The North Sea Storm Surge of 31 January and 1 February 1953

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THE NORTH SEA STORM SURGE OF 31 JANUARY AND 1 FEBRUARY 1953

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CONTENTS

Using observed hourly heights of tide at thirty-one stations in the North Sea and two in the English Channel, the storm surge of 31 January and 1 February 1953 has been investigated in the light of the meteorological conditions prevailing. The major cause of the disturbance is shown to be the strong northerly winds in and to the north of the North Sea, modified at each station by local wind and barometric effects.

An increase of 2 ft. in the mean level of the North Sea during the disturbance has been deduced, and the response of the sea as a whole to the disturbing winds has been examined.

Geostrophic effects have been remarked in both the growth and decay of the disturbance.

Estimates have been made of the air/sea frictional coefficient on two separate occasions during the period considered, assuming the tractive force of the wind to vary as the square of its velocity. These estimates are in agreement with accepted values.

The partial transmission of this large surge through the Straits of Dover has been shown as an important factor, influencing the levels immediately to the north of the Straits.

Prediction of the surge at Southend by a previously established formula has given only fair results, but the errors have been explained in terms of the facts previously presented and the approximations upon which the formula is based.

Suggestions for future research into the improvement of surge prediction formulae have been made.

Introduction

The exceptionally severe and prolonged gale of 31 January and 1 February 1953 caused extensive sea-flooding in south-east England and Holland, with attendant heavy loss of life and damage to land and property. A disturbance of mean sea-level amounting to 9 to 11 ft. was experienced near midnight in the southern portion of the North Sea, coinciding in many places with high water. The disturbance as such is not the greatest on record, but at Southend it appears to be the largest to have occurred within an hour either side of predicted high water.

The flooding and its causes have been the subject of much discussion; this paper is an analysis of the mechanism of the surge in the North Sea as a whole, using the method employed by Corkan (1950), together with a critical study of certain salient features.

1. Observations and datums

Hourly heights of tide were collected for all available stations on the shores of the North Sea and for Newhaven and Dieppe in the English Channel, for the period 27 January to 3 February 1953 inclusive, but those for 27 January were not required.

It is indeed unfortunate that, owing to the exceptionally high levels reached and the severity of the gale, some tide gauges on the British coast were put out of action for varying periods at the peak of the disturbance. Wherever possible, interpolation has been effected in the hourly heights or at a later stage. The ports in question are Aberdeen, River Tees Entrance, Immingham, Grimsby, Holland Sluice and Chatham. The automatic tide gauge at Felixstowe was completely destroyed, but a visual record of the maximum level reached has been utilized. Continental records received, however, were all continuous during the critical period with the exception of Stavanger and Ostend.

The Blyth Harbour Commission supplied records for Blyth, but the gauge had jammed at 15.30 h 31 January and was not in working order until 11.00 h 2 February. Observations for the River Tyne Entrance make up for this deficiency.

The Trent River Board supplied a schedule of water levels for Gainsborough, Owston Ferry and Keadby, but, owing to the restricted time scales employed and the shallow-water distortion of the curves, it has been found impossible to utilize these in the determination of hourly disturbances.

Data for Vlissingen have not been reproduced since the disturbance was virtually identical with that for Brouwershavn, while data for Delfzijl have been omitted in favour of those for Borkum, which is much nearer to the open sea.

The Deutsches Hydrographisches Institut supplied data for many places on the German coast, out of which five were carefully selected to give an even coverage and minimum shallow-water effect.

High-water observations for Lowestoft and Great Yarmouth have also been of assistance.

Details of the stations, their positions, the authority supplying the observations, the form of the data as received, the time kept, the datums and the values of mean sea-level used in the reductions, are given in table 1 *a* for the British Isles and table 1 *b* for the Continent.

The hourly heights are given in table 2, all data having been converted to G.M.T.

2. Reduction of data

For the purpose of studying the variations in sea-level due to meteorological causes, it is necessary to eliminate all tidal effects.

A simple but efficient method of eliminating the semi-diurnal tide has been devised by Doodson (1929) and has been used throughout in this paper. Application of this method requires only a provisional value of mean sea-level referred to the datum of the observations, and suitable values chosen are given in tables 1 *a* and 1 *b*. These provisional values

TABLE 1*a*. OBSERVATIONS AND LEVELS—BRITISH ISLES

place	lat. (°) (′)	long. (°) (′)	authority for observations	form of observation supplied	time kept	ordnance datum referred to zero of observations (ft.) O.D. (Liverpool)	O.D. (Newlyn)	provisional mean sea-level (ft.)	corrected mean sea-level (ft.)
Aberdeen	57 09 N	2 05 W	Harbour Engineer, Aberdeen	C	G.M.T.	8·62	—	10·25	9·7
Leith	55 59 N	3 10 W	Leith Dock Commission	C	G.M.T.	21·4	—	22·0	21·4
R. Tyne Entrance	55 01 N	1 24 W	Tyne Improvement Commission	C	G.M.T.	7·08	—	8·5	7·7
Hartlepool	54 41 N	1 11 W	Docks and Inland Waterways Executive	C	G.M.T.	19·25	—	19·6	19·6
R. Tees Entrance	54 38 N	1 09 W	Tees Conservancy Commission	C	G.M.T.	8·4	—	9·0	8·6
Hull	53 45 N	0 19 W	Docks and Inland Waterways Executive	C	G.M.T.	14·6	15·2	16·5	15·8
Immingham	53 37 N	0 11 W		HH	G.M.T.	36·00	—	38·25	38·0
Grimsby	53 35 N	0 04 W		VHH	G.M.T.	15·00	—	17·0	16·9
King's Lynn	52 45 N	0 24 E	King's Lynn Conservancy Board	HH	G.M.T.	—	12·2	14·5	13·2
Holland Sluice	51 49 N	1 14 E	Essex River Board	C	G.M.T.	0·0	1·8	2·75	1·8
Southend	51 31 N	0 45 E	Port of London Authority	HH	G.M.T.	—	0·00	0·0	0·0
Chatham	51 24 N	0 32 E	Hydrographic Dept., Admiralty	HH	G.M.T.	—	8·58	9·5	8·7
London Bridge	51 30 N	0 05 W	Port of London Authority	HH	G.M.T.	—	0·00	1·5	1·5
Dover	51 07 N	1 19 E	Dover Harbour Board	C	G.M.T.	8·42	—	9·5	9·4
Newhaven	50 47 N	0 30 E	Railway Executive, Southern Region	C	G.M.T.	13·33	14·08	14·5	14·4

TABLE 1*b*. OBSERVATIONS AND LEVELS—CONTINENT

place	lat. (°) (′)	long. (°) (′)	authority for observations	form of observation supplied	time kept	datum of observations	provisional mean sea-level (cm)	(ft.)	corrected mean sea-level (ft.)
Dieppe	49 56 N	1 06 E	Service Centrale Hydrographique	C	G.M.T. + 01.00	Chart datum	500	16·4	0·3
Ostend	51 14 N	2 55 E	Service Hydrographique	HH	G.M.T.	Zéro du Ponts et Chaussées	260	8·5	0·0
Brouwershavn	51 44 N	3 54 E	Rijkswaterstaat Directie Algemene Dienst	C	G.M.T. + 00.20	Nauwkeurigheids Amsterdamsch Peil (N.A.P.)	−10	−0·3	−0·3
Ijmuiden	52 28 N	4 34 E		C			0	0·0	0·1
Harlingen	53 10 N	5 25 E		C			−7·5	−0·2	0·4
Borkum	53 35 N	6 39 E	Deutsches Hydrographisches Institut	HH	G.M.T. + 01.00	Normalnull (N.N.)	0	0·0	−0·6
Norderney	53 42 N	7 10 E		HH			0	0·0	−0·2
Cuxhaven	53 52 N	8 43 E		HH			0	0·0	0·2
Busum	54 08 N	8 51 E		HH			0	0·0	0·3
List	55 01 N	8 27 E		HH			0	0·0	−0·3
Esbjaerg	55 28 N	8 27 E	Det Dansk Meteorologiske Institut	HH	G.M.T. + 01.00	Mean sea-level	0	0·0	0·4
Hansthlom	57 08 N	8 36 E		HH		Ordnance datum (D.N.N.)	30	1·0	−0·1
Hirtshals	57 36 N	9 57 E		HH		Mean sea-level	0	0·0	−0·1
Nevlunghavn	58 58 N	9 53 E	Norges Geografiske Oppmaling	HH	G.M.T. + 01.00	Mean sea-level	0	0·0	−0·2
Tregde	58 00 N	7 34 E		HH			0	0·0	−0·2
Stavanger	58 58 N	5 44 E		HH			0	0·0	0·0
Bergen	60 24 N	5 18 E		HH			0	0·0	−0·2
Maloy	61 56 N	5 07 E	Norges Sjokartverk	HH	G.M.T. + 01.00	Mean sea-level	110	3·5	3·7

C indicates tide gauge records; HH indicates hourly heights extracted from charts; VHH indicates visual hourly height readings.

TABLE 2. HOURLY HEIGHTS OF OBSERVED TIDE, 28 JANUARY TO 3 FEBRUARY 1953

hours ...	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Aberdeen (ft.), G.M.T.																								
date																								
28 Jan.	15·1	15·2	14·4	12·8	11·0	9·4	8·4	8·5	9·5	11·3	13·0	14·3	14·9	14·5	13·4	11·4	9·2	7·2	5·6	5·2	6·2	8·1	10·3	12·2
29	14·0	14·6	14·0	12·4	10·2	8·6	6·9	6·5	7·1	9·1	11·2	13·4	14·9	15·5	14·9	13·3	10·8	8·1	5·9	4·7	4·8	6·1	8·5	10·7
30	12·8	14·1	14·1	12·5	10·4	8·4	6·6	5·5	5·7	7·2	9·4	12·0	13·8	15·2	15·5	14·4	12·2	9·7	6·9	5·0	4·5	5·5	7·6	10·3
31	12·5	14·4	15·2	14·6	13·1	10·8	8·4	6·8	6·1	7·1	9·1	11·9	14·5	16·4	17·3	16·9	15·2	.	.	.	.	.	.	.
1 Feb.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2	.	.	.	.	.	.	.	.	.	.	5·3	7·0	9·7	12·3	13·6	14·5	14·1	12·7	10·3	7·6	5·0	3·6	3·9	5·2
3	7·7	10·1	11·8	13·1	13·4	12·4	10·3	7·9	5·8	4·5	4·4	5·8	8·2	10·7	12·5	14·0	14·1	13·3	11·5	8·9	6·5	4·6	4·0	4·8
Leith (ft.), G.M.T.																								
28 Jan.	25·6	27·6	28·2	27·4	25·3	22·5	20·5	19·4	19·0	20·0	23·3	25·5	27·0	27·6	28·0	27·2	25·0	21·6	18·4	16·6	15·7	15·8	18·1	21·0
29	24·4	26·7	28·1	27·9	26·4	23·6	20·0	17·9	17·5	17·9	20·0	23·0	25·6	27·5	28·8	29·0	27·5	24·5	20·6	17·2	15·6	15·2	16·3	19·4
30	22·7	25·4	27·5	28·4	27·5	24·9	21·4	17·9	16·5	16·0	17·5	21·0	24·5	26·8	28·1	29·0	28·6	26·5	23·0	18·6	16·0	15·3	15·4	18·2
31	21·8	24·8	27·0	28·4	28·5	26·9	23·9	20·1	17·0	16·1	16·4	19·0	23·6	26·9	28·7	30·8	31·5	30·1	27·5	23·8	19·8	17·5	16·5	17·6
1 Feb.	20·9	23·9	26·5	28·6	29·4	28·5	26·0	22·4	19·3	17·6	16·9	17·3	20·8	24·2	27·2	28·9	29·4	28·4	25·6	21·8	17·9	15·4	14·4	14·2
2	16·6	20·5	24·1	26·3	27·5	27·6	26·1	23·0	18·5	15·5	15·0	16·0	19·6	22·1	25·0	27·0	28·0	28·5	27·1	24·5	20·5	16·4	14·5	14·1
3	16·0	19·5	22·7	25·0	26·3	27·1	26·2	23·7	20·3	16·5	14·9	15·0	16·4	19·7	23·6	25·6	26·8	27·5	27·0	25·2	21·7	17·5	14·5	14·0
River Tyne Entrance (ft.), G.M.T.																								
28 Jan.	9·3	11·6	13·5	14·0	13·4	11·7	9·3	7·2	6·2	5·7	6·2	8·0	10·4	12·2	13·5	13·8	13·0	10·8	8·1	5·3	3·3	2·1	2·3	4·0
29	7·0	10·0	12·1	13·3	13·2	11·5	9·1	6·4	4·7	3·8	3·7	5·4	7·9	10·8	13·1	14·4	14·4	13·0	10·2	7·0	4·2	2·2	1·6	2·4
30	4·7	7·8	10·7	12·6	13·2	12·4	9·9	7·0	4·5	3·0	2·5	3·3	5·8	8·8	11·8	13·7	14·2	13·8	11·7	8·6	5·3	2·8	1·4	1·4
31	3·5	6·7	9·9	12·4	13·7	13·8	12·2	9·5	6·6	4·5	3·2	3·8	5·8	8·8	12·6	15·7	[17·8	18·6	17·4]	14·4	11·1	7·6	5·1	4·2
1 Feb.	4·9	7·1	9·8	12·6	14·6	15·5	14·7	12·5	9·4	6·4	4·8	3·8	4·4	6·6	9·4	12·5	14·5	15·0	14·1	11·6	8·4	4·9	2·4	1·2
2	1·3	2·8	5·9	9·1	11·8	13·1	13·2	11·5	8·8	5·7	3·4	2·3	2·9	[4·8	7·2	10·2]	12·8	14·7	14·4	13·0	10·5	7·0	4·1	2·2
3	1·4	2·2	4·7	7·6	10·5	12·2	12·9	12·2	10·0	6·8	3·9	2·2	1·8	2·8	5·2	7·9	10·9	12·8	13·5	13·2	11·4	8·4	5·2	2·8
Hartlepool (ft.), G.M.T.																								
28 Jan.	20·2	23·5	25·6	26·2	25·5	23·8	21·5	19·4	18·0	17·4	17·9	19·7	22·0	24·2	25·5	25·8	25·1	23·1	20·4	17·7	15·5	14·1	13·8	15·3
29	18·0	21·7	24·0	25·3	25·4	24·5	22·3	19·5	16·8	15·5	15·4	17·0	19·4	22·5	24·9	26·2	26·4	25·3	22·7	19·7	16·8	14·5	13·3	13·8
30	15·8	19·8	22·5	24·5	25·3	23·8	21·6	18·9	16·9	15·0	14·1	14·9	17·1	20·3	23·5	25·6	26·4	26·0	24·0	21·0	17·9	15·1	13·4	12·9
31	14·6	18·3	21·7	24·3	25·9	26·0	24·5	22·0	19·1	16·6	15·1	15·1	17·3	20·1	24·1	27·8	29·5	30·4	29·6	27·5	24·4	20·9	18·0	16·8
1 Feb.	17·3	19·2	22·1	24·6	27·0	27·5	27·0	25·0	22·0	19·1	17·3	16·5	16·5	18·5	21·2	24·2	26·5	27·0	26·3	24·2	21·3	18·0	15·3	13·6
2	13·0	14·7	17·1	20·8	23·7	25·2	25·2	23·9	21·3	18·4	15·7	14·1	14·1	15·8	18·2	21·9	24·6	26·0	26·2	25·0	22·7	19·2	16·2	14·0
3	13·0	13·9	16·3	19·5	22·5	24·1	24·8	24·0	21·9	18·5	15·8	14·0	13·3	14·1	16·2	19·5	22·6	24·6	25·4	25·0	23·2	20·3	17·3	14·8
River Tees Entrance (ft.), G.M.T.																								
28 Jan.	8·5	11·2	13·9	15·2	14·9	13·3	11·2	8·7	7·1	6·3	6·1	8·2	10·8	13·2	14·8	15·3	14·8	12·8	10·2	7·2	4·8	3·2	2·7	4·0
29	6·7	10·0	12·8	14·7	15·1	13·6	11·2	8·5	6·3	4·8	4·4	5·6	8·8	12·0	14·8	16·2	16·4	15·1	12·4	9·2	6·2	3·6	2·4	2·8
30	5·0	8·2	11·3	14·0	14·9	14·4	12·3	9·3	6·4	4·3	3·3	3·7	6·1	9·4	12·9	15·2	16·1	15·7	13·7	10·7	7·2	4·3	2·3	1·9
31	3·8	6·7	10·4	13·6	15·4	15·8	14·5	12·0	9·0	6·3	4·7	4·3	6·8	9·6	13·8	18·2	[20·7	21·0	19·7	17·7]	15·3	12·2	9·0	7·4
1 Feb.	7·8	9·2	11·8	15·1	17·6	18·7	18·3	16·7	13·6	10·8	8·4	6·3	6·8	8·4	11·2	14·8	17·4	17·9	17·3	15·0	12·2	8·8	5·6	3·4
2	2·7	3·9	6·6	10·0	13·3	15·3	15·7	14·5	12·1	9·0	6·1	4·3	3·6	5·0	7·6	11·2	14·5	16·1	16·3	15·2	12·8	9·5	6·2	3·8
3	2·3	2·7	4·8	8·0	11·4	13·7	14·7	14·2	12·3	9·3	6·1	3·7	2·6	3·2	5·2	8·4	11·8	14·3	15·2	15·1	13·4	10·7	7·5	4·7
Hull (ft.), G.M.T.																								
28 Jan.	7·2	9·7	13·7	17·9	21·4	24·2	25·4	24·0	21·2	17·2	13·5	11·0	10·4	12·6	16·0	19·8	23·2	24·9	24·4	21·9	18·2	14·5	10·9	8·5
29	7·0	7·8	10·7	14·9	19·2	22·3	24·2	23·7	21·0	17·0	13·2	10·2	8·7	9·4	13·0	16·8	21·1	24·6	26·2	24·9	22·0	18·0	13·9	10·2
30	8·0	6·2	7·7	11·8	16·2	20·6	23·6	24·5	22·4	19·3	15·2	11·4	8·2	7·0	8·8	13·6	17·7	22·5	25·2	26·1	23·5	20·2	16·2	11·8
31	8·8	6·5	5·4	8·8	13·9	18·6	22·7	25·0	24·5	21·8	18·2	14·7	10·7	8·0	7·8	12·2	17·0	23·0	28·2	30·3	30·2	28·2	24·5	20·2
1 Feb.	16·1	12·8	11·2	12·5	16·0	20·2	24·2	27·5	27·6	26·0	22·9	18·0	13·8	11·2	9·8	11·7	15·7	20·2	24·3	27·2	27·2	24·7	21·2	17·2
2	13·1	9·8	7·2	6·5	9·6	14·2	19·0	22·9	25·2	24·4	21·8	17·7	13·8	9·8	7·2	7·0	11·0	15·7	20·5	24·7	26·3	25·7	22·2	18·6
3	14·8	11·0	8·0	6·5	7·7	11·5	16·3	21·0	23·6	24·6	22·2	19·0	.	.	.	.	.	.	.	.	.	.	.	.

[ ] denote interpolated values.

Immingham (ft.), G.M.T.																							
28 Jan.	30·8	33·5	37·0	41·5	45·2	47·2	46·6	45·0	42·6	37·8	35·2	33·5	34·2	36·2	39·6	43·0	45·8	46·5	45·6	43·2	39·4	35·2	32·4	30·5
29	30·2	32·0	36·0	39·2	43·8	45·3	45·8	44·8	42·1	38·2	34·3	31·7	30·8	33·6	37·2	40·8	44·3	46·5	47·5	46·0	42·8	39·0	34·6	31·8
30	29·6	29·6	31·8	36·0	40·2	43·8	45·8	45·4	43·0	40·1	36·0	32·1	29·9	30·3	33·6	37·7	41·5	45·3	47·1	46·8	44·9	41·0	36·0	32·1
31	29·5	28·2	29·0	34·0	38·3	42·0	45·5	46·0	45·5	42·0	38·5	34·5	31·1	30·6	33·4	37·3	41·8	46·5	50·5	52·5	[51·2	48·4]	45·2	40·2
1 Feb.	37·6	35·2	35·0	37·0	40·3	44·8	48·2	49·5	49·0	46·8	42·4	38·1	35·7	33·0	33·2	35·8	39·5	45·5	46·9	48·9	48·5	45·5	41·7	37·0
2	33·6	32·0	29·5	31·2	34·0	38·0	42·0	45·5	46·7	45·5	42·7	38·5	33·0	31·0	29·7	31·7	36·0	39·5	44·5	46·7	47·7	46·2	43·5	39·2
3	35·0	31·7	29·5	29·8	33·0	37·1	41·5	44·6	45·7	45·2	42·5	39·8	35·3	31·8	29·5	29·4	32·8	37·0	41·2	44·5	46·5	46·3	44·0	40·5
Grimsby (ft.), G.M.T.																							
28 Jan.	11·3	14·2	17·0	21·0	23·9	25·2	25·2	23·3	18·8	16·0	13·6	12·5	13·3	15·9	19·2	22·3	24·8	25·4	24·0	21·2	18·0	14·0	11·0	9·7
29	9·7	11·3	14·0	18·0	22·0	24·2	24·2	23·0	20·2	16·0	13·0	10·7	11·2	13·2	16·0	19·7	23·5	25·8	25·9	24·0	21·5	17·0	13·2	10·2
30	8·7	9·2	11·8	15·0	19·7	23·0	24·6	23·3	21·5	17·7	13·6	10·5	9·2	10·2	13·3	17·3	21·3	24·3	26·0	25·3	23·8	18·5	14·7	11·2
31	8·5	7·3	9·0	13·8	17·2	21·7	24·5	25·3	24·5	21·1	17·5	13·5	10·8	9·0	13·0	17·0	22·0	26·8	29·5	29·5	[28·6]	27·5	24·5	20·0
1 Feb.	16·0	14·2	14·3	16·5	20·0	23·8	26·9	28·2	27·2	25·8	21·2	17·0	14·8	12·5	12·8	15·0	18·8	23·0	25·8	27·8	26·8	24·0	19·7	14·5
2	12·5	8·5	8·6	10·8	13·2	17·5	20·7	24·7	25·0	24·0	21·8	17·0	12·8	10·0	9·2	11·2	15·5	19·5	23·5	26·0	26·5	24·5	21·8	17·5
3	13·2	11·0	7·5	8·8	12·5	15·6	19·2	22·8	24·8	23·8	21·2	18·5	13·5	10·7	7·8	9·0	12·5	16·5	20·8	24·1	25·5	23·7	22·2	19·2
King's Lynn (ft.), G.M.T.																							
28 Jan.	7·0	6·5	6·3	10·5	17·1	21·1	22·3	21·8	19·3	15·5	12·5	10·3	8·6	8·3	10·6	14·1	18·8	22·1	22·4	20·3	16·8	13·6	11·0	8·7
29	7·3	6·5	6·1	7·2	12·4	18·3	21·5	21·9	19·6	16·1	13·0	10·5	8·3	7·2	7·0	9·9	14·9	20·3	23·2	23·1	20·4	16·7	13·5	10·7
30	8·4	6·8	6·1	5·8	7·4	14·4	20·0	21·8	20·7	17·5	14·1	11·1	8·6	6·9	6·1	5·9	9·1	16·2	21·3	22·9	21·3	17·7	14·3	11·3
31	8·7	6·7	5·7	5·5	5·2	11·1	18·6	22·5	23·3	21·5	18·8	15·3	11·1	9·7	8·1	7·5	10·8	19·3	26·4	30·3	30·8	28·5	25·9	23·0
1 Feb.	19·8	15·7	13·1	11·5	12·5	16·8	21·5	24·3	25·8	25·4	23·6	20·3	16·1	12·8	10·8	10·5	12·0	14·7	19·3	24·0	25·5	23·6	21·2	17·8
2	13·9	10·8	8·8	7·8	7·3	7·2	11·7	18·4	22·6	23·3	21·1	17·4	14·0	10·9	8·6	7·3	7·1	9·6	15·4	21·6	24·5	23·7	21·2	17·6
3	14·2	11·3	9·4	7·9	7·3	7·0	9·6	16·5	21·4	22·7	20·9	17·4	13·9	11·1	8·8	7·2	6·5	6·6	10·2	16·9	21·8	23·2	21·2	17·9
Holland Sluice (ft.), G.M.T.																							
28 Jan.	4·6	2·4	0·5	−0·7	−1·0	−1·2	−1·3	−0·2	2·6	5·2	7·8	8·5	7·4	5·7	2·5	1·4	−0·1	−0·8	−0·5	1·4	3·3	4·6	6·6	6·8
29	6·0	3·8	1·8	0·0	−0·9	−1·1	−1·2	−1·0	−0·1	1·9	5·3	7·3	7·4	5·5	3·4	1·7	0·0	−1·0	−1·3	−0·5	0·5	3·4	5·6	7·2
30	8·2	5·5	4·4	1·4	−0·4	−1·0	−1·2	−1·3	−1·0	−0·5	3·0	5·0	7·4	6·4	4·8	2·4	−0·2	−1·1	−1·4	−1·4	−0·8	0·7	2·4	5·0
31	7·0	6·7	4·8	1·6	−0·2	−0·8	−1·4	−1·3	−1·1	−1·0	2·0	5·2	8·4	8·8	6·5	4·9	2·0	0·0	−0·9	−0·3	2·2	5·0	9·1	11·8
1 Feb.	13·8	15·0	.	.	.	.	.	.	.	.	6·2	7·6	10·2	11·3	11·7	9·9	6·2	4·5	1·5	0·5	1·2	2·7	4·7	6·1
2	8·0	9·0	9·4	8·0	4·4	1·5	−0·1	−0·4	−0·7	−0·8	0·4	1·8	4·4	7·2	8·8	7·6	4·8	2·0	−0·6	−1·1	−1·1	−0·6	1·8	3·0
3	5·6	7·8	9·0	8·2	5·2	2·6	−0·6	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Southend (ft.), G.M.T.																							
28 Jan.	6·1	3·5	0·2	−2·7	−4·9	−6·1	−6·2	−4·6	−1·5	2·1	5·7	8·7	9·4	7·5	4·0	0·5	−2·3	−4·0	−4·3	−2·8	−0·1	2·7	4·9	6·8
29	7·7	6·1	2·9	−0·7	−3·8	−5·8	−6·8	−6·5	−4·3	−1·2	1·9	5·4	8·0	8·1	5·4	1·6	−1·9	−4·5	−5·8	−5·5	−2·9	0·4	3·5	6·0
30	8·3	8·6	6·3	2·5	−1·4	−4·6	−6·6	−7·4	−6·6	−4·1	−0·7	2·7	6·3	8·1	7·0	3·3	−0·7	−4·2	−6·3	−7·1	−6·0	−2·9	0·4	3·3
31	6·0	7·7	6·7	3·5	−0·6	−4·3	−7·0	−8·6	−9·2	−7·7	−2·2	1·3	6·2	9·4	9·1	6·1	2·1	−1·6	−4·7	−6·1	−4·5	1·0	6·4	10·8
1 Feb.	14·1	15·1	14·1	12·2	9·3	5·2	1·9	−0·4	−1·5	−0·4	2·7	6·1	9·3	11·6	12·2	10·5	7·1	3·4	−0·2	−3·0	−3·9	−1·6	2·1	5·4
2	7·2	8·6	9·8	8·9	5·8	1·6	−2·8	−6·1	−7·3	−6·8	−4·3	−0·8	2·8	6·4	9·2	9·1	6·2	2·2	−2·2	−5·5	−6·6	−5·5	−2·1	1·8
3	4·9	7·2	9·2	9·1	6·4	2·5	−1·9	−5·7	−7·6	−7·8	−5·8	−2·6	0·7	4·1	7·3	8·5	6·5	2·6	−1·7	−5·5	−7·4	−7·5	−5·3	−1·8
Chatham (ft.), G.M.T.																							
28 Jan.	16·2	13·5	9·8	6·5	3·9	2·6	2·0	2·6	5·6	9·1	12·8	16·5	18·9	17·8	14·0	10·6	7·5	4·8	4·2	4·5	7·0	10·2	12·6	14·6
29	16·4	16·7	13·6	9·5	6·0	3·1	1·9	1·3	2·2	5·8	8·8	12·0	15·5	17·8	16·6	13·0	9·1	5·5	3·2	2·6	3·5	7·0	10·5	13·2
30	15·6	17·8	17·6	13·8	9·6	5·7	2·4	1·4	1·0	3·4	6·8	10·0	13·8	17·2	17·0	13·0	9·0	5·0	2·3	1·5	1·5	4·8	8·5	11·2
31	13·9	16·6	16·6	12·8	8·5	4·2	1·3	−0·1	−1·1	−1·3	3·0	8·2	12·8	18·0	19·3	16·0	12·0	8·2	4·4	2·0	2·4	6·5	13·0	18·0
1 Feb.	21·8	[24·3	24·1]	22·1	19·0	15·4	11·5	8·4	6·9	7·0	9·2	13·7	17·0	19·9	21·6	21·1	18·1	14·2	10·3	6·7	4·9	5·4	8·4	12·8
2	15·7	16·6	17·8	19·2	17·0	12·4	8·2	3·7	1·3	1·6	4·2	7·7	11·4	14·8	18·3	19·5	16·4	12·0	8·0	3·5	2·1	2·8	6·0	10·1
3	13·8	16·1	18·3	19·4	16·5	12·2	8·0	3·3	1·6	0·8	2·2	5·8	9·0	12·1	15·6	18·4	17·2	12·7	8·4	3·8	1·4	1·1	2·5	6·6
London Bridge (ft.), G.M.T.																							
28 Jan.	9·0	9·0	6·0	2·3	−1·0	−4·0	−6·4	−7·6	−6·5	−2·8	1·6	6·1	10·0	12·4	10·9	6·6	2·6	−0·7	−3·6	−5·6	−5·4	−1·0	3·3	6·6
29	8·5	10·1	9·6	5·9	2·0	−1·4	−4·5	−7·0	−8·2	−6·4	−2·0	2·2	6·0	9·7	11·5	9·0	4·6	0·8	−2·4	−5·3	−7·2	−5·4	−0·1	4·3
30	7·6	9·8	11·8	10·0	5·6	1·8	−1·8	−4·9	−7·4	−8·7	−5·6	−1·0	3·0	7·0	10·6	11·0	7·0	2·8	−1·0	−4·2	−7·0	−8·4	−5·0	0·1
31	4·2	7·0	9·8	10·4	6·8	2·6	−1·1	−4·5	−7·5	−9·8	−10·8	−7·4	−1·2	4·5	10·0	12·0	9·0	4·3	0·4	−3·0	−6·0	−8·4	−4·4	3·6
1 Feb.	10·6	14·4	17·7	16·4	13·4	10·2	6·2	2·6	−0·6	−2·8	−3·6	0·0	6·4	10·9	13·6	14·8	13·6	9·6	5·4	1·4	−1·8	−4·6	−5·6	0·0
2	6·2	9·7	10·4	11·2	11·9	8·8	4·3	0·5	−3·2	−6·5	−9·0	−7·0	−1·4	3·2	7·3	10·9	13·0	10·5	5·8	1·6	−2·0	−5·4	−8·0	−5·4
3	0·8	5·7	8·8	11·0	12·6	10·6	6·0	2·0	−1·6	−5·1	−8·0	−9·4	−4·2	0·6	4·7	8·2	11·6	11·4	7·0	2·6	−1·1	−4·6	−7·6	−9·2

[ ] denote interpolated values.

TABLE 2. (*cont.*)

hours ...	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Dover (ft.), G.M.T.																								
date																								
28 Jan.	14·5	11·6	8·8	5·9	3·7	2·4	2·8	5·5	10·8	15·5	17·4	17·5	16·2	14·0	11·0	8·1	5·5	3·8	3·4	4·8	8·5	14·0	17·6	17·9
29	16·4	13·8	10·4	7·2	4·5	2·4	1·4	2·2	5·9	11·8	16·2	17·3	16·7	15·1	12·1	8·8	5·7	3·2	2·0	2·2	4·9	10·2	16·2	18·5
30	18·2	16·2	13·1	9·4	6·1	3·4	1·5	1·0	2·6	7·7	14·0	16·9	17·1	16·1	13·6	10·1	6·7	3·8	1·6	0·8	1·9	6·2	12·8	17·2
31	17·9	16·8	14·5	11·0	7·6	4·5	1·8	0·8	1·7	6·2	12·7	16·6	18·1	18·2	16·9	13·8	10·7	7·0	4·2	3·3	4·5	8·1	14·0	20·5
1 Feb.	24·2	24·5	22·6	19·4	15·6	12·0	9·1	7·0	6·0	7·1	11·0	17·7	21·8	22·2	20·4	17·3	13·4	10·1	7·4	5·1	3·7	4·6	7·5	13·2
2	19·6	21·0	19·3	16·3	12·0	8·3	5·4	2·8	1·4	1·5	4·2	11·1	17·1	18·7	17·9	16·1	12·5	9·0	5·9	3·3	1·7	1·7	4·5	9·6
3	16·5	19·5	18·7	16·7	13·0	9·1	5·8	3·1	1·1	0·6	2·5	7·6	14·2	17·1	17·5	16·1	13·4	9·6	6·1	3·2	1·2	0·5	1·9	5·9
Newhaven (ft.), G.M.T.																								
28 Jan.	19·0	15·4	12·0	9·0	7·7	8·2	10·2	13·2	17·1	21·0	22·4	21·7	19·5	15·9	12·6	9·8	8·0	8·1	9·6	12·6	16·3	20·7	23·2	23·2
29	21·4	17·5	13·9	10·1	7·5	6·8	8·0	10·9	14·3	19·0	22·4	22·7	21·2	17·7	13·8	10·1	7·4	6·4	7·2	9·8	13·6	18·3	22·3	23·6
30	22·8	19·7	16·0	11·8	8·4	6·5	6·6	8·4	11·4	15·9	20·9	23·0	22·8	20·6	16·9	12·8	8·9	6·4	5·7	7·4	10·3	14·6	19·6	23·3
31	24·0	22·8	19·4	16·5	11·2	7·3	6·4	7·6	9·9	14·0	19·0	22·5	23·6	22·5	19·2	16·0	11·9	8·5	6·9	7·2	9·6	13·4	19·0	24·0
1 Feb.	26·5	26·5	24·4	20·6	16·5	13·0	11·0	9·8	11·1	14·2	18·1	22·7	25·5	25·3	22·7	18·5	14·1	10·5	8·4	7·4	8·5	11·3	15·2	20·1
2	24·1	24·8	23·4	19·6	14·9	10·6	8·1	6·6	6·9	9·5	13·1	17·6	22·1	23·5	22·7	19·4	15·0	11·0	7·9	6·4	6·4	8·6	11·8	16·6
3	21·4	23·6	23·5	21·2	16·9	12·4	9·1	6·9	6·4	7·9	10·9	15·3	19·6	22·4	22·3	20·1	16·1	12·0	8·5	6·3	5·5	6·7	9·4	13·5
Dieppe (m), G.M.T																								
28 Jan.	6·0	4·8	3·6	2·5	2·0	2·1	3·1	4·9	6·6	7·7	8·2	7·6	6·4	5·1	3·8	2·6	1·9	1·7	2·3	4·0	6·0	7·5	8·3	8·1
29	6·9	5·5	4·2	2·9	1·9	1·5	1·9	3·4	5·5	7·2	8·2	8·4	7·3	5·9	4·5	3·1	1·9	1·4	1·4	2·5	4·7	6·7	8·0	8·6
30	7·9	6·5	5·0	3·6	2·4	1·5	1·4	2·2	4·2	6·4	7·8	8·6	8·2	6·8	5·3	3·8	2·5	1·5	1·1	1·5	3·3	5·6	7·4	8·6
31	8·6	7·4	6·0	4·6	3·2	2·4	1·8	2·1	3·7	5·7	7·4	8·7	9·0	8·0	6·8	5·3	3·8	2·6	1·8	1·7	2·7	4·9	7·0	8·7
1 Feb.	9·5	8·9	7·7	6·3	5·0	3·7	2·6	2·2	2·7	4·3	6·6	8·4	9·1	8·9	7·2	5·5	4·2	3·0	2·1	1·6	1·6	3·0	5·5	7·7
2	8·7	9·0	7·6	6·0	4·5	3·2	2·1	1·4	1·5	2·7	5·1	7·2	8·2	8·9	7·7	6·1	4·6	3·2	2·1	1·4	1·2	2·0	4·3	6·6
3	8·0	8·7	8·0	6·5	5·0	3·6	2·4	1·5	1·3	1·9	3·8	6·0	7·5	8·4	8·0	6·5	5·0	3·6	2·3	1·4	1·0	1·4	3·0	5·4
Ostend (cm), G.M.T.																								
28 Jan.	443	398	329	250	179	121	94	130	200	276	408	492	509	479	411	327	239	172	141	159	200	243	322	440
29	467	438	380	300	212	138	80	73	120	178	270	418	480	475	429	350	259	173	117	108	152	198	260	380
30	483	479	436	360	269	177	97	51	59	118	187	312	451	471	442	378	289	196	120	71	84	130	180	275
31	431	467	437	380	301	216	144	85	87	144	222	351	490	559	561	530	447	350	289	233	258	330	420	510
1 Feb.	618	[700	705	654	559	461	350	279	252	276	320]	374	461	580	623	600	527	410	300	228	202	220	258	289
2	359	463	544	517	442	348	228	138	79	68	120	180	252	400	510	507	457	370	270	158	107	100	156	203
3	266	378	497	490	443	360	243	142	67	31	53	117	188	301	452	470	441	370	270	165	90	53	73	132
Brouwershavn (cm), G.M.T.																								
28 Jan.	109	130	109	68	17	−36	−83	−92	−78	−62	−26	30	120	186	177	146	98	30	−23	−57	−59	−48	−30	−6
29	40	110	128	95	54	−6	−68	−109	−115	−108	−88	−50	11	117	150	130	90	40	−20	−70	−79	−76	−58	−32
30	0	77	130	128	82	29	−33	−101	−140	−134	−120	−102	−60	28	112	128	88	41	−12	−71	−101	−110	−110	−89
31	−62	−9	82	108	79	30	−24	−79	−93	−65	−59	−34	28	117	226	261	240	208	177	139	161	170	197	245
1 Feb.	281	329	387	427	396	330	266	189	138	126	135	140	150	168	218	282	298	266	199	129	51	30	40	39
2	49	64	88	142	186	153	100	30	−54	−110	−112	−101	−70	−48	11	125	180	156	102	49	−21	−79	−90	−88
3	−64	−32	0	70	134	126	80	22	−42	−121	−160	−150	−141	−110	−60	20	109	124	.	.	.	.	.	.
Ijmuiden (cm), G.M.T.																								
28 Jan.	5	52	90	82	58	31	17	18	−2	−29	−36	−25	14	85	141	148	128	108	78	41	15	−12	−28	−33
29	−38	−21	59	92	69	37	8	−10	−19	−41	−64	−66	−58	0	88	117	100	82	60	39	17	−12	−38	−45
30	−41	−38	19	94	84	49	11	−19	−30	−41	−71	−97	−96	−72	1	85	88	68	41	29	16	−11	−48	−70
31	−74	−71	−41	50	69	39	10	1	29	49	20	−16	0	29	108	190	209	215	228	261	290	260	231	221
1 Feb.	230	248	279	340	381	380	310	260	200	165	151	134	112	110	116	128	208	230	199	152	102	79	59	42
2	29	11	−1	6	60	137	100	55	11	−24	−34	−44	−68	−79	−69	−40	58	122	109	80	49	18	−11	−32
3	−51	−59	−52	−45	0	88	89	51	8	−31	−53	−69	−89	−111	−112	−90	−31	60	79	59	28	−8	−30	−50

[ ] denote interpolated values.

Harlingen (cm), G.M.T.																								
28 Jan.	28	4	−12	−15	31	80	110	129	132	118	90	52	28	8	−16	−18	29	96	141	170	179	155	112	76
29	40	8	−21	−41	−51	0	50	81	98	99	81	50	15	−12	−41	−61	−72	−28	40	90	127	135	123	70
30	28	−9	−35	−60	−82	−80	−20	30	60	75	70	49	13	−20	−49	−73	−99	−100	−40	25	69	99	110	90
31	48	8	−22	−52	−78	−90	−55	0	41	77	111	131	108	80	57	31	20	62	172	255	335	363	359	312
1 Feb.	300	284	290	299	292	295	322	331	321	300	271	240	199	160	125	100	71	44	50	130	190	211	209	185
2	139	92	52	18	−11	−36	−68	−38	30	78	91	90	75	40	0	−32	−61	−89	−111	−98	−20	48	88	100
3	86	48	8	−25	−60	−85	−108	−112	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Borkum (cm), G.M.T.																								
28 Jan.	30	9	−14	−16	5	50	95	116	138	137	125	100	65	31	6	−10	−10	38	85	131	165	180	162	120
29	61	10	−30	−58	−70	−40	14	52	90	110	117	96	44	−8	−45	−76	−93	−60	9	60	102	132	140	118
30	61	3	−50	−89	−114	−118	−56	0	40	70	90	88	55	0	−61	−105	−134	−138	−82	−2	45	82	108	106
31	80	29	−30	−82	−115	−129	−110	−40	20	68	102	120	110	90	55	0	−16	−6	37	103	175	238	265	270
1 Feb.	252	236	212	185	154	132	132	155	205	246	265	255	220	170	115	65	28	10	7	30	85	135	175	190
2	170	120	65	15	−35	−80	−91	−81	−22	30	64	86	89	65	15	−45	−100	−138	−157	−150	−25	2	50	88
3	95	71	26	−33	−88	−135	−160	−162	−110	−30	17	48	62	50	15	−40	−104	−150	−184	−190	−139	−45	12	.
Norderney (cm), G.M.T.																								
28 Jan.	100	63	35	12	2	30	80	119	139	150	155	143	115	75	50	15	−2	6	68	125	170	192	193	166
29	122	70	20	−20	−50	−58	−10	45	85	115	130	129	95	40	−2	−42	−68	−80	−36	35	85	127	152	152
30	110	50	−3	−50	−95	−123	−109	−25	23	62	95	117	102	45	−10	−60	−105	−180	−173	−35	32	78	115	141
31	129	80	25	−30	−79	−117	−123	−65	−2	37	79	107	142	132	87	50	23	7	15	72	150	213	260	285
1 Feb.	272	270	240	195	167	134	120	135	180	230	265	275	251	220	170	118	65	30	7	10	57	115	167	197
2	203	160	115	60	8	−41	−66	−75	−50	8	50	85	103	104	65	5	−50	−96	−135	−149	−118	−20	35	77
3	108	115	78	22	−39	−93	−135	−154	−136	−51	8	42	72	85	70	16	−46	−104	−147	−177	−165	−78	4	.
Cuxhaven (cm), G.M.T.																								
28 Jan.	210	172	121	75	42	18	6	30	95	135	168	185	185	158	120	78	42	12	−10	−12	60	140	205	238
29	245	211	150	85	27	−20	−56	−74	−35	56	112	150	170	158	110	50	0	−46	−84	−103	−69	40	114	158
30	185	180	133	68	0	−55	−110	−147	−140	−45	48	102	132	147	123	63	0	−58	−109	−146	−152	−66	95	122
31	150	171	156	100	35	−28	−75	−125	−146	−100	3	69	107	130	165	165	111	60	20	−10	−10	50	131	205
1 Feb.	270	299	300	275	222	169	125	91	73	87	144	212	258	280	262	210	145	85	39	−2	−36	−42	19	100
2	168	213	216	183	124	53	−11	−60	−100	−120	−100	−20	57	103	124	115	67	0	−69	−124	−170	−185	−150	−40
3	62	115	140	137	90	26	−43	−104	−152	−180	−170	−81	20	80	109	117	88	26	−44	−110	−160	−195	−185	.
Busum (cm), G.M.T.																								
28 Jan.	220	194	138	90	49	10	−11	14	78	135	172	188	182	163	125	82	37	−4	−37	−24	51	138	210	250
29	247	215	163	98	25	−53	−111	−99	−30	50	112	154	175	162	121	60	−13	−91	−135	−120	−62	34	107	162
30	189	180	140	74	−10	−104	−174	−179	−145	−51	44	100	135	150	133	78	4	−89	−170	−186	−157	−56	52	120
31	163	178	160	112	45	−36	−122	−167	−158	−94	8	76	120	150	175	175	124	66	19	−24	−23	48	132	208
1 Feb.	268	292	288	260	211	158	106	49	24	29	88	151	217	260	266	225	172	118	60	−24	−74	−72	−24	63
2	124	180	196	182	137	78	−20	−90	−136	−157	−145	−61	34	78	107	112	79	14	−64	−130	−173	−202	−212	−120
3	−74	−14	124	141	116	62	−20	−95	−153	−189	−208	−148	−17	57	98	116	106	56	−25	−98	−153	−191	−215	.
List (cm), G.M.T.																								
28 Jan.	164	176	174	155	117	81	50	34	42	64	88	117	140	148	138	119	96	58	38	20	38	64	96	127
29	151	166	154	134	100	62	22	−8	−21	−6	19	48	76	94	102	91	66	24	−14	−44	−52	−22	11	47
30	80	103	112	97	63	22	−23	−61	−88	−75	−40	−2	34	59	74	75	52	17	−24	−62	−86	−78	−44	12
31	52	85	110	110	94	60	20	−19	−52	−60	−40	−6	28	62	82	99	107	98	83	56	41	59	84	119
1 Feb.	157	193	220	227	214	186	154	124	106	98	110	130	160	188	197	182	156	126	88	45	5	−17	−6	20
2	51	78	98	99	82	60	26	−23	−69	−103	−117	−86	−46	−12	10	21	14	−8	−38	−80	−120	−154	−160	−116
3	−60	−8	27	45	43	22	−10	−53	−95	−130	−149	−120	−72	−20	16	35	36	16	−16	−56	−97	−132	−150	.
Esbjaerg (cm), G.M.T.																								
28 Jan.	171	182	174	150	119	86	58	46	50	73	95	121	134	134	128	113	88	68	42	31	44	69	98	124
29	147	151	148	129	102	69	34	7	−6	4	24	46	67	86	92	86	63	32	−1	−34	−39	−15	13	42
30	71	94	101	91	63	28	−11	−50	−71	−57	−30	2	27	52	68	71	57	26	−9	−45	−68	−53	−19	13
31	52	88	114	121	113	92	62	26	−7	−22	−12	9	37	67	84	94	97	93	83	66	55	64	88	120
1 Feb.	155	186	205	208	186	162	140	121	103	94	98	119	146	169	176	164	141	117	87	50	10	−18	−21	−1
2	24	44	60	67	64	43	15	−26	−72	−114	−131	−102	−63	−38	−18	−8	−7	−18	−42	−79	−121	−158	−171	−121
3	−70	−35	−3	19	27	14	−10	−43	−77	−122	−145	−122	−78	−38	−10	12	26	19	−3	−34	−69	−109	−137	−117

TABLE 2. (*cont.*)

hours …	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
date																								
Hanstholm (cm), G.M.T.																								
28 Jan.	95	104	105	101	93	85	75	67	68	72	79	93	98	93	91	82	71	65	54	54	56	61	71	71
29	71	74	67	.	.	.	.	.	.	.	44	45	48	50	50	49	44	35	27	25	23	25	29	33
30	30	34	33	35	31	25	22	17	13	11	13	13	13	13	15	19	21	21	16	14	10	7	11	16
31	16	19	30	36	43	42	38	34	28	25	19	20	21	15	24	25	24	28	25	23	15	13	20	26
1 Feb.	29	30	33	30	30	29	26	27	28	38	49	61	69	72	82	89	88	85	71	61	55	52	48	39
2	45	42	40	39	34	30	21	6	−4	−10	−15	−25	−29	−28	−32	−34	−34	−38	−42	−51	−58	−63	−67	−68
3	−61	−57	−51	−51	−48	−42	−37	−39	−42	−42	−43	−46	−45	−40	−39	−40	−34	−28	−23	−19	−21	−17	−20	−25
Hirtshals (cm), G.M.T.																								
28 Jan.	95	99	107	99	84	78	57	49	55	63	85	84	90	95	84	81	68	68	53	43	51	54	68	65
29	70	67	59	58	45	37	31	25	23	25	27	36	41	40	43	39	36	27	26	23	15	25	28	41
30	39	37	36	33	31	23	21	11	8	4	10	9	11	12	13	14	17	19	16	13	12	9	12	14
31	22	24	22	34	35	37	30	26	20	17	12	13	13	12	15	16	23	19	14	16	8	3	2	6
1 Feb.	10	10	9	6	−1	−3	−8	−12	−8	−2	5	25	29	42	53	62	60	61	51	49	44	37	31	31
2	41	39	41	33	38	28	19	3	−7	−15	−18	−20	−22	−26	−23	−26	−30	−30	−38	−44	−55	−58	−62	−65
3	−60	−55	−47	−46	−46	−44	−42	−42	−47	−47	−48	−48	−50	−44	−41	−41	−35	−34	−31	−21	−24	−18	−13	−17
Nevlunghavn (cm), G.M.T.																								
28 Jan.	61	64	68	66	61	43	39	36	38	46	53	61	66	66	59	49	44	34	29	28	28	34	44	47
29	46	41	38	33	24	16	11	8	6	6	11	16	19	19	20	18	14	9	6	3	3	2	8	18
30	19	16	14	13	11	8	3	−1	4	−4	−5	−2	−1	−1	−1	1	4	5	5	3	2	0	1	6
31	10	14	18	19	24	23	22	16	11	6	3	1	−1	1	0	2	3	1	−6	−5	−7	−11	−14	−12
1 Feb.	−9	−9	−12	−15	−19	−25	−30	−33	−32	−30	−25	−15	−3	10	15	20	22	21	16	10	7	7	8	8
2	10	11	15	14	12	10	3	−5	−13	−16	−18	−22	−20	−18	−16	−15	−15	−17	−20	−26	−34	−38	−40	−42
3	−40	−35	−29	−26	−25	−25	−24	−23	−24	−26	−27	−28	−28	−27	−24	−22	−21	−21	−18	−15	−15	−16	−15	.
Tregde (cm), G.M.T.																								
28 Jan.	64	68	64	63	54	46	38	31	32	38	46	52	56	59	54	48	41	33	31	25	29	31	34	38
29	39	39	34	28	19	14	9	6	2	3	4	8	9	14	14	11	9	4	1	−4	−4	−1	4	6
30	9	13	14	12	9	6	3	−1	−2	−2	−1	0	0	1	2	3	1	2	4	−3	1	1	3	3
31	8	12	16	21	23	24	22	19	15	11	9	8	2	6	6	8	8	5	3	1	−5	−7	−7	−9
1 Feb.	−7	−7	−9	−10	−15	−19	−27	−27	−25	−24	−17	−10	1	10	15	21	22	18	16	12	10	13	9	10
2	13	16	20	21	21	18	13	7	1	−4	−7	−7	−6	−5	−5	−4	−3	−7	−12	−17	−20	−25	−29	−28
3	−25	−20	−18	−15	−14	−11	−12	−15	−24	−16	−17	−18	−17	−17	−16	−14	−12	−12	−11	−11	−12	−12	−14	.
Stavanger (cm), G.M.T.																								
28 Jan.	62	43	35	30	44	49	53	65	70	70	60	55	54	45	44	21	27	30	30	40	54	60	50	45
29	43	35	25	12	13	21	24	25	35	43	40	32	20	18	6	−5	−11	−9	2	6	7	23	37	30
30	25	21	17	5	1	1	18	20	26	32	40	30	21	15	5	−5	−15	−16	−2	2	10	25	32	21
31	15	12	5	−5	−8	−3	7	12	18	30	40	47	34	25	20	−5	−20	−26	−25	−21	−23	−21	−3	5
1 Feb.	0	−11	−13	−21	−35	−39	−32	−25	−15	−3	15	35	.	.	.	.	.	.	.	.	.	.	.	.
2	.	.	.	.	.	.	.	.	.	.	3	10	12	2	−5	−12	−30	−41	−49	−45	−32	−26	−22	−14
3	−5	4	3	−5	−14	−22	−29	−34	−31	−26	−15	−3	2	−4	−13	−15	−25	−36	−41	−36	−24	−15	−10	.
Bergen (cm), G.M.T.																								
28 Jan.	45	18	1	−10	−11	−3	15	34	55	68	70	58	37	2	−14	−31	−43	−49	−34	−11	17	41	55	61
29	49	33	15	8	9	25	45	69	84	89	81	61	42	20	2	−11	−8	3	28	57	75	85	89	77
30	56	35	8	−18	−31	−32	−15	9	35	57	69	66	47	25	−3	−29	−45	−41	−21	1	26	45	55	50
31	33	9	−15	−32	−40	−33	−15	7	28	54	69	73	65	42	8	−23	−51	−71	−69	−58	−39	−13	7	17
1 Feb.	21	7	19	−43	−63	−72	−61	−43	−27	3	32	49	52	37	13	−12	−35	−51	−51	−33	−24	9	30	45
2	47	38	17	−7	−41	−60	−63	−51	−27	−5	16	30	32	19	13	−21	−53	−75	−84	−81	−59	−33	−8	10
3	17	13	1	−21	−53	−72	−77	−72	−51	−35	−2	21	30	27	15	−5	−33	−57	−65	−66	−51	−25	−2	.
Maloy (cm), G.M.T.																								
28 Jan.	180	157	136	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
29	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	72	56	60	81	111	144	171	180	173
30	158	128	97	74	67	73	94	124	160	188	202	197	180	148	115	78	64	60	73	100	140	173	193	194
31	184	161	128	97	80	79	90	116	148	182	202	205	191	167	122	85	50	22	11	13	37	68	105	133
1 Feb.	143	139	127	94	64	45	42	49	73	106	136	155	159	147	116	78	48	29	23	43	67	101	125	133
2	130	115	84	51	24	16	22	44	75	113	142	160	162	144	114	78	49	34	33	50	77	101	142	165
3	170	156	137	95	61	37	29	34	54	85	121	148	162	160	146	119	86	59	46	41	55	80	114	142

TABLE 3. DISTURBANCE OF MEAN SEA-LEVEL, 30 JANUARY TO 3 FEBRUARY 1953

	30 January								31 January								1 February							
hours (G.M.T.) …	0	3	6	9	12	15	18	21	0	3	6	9	12	15	18	21	0	3	6	9	12	15	18	21
Aberdeen	−2	−2	−1	−1	0	0	0	−1	−2	−2	−1	1	6	14	16	[11	8	7	8	7	6	3	1	−2]
Leith	5	7	8	9	8	7	5	3	3	2	2	3	7	18	32	31	24	19	20	20	18	15	12	9
R. Tyne Entrance	1	1	2	2	2	1	0	−2	−3	−4	−3	0	6	26	45	45	26	23	23	22	19	15	11	7
Hartlepool	6	2	−1	−1	1	2	1	0	−1	−1	−1	2	7	26	47	50	35	28	25	25	24	17	12	11
R. Tees Entrance	6	3	2	2	7	7	3	1	2	3	3	7	16	36	57	72	55	41	42	47	41	33	28	24
Hull	8	−5	−7	−3	4	9	7	2	−3	−7	−9	−7	0	19	40	59	60	45	33	27	28	38	37	17
Immingham	5	−2	−5	−4	3	7	6	0	−9	−13	−12	−7	1	18	37	61	67	44	32	31	32	32	24	18
Grimsby	4	−4	−6	−3	2	7	8	3	−6	−12	−10	−4	4	19	38	64	68	47	31	30	36	36	22	12
King's Lynn	9	7	5	3	0	−3	−6	−9	−9	−5	1	7	10	20	60	89	86	65	49	49	51	47	42	38
Holland Sluice	13	12	11	8	5	2	−2	−4	−5	−4	−1	3	5	3	8	48	78	·	·	·	52	44	34	30
Southend	12	11	7	4	1	−1	−2	−4	−6	−11	−14	−11	−4	2	4	46	72	60	73	69	52	43	39	43
Chatham	16	16	11	4	−2	−7	−5	−4	−6	−14	−18	−15	−7	3	7	49	77	68	74	68	53	47	49	45
London Bridge	11	10	8	6	3	1	−2	−4	−8	−11	−12	−9	−9	−8	−7	0	68	43	47	45	60	46	32	31
Dover	10	6	3	1	−1	−2	−3	−4	−3	−2	1	3	8	12	20	38	61	62	60	50	45	40	35	28
Newhaven	8	5	2	1	3	4	4	4	4	4	3	3	3	5	10	18	31	38	38	30	29	23	20	18
Dieppe	1	0	−1	−2	−3	−2	−2	−1	1	4	8	11	11	10	11	15	21	30	31	24	17	10	6	5
Ostend	13	10	6	2	−1	−2	−3	−3	−4	−3	1	9	20	27	38	65	78	72	69	65	52	43	38	34
Brouwershavn	10	9	6	2	−2	−4	−6	−8	−8	−8	−3	9	26	36	47	86	102	93	76	85	73	51	43	43
Ijmuiden	9	6	3	−2	−4	−2	−2	−3	−4	−5	−4	6	22	34	46	75	88	92	86	63	58	47	34	24
Harlingen	4	2	0	−2	−4	−6	−7	−6	−5	−7	−8	−5	5	24	61	78	59	102	111	67	38	40	42	33
Borkum	13	10	8	7	6	4	3	4	0	−3	−3	0	8	23	41	49	44	70	78	59	43	41	39	29
Norderney	12	10	9	7	6	4	2	1	0	−1	−2	−3	2	23	41	47	42	60	76	65	45	40	40	30
Cuxhaven	13	10	7	5	4	2	0	−2	−1	0	−2	−5	−5	9	24	38	35	42	62	66	45	27	31	28
Busum	5	4	4	3	1	0	−1	−3	−2	−3	−3	−4	−4	10	30	36	30	33	51	50	36	28	28	19
List	13	13	11	8	6	3	1	1	3	7	9	7	1	−1	20	34	34	35	47	59	52	35	25	20
Esbjaerg	7	6	5	3	1	−1	−4	−4	−2	5	13	8	−5	−5	10	26	29	27	27	46	42	30	19	11
Hanstholm	12	12	10	7	5	3	2	1	2	3	3	1	−2	−4	−5	−2	1	2	−2	0	20	25	23	17
Hirtshals	13	11	8	5	4	3	3	2	2	2	2	−1	−5	−7	−8	−7	−7	−8	−8	−4	7	15	16	15
Nevlunghavn	4	4	3	2	1	0	0	0	0	0	−1	−3	−7	−9	−12	−13	−13	−13	−14	−12	−3	4	5	6
Tregde	3	3	3	3	2	1	0	0	0	0	−2	−3	−6	−8	−10	−12	−12	−12	−12	−8	−2	4	7	8
Stavanger	5	7	6	5	3	1	−1	−3	−5	−5	−6	−7	−8	−11	−14	−16	−15	−14	−12	−6	[0	6	7	7]
Bergen	10	8	5	3	3	2	1	−2	−5	−6	−6	−4	−3	−7	−13	−17	−16	−13	−10	−6	−1	4	7	7
Maloy	2	2	3	4	3	2	1	0	−1	−1	0	−1	−4	−11	−22	−30	−19	−5	−7	−9	−7	−2	−1	−5

	2 February								3 February				
hours (G.M.T.) …	0	3	6	9	12	15	18	21	0	3	6	9	12
Aberdeen	[−3	−3	−2	−2]	1	3	4	4	3	2	1	−1	−2
Leith	8	7	6	7	8	10	13	13	13	11	8	5	3
R. Tyne Entrance	4	5	7	7	7	8	14	15	11	7	6	6	3
Hartlepool	10	8	8	6	5	5	8	12	13	10	6	2	0
R. Tees Entrance	19	15	18	20	19	18	18	17	16	13	11	8	7
Hull	11	8	7	6	7	10	14	18	19	17	10	3	·
Immingham	13	8	6	5	6	8	12	16	19	15	9	4	2
Grimsby	8	8	8	8	10	11	13	14	15	12	7	2	−1
King's Lynn	34	29	25	21	18	17	20	23	27	26	21	15	9
Holland Sluice	28	25	24	22	17	16	15	15	15	17	·	·	·
Southend	31	21	20	17	15	14	15	17	18	18	17	16	14
Chatham	28	22	22	19	17	17	19	22	22	20	17	13	11
London Bridge	29	23	16	16	16	15	14	13	13	13	13	13	12
Dover	21	18	14	10	8	9	10	11	11	10	8	7	5
Newhaven	15	10	7	6	5	7	8	9	9	8	7	6	5
Dieppe	5	3	2	0	0	0	0	0	−1	−1	−2	−2	−3
Ostend	26	17	13	12	10	10	10	10	10	9	7	5	3
Brouwershavn	39	22	17	13	12	10	8	7	5	3	4	3	2
Ijmuiden	22	17	12	8	4	2	0	0	−1	−1	1	3	1
Harlingen	15	10	9	7	3	−3	−7	−8	−7	−6	−4	·	·
Borkum	20	18	15	10	6	2	−1	−3	−3	−2	−2	−1	−1
Norderney	20	17	18	11	4	2	0	−2	−3	−3	−2	1	2
Cuxhaven	19	12	13	7	−3	−4	−4	−5	−6	−6	−5	−3	−1
Büsum	10	6	5	2	−5	−10	−13	−15	−15	−14	−10	−3	−2
List	13	7	4	0	−4	−9	−14	−17	−13	−8	−5	−3	−2
Esbjaerg	3	−3	−7	−9	−12	−16	−19	−20	−20	−17	−13	−10	−8
Hanstholm	15	14	8	2	−4	−8	−12	−13	−13	−11	−7	−5	−5
Hirtshals	13	12	7	2	−3	−6	−9	−11	−11	−10	−9	−8	−7
Nevlunghavn	7	6	3	2	0	−1	−2	−3	−3	−2	−1	0	0
Tregde	8	8	7	6	4	3	3	3	3	3	4	5	5
Stavanger	[7	6	5	3]	1	−1	−2	−2	0	3	4	3	2
Bergen	6	4	2	1	1	1	1	1	1	1	1	1	1
Maloy	−9	−10	−5	−1	0	2	4	7	6	5	3	1	1

[ ] denote interpolated values.

Units are $\frac{1}{10}$ ft.

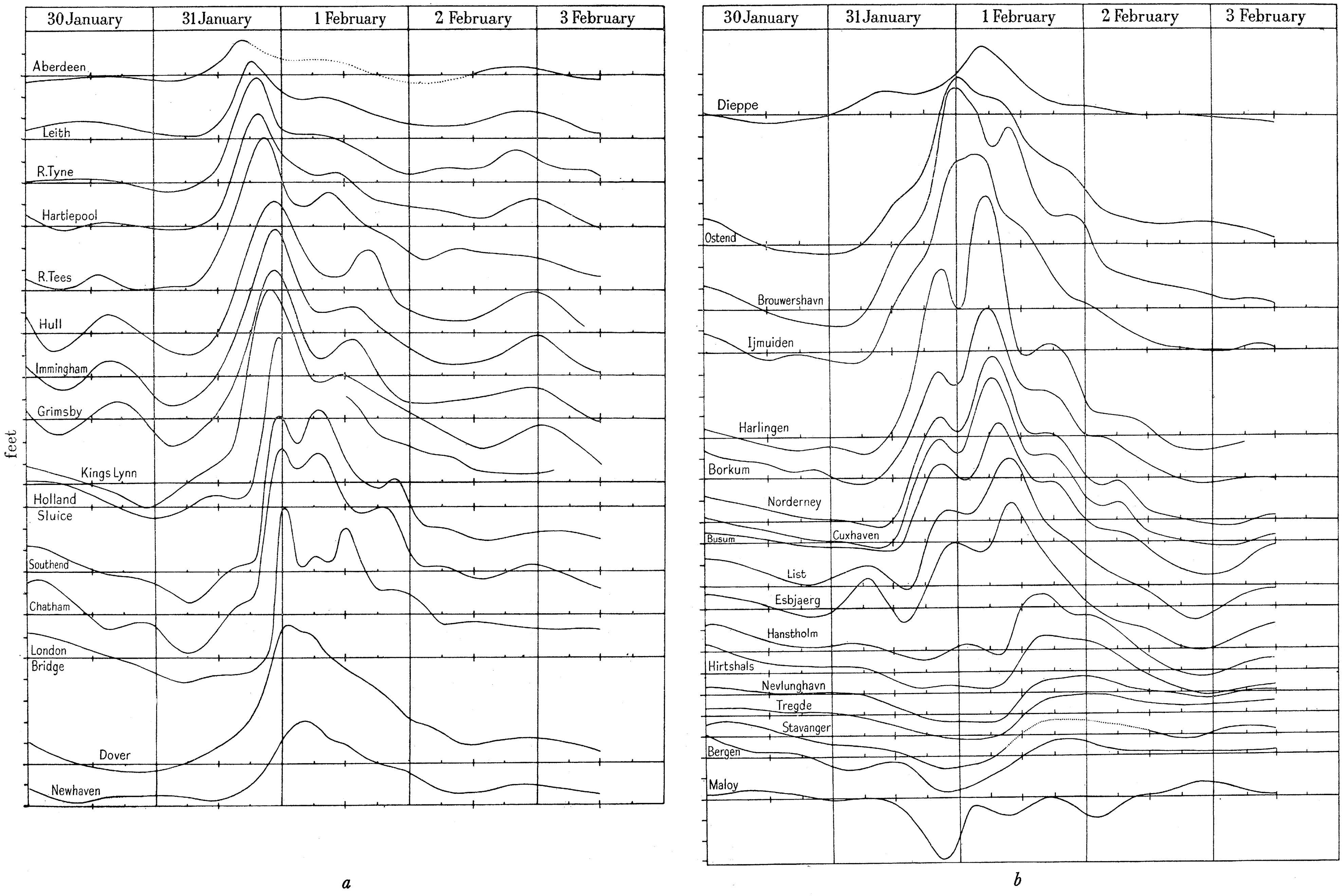


FIGURE 1. Disturbance of mean sea-level, 30 January to 3 February 1953.

are approximate, having been selected as much for simplifying the computations as for being close to the best that could be inferred from existing data after allowing for annual variations. A correction was later applied to allow for this approximation, and also to account for small discrepancies in the assumed values of mean sea-level. The amount of correction is indicated in tables 1*a* and 1*b* by the difference between the provisional and the corrected values of mean sea-level.

The residuals thus obtained were then plotted and smoothed to eliminate shallow-water effects, and the smoothed values tabulated at three-hourly intervals.

The diurnal tide was next eliminated by direct calculation using the Admiralty method (Doodson & Warburg 1936), and a correction was also applied for the local effect of barometric pressure assuming a statical relationship.

The corrected three-hourly residues were again plotted, and the heights of the several maxima and minima before the main disturbance of 31 January were examined. Suitable averages of the maxima and minima when the disturbance was slight may be expected to vary in a regular way from station to station, and small errors in calculations and in mean sea-level assumptions were traced and incorporated in the correction previously referred to.

The final residuals for the period 00.00h 30 January to 12.00h 3 February, referred to the corrected mean sea-level, are tabulated in table 3 and plotted in figures 1*a* and 1*b*. All times are in G.M.T. and all units of disturbance are tenths of a foot.

It should be borne in mind that the residuals thus prepared for the study of wind effects do not represent the true surge, since local barometric effects have been eliminated.

3. THE DISTURBANCE AT LOWESTOFT AND GREAT YARMOUTH AT 21.00H 31 JANUARY

The scarcity of the data for between the Wash and the Thames has made it necessary to utilize all available observations, even though they be of high waters only. In particular, the magnitude of the disturbance at 21.00h at Lowestoft and Great Yarmouth greatly assists in positioning the co-disturbance lines at that time.

Omitting King's Lynn, where the levels are abnormal, we have in table 4 the observed times and heights of the evening high water on 31 January at Immingham, Great Yarmouth, Lowestoft and Southend, together with the predicted times of high water and the heights of mean high-water spring tides. The visual observations for Great Yarmouth and Lowestoft have been supplied by the respective harbour masters.

TABLE 4. LEVELS BETWEEN THE HUMBER AND THE THAMES, 31 JANUARY

	Immingham	Great Yarmouth	Lowestoft	Southend
observed time of high water	1910	2204	2219	2445
predicted time of high water	1926	2253	2310	2542
observed height of high water (ft.)	15·3	10·8	11·3	15·1
mean high-water springs (ft.)	10·7	3·2	3·2	9·3

All heights are referred to ordnance datum (Newlyn).

It would be expected that the high water at Great Yarmouth, on a spring tide, would be 6·1 ft. less than that at Southend, but due to the surge it was actually 4·3 ft. less. We deduce that the disturbance at Great Yarmouth at 22.04h was 1·8 ft. greater than that at Southend at 24.45h. From the curve of residuals for Southend we then have 7·0+1·8 = 8·8 ft. for the disturbance at Great Yarmouth. A similar process, using the Immingham figures, gives a value of 9·0 ft. The average of 8·9 ft. may therefore be accepted with some confidence.

At Immingham, the average rate of rise 1h before high water, as estimated from the curve of residuals, was 0·5 ft./h and that at Southend 1·0 ft./h. Assuming a rate of rise of 0·8 ft./h for Great Yarmouth we obtain a disturbance of 8·1 ft. at 21.00h.

A similar process for Lowestoft gives a value of 8·3 ft. at 21.00h.

4. The disturbance at Harwich at 00.00h 1 February

The harbour master at Harwich has supplied the information that the extreme level reached on the night of 31 January to 1 February was 19·7 ft. above chart datum, but the exact time is doubtful. High water at Lowestoft was observed at 22.19h on 31 January; at Southend at 00.45h on 1 February. It may be therefore assumed that high water at Harwich occurred near midnight.

Adopting the same procedure as for Great Yarmouth and Lowestoft, we have:

	Southend	Harwich
observed high water above O.D. (Newlyn)	15·1 ft.	13·1 ft.
mean high-water springs above O.D. (Newlyn)	9·3 ft.	6·0 ft.

We may therefore assume that the disturbance at Harwich at midnight was 1·3 ft. greater than that at Southend at 00.45h 1 February, i.e. 8·3 ft.

5. The levels at Leith, Hartlepool, River Tees Entrance and King's Lynn

Owing to its sheltered position in the Firth of Forth, Leith is possibly not a suitable North Sea tidal station. The deduced water levels there have accordingly been treated with reserve, especially as the Leith Dock Commission state there is some doubt about the reliability of recordings made near low waters.

An examination of table 3 shows a marked discrepancy between the values of the disturbed levels at Hartlepool and at the River Tees Entrance. Both sets of original data were from automatic tide gauges, and both gauges appeared to be in good working order. The tidal station at Hartlepool is situated at the North Entrance to Hartlepool Docks, and is sheltered from northerly winds by a promontory, the Heugh, whereas the gauge at the Tees Entrance is in a position exposed to the full force of north winds. These local topographical features probably account for most of the differences between the recorded disturbances at two closely adjacent ports. The values for Hartlepool fit in with the general trend along the coast much better than those for the Tees Entrance, and when positioning the co-disturbance lines more reliance has been placed on the former set of values.

The levels at King's Lynn are abnormal at various times throughout the period under consideration, a fact which had been remarked by Corkan (1950) on another occasion and which is no doubt attributable to a combination of large stretches of shallow water in the Wash and the geographical shape and orientation of the Wash.

6. The transmission of the surge up the River Thames

While the purpose of this investigation is not particularly concerned with the propagation of the disturbance up various rivers and estuaries, the case of the River Thames is thought to be of some interest, though more information along its length would be required for a comprehensive survey.

From an examination of the curves of residuals, it will be seen that the first peak of the surge took approximately 1 h to travel from Southend to London Bridge, and was reduced in magnitude from 7·2 to 7·0 ft. The second peak took 5 h to travel and was reduced from 7·5 to 6·0 ft.

The first peak occurred at Southend approximately 2 h before the predicted time of high water there, whereas the second peak was an hour earlier than the following predicted low water. The large difference between the two rates of travel would appear to be related to the state of the tide in the Thames, and from qualitative considerations is in conformity with the established fact that low waters are retarded to a greater extent than high waters in shallow rivers. Thus the a.m. high water was predicted as taking 1 h 25 min to travel from Southend to London Bridge, whereas the following low water was expected to take 2 h.

Another notable feature of the curve for London Bridge is the exceedingly steep initial rise.

7. Meteorological conditions

The weather charts for the British Isles covering the period 00.00 h 31 January to 06.00 h 2 February are reproduced in figure 2.

For the period 12.00 h 31 January to 21.00 h 1 February the maps are given at three-hourly intervals, and were kindly supplied by the Director of the Meteorological Office; the remainder, at six-hourly intervals, were traced from the daily weather charts.

During 30 January a depression was deepening and travelling from the south of Iceland in an east-south-easterly direction. By midnight of 30 to 31 January it was due north of Scotland and travelling in an easterly direction; about noon, when it was at its greatest intensity, it swung southward into the North Sea and thereafter began to fill up, finally moving eastward over the German and Danish coasts. Figure 3 shows the track of the depression.

An outstanding feature of the depression was the very strong northerly winds in its wake, indicated by the crowding together of the isobars. These winds ultimately spread over the whole of the North Sea, and though they varied appreciably in strength from time to time, they remained at gale force until noon of 1 February and even longer in the lower half of the North Sea. From wind records available, the gale was quite abnormally severe, particularly in the northern areas of the British Isles.

Eastward-travelling depressions approaching the north of Scotland do not generally veer into the North Sea, tending rather to pass over Scandinavia, and it is a significant fact that the last storm surge which caused serious flooding in the Thames, on 6 and 7 January 1928, was associated with a similar incursion of a deep depression into the North Sea.

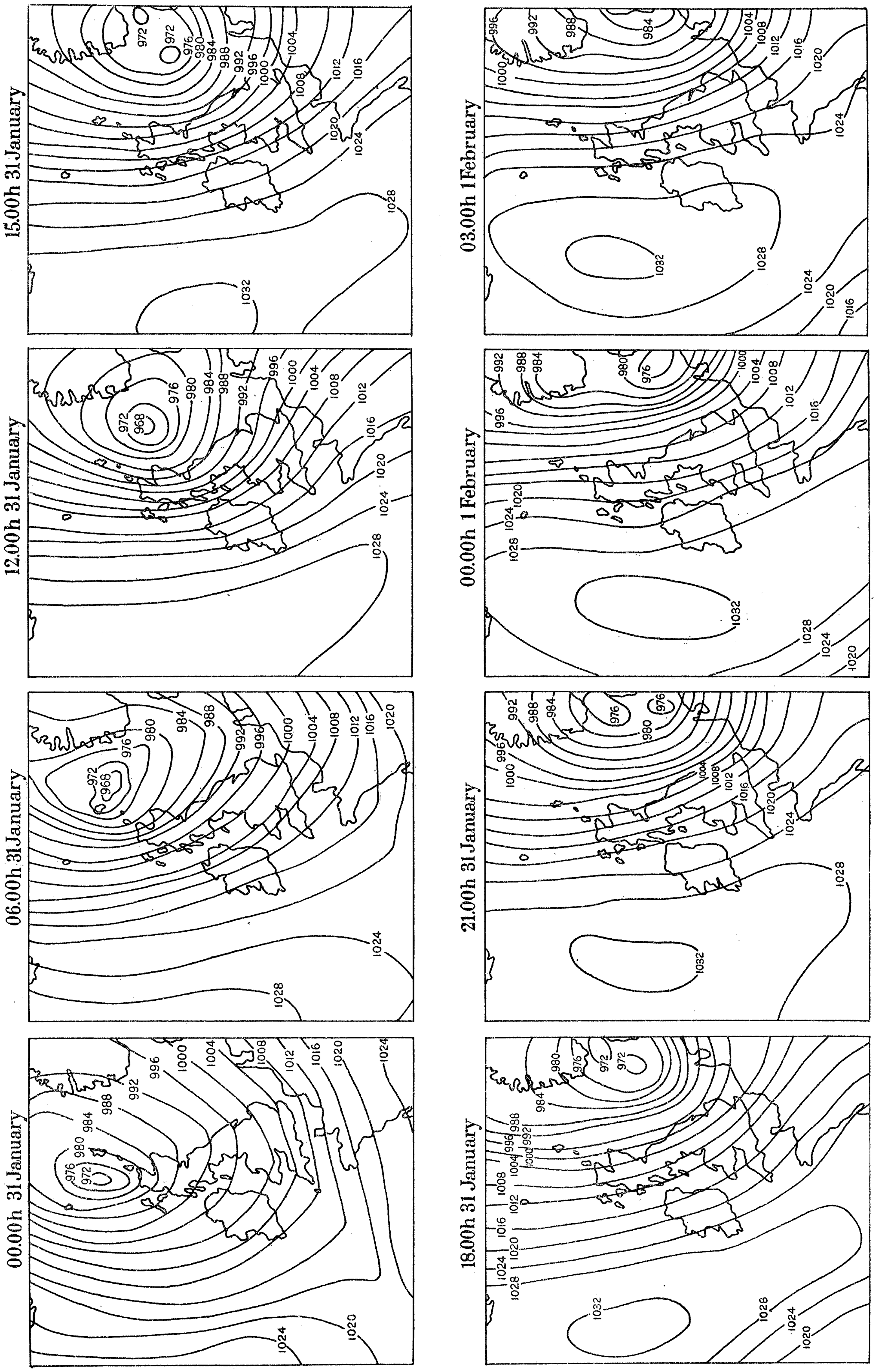


Figure 2a. Meteorological conditions, 00.00h 31 January to 03.00h 1 February 1953.

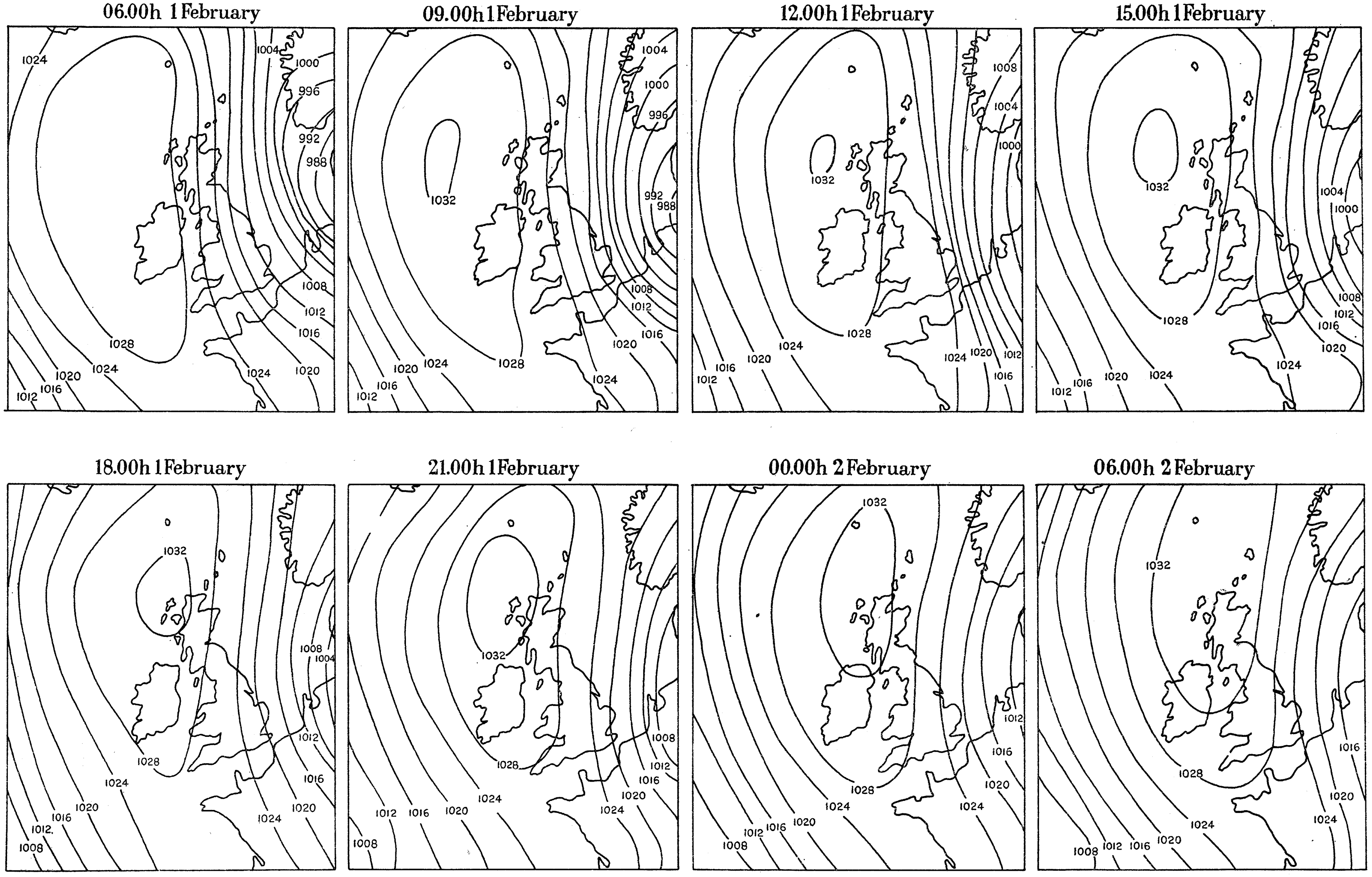


Figure 2*b*. Meteorological conditions, 06.00h 1 February to 06.00h 2 February 1953.

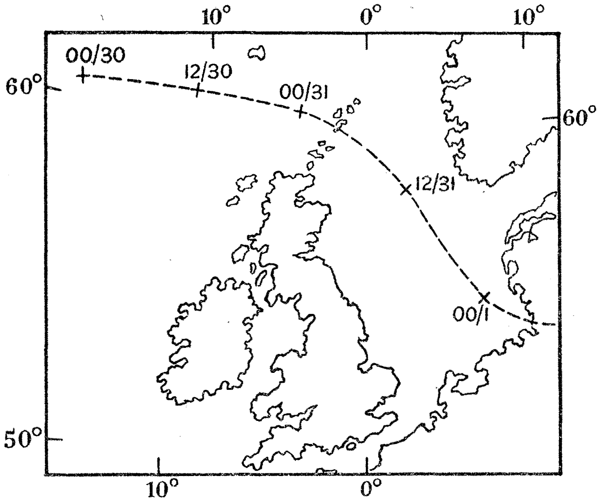


FIGURE 3. Track of depression, 30 January to 1 February 1953.

8. THE DEDUCED LEVELS OVER THE NORTH SEA, AND CHANGES IN AVERAGE LEVEL

The values of the disturbed level at all the stations available, as given in table 3, have been entered on charts of the North Sea for the period 09.00h 31 January to 03.00h 2 February, and lines of equal disturbance have been drawn. These co-disturbance charts are reproduced in figure 4, the units being tenths of a foot.

Although the positioning of the lines away from the coasts is somewhat conjectural, the data available for the main body of the North Sea leave little room for errors of any great magnitude. It is when the area south of the line joining the Wash and the Flemish Bight is considered that most difficulty has been encountered. This is due in part to the rapidity with which the waters shallow, but mainly to the paucity of data previously mentioned. Nevertheless, it is believed that the charts provide a fair representation of the water levels during the period considered, and may be linked with the meteorological conditions prevailing in terms of the known laws of dynamical oceanography.

One of the outstanding features of this surge is the large volume of water which flowed into the North Sea between Scotland and Norway. The changes in the average level over the sea have been deduced by measuring the areas enclosed between adjacent co-disturbance lines, using a planimeter (the charts used are close approximations to equal area projections). The North Sea has been considered as lying between the Straits of Dover in the south and a line drawn due east through the Shetland Isles in the north. The changes in mean level are plotted in figure 5.

The maximum transport of water took place during the afternoon of 31 January, and was caused by the gale-force north winds prevailing to the north and north-east of the British Isles. In the open sea the mean flow of water should be at right angles to the mean direction of the winds, but owing to the width of the gale belt and the presence of the east coast of Scotland, the Atlantic waters entered the North Sea.

Referring to figure 1*b*, it will be seen that at 21.00h the levels at Bergen had dropped by nearly 2 ft., and at Maloy (farther to the north) by 3 ft. It was at this time that the mean disturbed level of the North Sea reached its maximum value of over 2 ft. Taking the area of the North Sea as 7×10^{12} sq. ft., this means that an additional 15 billion cu. ft. of water was present in the area from 21.00 h 21 January till after noon on 1 February. This water must have come from the Norwegian shores of the Atlantic Ocean.

9. The levels in the North Sea and the associated meteorological conditions

(*a*) *The rise in level during the afternoon and evening of* 31 *January*

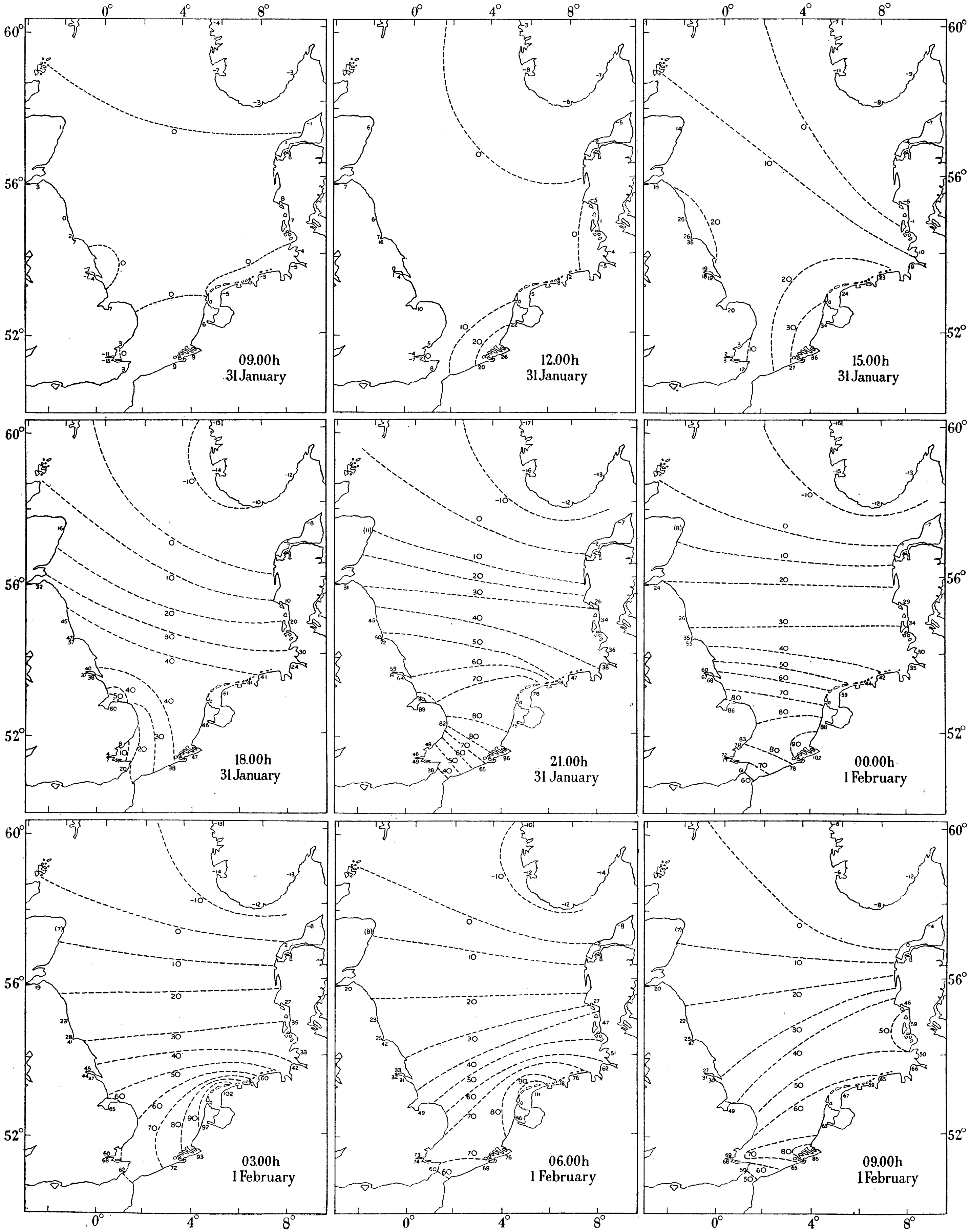
(i) 09.00*h* 31 *January*. The depression which is travelling in a south-easterly direction into the North Sea between Scotland and Norway, is at its deepest (968 mb). In the central and southern parts of the sea, west to south-west winds prevail. (*Note*. In the following discussion all references to winds imply geostrophic winds, i.e. the velocities and directions deduced from the density, direction and curvature of the mean sea-level isobars given in figure 2). These winds are maintaining a water gradient between the Thames and Scheldt estuaries of about 1·5 ft. continuing for the next 24h, apart from a period when it is neutralized by the arrival of the main disturbance. Apart from this raising of level on the coast of Holland, the level of the North Sea is undisturbed.

(ii) 12.00*h* 31 *January*. The progress of the depression has brought the gale-force northerly winds in its rear to bear on the waters off the coasts of Scotland, and the tractive forces brought into action have begun to drag water southwards. The north-west winds in the southern part of the sea are also strengthening, with an accompanying rise in level at the mouth of the Scheldt. At about this time the general level of the North Sea is beginning to rise (see figure 5).

(iii) 15.00*h* 31 *January*. Gale-force northerly winds are affecting all the western half of the North Sea, but in the southern part the winds remain north-westerly, maintaining the east to west water gradient already referred to. The general level of the North Sea is 1 ft. high, and rising rapidly. The main surge is travelling down the Scottish coast, and Aberdeen is experiencing its maximum disturbance (see figure 1*a*).

(iv) 18.00*h* 31 *January*. Geostrophic winds of approximately 140 miles/h are now in force over a belt of the western and central North Sea 150 miles wide, and the mean wind force over the sea as a whole is at its peak. The southward movement of water into the main body of the sea is being accelerated, and a level of 4 ft. is being experienced along a line between Northumberland and the East Friesian Islands. It may be noted that water levels have reached a minimum off the west coast of Norway. The easterly water gradient is still in evidence in the southern North Sea, but with the approach of the major surge the co-disturbance lines are beginning to rotate in an anti-clockwise direction. This rotation also seems related to a slight backing of the winds in that area, but this is probably of minor importance. The level in the Thames Estuary has started to rise, while the Firth of Forth area has experienced its maximum disturbance.

(v) 21.00*h* 31 *January*. Only the extreme easterly fringes of the North Sea remain unaffected by the gale-force north winds, though in the south the direction is still north-westerly. The Yorkshire coast in the west, the Zuider Zee and the German Bight area in the east, have all experienced a surge peak, and the major part of the disturbance is now between Norfolk and Holland and of the order of 8 ft. The crowding of the disturbance lines on the English coast between the Wash and the Thames, as compared with the Dutch


0°
4°
8°
60°
56°
52°
09.00h 31 January
12.00h 31 January
15.00h 31 January
18.00h 31 January
21.00h 31 January
00.00h 1 February
03.00h 1 February
06.00h 1 February
09.00h 1 February

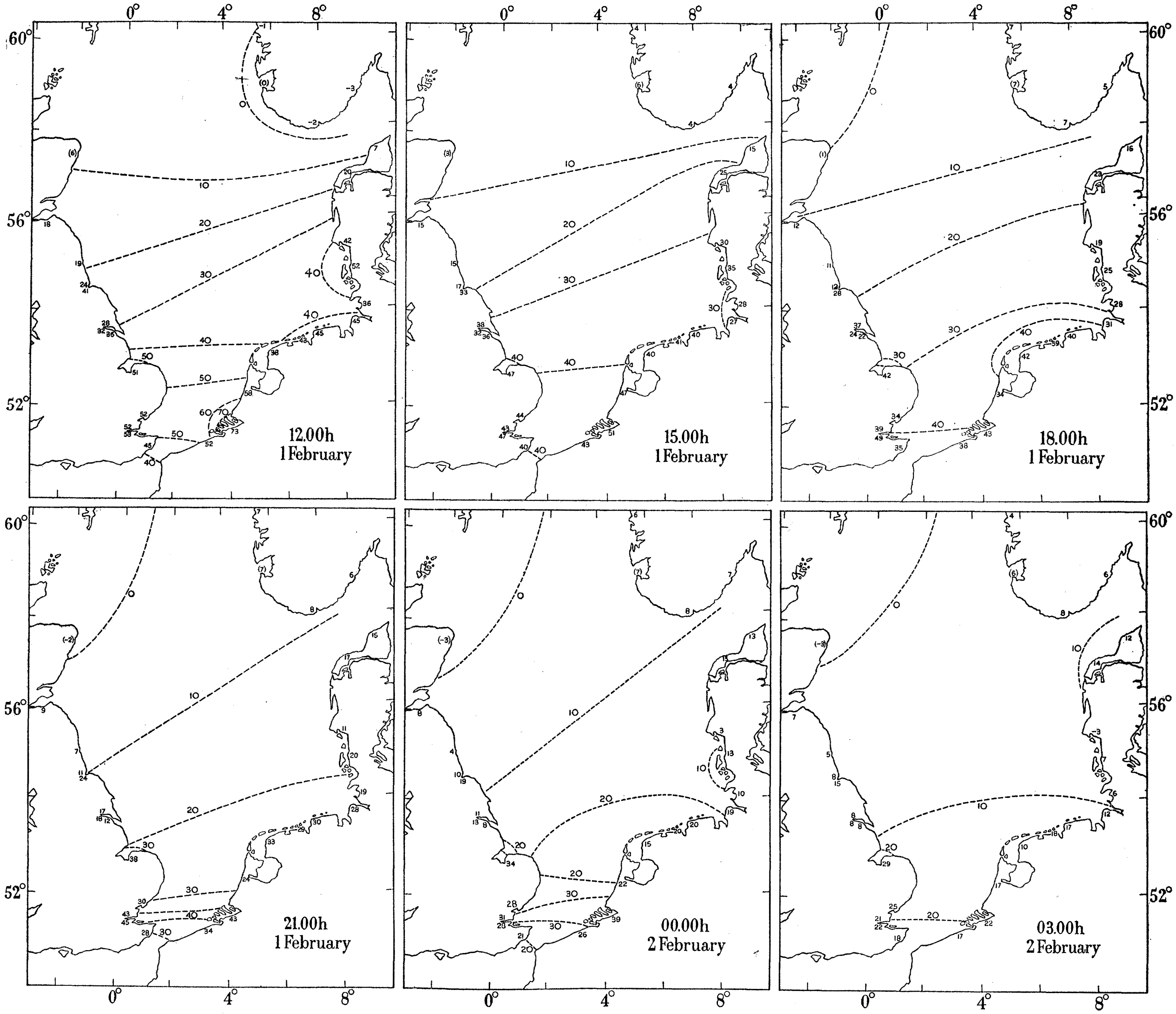


FIGURE 4. Lines of equal disturbance, North Sea, 09.00h 31 January to 03.00h 2 February 1953. (Unit, $\frac{1}{10}$ ft.)

and Belgian coasts, suggests that although the levels in the area are rising rapidly there is a greater influx of water along the English coast due to the earth's rotation. The mean level of the North Sea has now risen to a maximum of 2·2 ft. above the undisturbed level.

(vi) 00.00*h* 1 *February*. During the past 3h the meteorological conditions have changed little, apart from a slight veering of the winds in the south. The coastline between the Humber and the Thames has suffered the passage of the surge peak, as also has the south coast of Holland, and the disturbance is a maximum between the Thames (nearly 8 ft.) and the Scheldt (9 to 10 ft.).

The co-disturbance lines are now sensibly parallel over the North Sea as a whole.

An examination of figure 1 *b* shows that levels are falling in the North Sea, north of a line joining Den Helder and the Thames Estuary. This is clearly illustrated by the change in the shape of the disturbance curves for Ijmuiden and Harlingen, which are to the south and north of Den Helder respectively. The volume of water in the southern portion of the sea is at a maximum, and it will be shown later that the escape of water through the Straits of Dover is also a maximum.

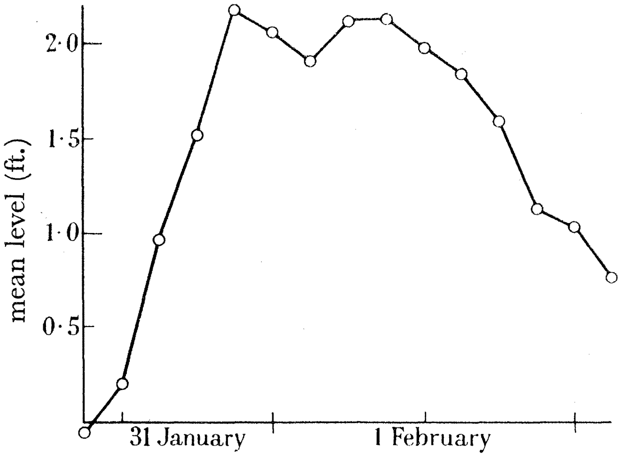


FIGURE 5. Mean level of the North Sea, 31 January to 2 February 1953.

(*b*) *The decay of the disturbance throughout* 1 *and* 2 *February*

(i) 03.00*h* 1 *February*. The isobars are now fairly uniform over the sea in a north-easterly direction, but the geostrophic wind has not moderated appreciably. This is perhaps the only time during the storm when steady conditions may be said to have been most nearly attained. Although there is no indication of water flowing out of the North Sea in a northerly direction as yet (figure 5 shows that the mean level remains near +2 ft.) a definite redistribution of the levels has begun. Having reached the Straits of Dover and no doubt been reflected, the disturbance is concentrating on the coast of Holland and travelling northward, as shown by the anti-clockwise rotation of the co-disturbance lines. In the Thames Estuary levels have dropped slightly, giving a trough in the disturbance curves.

(ii) 06.00*h* 1 *February*. The rotation of the lines of equal level continues, together with a movement northwards of the lines as a whole. The main surge is progressing along the Friesian Islands, causing the well-defined second peaks in the curves for Harlingen, Borkum and Norderney, the maximum level of more than 11 ft. having just been attained at Harlingen.

(iii) 09.00*h* 1 *February*. In the central and southern areas of the North Sea the weather chart shows a crowding together of the isobars and presumably an associated strengthening of the wind. It is probable that this increase in wind velocity in the Thames and Scheldt area partly accounts for the second pronounced peak in the disturbance curves for Southend, Sheerness and Brouwershavn. The mean wind over the North Sea is apparently still strong enough to maintain the southerly water gradient in existence, and the total volume of displaced water remains the same. The main surge continues to travel northward along the European coastline, causing surge peaks in the North Friesian Islands.

(iv) 12.00*h* 1 *February*. Over the whole sea the winds are beginning to moderate, and in the south are almost due north. This latter fact manifests itself in the decay of the easterly water gradient between England and Holland which has been in evidence almost throughout. The southern coasts of Denmark have experienced their maximum disturbances, and the effect of the earth's rotation is evident as the disturbance decays. This effect has been well established in previous investigations, but it is of interest to note that even when such an exceptionally large disturbance is concerned, the geostrophic effect can be detected in both the growth and the decay of the oscillation.

(v) 15.00*h* 1 *February to* 03.00*h* 2 *February*. The further subsidence of the perturbation of mean sea-level can be traced in the subsequent diagrams. During this period the winds continued to moderate, but it was not until after 15.00h on 1 February that the mean level of the North Sea began to fall.

10. Estimates of the air/sea frictional coefficient k

On the assumption that a steady state has been reached, a water gradient which is wind-generated offers suitable data for calculating the value of k in the equation

$$\frac{\partial\zeta}{\partial x}=\frac{nk}{gh}\frac{\rho_a}{\rho}V_a^2,$$

using the notation

$\partial\zeta/\partial x$ = water gradient, measured in the direction of the wind,

h = mean depth of water,

ρ_a/ρ = the ratio of densities of air and water $=1{\cdot}2\times10^{-3}$,

k = frictional constant defined by the equation $T=k\rho_a V_a^2$, where T is the tractive force of the wind,

n = a constant which is theoretically $\frac{3}{2}$ when there is no bottom current, and unity when there is no bottom friction.

Two cases will be considered.

(*a*) 12.00*h* 31 *January*

Reference to the isobars and co-disturbance lines for this time shows the existence of a water gradient between Harwich and the mouth of the Scheldt due to the north-westerly winds in that region. The period of a free oscillation in this direction is much less than that of the winds concerned, and any oscillatory approach to the steady state will be subject to heavy damping due to the shallow depths in this area. We may therefore assume statical conditions to exist at 12.00h 31 January.

From the co-disturbance charts we have

$$\delta\zeta=2{\cdot}0\text{ ft.}=0{\cdot}61\times10^2\text{ cm},$$
$$\delta x=1{\cdot}4\times10^7\text{ cm},$$

and a suitable value of h for the area is 3×10^3 cm.

The gradient winds deduced from the isobars have a velocity of $2{\cdot}5\times10^3$ cm/s, and assuming that the surface winds have approximately two-thirds of this value, we find

$$V_a=1{\cdot}7\times10^3\text{ cm/s}.$$

Then $$k=\frac{0{\cdot}61\times10^2\times0{\cdot}981\times10^3\times3\times10^3}{\frac{3}{2}\times1{\cdot}4\times10^7\times1{\cdot}2\times10^{-3}\times1{\cdot}7^2\times10^6}=0{\cdot}0025.$$

The daily weather report of the Air Ministry gives the observed surface wind at Felixstowe at noon as 33 knots ($1{\cdot}7 \times 10^3$ cm/s) from a direction of 310°. These agree well with the values deduced above, and the figure obtained for k should be reliable for the conditions stated.

(*b*) 03.00*h* 1 *February*

At no time during the disturbance can a truly steady state be considered as existing in a southerly direction over the whole of the North Sea, but an inspection of the isobars and co-disturbance lines at 03.00h 1 February show they are reasonably at right angles and distributed in a fairly uniform manner.

Considering only the western half of the North Sea, between the current line of zero disturbance and a line due east from the Wash, we have

$$\delta\zeta = 5{\cdot}0 \text{ ft.} = 1{\cdot}52 \times 10^2 \text{ cm},$$

$$\delta x = 4{\cdot}4 \times 10^7 \text{ cm},$$

$$h = 6{\cdot}5 \times 10^3 \text{ cm}.$$

Ignoring the rather localized crowding together of the isobars evident in the central section of the North Sea, we deduce a mean gradient wind of $4{\cdot}1 \times 10^3$ cm/s, or a surface wind of $2{\cdot}7 \times 10^3$ cm/s.

Applying the formula as before, we have

$$k = 0{\cdot}0017.$$

No actual observations of wind velocity and direction are given in the daily weather report for 3 a.m., but from those entered at midnight and 6 p.m. it would appear that the isobars give slightly too high a value for the deduced surface wind.

The data do not warrant a more precise value than $k = 0{\cdot}002$.

11. THE TRANSMISSION OF THE SURGE THROUGH THE STRAITS OF DOVER

The possession of data for Dover, Newhaven and Dieppe has made it possible to trace the transmission of a North Sea storm surge through the Straits of Dover for the first time with any reliability, though it must be borne in mind throughout the following discussion that no corrections have been possible to the residuals at Newhaven and Dieppe for wind effects in the English Channel. It is not considered that this fact seriously invalidates the conclusions drawn for an area which is relatively small and sheltered in respect to the prevailing north to north-westerly winds.

Co-disturbance charts have been drawn at six-hourly intervals for the period 12.00h 31 January to 00.00h 2 February covering both the northern and southern approaches to the Straits, and are reproduced in figure 6. Harmony has been maintained between these charts and those for the North Sea, and the fact that the charts are based on only two ports in the English Channel has been partly compensated for by the assumption that the lines of equal level will be densest at the narrowest cross-section.

At noon on 31 January a difference of level of the order of 1 ft. existed between the English and French coasts, which may be attributed to the west-north-westerly winds prevailing. As these winds remained in existence throughout the surge, it may be presumed that there was a tendency for this difference in level to be maintained, but the transport of

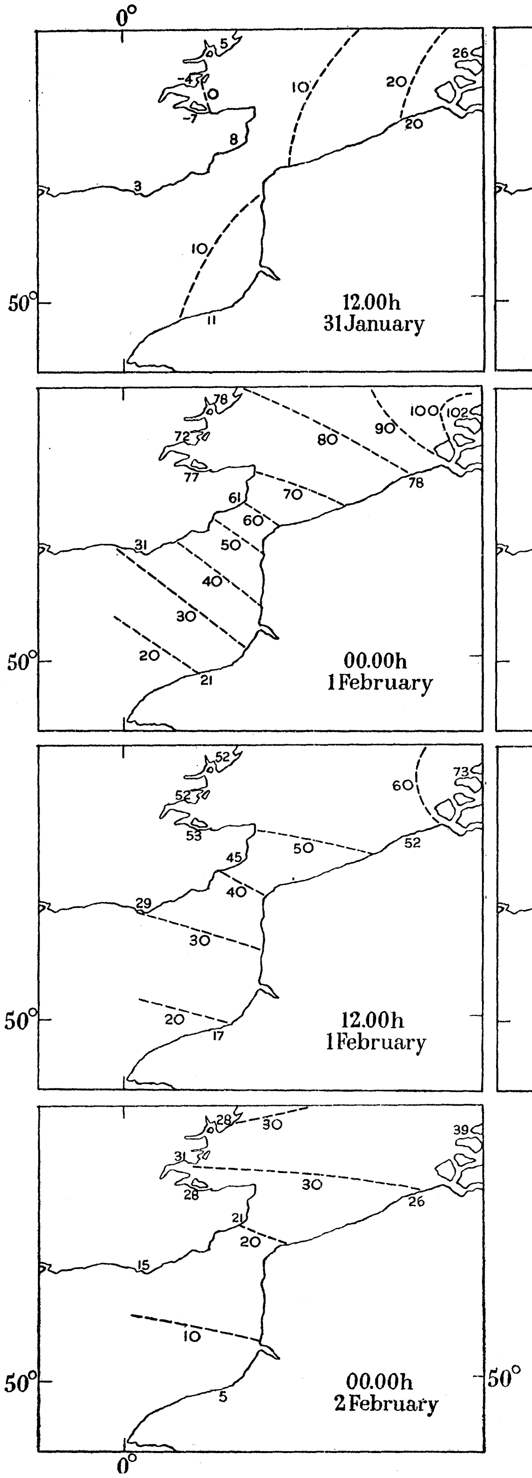


FIGURE 6. Lines of equal disturbance, English Channel, 12.00h 31 January to 00.00 2 February 1953.

water from the North Sea soon became large enough to overcome it. By 18.00h a strong water gradient had become established through the Straits. Thenceforth the levels in the English Channel rose until, at approximately 04.30h on 1 February, a maximum level of 4 ft. was reached at Newhaven and over 3 ft. at Dieppe.

It is apparent that after 18.00h 31 January the levels were higher on the English coast than on the French, despite the northerly direction of the local winds. This can only be accounted for by a geostrophic effect tending to concentrate the disturbance on to the English coast.

The transport of water through the Straits due to a surface gradient is a matter of general interest, and one which has an important bearing on the prediction of the storm surge at Southend. This aspect is considered later.

The equation of motion for a uniform channel is

$$-g\frac{\partial\zeta}{\partial x}=\frac{\partial u}{\partial t}+\frac{ku|u|}{h},$$

where $\partial\zeta/\partial x$ is the surface gradient measured in the direction of the channel,

u	the current in the x-direction,
$\lvert u\rvert$	the value of u irrespective of sign,
t	the time,
h	the mean depth of the channel, and
k	the frictional constant for the bed of the water channel, and taken as 0·0025.

We shall assume

(*a*) that this equation can be applied to a short section of the Straits of Dover;

(*b*) that we can confine our considerations to steady conditions, and may therefore neglect the term $\partial u/\partial t$ and discuss mean values only.

Then, the flow of water being in the same direction throughout the period considered, we have

$$u=\sqrt{\left(\frac{gh}{k}\frac{\partial\zeta}{\partial x}\right)}.$$

Table 5 gives the values of $\partial\zeta/\partial x$ at six-hourly intervals measured along 50 km of the median line through the Straits of Dover, and the mean values of u for each time interval. The mean depth has been taken as 20 fathoms.

We may therefore conclude that a current of the order of 2 knots, in excess of that normally expected, was in evidence through the Straits of Dover throughout 1 February.

TABLE 5. CURRENT THROUGH THE STRAITS OF DOVER

		$\partial\zeta/\partial x$	$\frac{gh}{k}\frac{\partial\zeta}{\partial x}$	mean values of u	
	hour	10^{-6}	10^2 (cm/s)^2	(cm/s)	(knots)
31 Jan.	12.00	0·6	9	52	1·0
	18.00	3·0	45	102	2·0
1 Feb.	00.00	11·0	165	117	2·3
	06.00	7·4	111	102	2·0
	12.00	6·6	99	97	1·9
	18.00	6·0	90	85	1·6
2 Feb.	00.00	3·6	54		

If we take the mean breadth of the Straits as 22 miles, the quantity of water escaping per hour with a velocity of 2 knots

$$=2\times6080\times22\times5280\times120=1{\cdot}7\times10^{11}\ \text{cu.ft.},$$

which if considered as coming from a surface of 7000 square miles, an area equal to that portion of the North Sea south of the line Orfordness to Brouwershavn, would cause a fall in level of

$$\frac{1{\cdot}7\times 10^{11}}{7000\times 5280^2}\,\text{ft.} = 0{\cdot}9\ \text{ft.}$$

Despite the approximate nature of the calculations, it is clear that the efflux of water through the Straits of Dover during a very severe storm surge in which the level in the North Sea has been appreciably raised is an important factor. The Straits do indeed act as a minor safety valve, and would appear in the present surge to have caused the levels between the Thames and Belgium to fall at the rate of 1 ft./h.

12. Prediction of the surge at Southend

In his 1948 paper Corkan developed a formula for predicting the disturbance at Southend, using the pressure gradients in the North Sea and Flemish Bight and the tidal disturbance observed at Dunbar 9h earlier. In all previous disturbances studied, the predicted surge was in close agreement with the observed surge, but in the case under discussion the agreement is not so close.

As such widespread interest has been displayed in this surge, and in view of the existence of at least one other curve of Southend residuals the author has seen in print, it has been considered advisable to include some prefatory remarks on the method used for extracting the meteorological disturbance from the original hourly heights. The procedure, devised by Doodson, only requires a knowledge of mean sea-level at the port related to the datum of the observations, and the diurnal tide. As the latter is relatively small in the North Sea, no great inaccuracy is incurred when the diurnal constants are known only approximately. Shallow-water effects can be smoothed out graphically.

The alternative to this method is to prepare full tidal predictions of hourly heights, using a tide-predicting machine, which, even when the necessary harmonic constants are known, is a costly process. In the case of Southend and the majority of the estuaries in the southern half of the North Sea, shallow-water effects make the machine prediction of hourly heights a highly complex and laborious task, and one which has not yet been satisfactorily conquered. This difficulty may be avoided by using reduction tables, which give the height of tide at hourly intervals before or after high water in terms of the range of tide, in conjunction with accurate machine predictions of high and low water. Care has to be taken, however, to eliminate diurnal effects before applying the tables, if great accuracy is required.

For simplicity, uniformity and general efficiency, therefore, Doodson's method was used throughout by Corkan, and has also been used in this paper.

The prediction formula

$$10(R_S - R_D) = 0{\cdot}33N|N| - 0{\cdot}55E|E| - 0{\cdot}75n|n| - 0{\cdot}95e|e|,$$

and the notation used is the same as in the paper by Corkan (1950), namely,

R_S is the observed disturbance in feet at Southend after correction for the effect of local pressure assuming a statical law,

R_D is the observed disturbance in feet at Dunbar after correction for the effect of local pressure assuming a statical law, 9h earlier,

N and E are the north and east pressure gradients at a point A (figure 7) near the south of the North Sea. The gradients are measured as the difference in the pressures in millibars at the ends of the lines shown,

n and e are the average, of the north and east pressure gradients, at two points C and D (figure 7) between Scotland and Denmark, 6h earlier.

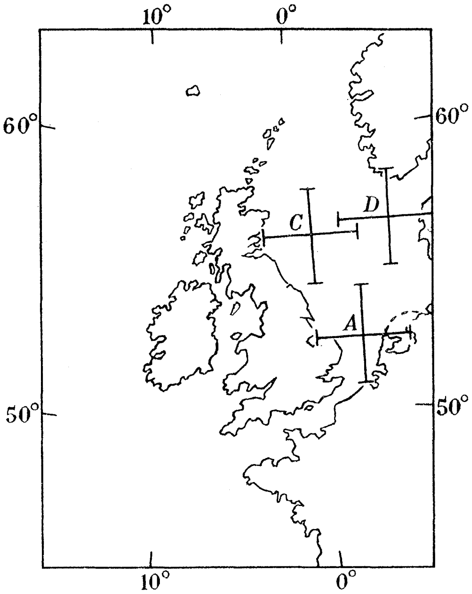


FIGURE 7. Positions of points A, C and D.

The expressions $|N|$, $|E|$, etc., mean that the gradients are taken without regard to the sign.

We shall also follow his notation for

B, the barometric disturbance of sea-level at Southend,

R'_S, the predicted residual at Southend, including the barometric disturbance,

R''_S, the observed residual at Southend before correction for the barometric disturbance. Thus the values of $R''_S - R'_S$ are a measure of the accuracy of the formula.

On 31 December 1950, Dunbar tidal observatory was closed down. The Dunbar residuals (R_D) have therefore had to be inferred from the co-disturbance lines, a procedure which should not detract appreciably from the accuracy of the predictions.

Table 6 gives the calculations for the period 15.00h 31 January to 06.00h 2 February 1953, at three-hourly intervals, together with a comparison of the observed and predicted residuals.

Figure 8 shows the curves of R'_S and R''_S. The errors in prediction are larger than had been encountered by Corkan in his investigations (1948), though it must be stated that he had not dealt with a surge of this magnitude and long duration.

It will be seen that the rise and the first peak were reproduced with some accuracy, but thenceforward the predicted surge was higher than the observed. The prominent double crest is also missing from the prediction.

TABLE 6. PREDICTION OF SURGE AT SOUTHEND AND COMPARISON WITH OBSERVATIONS

date	hour	N (mb)	E (mb)	n (mb)	e (mb)	R_S-R_D (ft.)	R_D (ft.)	B (ft.)	R'_S (predicted) (ft.)	R''_S (observed) (ft.)	$R''_S-R'_S$ (ft.)
31 Jan.	15	−18	−8	−11	−1	0·1	−0·1	0·5	0·5	0·7	0·2
	18	−21	−8	−8	−9	0·1	0·1	0·4	0·6	0·8	0·2
	21	−14	−18	−4	−14	3·2	0·6	0·4	4·2	5·3	1·1
1 Feb.	0	−16	−26	0	−17	5·6	2·0	0·3	7·9	7·5	−0·4
	3	−11	−19	0	−18	4·6	3·4	0·2	8·2	6·2	−2·0
	6	−9	−17	3	−20	5·0	3·0	0·1	8·1	7·4	−0·7
	9	−8	−24	2	−18	6·0	2·1	−0·1	8·0	6·6	−1·4
	12	−8	−21	2	−21	6·4	1·9	−0·3	8·0	4·9	−3·1
	15	−2	−18	3	−19	5·1	1·8	−0·3	6·7	4·0	−2·7
	18	−2	−16	4	−17	4·0	1·6	−0·3	5·3	3·6	−1·7
	21	0	−16	4	−15	3·3	1·5	−0·3	4·5	4·0	−0·5
2 Feb.	0	0	−12	3	−13	2·3	1·3	−0·3	3·3	2·8	−0·5
	3	2	−14	4	−12	2·3	1·1	−0·4	3·0	1·7	−1·3
	6	1	−12	3	−12	2·1	0·4	−0·4	2·1	1·6	−0·5

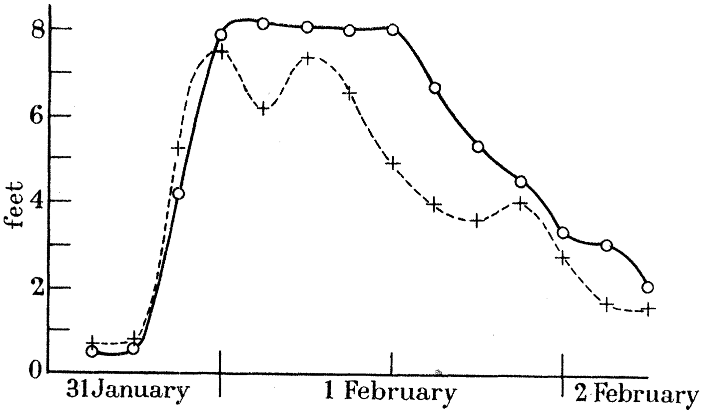


FIGURE 8. Observed (R''_S) and predicted (R'_S) disturbances at Southend. +, R''_S; ○, R'_S.

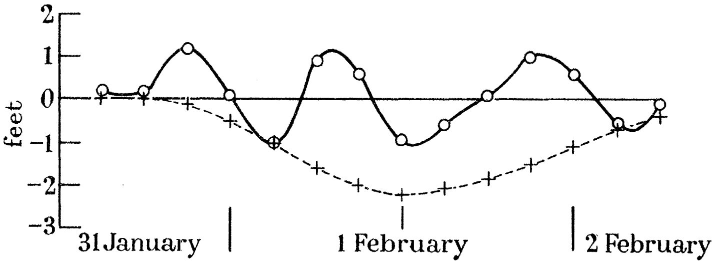


FIGURE 9. α- and β-components of $R''_S-R'_S$. +, α; ○, β.

The values of $R''_s-R'_s$ may be resolved into two major components, shown in figure 9, one with a period equal to that of the wind and the other with a period varying from 9 to 15h. These two components are indicated by α and β respectively.

The most probable explanation for the α-oscillation is that it was a lowering of level due to the escape of water through the Straits of Dover. It has been shown earlier that this efflux assumed an appreciable magnitude about 18.00h 31 January, reached its maximum just after midnight, and remained steady and of importance to near the end of 1 February.

It has also been shown that it would have the effect of lowering the level of that area just north of the Straits at the rate of nearly 1 ft./h. It therefore seems feasible that a gradual lowering of level at Southend, reaching a maximum of 2 ft., can be attributed to the loss of water through the Straits of Dover.

If we accept this explanation of the α-oscillation, we are now left with the β-oscillation. As this is only of the order of a foot, we may consider the prediction to have reached the standard obtained by Corkan. The β-oscillation may be compounded of errors arising from incorrect smoothing of the original observed residuals and minor incorrect drawings of the isobars quite apart from other considerations discussed in the conclusion.

An examination of table 6 shows that the double peak experienced during the early hours of 1 February was due, in the main, to variations in the local wind, as indicated by the N, E columns. In the final prediction this effect has been masked by the addition of the Dunbar residual (R_D).

13. Conclusion

In the light of the facts and deductions made in this paper, it is desirable to consider past and future methods of approach to research on storm surges in the North Sea, and in particular to the problem of improving the prediction formula quoted. The conclusions arrived at, with suitable modifications, will apply equally to the Irish Sea and English Channel. The author is greatly indebted to Dr Doodson for his interest in this aspect of the present paper, and for the history of previous research both by himself and his associates.

Doodson (1924), envisaging the possibility of daily meteorological corrections to Liverpool tidal predictions, made extensive correlations between meteorological perturbations and barometric pressure deviations and gradients. His main conclusions were that

(i) local pressure gradients needed to be supplemented by gradients taken in the Atlantic approaches to the Irish Sea to give best results,

(ii) time relations between cause and effect were of great importance.

Doodson's paper, however, dealt with mean values for the day, and it was evident that the formulae could not give large values. It really gave steady conditions, and dynamical considerations led to a method being devised (Proudman & Doodson 1924) whereby the oscillatory approach to the steady state, due to a steady wind, was expressed in terms of the velocity of the disturbing wind and the damping factor and free period of the body of water considered. This could easily be extended to include the case of variable winds.

An investigation (Doodson 1929) into notable North Sea storm surges in 1928 and earlier years revealed a tendency for the disturbances to rotate inside the sea in an anticlockwise direction. It further confirmed that local winds were quite inadequate to account for the effects observed.

Basing their approach on these results, Doodson and Corkan proceeded to establish a formula for the prediction of Southend storm surges, utilizing data for the years 1928 to 1938. The disturbance at Southend was predicted by integration of surge contributions from areas of the North Sea, pressure gradients at six stations (two in the Flemish Bight and four in the main body of the sea) being used for the purpose. The oscillatory approach was allowed for. Good results were obtained in many cases, but there were notable exceptions. Corkan later abandoned this attack in favour of the present formula. In this he appears to have been motivated by the following considerations:

(*a*) The six stations necessitated determination of twelve constants. Since he attempted to obtain a formula for each type of surge, the number of surges available for study in the period used did not facilitate sufficiently accurate determinations. The number of stations was therefore reduced to three (figure 7), the gradients at two of these being averaged.

(*b*) The damping ratio of 1/6, which had been derived from a lengthy investigation for the North Sea, suggested that only the first peak (or trough) of the surge was of importance.

(*c*) Maximum simplification of the calculations was needed for application of the formula.

(*d*) Failure of the original method in certain cases.

We shall now consider these items in the light of the facts deduced in this paper.

(*a*) The most effective winds were mainly concentrated in the western half of the North Sea, and averaging the pressure gradients at points C and D is an obvious source of error. General reasoning shows that if more weight were given to the gradients at point C the prediction of the initial surge peak would have been more accurate. This weighting would also have the effect of increasing the subsequent excessively high prediction, but it has been shown that the outflow through the Straits of Dover is a probable neutralizing factor.

Meteorological conditions are conceivable, however, whereby a raising of level at Southend due to the North Sea winds could co-exist with winds in the English Channel such as to prevent an outflow.

Sufficient data should now be available for a return to the integration method over the whole of the North Sea, together with the addition of a station in the English Channel and one or more stations off the coast of Norway. The former should allow for the Straits of Dover effect, and the latter are indicated as being desirable owing to the fact that much of the water which entered the North Sea came from the north-east Atlantic Ocean.

(*b*) With excessively large surges the damping ratio is not sufficient to eliminate oscillations of appreciable magnitude occurring after the initial surge, and for a complete explanation of surge phenomena the comprehensive oscillatory theory must be used.

(*c*) Simplification is desirable whenever possible, but it should not be allowed to override primary factors.

(*d*) It seems probable that apparent failures of the earlier methods were due to the existence of 'external surges' which at that time may not have been fully appreciated. Moreover, local barometric effects obeying a statical law do not seem to have been allowed for. Corkan (1948, 1950) has illustrated the existence of these 'external surges', the main characteristics of which are that they are propagated southwards into the North Sea at a speed approximately equal to that of the diurnal tide, and travel around the shores of the sea in an anticlockwise direction. He was led to the opinion that they did not decay appreciably, probably because loss of energy due to friction is balanced by decreasing depth. Goldsbrough (1952) has theoretically approximated to the problem with constant depth in the absence of the earth's rotation, and finds a steady increase in amplitude as the surge progresses southward. The origin of this type of disturbance is still not satisfactorily explained, though Corkan (1948, 1950) has indicated possible solutions which are in need of investigation.

The surge discussed in this paper does not appear to have contained any 'external surge' component, being directly attributable to winds in, and to the north of, the North Sea.

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