03	0.01	0.08	78003	Portpatrick	0.14	0.03	0.10	0.20
65001	Holyhead	0.06	0.02	0.02	0.13	79002	Heysham	0.19	0.02	0.10	0.27
66001	Holyhead	0.10	0.05	0.04	0.17	79002	Portpatrick	0.20	0.03	0.12	0.28
66001	Liverpool P P	0.05	0.04	0.03	0.10	79005	Heysham	0.14	0.03	0.10	0.23
66001	Liverpool G D	0.07	0.06	0.02	0.14	79005	Portpatrick	0.15	0.03	0.08	0.22
67015	Holyhead	0.13	0.05	0.05	0.22	81002	Heysham	0.07	0.02	0.03	0.10
67015	Liverpool P P	0.08	0.04	0.04	0.14	81002	Portpatrick	0.11	0.03	0.06	0.17
67015	Liverpool G D	0.15	0.09	0.08	0.24	82001	Portpatrick	0.13	0.02	0.08	0.20
68020	Holyhead	-0.01	0.04	-0.01	0.03	82001	Millport	0.10	0.03	0.05	0.18
68020	Liverpool G D	-0.01	0.08	-0.01	0.06	83005	Portpatrick	0.02	0.04	-0.01	0.07
69002	Liverpool P P	0.10	0.04	0.06	0.17	83005	Millport	0.01	0.05	-0.01	0.06
69002	Liverpool G D	0.09	0.06	0.04	0.24	84001	Millport	0.04	0.04	-0.01	0.10
69007	Liverpool P P	-0.01	0.06	-0.01	-0.01	84013	Millport	0.10	0.05	0.01	0.14
69007	Liverpool G D	0.06	0.07	-0.01	0.14	85001	Millport	0.05	0.04	0.02	0.11
70004	Liverpool P P	0.06	0.04	-0.01	0.16	86001	Millport	0.03	0.03	-0.01	0.07
70004	Liverpool G D	0.04	0.07	-0.01	0.22	93001	Tobermory	0.02	0.07	-0.01	0.06
70004	Heysham	0.03	0.04	-0.01	0.07	93001	Ullapool	0.07	0.07	0.01	0.12
71001	Liverpool P P	0.13	0.03	0.08	0.19	94001	Tobermory	0.05	0.09	-0.01	0.11
71001	Liverpool G D	0.10	0.04	-0.01	0.17	94001	Ullapool	0.10	0.06	0.04	0.16
71001	Heysham	0.09	0.03	0.04	0.14	95001	Ullapool	0.05	0.06	0.00	0.14
72004	Liverpool P P	0.16	0.04	0.08	0.27	95001	Wick	0.04	0.05	-0.01	0.09
72004	Liverpool G D	0.12	0.04	-0.01	0.23	95002	Ullapool	0.09	0.06	0.01	0.19
72004	Heysham	0.11	0.03	0.04	0.16	96001	Ullapool	0.02	0.04	-0.01	0.07
72008	Liverpool P P	0.09	0.04	0.01	0.18	96001	Wick	0.03	0.03	-0.01	0.06
72008	Liverpool G D	-0.01	0.07	-0.01	0.08	96001	Lerwick	0.03	0.04	-0.01	0.07
72008	Heysham	0.03	0.02	0.00	0.07	97002	Ullapool	0.01	0.03	-0.01	0.06
73002	Heysham	0.05	0.03	0.03	0.10	97002	Wick	0.00	0.03	-0.01	0.04
73002	Portpatrick	0.05	0.04	0.03	0.10	97002	Lerwick	0.05	0.04	-0.01	0.09
73005	Heysham	0.11	0.03	0.05	0.21						

Table B2 **Dependence measure χ, values of χ corresponding to the 5% significance level and to the upper and lower limits of the 90% confidence interval, for dependence between extreme daily mean river flow and daily maximum sea surge occurring at high tide.**

Flow station	Surge station	χ	5% signif. level	90% conf. interval, lower limit	90% conf. interval, upper limit
2001	Wick	0.05	0.04	0.01	0.11
2001	Aberdeen	0.04	0.03	-0.01	0.09
4001	Wick	0.12	0.03	0.05	0.19
4001	Aberdeen	0.10	0.04	0.04	0.16
7002	Wick	0.04	0.02	0.01	0.10
7002	Aberdeen	0.06	0.03	0.02	0.10
7004	Wick	0.13	0.04	0.07	0.18
7004	Aberdeen	0.10	0.04	0.03	0.15
8006	Wick	0.07	0.03	0.02	0.11
8006	Aberdeen	0.08	0.03	0.04	0.13
9002	Wick	0.00	0.02	-0.01	0.02
9002	Aberdeen	0.01	0.02	-0.01	0.03
10003	Wick	0.01	0.06	-0.01	0.05
10003	Aberdeen	0.04	0.04	-0.01	0.07
11001	Aberdeen	0.03	0.03	-0.01	0.08
12001	Aberdeen	0.10	0.03	0.06	0.17
12002	Aberdeen	0.07	0.03	0.04	0.13
13007	Aberdeen	0.02	0.02	-0.01	0.09
13007	North Shields	0.02	0.02	-0.01	0.08
14001	Aberdeen	0.06	0.04	0.02	0.14
14001	North Shields	0.05	0.03	-0.01	0.14
14002	Aberdeen	0.05	0.04	0.00	0.10
14002	North Shields	0.05	0.03	-0.01	0.12
15006	Aberdeen	0.17	0.03	0.12	0.22
15006	North Shields	0.10	0.03	0.07	0.17
15013	Aberdeen	0.11	0.03	0.06	0.19
15013	North Shields	0.08	0.03	0.03	0.13
16004	Aberdeen	0.23	0.04	0.15	0.30
16004	North Shields	0.16	0.04	0.07	0.24
17002	Aberdeen	0.11	0.04	0.04	0.17
17002	North Shields	0.07	0.05	0.02	0.13
18002	Aberdeen	0.16	0.04	0.10	0.23
18002	North Shields	0.13	0.04	0.06	0.22
18003	Aberdeen	0.19	0.04	0.15	0.28
18003	North Shields	0.13	0.04	0.07	0.20
18011	Aberdeen	0.18	0.04	0.10	0.24
18011	North Shields	0.12	0.05	0.06	0.21
19001	Aberdeen	0.03	0.03	0.00	0.11
19001	North Shields	0.01	0.03	-0.01	0.04
19006	Aberdeen	0.03	0.03	-0.01	0.07
19006	North Shields	0.00	0.03	-0.01	0.03
19007	Aberdeen	0.04	0.03	0.00	0.09
19007	North Shields	0.03	0.03	0.00	0.08
20001	Aberdeen	0.02	0.02	-0.01	0.04
20001	North Shields	-0.01	0.02	-0.01	-0.01
21009	Aberdeen	0.11	0.03	0.07	0.19
21009	North Shields	0.08	0.03	0.03	0.13
22001	Aberdeen	0.01	0.04	-0.01	0.04
22001	North Shields	-0.01	0.03	-0.01	0.01
22006	Aberdeen	-0.01	0.04	-0.01	-0.01
22006	North Shields	-0.01	0.03	-0.01	-0.01
23001	North Shields	0.06	0.03	0.03	0.10
24009	North Shields	0.04	0.03	-0.01	0.08
24009	Immingham	0.04	0.03	0.01	0.08
25001	North Shields	0.04	0.03	0.02	0.09
25001	Immingham	0.03	0.02	0.00	0.07
26002	Immingham	0.01	0.03	-0.01	0.03
27002	Immingham	0.06	0.02	0.03	0.11
27003	Immingham	0.06	0.03	0.02	0.10
27021	Immingham	0.03	0.03	0.00	0.05
28009	Immingham	0.00	0.03	-0.01	0.02
28022	Immingham	0.00	0.03	-0.01	0.02
29001	Immingham	0.02	0.02	-0.01	0.04
29002	Immingham	0.04	0.03	0.01	0.06
29002	Lowestoft	0.03	0.03	0.00	0.06
31002	Immingham	0.01	0.02	-0.01	0.04
31002	Lowestoft	0.01	0.02	-0.01	0.04
32001	Immingham	0.01	0.03	0.00	0.03
32001	Lowestoft	0.00	0.03	-0.01	0.01
33006	Immingham	0.00	0.03	-0.01	0.02
33006	Lowestoft	-0.01	0.03	-0.01	0.01
33007	Immingham	0.00	0.03	-0.01	0.02
33007	Lowestoft	0.00	0.03	-0.01	0.03
33024	Immingham	0.01	0.03	-0.01	0.04
33024	Lowestoft	0.01	0.03	0.00	0.04
33039	Immingham	-0.01	0.03	-0.01	0.01
33039	Lowestoft	-0.01	0.03	-0.01	-0.01
34003	Immingham	0.00	0.03	-0.01	0.03
34003	Lowestoft	0.02	0.02	-0.01	0.05
34006	Immingham	0.00	0.04	-0.01	0.03
34006	Lowestoft	0.01	0.03	0.00	0.04
34013	Immingham	0.01	0.05	-0.01	0.03

Table B2 Continued.

Flow station	Surge station	χ	5% signif. level	90% conf. interval, lower limit	90% conf. interval, upper limit	Flow station	Surge station	χ	5% signif. level	90% conf. interval, lower limit	90% conf. interval, upper limit
34013	Lowestoft	-0.01	0.05	-0.01	-0.01	44001	Newlyn	0.09	0.06	0.04	0.15
34019	Immingham	-0.01	0.04	-0.01	0.00	45001	Weymouth	0.12	0.06	0.02	0.21
34019	Lowestoft	0.00	0.03	-0.01	0.03	45001	Newlyn	0.08	0.05	0.03	0.14
35004	Lowestoft	0.05	0.03	0.00	0.09	45005	Weymouth	0.22	0.05	0.03	0.35
35004	Sheerness	0.08	0.03	0.03	0.11	45005	Newlyn	0.18	0.03	0.11	0.24
35013	Lowestoft	0.04	0.03	0.00	0.08	46002	Weymouth	0.18	0.07	0.07	0.31
35013	Sheerness	0.10	0.04	0.03	0.15	46002	Newlyn	0.20	0.05	0.13	0.25
36006	Lowestoft	0.00	0.03	-0.01	0.01	46003	Weymouth	0.10	0.07	-0.01	0.21
36006	Sheerness	0.01	0.03	-0.01	0.05	46003	Newlyn	0.12	0.05	0.08	0.19
37001	Sheerness	0.03	0.03	0.00	0.07	47001	Weymouth	0.18	0.05	0.05	0.28
37005	Lowestoft	0.02	0.03	-0.01	0.04	47001	Newlyn	0.14	0.04	0.07	0.21
37005	Sheerness	0.06	0.03	0.01	0.11	47004	Weymouth	0.25	0.09	0.10	0.39
37009	Lowestoft	0.01	0.03	-0.01	0.03	47004	Newlyn	0.17	0.05	0.09	0.23
37009	Sheerness	0.04	0.03	0.00	0.08	47007	Weymouth	0.17	0.09	0.03	0.40
37010	Lowestoft	0.02	0.02	0.00	0.04	47007	Newlyn	0.13	0.05	0.08	0.20
37010	Sheerness	0.05	0.04	0.01	0.08	48007	Weymouth	0.19	0.09	0.09	0.30
39001	Sheerness	0.00	0.04	-0.01	0.01	48007	Newlyn	0.13	0.05	0.08	0.18
40011	Sheerness	0.00	0.03	-0.01	0.02	48011	Weymouth	0.26	0.06	0.11	0.38
40011	Dover	0.00	0.03	-0.01	0.02	48011	Newlyn	0.16	0.05	0.08	0.23
40012	Sheerness	0.01	0.03	-0.01	0.04	49001	Newlyn	0.16	0.03	0.10	0.23
40021	Dover	-0.01	0.04	-0.01	0.04	49001	Ilfracombe	0.08	0.03	0.03	0.15
40021	Newhaven	0.02	0.08	-0.01	0.11	49002	Newlyn	0.11	0.05	0.07	0.17
41004	Dover	0.01	0.04	-0.01	0.05	49002	Ilfracombe	0.08	0.04	0.04	0.13
41004	Newhaven	0.04	0.05	-0.01	0.12	50001	Newlyn	0.07	0.04	0.04	0.12
41017	Dover	0.01	0.04	-0.01	0.05	50001	Ilfracombe	0.03	0.03	-0.01	0.12
41017	Newhaven	0.04	0.05	-0.01	0.07	50002	Newlyn	0.07	0.04	0.03	0.11
41023	Newhaven	0.02	0.06	-0.01	0.05	50002	Ilfracombe	0.05	0.04	0.01	0.16
41023	Portsmouth	0.04	0.07	0.00	0.08	51003	Ilfracombe	0.05	0.04	0.01	0.15
42003	Portsmouth	0.11	0.07	0.05	0.27	51003	Avonmouth	0.08	0.04	0.02	0.11
42003	Weymouth	0.17	0.06	0.06	0.34	52009	Ilfracombe	0.02	0.02	-0.01	0.08
42003	Newlyn	0.06	0.04	0.02	0.15	52009	Avonmouth	0.02	0.04	-0.01	0.09
42004	Portsmouth	0.04	0.08	-0.01	0.18	53018	Avonmouth	0.10	0.03	0.01	0.12
42004	Weymouth	0.06	0.03	-0.01	0.13	54001	Avonmouth	0.08	0.04	0.02	0.11
42004	Newlyn	0.05	0.04	0.02	0.07	54032	Avonmouth	0.06	0.05	0.01	0.10
42006	Portsmouth	0.06	0.07	0.00	0.13	55023	Avonmouth	0.06	0.04	0.01	0.10
42006	Newlyn	0.05	0.05	0.03	0.07	56001	Avonmouth	0.14	0.04	0.05	0.23
43021	Portsmouth	0.06	0.08	0.00	0.14	56002	Avonmouth	0.13	0.08	0.04	0.20
43021	Weymouth	0.04	0.06	0.00	0.08	57005	Avonmouth	0.10	0.05	0.04	0.24
43021	Newlyn	0.05	0.06	0.02	0.08	58001	Avonmouth	0.05	0.04	-0.01	0.13
44001	Portsmouth	0.11	0.10	0.01	0.27	58001	Milford Haven	0.06	0.03	0.00	0.09
44001	Weymouth	0.13	0.07	0.01	0.24	59001	Avonmouth	0.08	0.04	0.02	0.21

Table B2 Continued.

Flow station	Surge station	χ	5% signif. level	90% conf. interval, lower limit	90% conf. interval, upper limit	Flow station	Surge station	χ	5% signif. level	90% conf. interval, lower limit	90% conf. interval, upper limit
59001	Milford Haven	0.13	0.03	0.06	0.17	73005	Portpatrick	0.11	0.05	0.07	0.17
60003	Avonmouth	0.07	0.06	0.01	0.14	74001	Heysham	0.09	0.02	0.04	0.14
60003	Milford Haven	0.12	0.04	0.02	0.22	74001	Portpatrick	0.09	0.03	0.04	0.14
60010	Avonmouth	0.09	0.06	0.01	0.16	74006	Heysham	0.04	0.02	0.00	0.08
60010	Milford Haven	0.14	0.03	0.06	0.18	74006	Portpatrick	0.05	0.02	0.01	0.10
61002	Milford Haven	0.12	0.04	0.05	0.18	75002	Heysham	0.08	0.04	0.03	0.11
62001	Fishguard	0.13	0.04	0.07	0.19	75002	Portpatrick	0.12	0.03	0.06	0.15
62001	Holyhead	0.14	0.04	0.07	0.19	76007	Heysham	0.14	0.04	0.06	0.21
63001	Fishguard	0.04	0.03	0.01	0.09	76007	Portpatrick	0.08	0.04	0.05	0.13
63001	Holyhead	0.03	0.02	-0.01	0.06	77001	Heysham	0.11	0.03	0.06	0.17
64006	Fishguard	0.03	0.02	0.00	0.08	77001	Portpatrick	0.11	0.04	0.07	0.21
64006	Holyhead	0.02	0.01	-0.01	0.06	78003	Heysham	0.10	0.03	0.05	0.16
65001	Fishguard	0.06	0.03	0.03	0.11	78003	Portpatrick	0.13	0.03	0.08	0.19
65001	Holyhead	0.09	0.04	0.04	0.14	79002	Heysham	0.17	0.02	0.11	0.21
66001	Holyhead	0.08	0.03	0.01	0.16	79002	Portpatrick	0.19	0.03	0.10	0.25
66001	Liverpool P P	0.04	0.04	0.01	0.09	79005	Heysham	0.11	0.02	0.06	0.19
66001	Liverpool G D	0.09	0.06	-0.01	0.17	79005	Portpatrick	0.14	0.03	0.09	0.21
67015	Holyhead	0.16	0.04	0.08	0.24	81002	Heysham	0.05	0.03	0.02	0.10
67015	Liverpool P P	0.11	0.04	0.05	0.20	81002	Portpatrick	0.10	0.03	0.03	0.13
67015	Liverpool G D	0.15	0.09	0.03	0.26	82001	Portpatrick	0.12	0.03	0.06	0.18
68020	Holyhead	-0.01	0.03	-0.01	0.03	82001	Millport	0.09	0.03	0.01	0.15
68020	Liverpool G D	-0.01	0.05	-0.01	-0.01	83005	Portpatrick	0.05	0.03	0.01	0.09
69002	Liverpool P P	0.11	0.04	0.03	0.15	83005	Millport	0.01	0.03	-0.01	0.06
69002	Liverpool G D	0.09	0.07	-0.01	0.23	84001	Millport	0.06	0.05	0.01	0.10
69007	Liverpool P P	0.03	0.04	-0.01	0.08	84013	Millport	0.07	0.03	0.01	0.11
69007	Liverpool G D	0.10	0.04	-0.01	0.19	85001	Millport	0.06	0.04	0.03	0.11
70004	Liverpool P P	0.03	0.06	-0.01	0.20	86001	Millport	0.03	0.03	-0.01	0.10
70004	Liverpool G D	0.04	0.04	-0.01	0.19	93001	Tobermory	0.05	0.07	-0.01	0.09
70004	Heysham	0.04	0.03	0.01	0.08	93001	Ullapool	0.04	0.05	-0.01	0.09
71001	Liverpool P P	0.11	0.03	0.05	0.19	94001	Tobermory	0.09	0.09	0.01	0.18
71001	Liverpool G D	0.07	0.04	-0.01	0.20	94001	Ullapool	0.12	0.04	0.04	0.19
71001	Heysham	0.07	0.03	0.03	0.13	95001	Ullapool	0.05	0.05	-0.01	0.12
72004	Liverpool P P	0.13	0.03	0.03	0.21	95001	Wick	0.04	0.04	0.00	0.08
72004	Liverpool G D	0.07	0.04	-0.01	0.21	95002	Ullapool	0.07	0.07	0.02	0.15
72004	Heysham	0.08	0.04	0.03	0.16	96001	Ullapool	0.03	0.03	-0.01	0.06
72008	Liverpool P P	0.09	0.02	0.02	0.17	96001	Wick	0.05	0.03	-0.01	0.10
72008	Liverpool G D	-0.01	0.05	-0.01	0.05	96001	Lerwick	0.02	0.04	-0.01	0.07
72008	Heysham	0.05	0.03	0.03	0.11	97002	Ullapool	0.01	0.03	-0.01	0.05
73002	Heysham	0.07	0.03	0.04	0.10	97002	Wick	0.03	0.04	-0.01	0.07
73002	Portpatrick	0.05	0.04	0.03	0.10	97002	Lerwick	0.03	0.04	-0.01	0.07
73005	Heysham	0.10	0.04	0.05	0.20						

APPENDIX C

CLIMATE CHANGE IMPACT ON DEPENDENCE

The study on climate change impacts presented in this Appendix was carried out as a contract extension after the main body of the report had been completed. The scope was for this investigation to cover the entire coast of Great Britain. Therefore results are presented also for the east coast, in addition to results for the south and west coasts.

C.1 INTRODUCTION

There is a growing body of observational evidence giving a collective picture of a warming world and other changes in the climate system (IPCC, 2001). Modelling studies of river flow derived using output from Global Climate Models (GCM) as input to hydrological models suggest that a future, greenhouse gas-induced warmer climate will result in increased flooding in different parts of the world, including Britain (e.g. Miller and Russell, 1992; Nijssen *et al*., 2001; Reynard *et al*., 2001, Milly *et al*., 2002). A shelf-seas model driven by a Regional Climate Model (RCM) suggests that the height of sea surges can also be expected to rise around Britain in the future (Lowe and Gregory, 2005).

If a predicted increase in the flood-producing variables is combined with an increase in the dependence between them, the effect on the total water level corresponding to a particular return period can become very significant. Because flood defence structures are typically designed to last for several decades, it is important to assess the effect of climate change on dependence as well.

The climate change impacts study uses available model output to make a preliminary assessment of any changes in the dependence between sea surge and river flow, using precipitation as a proxy for river flow. The study is brief and using a proxy variable, because hydrological modelling of river flows is time consuming, and unduly costly considering that a more thorough study with improved surge data may be undertaken shortly. Better surge data are expected to become available within the next year through an improved shelf-seas model.

C.2 DATA

Daily precipitation totals were used as a proxy for river flow. Unfortunately, these variables differ in possibly important ways. River flow is influenced by other variables as well as rainfall, such as evaporation, infiltration and groundwater flow. The most important variable apart from rainfall is probably the soil moisture deficit. However, the influence of antecedent soil moisture conditions becomes less important the larger the rainfall event, as once the deficit is overcome the rainfall-runoff relationship becomes more direct. The absolute values of dependence calculated from the climate model data are less reliable than those determined from measurements. Also, precipitation is averaged over a grid box, rather than representing any particular catchment. Nevertheless, because consistent data sources, locations and methods are used between the present day and future time slices, any significant differences in dependence seen between the two time slices should be a reasonably reliable projection of future change in dependence.

Thirty-year time slices for the control run (1961-1990) and for the future climate change scenario (2071-2100, also referred to as the 2080s) were used for both variables. Precipitation is output from the RCM, HadRM3 (runs achgi [control] and ackda [future, emission scenario 2A] (Mark Gallani and Jason Lowe, Met Office, personal communication)), at a grid resolution of approximately 50km*50km (Hulme *et al.*, 2002). Sea surge data are output from the Proudman Oceanographic Laboratory's shelf-seas model (which is driven by output from the above RCM runs), at a resolution of approximately 35km*35km (Flather and Smith, 1998; Lowe and Gregory, 2005). The daily maximum sea surge data were derived from hourly values from 0 to 23 hours, to correspond to the time period over which precipitation was accumulated.

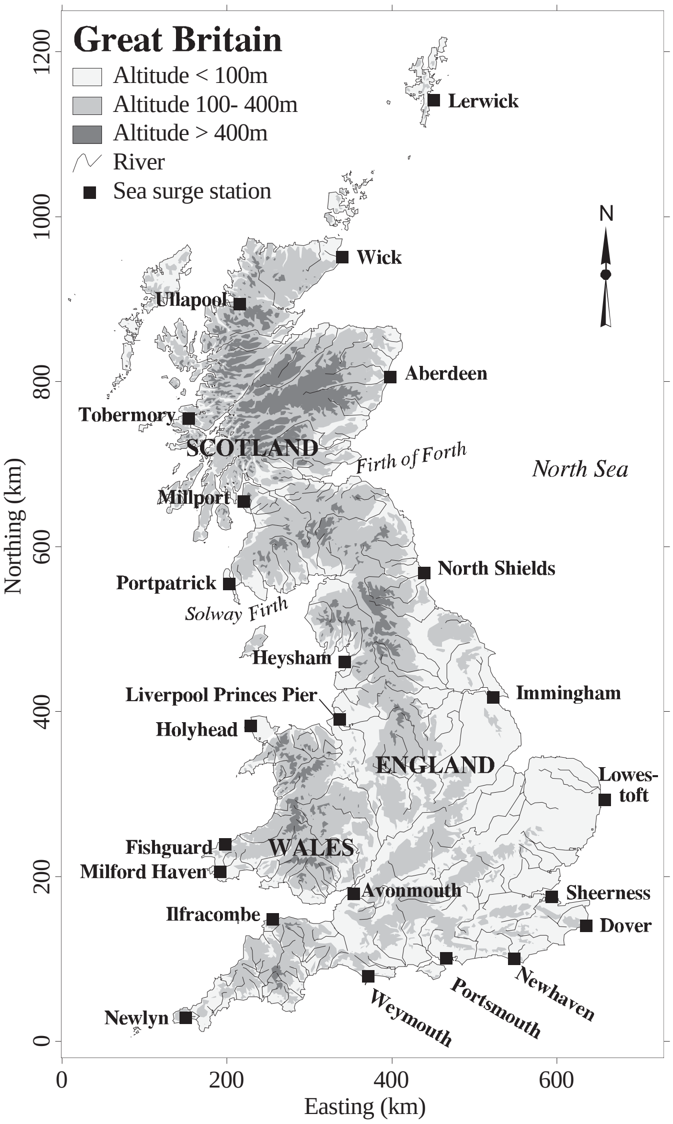

Figure C1 Location of the 23 stations for which regional climate model (precipitation) and shelf-seas model (sea surge) data for the nearest land and sea grid boxes, respectively, have been extracted.

RCM and surge data were obtained for 23 points around the coast of Britain (Figure C1, Table C1), corresponding to the sea surge stations used in the main study of observed data plus five stations on the east coast. The modelled sea surge data were taken from the grid box closest to the selected point, with the constraint that it should be over the sea. Each precipitation box is similarly selected, but with the constraint that it should be located over land. Thus, the sea surge and precipitation data are represented by an areal average value over the size of one grid box.

The definition of a year is simplified in climate models, with each month consisting of 30 days, making a year of in total 360 days. There are no leap years.

Table C1 Location of the 23 stations for which regional climate model (precipitation) and shelf-seas model (sea surge) data for the nearest land and sea grid boxes, respectively, have been extracted. The easting and northing coordinates are in the Great Britain national grid coordinate system.

Station	Easting (km)	Northing (km)
Wick	336.7	950.8
Lerwick	447.8	1141.4
Ullapool	212.9	893.9
Tobermory	150.8	755.3
Millport	217.7	654.5
Portpatrick	199.8	554.2
Heysham	340.3	460.1
Liverpool Princes Pier	333.6	390.6
Holyhead	225.5	382.9
Fishguard[1]	195.1	238.8
Milford Haven[1]	189.2	205.3
Avonmouth	350.6	179.0
Ilfracombe	252.6	147.9
Newlyn	146.8	28.6
Waymouth	368.4	78.9
Portsmouth	462.7	100.5
Newhaven	545.1	100.1
Dover	632.7	140.3
Sheerness	590.7	175.4
Lowestoft	654.8	292.7
Immingham	519.9	416.7
North Shields	435.9	568.2
Aberdeen	395.2	805.9

[1] The nearest precipitation grid box over land is the same for Fishguard and Milford Haven.

C.3 METHODOLOGY

The sea surge and precipitation data are model outputs provided by a climate and a shelf-seas model. Lowe and Gregory (2005) describe how these models relate to each other. A regional climate model over Europe (HadRM3) provides the precipitation data. The RCM drives a shelf-seas model which covers the seas around Britain and produces surge data (Flather and Smith, 1998). The RCM in turn is driven using the boundary conditions over Europe provided by an atmospheric GCM (HadAM3H). This atmospheric model is fed by observed sea surface temperatures from the HadISST dataset (Rayner *et al.*, 2003), and anomalies from a low-resolution coupled ocean-atmosphere global climate model (HadCM3). Further information about the climate models and experiments can be found in Appendix 2 of Hulme *et al.* (2002), and on the LINK web page at www.cru.uea.uk/link/.

The emission scenario for the future time slice was the Special Report on Emission Scenarios' (SRES) scenario A2, the UKCIP02 Medium-High Emissions Scenario. This scenario assumes that future societies have self-reliance, preservation of local identities, continuously increasing population and economic growth on regional scales (e.g. Appendix 5 of Hulme *et al*., 2002).

The same pair-wise measure of dependence is used in this climate change impacts study as in Chapter 3 for the study of observed values, i.e. the measure χ is used to express dependence between the extremes of the variables. Events were considered to be extreme if they exceeded a certain threshold. The threshold was set so that on average, about 2.3 independent events per year exceed the threshold. Events were considered to be independent if they were separated by at least 3 days. Similarly, significance levels and confidence intervals were estimated using the same re-sampling techniques as described in Section 3.5.

C.4 RESULTS

Results of the climate change impact study are shown on sets of three maps, one for dependence between the variable-pair in the current climate, one for the future climate and one for the difference between the future and the current climate (Figures C2 and C3). Dependence is shown using different sized filled circles, the larger the circle the stronger the dependence. Three examples of circle-sizes are shown on each map. Dependence is shown for all of the 23 sites, although for small amounts of dependence the circles may be too small to be readily visible on the map. Increased (decreased) dependence in the future is shown in black (grey). However, none of the grey circles are easily visible as negative differences in dependence are never below about -0.01.

Figure C2 shows the same-day same-location dependence between extreme sea surge and precipitation. The spatial pattern of dependence is a reasonable reflection of the dependence between sea surge and river flow on the south and west coasts. The latter is strongest on the western part of the south coast, in south Wales and around the Solway Firth. In these regions, hilly, south to west facing catchments promote quick runoff from orographically enhanced precipitation, and surges are formed locally as depressions approach Britain from the southwest. However, it can be noted that there is no dependence between modelled surge and precipitation on the east coast. This does therefore not adequately represent the observed spatial pattern of dependence between sea surge and river flow, which show strong dependence in the northern part of the east coast. There are probably two reasons for this discrepancy. Firstly, the east coast precipitation grid cells are located in rain shadow from westerly winds, whereas the headwaters of the catchments draining to the east receive heavier precipitation, more similar to the windward catchments in the west. Just north of the Firth of Forth, precipitation is likely to be orographically enhanced over most of the catchments, since this is the first hilly area encountered by air from a southwesterly direction. There are indications that rain shadow effects in eastern Britain are amplified in the RCM (Kay *et al*., 2005)

Secondly, a lag in the dependence between surge and precipitation occurs because of the combination of large, relatively slowly responding, east coast catchments and the delay involved when an external surge wave generated northwest of Scotland travels down the east coast. Svensson and Jones (2002) found that in the northern part of the east coast, surge-flow dependence is strongest on the same day, whereas surge-precipitation dependence is strongest when precipitation precedes the surge by one day. This is in contrast to the south and west coasts, where (generally) both surge-flow and surge-precipitation dependences are strongest on the same day.

To make optimum use of precipitation as a proxy variable for river flow for the northern part of the east coast, the sea surge at Aberdeen and North Shields were paired up with the previous day's precipitation at Tobermory and Heysham, respectively. The combination of same-day, same-site dependence, and lagged, different-site dependence, are shown in Figure C3 and Table C2. In agreement with the observed surge-flow dependence, Figure C3a shows dependence between surge and precipitation also in the northern part of the east coast. It can be noted that either applying a 1-day lag, or changing the locations in isolation, does not significantly increase the surge-precipitation dependence.

Figures C3c shows the difference in surge-precipitation dependence between the future and current time slices. The dependence generally increases on the south and west coasts, and also in the northern part of the east coast.

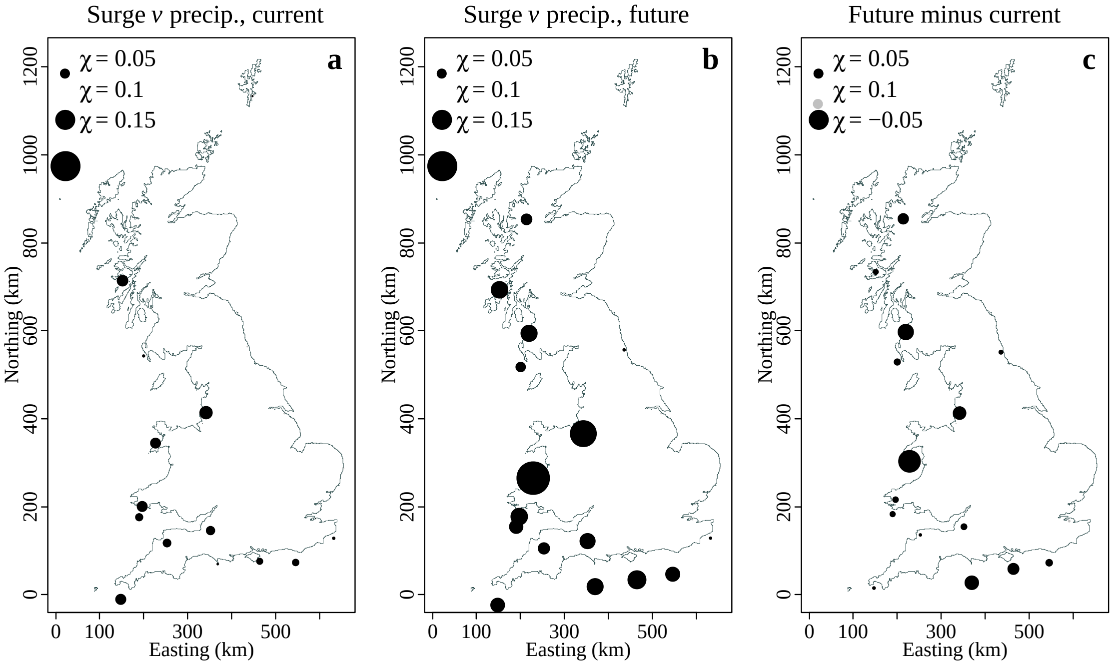

Figure C2 **Dependence between daily maximum sea surge and daily precipitation total occurring on the same day and at the same location for a) the current climate, b) the future climate, and c) the difference in dependence between the future and the current climate.**

These increases are consistent with an increasing number of deep atmospheric depressions (central pressure < 970 hPa) passing eastward across, or just to the north, of Scotland during the three winter months in the 2080s (A2 emission scenario) compared to the current climate (Figure 4b in McDonald, 2002). Winter is a season of vigorous cyclonic activity (e.g. Wallén, 1970). Because deep depressions are more likely to bring heavy rainfall and large sea surges than weak depressions are, changes in storm tracks during winter can be expected to have a strong influence on the changes in extremal dependence.

The increase in storm frequency over the UK is related to a slight southward shift in the predominant storm track (Hulme *et al.*, 2002; McDonald, 2002), currently passing eastward in latitudes to the north of Scotland, or northeastward past the Hebrides (Manley, 1970). On average, eight depressions (central pressure < 1000 hPa) per winter are expected to cross Britain in the 2080s (A2 emission scenario), compared to five in the current climate (1961-1990). The number of deep depressions (< 970 hPa) is expected to increase by about 40%. In summer, there is a slight decrease in the total number of depressions (< 1000 hPa) crossing the UK, from five to four, with little change in the spring and autumn (Hulme *et al.*, 2002).

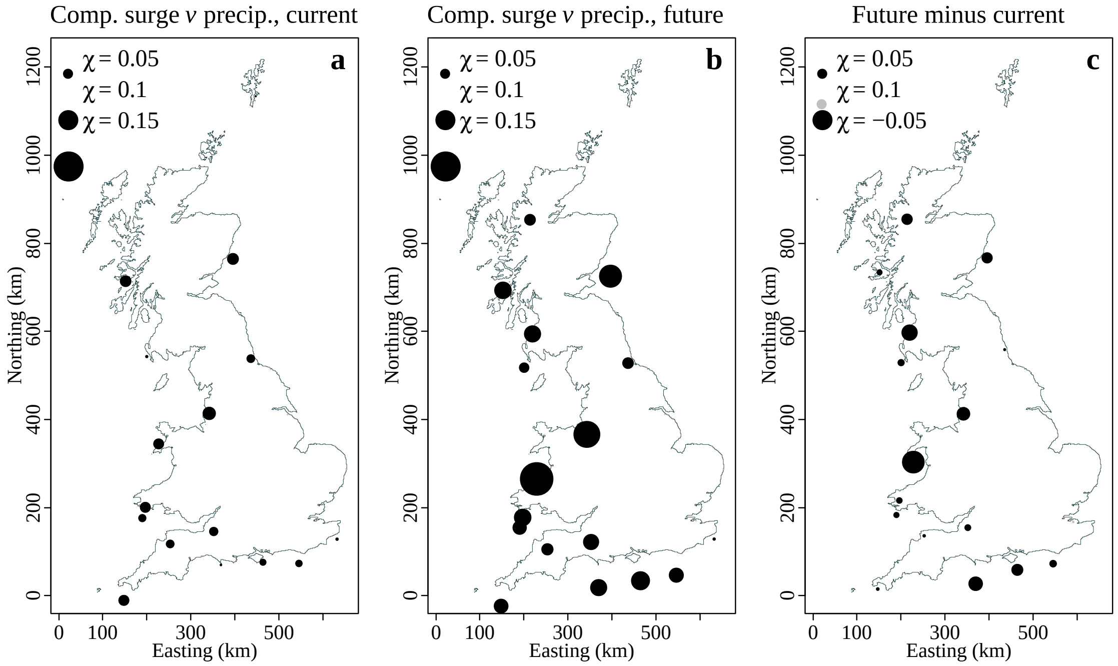

Figure C3 **Composite figure of dependence between daily maximum sea surge and daily precipitation total, for a) the current climate, b) the future climate, and c) the difference in dependence between the future and the current climate. All station-pair analysis are for the same day and same station, except in the northern part of the east coast. Sea surge at Aberdeen and North Shields is paired with the previous day's precipitation at Tobermory and Heysham, respectively.**

Table C2 Composite table of dependence, χ, for the current future climates. Values of dependence significant at the 95% level are shown in bold. Note that the measure χ is not suitable for measuring negative dependence, and that values smaller than the significance level may indicate independence or negative dependence.

Sea surge location	Precipitation location	χ, current	χ, future
Wick	Wick	-0.01	-0.01
Lerwick	Lerwick	0.01	0.00
Ullapool	Ullapool	0.00	**0.06**
Tobermory	Tobermory	**0.06**	**0.09**
Millport	Millport	0.00	**0.09**
Portpatrick	Portpatrick	0.02	**0.05**
Heysham	Heysham	**0.07**	**0.13**
Liverpool Princes Pier	Liverpool Princes Pier	0.00	0.00
Holyhead	Holyhead	**0.05**	**0.17**
Fishguard	Fishguard[1]	**0.05**	**0.09**
Milford Haven	Fishguard[1]	**0.04**	**0.07**
Avonmouth	Avonmouth	**0.05**	**0.08**
Ilfracombe	Ilfracombe	**0.04**	**0.06**
Newlyn	Newlyn	**0.06**	**0.07**
Waymouth	Waymouth	0.01	**0.09**
Portsmouth	Portsmouth	**0.04**	**0.09**
Newhaven	Newhaven	**0.04**	**0.08**
Dover	Dover	0.02	0.02
Sheerness	Sheerness	0.00	-0.01
Lowestoft	Lowestoft	-0.01	-0.01
Immingham	Immingham	-0.01	-0.01
North Shields	Heysham	**0.04**	**0.06**
Aberdeen	Tobermory	**0.06**	**0.11**

[1] The nearest precipitation grid box over land is the same for Fishguard and Milford Haven.

Except for the south coast, the regions of increasing surge-precipitation dependence are broadly similar to the regions with increased observed surge-flow dependence in winters with high a North Atlantic Oscillation Index (NAOI), compared with winters with a low NAOI (Section 4.6 and Appendix A of this report). Most climate models suggest a shift toward a higher NAOI in the future (Gillett et al., 2002).

Figure C4 shows 90% confidence intervals obtained using balanced bootstrapping of the surge-precipitation dependences for the current time slice. These are helpful for interpreting whether a change in dependence in the future is significant or not. Confidence intervals were not estimated for the differences directly, because of time and financial constraints. Figure C4 suggests that for smaller amounts of dependence, up to about $\chi = 0.1$, a change in the dependence of about 0.05 can be considered significant. Applying these significance levels to the changes in the dependence suggest that there is significant positive change at several locations on the south, west and northeast coasts of Britain.

It should be kept in mind that the present study uses a proxy variable, and that a more comprehensive study of climate change impacts on dependence may be undertaken involving hydrological modelling of river flows and improved modelling of sea surges. It is therefore recommended that the adoption of an allowance for climate change be deferred until the results of the new work become available (Section 4.5 of

Defra/Environment Agency, 2005a and Section 4.4.6 of Defra/Environment Agency, 2005b).

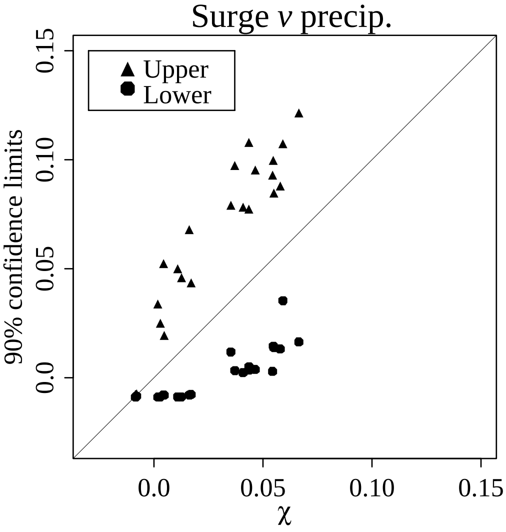

Figure C4 Confidence intervals (90% level) of the dependence estimates, χ, for dependence between surge and precipitation in the control run.

C.5 SUMMARY AND CONCLUSION

There is a growing body of observational evidence giving a collective picture of a warming world and other changes in the climate system. Modelling studies suggest that sea surges and river flows may increase in a future, greenhouse gas-induced warmer climate. If a predicted increase in the flood-producing variables is combined with an increase in the dependence between them, the effect on the total water level corresponding to a particular return period can become very significant. Because flood defence structures are typically designed to last for several decades, it is important to assess the effect of climate change on dependence as well.

Regional climate model and shelf-seas model outputs are used to make a preliminary assessment of any changes in the dependence between sea surge and river flow using precipitation as a proxy for river flow. The UKCIP02 Medium-High emission scenario (SRES A2) was assumed. A measure of dependence suitable for measuring pair-wise dependence between the extremes of variables was used, and 90% confidence intervals were estimated using a block bootstrapping method. Several locations on the south, west and northeast coasts of Britain show significant increases in the dependence between sea surge and precipitation in the period 2071-2100, compared to the control run 1961-1990. These significant changes are supported by smaller increases at other locations on these coasts.

Except for the south coast, the regions of increasing surge-precipitation dependence are broadly similar to the regions with increased observed surge-flow dependence in winters with a high North Atlantic Oscillation Index (NAOI), compared with winters with a low NAOI. Most climate models suggest a shift toward a higher NAOI in the future.

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