PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Levels in the North Sea Associated with the Storm Disturbance of 8 January 1949

R. H. Corkan

Phil. Trans. R. Soc. Lond. A 1950 **242**, 493-525
doi: 10.1098/rsta.1950.0008

THE LEVELS IN THE NORTH SEA ASSOCIATED WITH THE STORM DISTURBANCE OF 8 JANUARY 1949

By R. H. CORKAN, *Liverpool Observatory and Tidal Institute*

(*Communicated by A. T. Doodson, F.R.S.—Received* 5 *September* 1949—*Read* 30 *March* 1950)

CONTENTS

Observations, around the North Sea, have been collected for twenty stations in the British Isles and for fifteen stations on the Continent during the period 6 to 10 January 1949, and used in a discussion of a large storm disturbance on 8 January.

The primary object of the investigation has been to get a picture of the water movements inside the North Sea, and of the way in which these movements are produced, in the course of a storm. Maps of co-disturbance lines in the North Sea have been drawn at frequent intervals and compared with the simultaneous meteorological conditions.

The disturbance around the coast, and in the Thames and Humber estuaries, has been examined in detail, and the progression around the coast has been shown to be similar to that of the diurnal tide.

Estimates have been made of the changes, during the storm, in the average level of the North Sea, and it has been shown that when the level was rising there was a large inflow of water down the western half; when the level was falling the outflow was up the eastern North Sea.

New light has been thrown on several problems connected with storm surges.

In particular, it would appear that storm surges of external origin, which hitherto could not be explained in terms of the winds, may be a direct result of an earlier outflow of water produced during a surge when the level has been lowered; also the excessive damping normally observed in the disturbed tide at Southend, which leads to an average value of eddy viscosity in the North Sea somewhat larger than that normally accepted, may be due to a reflexion from the German bight which arrives near the time when the lowest levels are expected.

Two estimates have been made of the frictional constant, on the assumption that the tractive force of the wind varies as the square of the wind velocity, and are in agreement with accepted values.

Prediction of the disturbance at Southend using a previously established formula has given good results.

The disturbance transmitted through the Straits of Dover has been investigated.

1. Introduction

In this paper the disturbed levels over the North Sea during the period 6 to 10 January 1949 have been deduced and used in a discussion of the large storm disturbance on 8 January.

Earlier works on storm surges (Doodson 1929; Schalkwijk 1947; Corkan 1948) have been largely confined to the discussion of observations at a few selected places, though Doodson (1929) showed that storm surges tend to travel.

In the present paper, data for a single storm have been collected around the whole of the North Sea, and maps of co-disturbance lines have been drawn at frequent intervals and compared with the simultaneous meteorological conditions.

Corkan (1948) made a detailed examination of storm surges at Southend and Dunbar, and a numerical method was evolved which provides satisfactory predictions of storm surges at Southend.

For places on the east coast other than Southend and Dunbar very little concerning storm effects is known, though information is eagerly sought by the authorities responsible for the flood defences, especially along the Essex coast and in the Wash and Humber estuaries. One object of the present paper has been to provide an estimate of the relative disturbances likely to be observed along the east coast and at Southend.

The extent to which a disturbance in the North Sea may be transmitted through the Straits of Dover has often been a subject for discussion; the portion transmitted in the present storm has been investigated.

Doodson (1929) has shown that storm surges appear to travel counter-clockwise around the North Sea. Corkan (1948) made use of this when predicting storm surges at Southend. The progression around the North Sea in the present storm has been examined, and the existence has been shown of a close relation with the progression of the diurnal tide.

The detail which has been possible in the comparison of the disturbed levels over the sea and the associated meteorological conditions has thrown new light on several problems connected with storm surges.

In particular it would appear that storm surges of external origin, which hitherto could not be explained in terms of the winds, may be a direct result of an earlier outflow of water from the North Sea to the ocean, produced during a surge when the level has been lowered. Normally surges of external origin are preceded by surges of the latter type with strong southerly winds over the North Sea and well to the north. The external surge arrives when these winds moderate, which they may do with very little change in direction.

The present investigation suggests that as the winds moderate the expelled water returns into the North Sea but the flow is not uniform across the northern section. Instead, the water is deflected to the right and piled up against the north-east Scottish coast and then travels southwards, hugging the coast, in the form of a progressive wave. The suggestion requires further investigation, but the existence of a large outflow and inflow of water and the tendency for the inflowing water to move down the western North Sea have been well established in the paper.

The existence of what appears to be excessive damping in the curves of disturbed tide at Southend has also given concern in the past, for it leads to an average value of eddy viscosity in the North Sea which is larger than that normally accepted.

When a large head of water is built up by wind in the southern North Sea, and then subsides as in the present example, it is shown that the major transport of water is up the eastern North Sea, but a portion is also reflected westwards from the German bight on to the east coast of England and into the Flemish bight. The time of arrival of this rise at Southend may coincide with the time when the lowest levels are expected, as it did in the present disturbance, and so would explain the abnormal lowering which is generally observed.

Two estimates of the frictional constant, one when the level was raised and the other when the level was lowered, which have been made in the paper, on the assumption that the tractive force of the wind varies as the square of the wind velocity, are in agreement with accepted values.

Prediction of the disturbance at Southend, using a previously established formula (Corkan 1948), has given good results.

2. Observations and datums

Observations of hourly heights of tide, around the North Sea, covering the period 6 to 10 January 1949, were collected for twenty stations in the British Isles and for fifteen stations on the Continent.

(Additional observations of hourly heights for Emden, Wilhelmshaven, and Bremerhaven, provided by the German Hydrographic Institute, have not been used, since these places are well up estuaries and are unsuitable for the present investigation.)

Observations of high water, and, in some cases also of low water, were collected for an additional six stations in the British Isles.

Details of the stations, their positions, the authority who supplied the observations, the form of the observations, 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 in table 1 *b* for the Continent.

In the British Isles all heights are referred to the zero of the observations. Ordnance Datum Liverpool (o.d.l.) and Ordnance Datum Newlyn (o.d.n.) are both given when they have been used in the reductions. Levels in brackets are only approximate and have been deduced from a diagram, showing contours of the difference in height between the Newlyn and Liverpool datum levels, prepared by the Ordnance Survey (1921).

The Netherlands and German heights are referred to the respective Land Survey Datums.

In Denmark the zero level is 'normal height of sea-level' which is based on all available observations allowing for secular variations in mean sea-level, due to rising and sinking of the ground (Egedal 1934, 1946).

In Norway the datums are local but fixed, and mean sea-level from observations over a number of years, referred to the fixed datum, is known at each place.

The hourly heights are given in table 2. The heights are in the form in which they were received or read off from curves, and the relative details are in tables 1 *a* and 1 *b*.

Hourly heights which are available for Keadby and Owston Ferry on the river Trent have not been given, since, owing to the large distortion of the tide from shallow-water effects, it has not been found possible to deduce from them the hourly values of the disturbed tide.

Hourly heights for Holland Haven have also been omitted, since the tide gauge was prevented from recording when the level was below (o.d.l.—1·5 ft.).

High-water data at the last three stations have been used in the reductions.

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

place	lat. (°) (′)	long. (°) (′)	authority for observations	form of observations 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	—	10·0	10·4
Dunbar	56 00 N	2 31 W	Director, Ordnance Survey	HH	G.M.T.	8·90	8·82	9·9	9·9
Blyth	55 07 N	1 29 W	Blyth Harbour Commission	C	G.M.T.	6·35	6·15	7·0	7·5
Hartlepool	54 41 N	1 11 W		C	G.M.T.	19·25	(19·00)	19·8	19·8
Middlesbrough	54 35 N	1 13 W	Docks and Inland Waterways Executive	HL	G.M.T.	0·00	—	—	—
Grimsby	53 35 N	0 04 W		C	G.M.T.	15·00	(16·5)	17·0	17·0
Immingham	53 37 N	0 11 W		HL	G.M.T.	36·00	(37·3)	—	—
Keadby	53 35 N	0 45 W	River Trent Catchment Board	C	G.M.T.	—	0·00	—	—
Owston Ferry	53 29 N	0 47 W		C	G.M.T.	—	0·00	—	—
King's Lynn	52 45 N	0 24 E	King's Lynn Conservancy Board	C	G.M.T.	11·00	(12·2)	12·4	12·7
Great Yarmouth Haven	52 34 N	1 44 E	Great Yarmouth Haven Commissioners	HL	G.M.T.	—	3·25	—	—
Felixstowe	51 56 N	1 19 E	Director, Ordnance Survey	HH	G.M.T.	4·88	6·57	6·6	6·7
Walton on Naze	51 51 N	1 16 E		H	G.M.T.	0·00	—	—	—
Holland Haven	51 48 N	1 12 E	Essex Rivers Catchment Board	C	G.M.T.	0·00	1·8	—	—
Hythe	51 53 N	0 55 E		H	G.M.T.	—	0·00	—	—
Southend	51 31 N	0 45 E	Port of London Authority	C	G.M.T.	8·53	10·00	10·0	10·0
Canvey Island Bridge	51 32 N	0 33 E	Essex Rivers Catchment Board	H	G.M.T.	−2·02	—	—	—
London, Tower Pier	51 30 N	0 05 W	Port of London Authority	C	G.M.T.	8·87	10·00	11·5	11·1
Dover	51 07 N	1 19 E	Dover Harbour Board	C	G.M.T.	8·42	9·67	8·3	9·6
Newhaven	50 47 N	0 03 E	Railways Executive, Southern Region	C	G.M.T.	13·33	14·08	14·2	14·2

C indicates tide charts; HH indicates hourly heights; HL indicates high and low waters; H indicates high waters.

TABLE 1 *b*. OBSERVATIONS AND LEVELS—CONTINENT

place	lat. (°) (′)	long. (°) (′)	authority for observations	form of observations supplied	time kept	datum	provisional mean sea-level (cm.)	(ft.)	corrected mean sea-level (ft.)
Vlissingen	51 27 N	3 36 E	Rykswaterstaat Directie Algemene Dienst	HH	G.M.T. + 0020	Nauwkeurigheids Amsterdamsch Peil (N.A.P.)	−11	(−0·3)	−0·5
Hoek-van-Holland	51 59 N	4 07 E		HH	G.M.T. + 0020		− 6	(−0·2)	−0·3
Den Helder	52 58 N	4 45 E		HH	G.M.T. + 0020		−12	(−0·4)	−0·3
Borkum	53 34 N	6 45 E		HH	M.E.T.		− 2	(−0·1)	0·4
Norderney	53 42 N	7 10 E		HH	M.E.T.		− 5	(−0·2)	0·0
Cuxhaven	53 52 N	8 43 E		HH	M.E.T.		8	(0·2)	0·1
Busum	54 07 N	8 51 E	German Hydrographic Institute	HH	M.E.T.	Normal Null (N.N.)	10	(0·3)	0·1
Husum	54 28 N	9 02 E		HH	M.E.T.		0	(0·0)	0·2
Wyk, Fohr	54 42 N	8 35 E		HH	M.E.T.		0	(0·0)	0·0
Hornum, Sylt	54 46 N	8 18 E		HH	M.E.T.		−4	(−0·1)	0·0
Esbjerg	55 28 N	8 27 E	Det Danske Meteorologiske Institut	HH	G.M.T.	'normal height of sea-level'	0	(0·0)	0·4
Hirtshals	57 36 N	9 58 E		HH	G.M.T.		0	(0·0)	0·2
Tregde	58 00 N	7 34 E	Norges Geografiske Oppmaling	HH	M.E.T.	60·8 cm. below mean sea-level (18 years)	54	(1·6)	1·8
Stavanger	58 58 N	5 44 E		HH	M.E.T.	101·0 cm. below mean sea-level (20 years)	110	(3·3)	2·9
Bergen	60 24 N	5 19 E	Norges Sjokartverk	HH	M.E.T.	100 cm. below mean sea-level	108	(3·3)	3·4

HH indicates hourly heights.

Table 2. Hourly heights of observed tide, 6 to 10 January 1949

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.																								
6	6·5	7·9	9·6	11·0	12·4	13·1	13·0	12·0	10·6	9·0	7·6	6·9	7·3	8·7	10·5	11·8	12·8	13·8	13·8	13·0	11·7	9·9	8·1	7·1
7	6·7	6·9	7·9	9·2	10·4	11·3	11·9	11·7	11·0	9·4	8·1	7·0	6·7	7·2	8·2	9·6	10·8	12·1	13·0	13·0	12·5	11·3	9·8	8·4
8	7·6	7·5	8·1	9·2	10·3	11·7	12·9	13·3	13·1	12·1	10·8	9·5	8·8	8·1	8·1	8·6	9·5	10·6	11·6	12·0	11·9	11·2	9·8	8·3
9	7·2	6·5	6·3	6·8	7·9	8·9	10·2	11·3	11·6	11·3	10·7	10·1	9·2	7·6	6·6	6·7	7·9	9·2	10·4	11·5	12·0	12·0	11·5	10·5
10	9·6	8·7	7·6	7·0	7·2	8·2	9·4	10·8	12·0	12·9	12·9	12·4	11·3	10·2	8·9	8·2	8·1	8·8	10·0	11·3	12·6	13·3	13·6	13·1
Dunbar (ft.), G.M.T.																								
6	4·9	5·2	6·5	8·3	10·3	12·1	13·4	13·8	13·1	11·0	8·9	7·1	6·2	6·3	7·5	9·4	11·2	12·9	14·2	14·7	14·0	12·5	10·2	8·0
7	6·6	5·9	6·2	7·2	8·6	10·0	11·6	12·6	12·6	11·2	9·3	7·5	6·2	5·6	5·9	7·1	8·7	10·4	11·8	13·0	13·5	13·0	11·5	9·4
8	7·4	6·5	6·3	7·0	8·2	9·7	11·8	13·7	14·8	14·5	13·1	11·3	9·8	8·6	7·9	7·6	7·6	8·7	10·1	11·6	12·4	12·6	11·6	10·0
9	8·2	6·9	6·0	5·7	5·8	6·5	8·2	9·9	11·3	12·0	11·7	10·7	9·4	7·9	6·7	6·1	6·2	6·9	8·1	9·6	11·1	12·1	12·6	12·1
10	10·7	8·8	7·1	6·1	5·7	6·2	7·4	8·8	10·4	11·8	13·0	13·3	12·7	11·4	9·7	8·3	7·2	7·0	7·6	9·2	10·7	12·2	13·4	14·0
Blyth (ft.), G.M.T.																								
6	3·7	2·7	2·5	3·4	5·2	7·3	9·2	10·7	11·2	10·5	9·0	7·0	5·2	4·1	3·7	4·5	6·1	8·1	10·3	11·5	12·2	11·8	10·4	8·3
7	6·2	4·7	3·7	3·5	4·2	5·7	6·2	8·5	9·5	9·7	8·9	7·2	5·5	4·0	3·1	3·0	4·0	5·6	7·3	9·1	10·3	10·8	10·3	9·2
8	7·3	5·6	4·2	3·5	4·0	5·3	7·2	9·2	11·0	12·3	12·6	11·7	10·0	8·1	6·7	5·7	5·3	5·6	6·4	7·7	9·1	10·0	10·2	9·7
9	8·3	6·4	4·9	3·8	3·1	3·3	4·2	5·6	7·2	8·6	9·4	9·4	8·5	7·1	5·8	4·6	3·6	3·2	4·1	5·4	6·8	8·3	9·6	10·2
10	10·0	8·3	6·7	5·2	4·0	3·2	3·4	4·5	6·0	7·8	9·2	10·4	10·7	10·1	9·0	7·5	6·1	5·0	4·6	5·1	6·2	7·8	9·3	10·7
Hartlepool (ft.), G.M.T.																								
6	16·0	15·0	14·6	15·5	17·6	19·7	21·6	23·1	23·6	23·0	21·1	19·7	18·0	16·5	15·5	16·5	18·2	20·5	22·6	24·0	24·7	24·3	23·2	21·2
7	18·7	17·0	16·1	16·0	16·6	18·0	19·5	20·9	21·9	22·0	21·2	19·5	17·6	16·4	15·5	15·2	15·8	17·3	19·2	21·2	22·6	23·2	23·0	22·0
8	20·0	18·2	16·9	16·0	16·2	17·6	19·3	21·2	23·5	25·0	25·2	24·5	23·5	21·0	19·7	18·7	18·0	18·0	18·5	19·7	21·2	22·3	22·7	22·0
9	20·7	19·2	17·5	16·6	16·0	16·0	16·7	18·0	19·3	21·0	21·9	22·0	21·3	20·1	19·0	17·5	16·5	16·2	16·3	17·1	18·8	20·7	21·8	22·5
10	22·5	21·0	19·4	18·0	16·8	15·9	15·6	16·7	18·1	19·9	21·8	23·0	23·2	22·8	22·0	20·5	18·9	17·6	17·2	16·6	17·0	18·5	20·6	23·0
Grimsby (ft.), G.M.T.																								
6	18·2	14·7	11·7	10·1	10·0	11·5	14·0	16·8	19·8	22·0	22·5	21·6	19·5	16·7	13·6	11·9	11·5	12·9	15·3	18·2	21·2	23·3	24·0	23·3
7	21·4	19·0	15·3	13·0	11·8	11·8	12·6	14·2	16·6	18·9	20·0	20·2	19·2	17·4	14·3	11·7	10·5	10·5	12·0	14·2	17·0	19·4	21·3	22·0
8	21·8	20·2	18·0	15·3	12·8	11·5	11·8	13·6	16·2	19·2	22·0	24·5	25·2	24·5	22·8	20·4	17·5	15·4	14·8	15·5	16·2	17·5	19·5	20·8
9	20·9	20·3	19·0	16·8	14·5	12·8	12·2	12·5	13·2	15·0	17·0	19·1	20·5	20·8	20·2	18·3	15·9	13·5	12·2	12·0	13·0	14·5	16·7	19·0
10	20·5	21·2	20·9	19·5	17·2	14·6	12·3	11·3	11·5	12·9	15·0	17·7	20·2	21·8	22·0	21·2	19·9	17·8	15·3	13·6	13·2	13·7	15·4	17·6
King's Lynn (ft.), G.M.T.																								
6	16·1	13·4	11·7	9·6	7·4	6·7	6·4	7·8	11·1	15·2	18·2	18·7	17·3	15·1	12·7	10·3	8·6	7·5	7·5	9·3	12·8	17·0	19·9	20·4
7	18·8	16·4	13·8	11·5	9·4	8·0	7·4	7·3	8·3	11·2	14·3	16·2	15·9	14·5	12·9	10·6	8·5	7·0	6·3	6·3	8·0	10·6	13·9	16·9
8	17·9	18·0	16·4	13·9	11·6	9·4	7·8	7·1	7·8	10·8	15·1	18·9	21·0	22·9	22·6	20·6	17·2	14·4	12·3	11·1	11·1	12·3	13·3	15·0
9	17·0	17·2	16·1	14·1	12·6	10·9	9·3	8·4	8·5	9·1	10·2	12·5	15·1	17·1	17·4	16·2	14·3	11·9	9·9	8·5	8·0	8·3	9·9	11·9
10	14·7	17·0	17·6	16·5	14·8	12·6	10·6	8·9	7·7	7·2	7·5	9·5	12·6	15·9	17·6	17·9	16·9	15·0	13·1	11·1	9·6	8·6	8·6	9·7
Felixstowe (ft.), G.M.T.																								
6	5·1	6·6	8·1	9·6	9·9	8·6	6·5	4·6	3·3	2·6	2·4	2·5	3·9	5·5	7·4	9·4	10·4	9·6	8·0	6·2	4·7	3·7	3·3	4·1
7	5·5	7·1	8·6	10·3	11·0	10·6	8·9	6·9	5·1	3·7	2·9	2·5	2·6	3·4	4·8	6·4	8·0	8·6	7·6	5·9	4·4	3·2	2·7	2·4
8	2·6	3·8	5·4	7·3	9·3	10·4	9·9	8·5	6·9	5·2	4·0	3·5	4·0	5·2	7·0	9·4	11·7	13·5	14·2	12·9	11·2	9·5	8·0	6·5
9	5·5	5·2	5·6	6·6	7·7	8·5	9·2	9·0	7·6	5·9	4·6	3·5	2·8	3·2	4·1	5·2	6·6	7·8	9·1	9·6	8·8	7·3	5·7	4·4
10	3·4	3·0	3·6	4·7	6·0	7·2	8·4	9·3	8·9	7·5	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Southend (ft.), G.M.T.																								
6	6·0	8·7	11·3	13·6	15·5	15·5	13·3	10·0	6·4	4·0	3·1	3·2	4·8	7·2	9·8	12·8	15·3	16·0	14·6	11·5	8·5	5·8	4·3	4·4
7	5·8	8·2	11·2	13·7	15·8	16·7	15·7	13·2	9·2	6·8	4·6	3·7	3·8	5·0	6·8	9·3	11·8	13·7	13·8	12·1	9·2	6·3	4·0	3·1
8	3·2	4·4	6·7	9·2	12·0	14·6	16·0	15·3	12·7	9·5	6·8	5·0	4·3	5·3	8·0	11·1	14·5	17·5	19·3	19·6	17·9	14·8	11·7	9·3
9	7·8	7·3	7·4	8·1	9·7	11·7	13·5	14·4	13·8	11·8	9·0	6·3	4·7	4·2	5·3	7·1	9·2	11·1	13·2	14·6	14·9	13·3	10·6	8·0
10	5·6	4·6	4·6	5·8	7·8	10·0	12·0	13·7	14·7	14·0	11·7	9·0	6·2	4·2	3·6	4·3	6·0	8·3	10·9	13·5	15·2	15·7	14·4	11·8
London, Tower Pier (ft.), G.M.T.																								
6	2·5	6·2	10·3	13·6	16·1	18·0	18·1	15·1	11·3	8·1	5·0	2·6	2·2	5·0	8·4	11·8	14·9	17·7	18·9	16·7	13·0	9·6	6·5	4·0
7	3·0	5·7	9·4	13·3	16·1	18·0	19·1	17·5	14·0	10·6	7·6	4·8	2·7	3·2	5·4	8·2	10·9	13·8	16·2	16·7	14·1	10·3	7·2	4·3
8	2·2	1·9	4·6	7·7	11·0	14·0	16·9	18·9	17·7	15·0	11·7	8·2	5·4	3·5	3·5	7·0	11·8	15·8	19·3	21·6	22·3	20·3	16·7	12·7
9	9·7	7·5	6·4	7·5	8·6	10·1	12·7	15·3	17·0	16·6	14·2	10·7	7·7	4·8	3·1	4·3	7·8	10·8	13·1	14·8	16·5	17·5	16·0	12·7
10	9·6	6·5	4·0	3·1	5·4	8·4	11·4	13·9	15·5	16·9	16·5	14·0	10·6	7·5	4·9	2·9	3·2	6·1	9·1	12·3	15·0	17·4	18·5	16·9

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.																								
6	6·6	11·4	14·8	16·7	16·0	13·0	10·3	7·6	5·2	3·4	2·6	3·3	5·8	10·0	13·2	15·2	15·2	14·0	11·8	9·3	6·7	4·7	3·6	3·8
7	5·7	9·2	13·4	16·8	16·2	15·0	12·8	10·3	7·8	5·7	4·2	3·6	4·5	6·9	10·4	12·8	13·6	13·3	12·0	10·0	7·7	5·4	3·8	3·2
8	3·8	6·0	9·5	12·5	14·1	14·6	14·1	12·5	10·5	8·2	6·0	4·8	4·9	6·4	9·3	12·9	15·9	17·4	17·3	16·3	14·3	12·2	9·8	7·8
9	6·6	6·1	6·6	8·5	11·5	13·6	13·9	13·1	11·3	9·2	7·3	5·7	4·6	4·4	5·2	7·4	10·6	13·4	14·4	14·1	12·8	10·8	8·6	6·6
10	5·0	4·2	4·4	5·7	8·5	11·7	13·8	14·3	13·5	12·0	9·9	7·6	5·6	4·2	3·8	4·6	7·0	10·5	13·4	14·6	14·7	13·8	12·1	9·8
Newhaven (ft.), G.M.T.																								
6	·	·	·	·	·	·	14·5	11·5	9·0	7·8	8·0	9·7	12·3	15·4	18·6	20·0	19·0	17·5	15·0	12·2	9·4	8·1	7·8	8·9
7	11·1	14·1	17·1	19·5	20·1	18·9	17·0	14·5	11·9	10·0	9·0	9·5	11·0	13·4	16·1	18·3	19·0	18·2	16·4	14·0	11·5	9·4	8·3	8·1
8	9·4	11·5	14·4	17·0	18·4	18·6	17·8	16·0	14·0	11·6	10·0	9·7	10·0	11·5	14·0	16·6	18·7	19·5	19·4	18·0	16·0	14·1	12·4	11·1
9	10·5	11·0	12·4	14·1	15·9	17·4	17·7	17·0	15·1	13·1	11·1	9·5	8·9	9·6	11·0	13·1	15·8	17·9	18·8	18·3	16·6	14·4	12·6	10·0
10	8·9	8·6	9·5	11·3	13·5	16·1	18·0	18·7	18·0	16·3	14·1	11·9	10·0	8·9	9·0	10·5	13·0	15·7	17·9	19·0	19·0	17·6	15·7	13·2
Vlissingen (cm.), G.M.T.+0020																								
6	−182	−154	−112	−54	38	123	122	84	28	−50	−126	−178	−193	−169	−129	−66	30	127	149	122	76	5	−69	−126
7	−149	−130	−100	−53	14	101	150	130	87	22	−61	−129	−178	−194	−177	−136	−74	27	90	91	61	17	−49	−111
8	−159	−174	−158	−122	−55	37	121	150	130	92	36	−31	−90	−119	−104	−69	2	77	156	204	223	191	123	38
9	−34	−90	−109	−110	−90	−60	−19	31	81	78	45	−10	−76	−139	−164	−162	−135	−96	−41	30	99	115	92	45
10	−24	−92	−145	−165	−154	−123	−83	−24	50	96	88	56	1	−65	−123	−160	−164	−138	−99	−35	47	120	139	125
Hoek-van-Holland (cm.), G.M.T.+0020																								
6	−83	−87	−81	−74	−35	30	50	42	24	−2	−46	−80	−85	−90	−90	−81	−52	10	66	78	68	46	13	−24
7	−37	−50	−52	−50	−32	0	50	72	65	45	3	−52	−88	−105	−102	−106	−102	−72	−4	29	31	18	−10	−41
8	−65	−73	−75	−80	−68	−26	35	69	81	80	62	39	8	−9	−27	−6	20	32	75	122	165	156	136	93
9	48	−11	−40	−48	−44	−45	−46	−28	−1	28	38	13	−21	−64	−92	−92	−90	−82	−70	−43	2	43	57	46
10	20	−20	−60	−81	−85	−90	−86	−69	−39	10	30	40	15	−19	−46	−71	−72	−79	−76	−60	−25	28	74	86
Den Helder (cm.), G.M.T.+0020																								
6	19	−15	−53	−81	−99	−105	−91	−31	0	6	12	15	8	−10	−40	−69	−85	−85	−70	−13	24	33	49	58
7	55	39	5	−30	−47	−56	−59	−35	8	24	24	21	8	−10	−35	−66	−94	−110	−113	−82	−28	−8	0	9
8	15	16	8	−16	−39	−50	−59	−43	0	25	44	56	62	66	69	58	27	12	12	18	37	67	86	95
9	90	81	58	31	0	−29	−50	−70	−72	−62	−30	−10	−3	−3	−12	−26	−50	−71	−84	−93	−92	−73	−37	−1
10	12	20	20	8	−20	−50	−76	−96	−102	−100	−70	−30	−6	5	13	13	4	−11	−39	−60	−68	−61	−39	3
Borkum (cm.), G.M.T.+0100																								
6	508	547	575	587	577	535	475	421	380	355	364	425	481	516	546	563	569	548	505	450	410	386	388	444
7	502	542	577	600	606	586	546	491	443	406	392	409	463	500	530	551	558	552	520	469	416	384	363	383
8	441	485	518	547	568	574	558	520	478	438	418	429	470	508	542	578	614	638	637	612	572	551	531	509
9	489	518	558	602	635	638	614	573	520	470	425	395	386	395	431	475	510	533	546	528	499	452	417	389
10	395	384	425	473	514	545	560	554	530	486	432	390	364	359	386	443	491	531	558	570	565	536	500	459
Norderney (cm.), G.M.T.+0100																								
6	501	535	575	595	588	542	487	435	390	362	360	405	475	508	543	570	583	560	511	466	429	394	391	424
7	494	538	572	601	615	595	551	501	456	418	393	400	454	495	525	551	567	565	530	481	440	402	374	381
8	427	477	514	547	573	587	566	530	489	456	427	430	458	498	536	576	619	641	640	610	585	565	539	520
9	501	520	565	603	635	644	626	588	537	490	445	414	399	396	421	466	504	529	547	541	510	472	438	409
10	384	381	411	460	503	537	561	595	538	496	450	406	374	363	379	435	486	525	559	578	575	549	510	475
Cuxhaven (cm.), G.M.T.+0100																								
6	343	413	508	572	603	619	603	552	492	433	390	356	346	388	477	543	580	600	601	569	516	463	420	390
7	375	405	495	565	607	630	636	611	560	503	454	413	384	381	435	510	557	580	591	578	538	486	440	400
8	372	367	410	485	545	581	600	603	583	540	490	452	423	409	435	500	561	607	641	669	665	637	606	556
9	507	477	418	499	560	611	646	661	644	597	540	483	434	400	377	373	409	470	528	559	570	552	511	462
10	415	380	355	352	388	459	526	568	585	585	554	502	445	396	363	347	364	427	501	556	585	599	593	562
Busum (cm.), G.M.T.+0100																								
6	351	434	528	584	617	627	603	550	478	386	316	315	345	406	494	559	596	613	605	568	510	436	366	341
7	368	436	520	583	624	645	640	604	550	482	401	349	352	388	452	524	572	599	608	594	553	492	416	355
8	347	380	440	516	571	608	627	623	598	553	496	439	400	402	448	519	576	623	661	680	660	616	580	526
9	462	423	448	506	564	616	654	668	645	595	527	448	364	343	360	378	422	488	544	573	579	551	497	424
10	358	336	338	359	413	490	550	587	601	596	562	504	430	356	324	339	379	440	516	572	606	620	612	578

Husum (cm.), G.M.T. +0100																								
6	308	362	466	542	592	624	632	608	560	498	404	342	324	340	440	514	572	608	626	618	580	530	472	386
7	350	370	458	534	594	634	654	654	620	570	510	430	364	348	400	484	546	590	614	622	604	568	514	440
8	370	354	400	470	540	590	622	644	642	616	570	522	462	390	376	480	544	596	644	674	678	656	620	572
9	510	428	433	446	502	560	614	648	664	642	592	536	464	414	360	338	376	450	500	550	576	576	544	490
10	412	358	332	320	376	436	498	554	590	602	590	548	498	420	358	332	340	410	480	542	590	620	632	620
Wyk (cm.), G.M.T. +0100																								
6	334	348	422	484	538	580	598	592	554	510	456	406	362	332	402	466	522	564	590	596	576	538	492	444
7	406	388	420	482	536	580	610	624	608	568	524	478	432	396	396	434	492	540	576	594	594	570	528	482
8	442	408	390	426	482	536	576	606	620	608	576	540	496	454	430	448	490	544	590	624	638	636	602	560
9	510	462	422	432	476	524	564	600	624	622	588	544	492	442	388	350	348	388	444	492	528	544	538	512
10	466	420	372	340	340	392	448	502	544	570	574	560	522	476	424	382	356	370	428	484	538	576	600	606
Hornum (cm.), G.M.T. +0100																								
6	380	416	470	520	552	568	572	564	530	488	448	410	392	410	455	502	536	562	572	570	552	516	480	446
7	424	435	474	520	554	582	597	598	580	550	508	470	438	426	444	484	522	552	568	572	570	544	508	472
8	444	421	440	480	520	554	578	596	596	588	560	520	486	458	468	496	534	568	590	608	624	594	560	536
9	516	500	484	492	516	544	578	596	602	592	570	524	478	432	400	388	396	428	466	496	514	515	509	490
10	454	416	390	375	388	428	480	516	540	548	548	534	498	460	424	398	396	420	470	516	550	574	584	586
Esbjerg (cm.), G.M.T.																								
6	−89	−51	−18	12	43	59	63	54	33	2	−29	−59	−69	−49	−17	12	37	58	65	64	48	23	−4	−29
7	−49	−37	−11	19	48	72	84	85	66	44	19	−8	−30	−34	−12	15	41	65	79	81	75	57	31	4
8	−20	−36	−20	5	36	63	86	100	100	80	53	23	−6	−18	−3	17	36	53	64	66	49	34	25	18
9	16	6	1	2	26	47	66	80	79	68	44	15	−22	.	.	.	.	.	.	.	.	.	.	.
10	.	.	.	.	.	.	.	.	.	45	46	36	14	−9	−36	−59	−62	−43	−9	22	55	83	93	96
Hirtshals (cm.), G.M.T.																								
6	9	4	−2	7	3	4	12	17	25	23	19	14	4	−6	−10	−13	−17	−7	−5	−3	3	16	16	10
7	12	0	1	2	−1	0	6	10	15	20	21	14	12	5	−3	5	10	12	11	9	19	24	23	19
8	12	4	−1	−3	−5	1	−2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
9	.	.	.	.	.	.	.	.	.	.	34	32	28	18	8	−1	−20	−22	−22	−20	−15	−12	−10	−12
10	−15	−16	−23	−19	−27	−25	−26	−18	−15	−7	0	8	16	16	14	11	1	−5	−5	−2	5	10	17	27
Tregde (cm.), G.M.T. +0100																								
6	68	64	62	59	59	60	64	69	71	73	72	68	62	53	48	43	40	39	40	43	48	52	54	54
7	54	51	52	47	43	44	45	53	53	59	59	61	60	59	58	59	55	59	58	60	63	65	67	66
8	64	60	56	52	48	43	48	49	51	56	59	62	59	54	45	36	28	24	23	27	34	44	58	64
9	75	83	86	89	90	93	91	90	90	92	93	94	92	89	85	77	67	58	52	47	44	45	49	52
10	55	54	54	54	53	52	51	51	52	53	58	63	67	70	70	67	63	59	56	53	54	59	65	74
Stavanger (cm.), G.M.T. +0100																								
6	114	114	122	121	113	110	103	95	88	84	85	96	99	105	110	112	106	97	91	86	81	80	84	90
7	90	95	103	107	101	94	90	82	88	88	94	96	96	100	110	118	120	109	105	105	99	99	97	95
8	95	98	102	109	119	107	97	91	89	89	88	81	76	74	75	87	96	94	92	85	82	86	90	88
9	91	95	102	109	115	125	124	119	116	115	112	105	103	105	102	105	106	107	105	100	92	88	79	72
10	70	74	80	82	89	92	95	97	90	90	90	88	88	92	96	98	104	111	114	117	115	115	113	111
Bergen (cm.), G.M.T. +0100																								
6	118	131	141	144	141	127	104	89	78	71	78	92	109	125	138	146	144	128	113	93	84	76	76	84
7	96	111	120	130	132	125	108	92	84	77	76	87	98	110	130	141	146	140	128	113	104	98	89	88
8	92	101	116	127	138	137	121	106	92	80	74	72	72	80	90	107	118	127	124	111	99	90	81	78
9	78	80	89	108	123	134	135	133	124	113	104	97	94	94	98	108	118	127	128	126	116	100	84	72
10	62	63	72	85	96	110	124	128	123	117	107	96	90	88	94	105	116	129	143	150	153	146	131	120

3. Hourly values of disturbances of sea-level

A convenient method of determining the disturbances of sea-level from hourly heights of observed tide has been given in detail by Doodson (1929) and Corkan (1948).

Briefly, the semi-diurnal tide was first eliminated by a graphical method using the observed heights at six-hourly intervals. Application of this method requires a provisional value of mean sea-level referred to the zero of the observations, and the chosen values are tabulated in tables 1*a* and 1*b*. These values are the best that can be inferred from existing data after allowing for the annual variation in mean sea-level. Much use has been made in this part of the work of a special publication by the Association d'Océanographie Physique (1940).

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

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

The corrected three-hourly residuals were again plotted, and the heights of the several maxima and minima before and after the large disturbance on 8 January were tabulated and carefully examined from station to station along the coast.

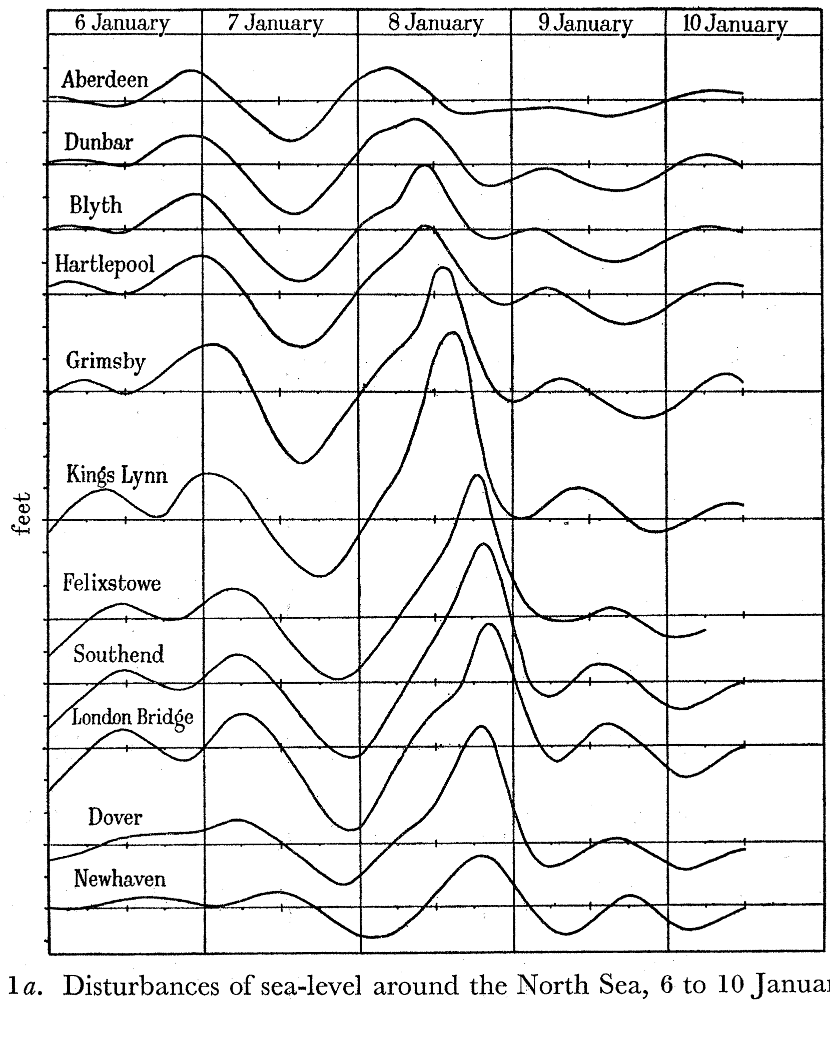

Figure 1*a*. Disturbances of sea-level around the North Sea, 6 to 10 January 1949.

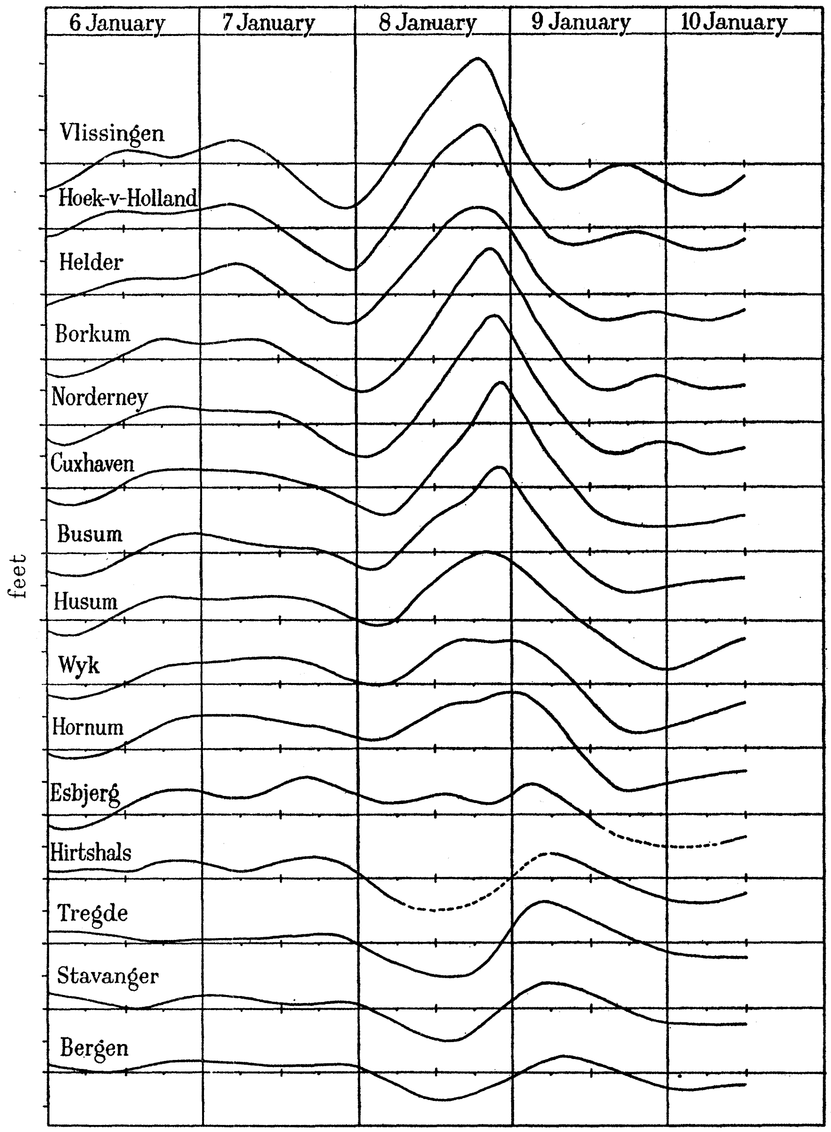

FIGURE 1*b*. Disturbances of sea-level around the North Sea, 6 to 10 January 1949.

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 in this way small errors in datums, errors in the provisional value of mean sea-level or errors in the calculations, if they exist, can be easily detected.

The corrected and finally accepted values of the undisturbed mean sea-level appropriate to the time of the surge are tabulated in tables 1*a* and 1*b* for all stations where they have been used. In general, the difference between the provisional and corrected values of mean sea-level is small, but one station, Dover, requires special mention.

At Dover, mean sea-level is given as 8·34 ft. above the zero of the observations, the same zero as at present, and is based on one year's analysis (1910) by Roberts (1913). Comparison of the levels at Southend, Dover and Newhaven in the 'undisturbed' part of the period now examined suggest a value of 9·6 ft. at Dover or a mean sea-level 1·3 ft. higher than the original value. It is of interest that the suggested value is very nearly the level of Newlyn Datum, and in this it agrees with Southend and Newhaven, where the mean sea-levels are

TABLE 3. DISTURBANCES OF SEA-LEVEL AROUND THE NORTH SEA, 7 TO 9 JANUARY 1949

	7 January								8 January								9 January							
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	8	3	−3	−8	−12	−13	−8	1	6	10	10	7	2	−4	−3	−3	−3	−1	−1	−1	−4	−5	−4	−2
Dunbar	9	5	0	−9	−14	−15	−11	−5	3	9	11	14	12	4	−5	−7	−4	−2	−1	−3	−7	−9	−8	−7
Blyth	10	5	−2	−10	−14	−16	−14	−7	−1	4	6	19	19	7	−1	−3	−1	0	−1	−5	−8	−10	−10	−7
Hartlepool	12	9	2	−8	−15	−17	−15	−7	−1	7	11	19	20	14	2	−2	−3	1	2	−1	−5	−9	−10	−8
Grimsby	15	14	9	−5	−16	−22	−19	−11	−2	5	12	18	36	37	16	2	−3	1	3	4	0	−4	−8	−8
King's Lynn	11	9	7	−3	−12	−17	−21	−19	−10	0	8	22	43	55	39	10	−3	−2	2	7	7	4	−2	−6
Felixstowe	5	7	9	6	−3	−12	−18	−19	−17	−10	−2	6	14	26	43	34	13	1	−1	−1	−1	3	1	−3
Southend	1	7	9	4	−1	−10	−18	−22	−23	−16	−7	3	14	25	41	40	21	−1	−5	−1	5	5	3	−2
London	1	8	11	7	2	−9	−20	−25	−25	−15	−4	4	12	15	33	37	23	5	−5	−1	5	7	4	−1
Dover	4	7	7	5	0	−4	−9	−13	−11	−4	0	5	12	23	34	31	14	−5	−7	−5	−2	1	1	−2
Newhaven	0	1	2	5	5	3	−1	−7	−10	−9	−9	−4	3	10	15	15	7	−2	−8	−9	−5	1	3	0
Vlissingen	4	6	7	5	0	−6	−11	−14	−13	−8	1	10	19	26	32	28	12	2	−7	−8	−5	−2	0	−3
Hoek-van-Holland	6	7	7	5	0	−5	−8	−13	−13	−6	2	11	19	25	31	30	15	5	−2	−6	−5	−3	−2	−3
Den Helder	6	8	8	6	1	−4	−9	−10	−9	−4	2	10	17	23	25	25	19	7	−1	−3	−8	−8	−8	−6
Borkum	4	4	5	5	2	0	−5	−9	−10	−10	−6	2	10	19	27	34	25	13	6	−3	−9	−11	−9	−6
Norderney	4	4	4	4	3	1	−4	−8	−10	−10	−5	2	9	18	26	33	28	15	8	0	−6	−9	−9	−6
Cuxhaven	6	4	5	4	2	2	0	−3	−6	−9	−8	−1	6	12	19	31	30	17	8	−2	−5	−11	−12	−12
Busum	5	3	3	1	0	2	0	−2	−5	−6	−2	4	9	12	17	25	24	14	6	−1	−7	−12	−13	−14
Husum	6	6	7	6	6	6	5	2	0	−1	1	6	12	16	19	20	18	14	8	3	−1	−6	−11	−15
Wyk	6	6	8	8	7	7	6	2	0	−1	1	4	10	13	13	13	13	11	7	2	−5	−13	−15	−15
Hornum	9	10	10	9	7	7	7	5	2	2	4	7	11	13	14	16	17	16	11	2	−5	−12	−13	−13
Esbjerg	6	5	4	7	8	11	11	9	6	4	3	4	6	6	4	3	8	10	7	3	1	.	.	.
Hirtshals	5	3	2	4	5	5	6	5	2	−3	−8	.	.	.	.	.	.	.	.	7	3	1	−3	−4
Tregde	1	2	1	1	2	3	3	3	−1	−3	−7	−8	−10	−10	−10	−4	5	12	13	10	7	4	2	−1
Stavanger	5	5	3	3	2	2	3	3	2	−1	−4	−7	−10	−10	−6	−2	4	6	8	8	4	3	1	−3
Bergen	3	4	2	2	1	1	2	2	1	−1	−5	−8	−9	−9	−6	−5	−1	1	3	5	3	1	0	−5

Levels are in units of $\frac{1}{10}$ ft. above or below the undisturbed level.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

also near Newlyn Datum. It is very difficult to believe that mean sea-level at Dover can be more than 1 ft. lower than at Southend and Newhaven, and during the 'undisturbed' part of the present observations there is no indication of such a difference.

The resulting residuals for the period 7 to 9 January, corrected as above and referred to the 'corrected mean sea-level', are tabulated at three-hourly intervals in table 3; all times are in G.M.T.

In figures 1*a* and 1*b* the same residuals for the period 6 to 10 January have been plotted for all coastal stations, in order, from Aberdeen, anti-clockwise around the North Sea, to Bergen.

The complete period, 6 to 10 January, has been given, since the close similarity of the variations in level from station to station, even when there was comparatively little disturbance, is considered interesting.

4. Maximum disturbance deduced from high-water observations

The maximum disturbance on 8 January coincided, within an hour or so, with the midday high water along the whole of the east coast of the British Isles.

An estimate of the size of the maximum disturbance can thus be made when the disturbance of the midday high water is known.

(*a*) *Middlesbrough*

Comparing the observed midday high waters at Middlesbrough and Hartlepool on 8 January, we have, referring all levels to O.D.N.:

	Hartlepool	Middlesbrough
observed time of high water	1001 hr.	1014 hr.
observed height of high water	6·6 ft.	7·1 ft.
mean high-water springs	7·8 ft.	7·9 ft.
mean high-water neaps	4·2 ft.	4·5 ft.

The tides were near neaps, and the normal height of high water at Middlesbrough may be expected to be about 0·3 ft. higher than at Hartlepool.

The observed tide at Middlesbrough was 0·5 ft. higher than at Hartlepool, indicating a disturbance 0·2 ft. greater. We may infer then that the maximum disturbance at Middlesbrough was only slightly greater than at Hartlepool and of the order of 2·3 ft.

(*b*) *Humber estuary and river Trent*

Referring all heights to O.D.N. we have the following data:

	Grimsby	Immingham	Keadby	Owston Ferry
observed time of high water	1200 hr.	1203 hr.	1340 hr.	1335 hr.
observed height of high water	8·7 ft.	9·25 ft.	11·6 ft.	13·1 ft.
mean high-water springs	9·9 ft.	10·7 ft.	*13·0 ft.	*12·75 ft.
mean high-water neaps	5·5 ft.	6·0 ft.	*8·25 ft.	*8·0 ft.

* Supplied by the engineer to the River Trent Catchment Board.

In the Trent, the times at Keadby and Owston Ferry are uncertain, due to the use of a very restricted time scale on the charts; the heights of high water should be reliable.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The values of mean high-water springs and mean high-water neaps in the Trent should also be accepted with some caution, since the levels at a particular time will depend on the amount of water in the river.

From the average difference in levels near neaps and the observed levels on 8 January, we deduce an increase of 0·2 ft. in the size of the maximum disturbance between Grimsby and Keadby and an increase of 1·9 ft. between Grimsby and Owston Ferry. The latter figure seems too large, and we may try an alternative method of approach.

Differences between the high-water levels at Keadby and Grimsby and between Owston Ferry and Grimsby for the four high waters immediately preceding and the four high waters immediately following the disturbed high water, in proper sequence, are given in table 4; the average difference for the eight tides and the expected difference from the data for mean high-water neaps are also given.

TABLE 4. LEVELS AT KEADBY AND OWSTON FERRY (COMPARED WITH GRIMSBY)

	Keadby-Grimsby (ft.)	Owston Ferry-Grimsby (ft.)
four preceding high waters	2·9	3·7
	3·1	3·6
	2·7	4·3
	2·5	3·3
disturbed high water	2·9	4·4
four following high waters	2·4	4·2
	2·3	3·3
	2·5	3·1
	2·0	2·3
average for eight tides	2·6	3·5
difference from mean high-water neap data	2·4	2·6

The figures show clearly that in the period, the levels at Owston Ferry were running nearly 1 ft. high. The values of maximum disturbance at Keadby and Owston Ferry are now respectively 0·3 and 0·9 ft. greater than at Grimsby. These results are reasonable and would imply that there was a very slight increase in the disturbance in the Humber and a more important, though not a marked increase, in the Trent. The inferred maximum disturbances at Keadby and Owston Ferry were respectively 4·1 and 4·7 ft. It would be interesting to discover whether the increase was due to local wind or to natural features in the estuary and river.

(*c*) *Suffolk and Essex coasts*

At several of the places on the Suffolk and Essex coasts where high-water observations are available, mean spring and neap data are unfortunately not known.

At Walton, Hythe and Canvey Island, observations are taken for the Essex Rivers Catchment Board solely as a check on the abnormal levels which may result in flooding.

In the reduction of the data a method has been used which is independent of datum, provided the datum remains constant, and the procedure has been as follows.

At all stations along the coast averages have been taken of the four high waters immediately preceding and the four high waters immediately following the disturbed high water. The average for the eight tides is called the *normal height* of the disturbed high water. The difference between the *observed height* and the *normal height* is called the *normal disturbance*.

At Grimsby, Felixstowe, Southend and London Bridge, where hourly values of the disturbance are known, the disturbance at high water is known and is called the *surge disturbance*.

The *surge disturbance* and the *normal disturbance* should be approximately the same, and their difference should vary regularly along the coast, and may be interpolated, and will be called the *correction*.

Addition of the *correction* to the *normal disturbance* at places where only high-water observations are known gives the *surge disturbance*.

Addition of the difference between the *maximum disturbance* and the *surge disturbance*, which may also be interpolated along the coast, to the *surge disturbance* gives the *maximum disturbance*.

The results are given in table 5, where heights in brackets have been deduced in the manner indicated.

Table 5. Levels on Norfolk and Essex coasts

	Grimsby	Great Yarmouth Haven	Felixstowe	Walton on Naze	Holland Haven
stated datum of heights	O.D.N.	O.D.N.	O.D.N.	O.D.L.	O.D.L.
observed height of high water (ft.)	8·7	4·8	7·6	10·5	9·7
normal height (ft.)	5·2	1·7	3·2	8·4	5·2
normal disturbance (ft.)	3·5	3·1	4·4	2·1	4·5
surge disturbance (ft.)	3·6	(2·9)	4·0	(1·8)	(4·2)
correction (ft.)	+0·1	(−0·2)	−0·4	(−0·3)	(−0·3)
maximum disturbance (ft.)	3·8	(3·2)	4·4	(2·2)	(4·6)

	Hythe	Southend	Canvey Is.	London Bridge
stated datum of heights	O.D.N.	O.D.N.	O.D.L. + 2·02 ft.	O.D.N.
observed height of high water (ft.)	11·1	9·7	11·8	12·3
normal height (ft.)	6·8	5·4	7·2	8·0
normal disturbance (ft.)	4·3	4·3	4·6	4·3
surge disturbance (ft.)	(4·0)	4·0	(4·2)	3·7
correction (ft.)	(−0·3)	−0·3	(−0·4)	−0·6
maximum disturbance (ft.)	4·4	4·3	(4·3)	3·8

King's Lynn has not been used to determine the disturbance at Great Yarmouth, since the levels in the Wash Estuary are clearly abnormal.

The maximum disturbance at Great Yarmouth is lower than might be expected and may be influenced by a local wind effect in the Haven.

At Walton on Naze, where the original observations were only to the nearest half foot, the observed disturbance is in marked disagreement with the stations on either side and cannot be accepted.

All other stations are in good agreement and indicate that there was comparatively little change in the size of the maximum disturbance along the whole of the Essex coast.

If we leave out the Wash Estuary and assume the disturbance in Yarmouth Haven with northerly winds to be slightly lower than on the open coast, we may infer that the disturbance increased between Grimsby and Felixstowe, but only slowly.

5. Transmission of the disturbance in the river Thames

Comparison of the residuals at Southend and Tower Pier (figure 1*a*) indicates a very close relation between the disturbances at the two places and presumably in the Thames as a whole up to Tower Pier.

On 8 January the maximum disturbance seems to have travelled up the river at practically the same rate as the tide, and there was an appreciable decrease in the size of the greatest disturbance from 4·3 ft. at Southend to 3·8 ft. at Tower Pier. At Canvey Island the greatest disturbance was 4·3 ft., the same as at Southend.

There is some indication from a distortion in the curve of residuals at Tower Pier that the progression up the Thames of a disturbance in which the level is raised is more retarded near low water than near high water.

6. Transmission of the disturbance through the Straits of Dover

The effect in the English Channel of a disturbance in level in the southern North Sea will depend on the volume of water which can pass through the Straits of Dover while the disturbance lasts. Thus the narrow bottleneck at the Straits may be expected to offer a considerable hindrance to the transmission of a disturbance either from the North Sea to the English Channel or the reverse, and any disturbance built up in the Straits should diminish rapidly away from the Straits because of the rapidly increasing section.

As a result of the earth's rotation, the moving water, after passing through the Straits, will be deflected to the right and in the English Channel, from a raising of level in the southern North Sea, a larger disturbance should be experienced along the southern English coast than on the opposite French coast.

The residuals at Newhaven, shown in figure 1*a*, immediately after those for Dover, give some indication of the disturbance transmitted on the present occasion, though it must be remembered the meteorological effects in the channel have not been eliminated.

The maximum disturbance observed at Dover on 8 January was 3·6 ft. At Newhaven there was a very appreciable reduction in the disturbance and a maximum of only 1·6 ft., but this is still very nearly twice what might be expected from consideration of the increased section. To test out the conclusion that the earth's rotation plays an important part, and that in consequence the disturbance tends to hug the southern English coast, we require simultaneous observations on the English and French coasts, but, unfortunately, the latter are not available for the present disturbance.

7. Progression of maximum disturbance and progression of diurnal tide

The curves of residuals (figures 1*a* and 1*b*) clearly indicate what appears to be a progression of the maximum disturbance, counter-clockwise, around the North Sea.

In figure 2 the times of maximum disturbance, measured from the time of maximum at Dunbar, have been plotted against distance measured, approximately, along the coastline.

For comparison, the times of diurnal high water measured from the time of diurnal high water at Dunbar have been similarly plotted. These times have been deduced from the averages of the differences in the phase lags of K_1 and O_1.

The existence of a close similarity between the two progressions is immediately evident.

Along the east coast of the British Isles the disturbance took 10 hr. to pass from Dunbar to Southend as against 9 hr. taken by the diurnal tide. Experience has shown (see Corkan 1948) that when a disturbance originates externally its progression along the east coast is almost identically the same as that of the diurnal tide. On the present occasion the greater part of the disturbance originated inside the North Sea, and the progression will naturally be influenced by the meteorological distribution and by the rate at which the depression crossed the North Sea.

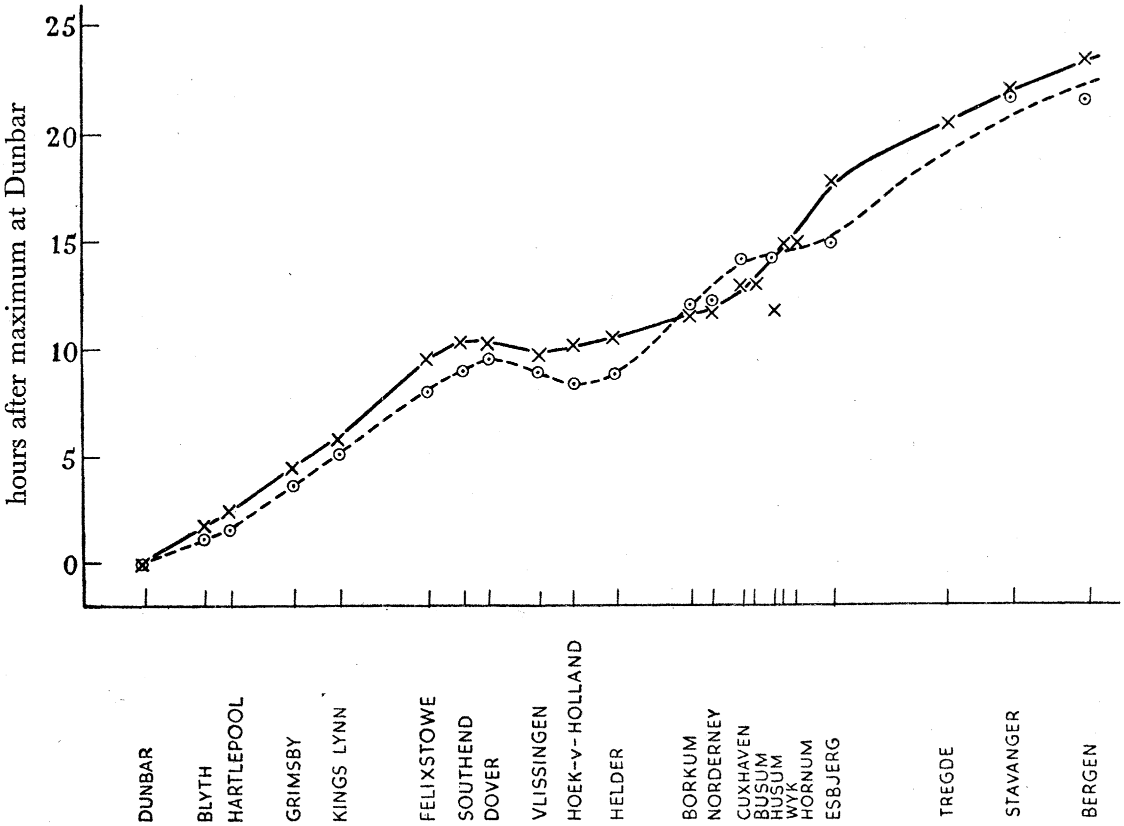

FIGURE 2. Progression of maximum disturbance and of diurnal tide.
—×— maximum disturbance. --⊙-- diurnal tide.

In the Flemish bight the disturbance was a maximum at Felixstowe and Vlissingen at practically the same times. Later the progression was south-westwards into the Thames Estuary and the Straits of Dover, and eastwards into the German bight.

Over the whole of the southern North Sea the times of maximum disturbance fell within an interval of 3 hr., and the time taken to travel from Southend to Cuxhaven was only $2\frac{1}{2}$ hr. as compared with 10 hr., the time taken to travel from Dunbar to Southend, a distance only slightly greater.

Northwards from Cuxhaven, along the coasts of Schleswig-Holstein and Denmark, the progression was again retarded, and the disturbance ultimately completed a circuit of the North Sea from Dunbar to Bergen in a time only 1 hr. different from that taken by the diurnal tide.

The maximum disturbance and the amplitude of the diurnal tide have been plotted against distance measured along the coast in figure 3.

The amplitude of the diurnal tide has been taken as the sum of the amplitudes of K_1 and O_1.

Southwards along the east coast of the British Isles the maximum disturbance built up steadily and was greatest at King's Lynn, where it exceeded 5 ft. The disturbance at King's

Lynn was probably accentuated by a local funnel effect in the Wash Estuary and by the traction of the local winds over large stretches of shallow water.

At Great Yarmouth the disturbance was lower than might be expected from the general run of the levels and was probably influenced by a sheltering effect in the haven.

For all practical purposes the disturbance along the Essex coast was the same as at Southend.

In the Flemish bight the maximum levels on the Netherlands coast were 1 to $1\frac{1}{2}$ ft. lower than on the opposite English coast.

Along the north German coast the maximum disturbance was greater than on the Netherlands coast but less than on the south-east English coast.

At Cuxhaven the maximum disturbance was just over 3 ft., but immediately the coastal direction turned to face west instead of north, the disturbance decreased rapidly and at Esbjerg was 1·0 ft.

The only comparison of importance which can be made with the diurnal tide is the closely similar decrease, in the amplitude of the diurnal tide, and in the size of the maximum disturbance, from near King's Lynn, the place where the largest disturbance was observed.

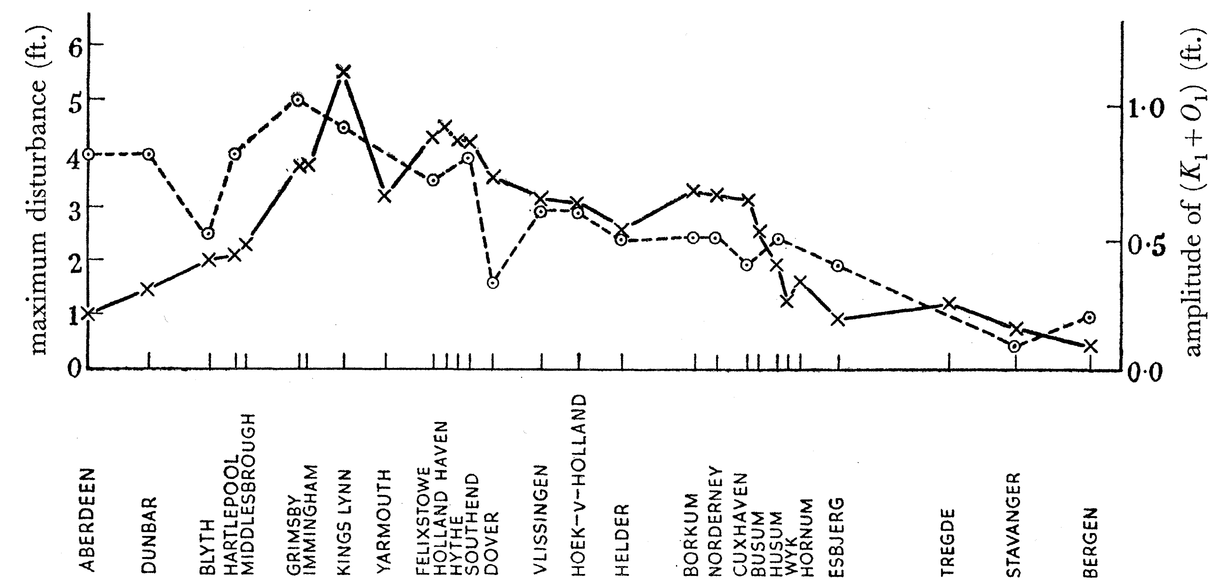

FIGURE 3. Maximum disturbance and amplitude of (K_1+O_1).
—×— maximum disturbance. --⊙-- amplitude of (K_1+O_1).

8. THE METEOROLOGICAL CONDITIONS

The weather charts for the period have been reproduced in figure 4.

From 0900 hr. on 8 January to 0900 hr. on 9 January the charts are given at three-hourly intervals, and these have been very kindly supplied by the Director of the Meteorological Office; the remainder of the maps have been traced from the Daily Weather Maps.

The origin of the disturbance as indicated by the weather maps was a deep depression which developed very rapidly off the north-west coast of Scotland and then passed quickly eastwards across the extreme north of the North Sea and southern Norway. The passage of the centre of the depression across the North Sea was accompanied by a rapid veering of

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

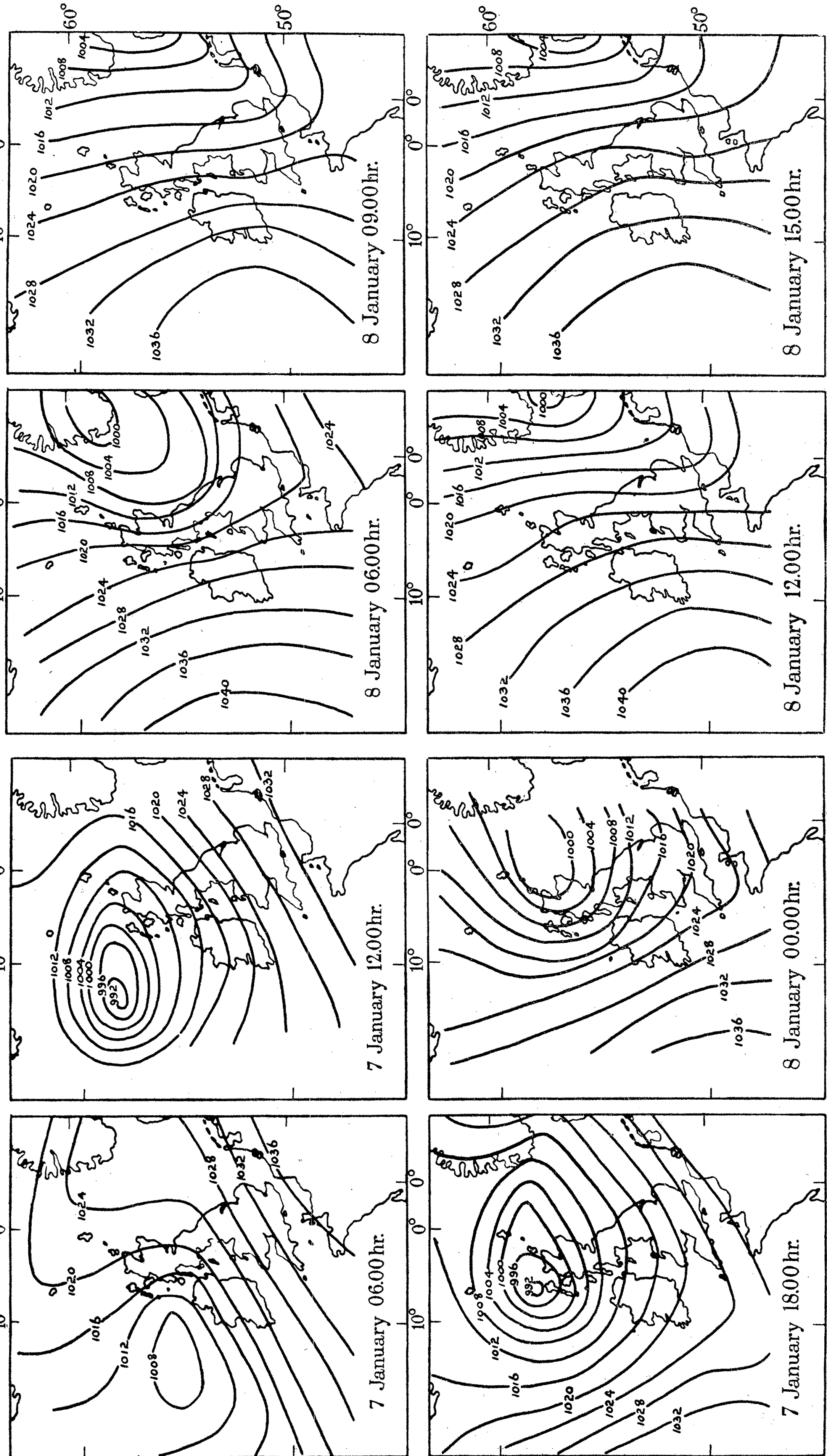

FIGURE 4*a*. Meteorological conditions, 7 January, 0600 hr. to 8 January, 0000 hr.

FIGURE 4*b*. Meteorological conditions, 8 January, 0600 to 1500 hr.

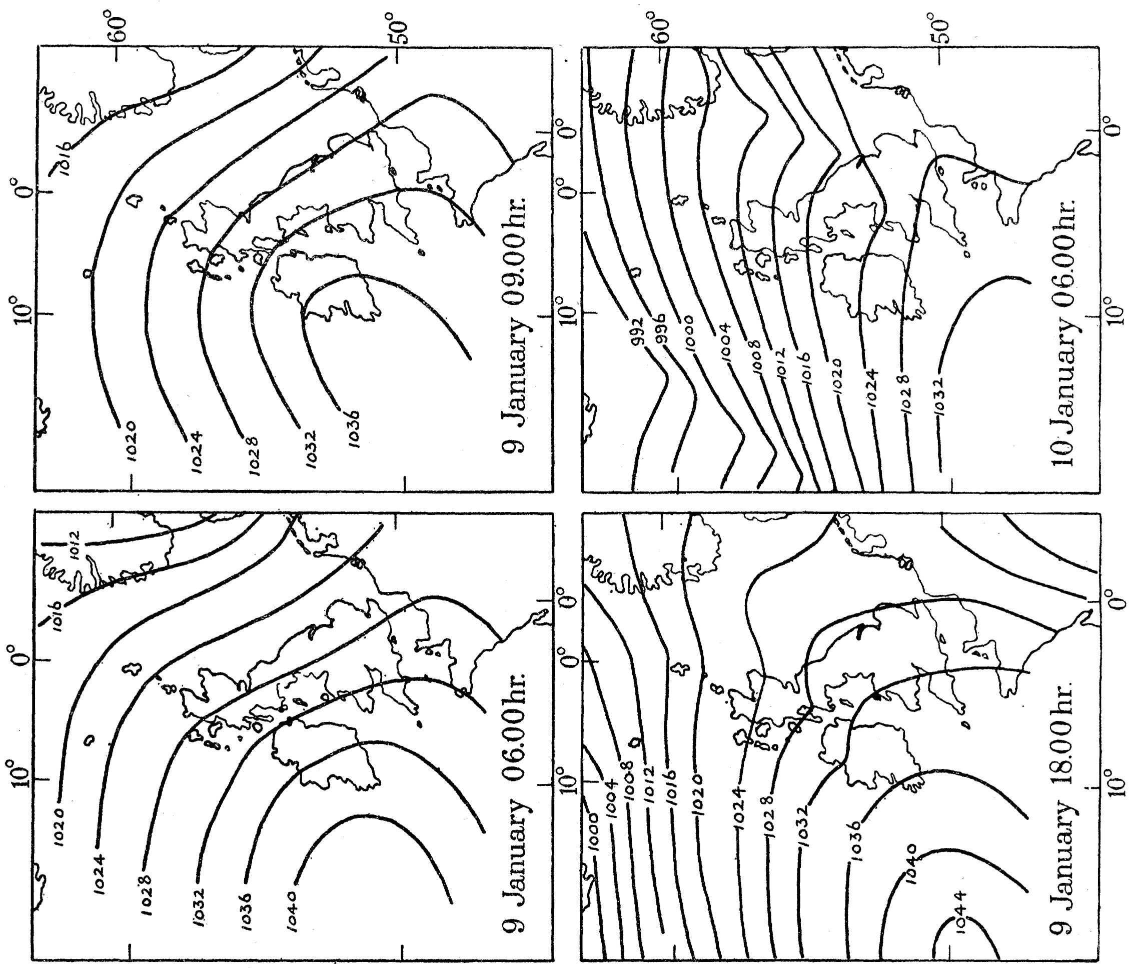

FIGURE 4*d*. Meteorological conditions, 9 January, 0600 hr. to 10 January, 0600 hr.

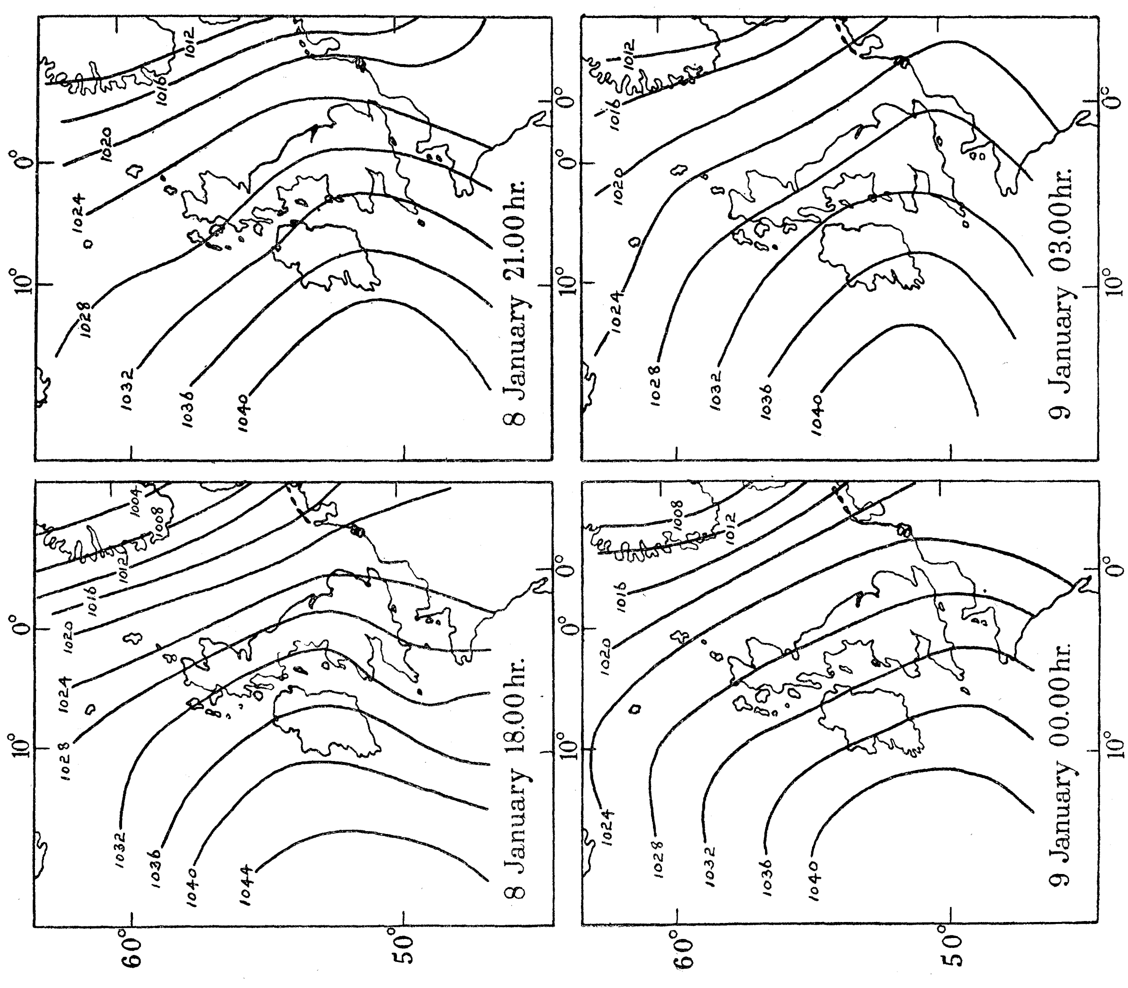

FIGURE 4*c*. Meteorological conditions, 8 January, 1800 hr. to 9 January, 0300 hr.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the winds in the rear of the depression, from south-west to north-west and north, and it is of some importance that for a short time strong northerly winds were localized in the western half of the North Sea and were particularly affecting the east coast of the British Isles. These conditions were very soon followed by nearly uniform conditions of a northerly type over the whole North Sea which lasted until the disturbance subsided. In the later stages of the disturbance, though there were important changes in the wind intensities, the changes in the wind directions were slight and the disturbance subsided as the winds moderated.

9. Deduced levels over the North Sea and the changes in the average level

If the disturbed levels for a fixed hour, tabulated in table 3, are plotted around the coast of the North Sea, lines of equal disturbance can be drawn as in figure 5. The maps cover the period 0600 hr., 7 January, to 0600 hr., 10 January, and the lines give the disturbance in units of 0·1 ft.

Over the sea area the lines may be a little conjectural, but with so many coastal observations and with relatively simple surface disturbances, the maps, though they are not accurate, give a good picture of the disturbance at a fixed hour and of the progressive changes in the course of the storm.

If we exclude direct pressure effects, the level changes inside the North Sea are clearly made up of at least two parts.

First, there are the gradients set up internally by the traction of the wind over the sea surface. When the wind is from certain directions the coastal conditions may approximate to those of an enclosed sea and the law of constant volume may be expected to hold. These gradients and the related meteorological conditions will be examined in some detail in § 10.

Secondly, there are changes in the average level due to the sea not being perfectly closed. In the open ocean, when coastal barriers are absent, there is no gradient in the steady state when the wind blows over water; the energy of the wind is entirely absorbed in transporting the water, and this transport is at right angles to the wind.

To a lesser degree similar conditions are experienced when strong northerly or southerly winds blow over the upper part of the North Sea; across the northern entrance they set up an inward or outward flow of water from the ocean; the effects of these flows propagate southwards and are observed as a raising or lowering of the level of the North Sea as a whole. (See maps for 8 January, 1800 hr. and 2100 hr., in particular.)

An estimate of the changes in the average level of the North Sea during the present disturbance, when the direct effect of pressure is neglected, has been made by placing a piece of transparent small squared paper over each map and counting the squares between the lines of equal level. For the northern boundary a line has been taken due east through the Shetland Islands.

The results are illustrated in figure 6. No importance should be attached to the minor irregularities in the curve, since these are probably due to errors in the positioning of the lines of equal disturbance over the sea.

There was a considerable outflow of water on 7 January when the average level fell 0·7 ft. in 9 hr. and at 1500 hr. was 0·5 ft. low.

This was followed by an inflow of water lasting 21 hr. when the average level rose 1·2 ft. and at midday on 8 January was 0·7 ft. high. The level remained high until well into the morning of 9 January and later fell until 0000 hr. on 10 January, when the level was 0·4 ft. low.

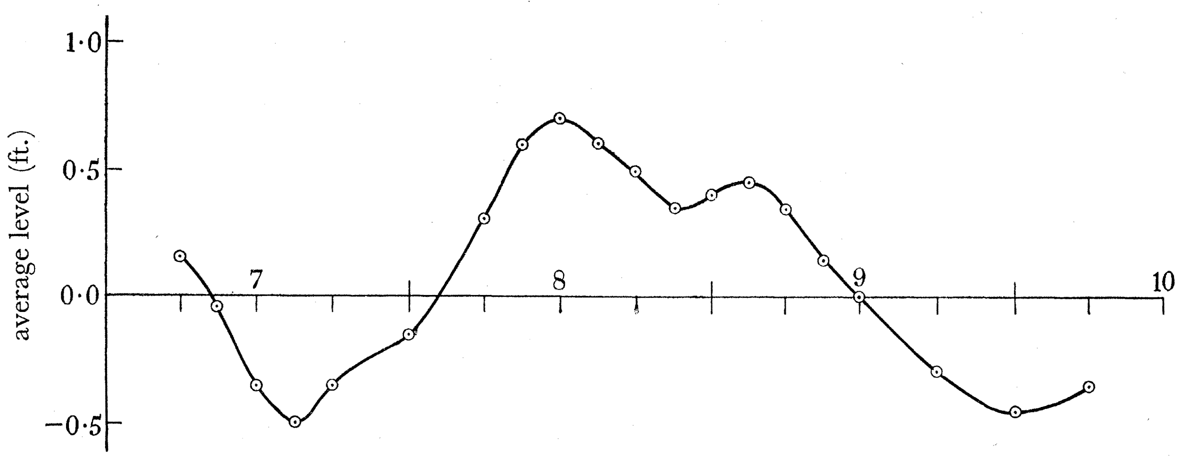

FIGURE 6. Average level of the North Sea, 7 to 10 January 1949.

An estimate of the currents likely to be experienced across the northern entrance when these changes were taking place is of some interest.

For the section due east from the Shetlands to the Norwegian coast we have:

length of section $= 200 \times 5280$ ft.

average depth of section $= 500$ ft.

area of North Sea $= (500 \times 5280)^2$ sq.ft.

average rise in level of North Sea in 21 hr. $= 1{\cdot}2$ ft.

average speed of water across section $= \dfrac{500^2 \times 5280^2 \times 1{\cdot}2}{200 \times 5280 \times 500 \times 21 \times 3600}$ ft./sec.

$= 0{\cdot}21$ ft./sec.

One knot $= 1{\cdot}69$ ft./sec., so the average speed was of the order of one-tenth of a knot.

There are indications that the inflow was much greater near the Shetlands than near the Norwegian coast, so it is not improbable that currents of at least $\frac{1}{4}$ knot were experienced near the Orkneys during the inflow of 7 to 8 January.

10. THE LEVELS OVER THE NORTH SEA AND THE RELATED METEOROLOGICAL CONDITIONS

(*a*) *The lowering of level in the afternoon of* 7 *January*

At 0600 hr. on 7 January conditions over the North Sea were comparatively quiet. A depression was developing west of Scotland, and in the southern and eastern parts of the North Sea the level was raised 0·5 to 1·0 ft.

By 0900 hr. strong south to south-westerly winds were being experienced in the north-western part of the North Sea; a lowering of level was developing along the coasts of Scotland and north-east England, and spreading eastwards across the North Sea.

By 1200 hr. there were strong south-westerly winds over the whole of the western North Sea; the lowering of level continued to spread eastwards and the greatest disturbance was between Blyth and the Humber, where the level was approximately 1·5 ft. low.

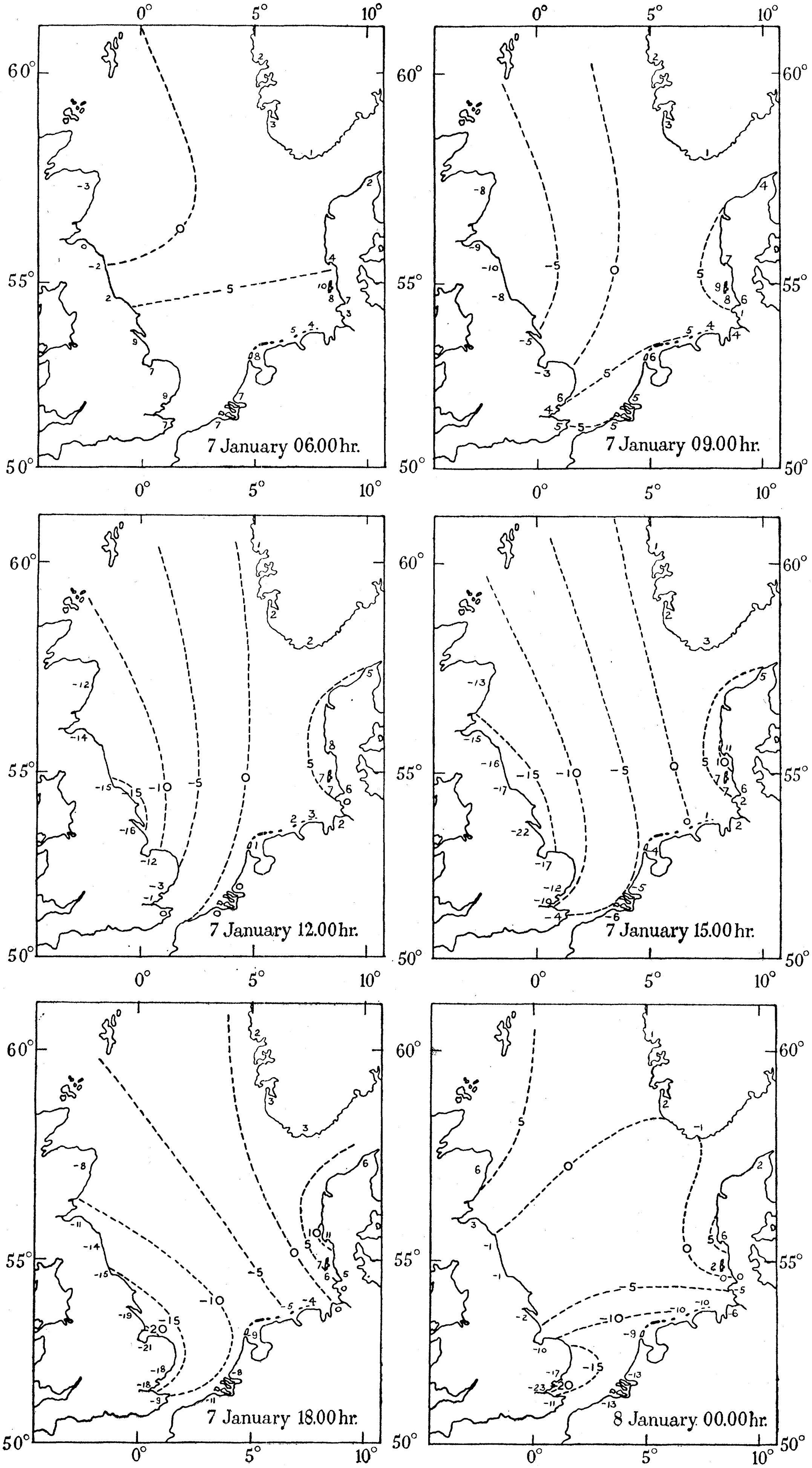

FIGURE 5*a*. Lines of equal disturbance, 7 January, 0600 hr. to 8 January 0000 hr.

There was still no indication of any change in level on either the north German or Danish coasts.

At 1500 hr. the conditions were similar; the eastwards progression continued and the line of undisturbed level ran from near Borkum to a point a little west of south-west Norway; the other lines of equal disturbance ran nearly parallel to this direction. The greatest disturbance, a lowering of 2·0 ft., was in the region of the Humber.

From figure 6, the average level of the North Sea was now nearly 0·5 ft. low, so there had been a considerable transport of water out of the North Sea, presumably mainly by the winds over the extreme northern part. The effect of this transport, in the form of a lowering of level, had been transmitted southwards *mainly down the western half of the North Sea*, for there were still no signs of any appreciable change in level on either the Norwegian or Danish coasts. The line of average level (0·5 ft. low) lay practically down the centre of the sea, so it may be presumed that the gradients between the Humber and the Danish coast were due mainly to the wind.

By 1800 hr. the south-westerly winds were near their maximum and the isobars were nearly uniform. The water gradients between the Wash and the Danish coast were also nearly uniform.

A matter of some interest is whether we would be justified in comparing the gradient winds and the simultaneous water gradients at 1800 hr. on the assumption that we have an enclosed canal in the steady state.

The free period of an oscillation between the Wash and the centre of Denmark may be estimated from the formula

$$t = \frac{2L}{\sqrt{(gh)}},$$

where L = distance = $5{\cdot}5 \times 10^7$ cm.,

h = average depth = $4{\cdot}0 \times 10^3$ cm.,

$$t = \text{period} = \frac{2 \times 5{\cdot}5 \times 10^7}{(981 \times 4 \times 10^3)^{\frac{1}{2}}} \times \frac{1}{3600} = 15{\cdot}3 \text{ hr.}$$

The period of the wind is at least twice this, so a near approach to a statical response may be expected. Comparing then the average winds and the average water gradients between the Wash and Esbjerg at 1800 hr. we have

$$\frac{\delta\zeta}{\delta L} = \frac{nk}{gh}\frac{\rho_a}{\rho} V^2,$$

where $\delta\zeta$ = difference in water level = $3{\cdot}0 \times 30{\cdot}5$ cm.,

δL = distance = $5{\cdot}5 \times 10^7$ cm.,

h = average depth = $4{\cdot}0 \times 10^3$ cm.,

$\frac{\rho_a}{\rho}$ = ratio of densities of air and water = $1{\cdot}2 \times 10^{-3}$,

V = velocity of wind (determined below),

k is a constant such that the tractive force (T) of the wind over the surface is given by $T = k\rho_a V^2$,

n is a constant which theoretically in the steady state is $\frac{3}{2}$ when there is no bottom current, 1 when there is no bottom friction.

From the daily weather charts, scale $1:2\times10^7$, the average gradient wind between the Wash and Esbjerg was

$$2\cdot0\times10^3\,\text{cm.sec.}$$

If we accept the factor $\frac{2}{3}$ as giving the wind over the sea surface and substitute in our formula we obtain

$$nk=\frac{3\cdot0\times30\cdot5\times981\times4\cdot0\times10^3}{1\cdot2\times10^{-3}\times1\cdot33^2\times10^6\times5\cdot5\times10^7}=0\cdot0031.$$

Assuming no bottom current and $n=\frac{3}{2}$

$$k=0\cdot0021.$$

If there is some bottom slip k will be larger. If allowance is made for the angle between the directions of the wind and the water gradient, k will also be larger but of the same order of magnitude. The direction of the water gradient was to the left of the isobars and probably a few degrees to the right of the wind.

(*b*) *The raising of level on* 8 *January*

Between 1800 hr. on 7 January and 0600 hr. on 8 January, as the centre of the depression crossed the upper North Sea, there were rapid changes in the winds and corresponding changes in the water gradients.

The uniform conditions which were so prominent at 1800 hr. on 7 January very soon disappeared and at 0000 hr. on 8 January the lines of equal disturbance in the southern North Sea ran practically east–west, and in the region of greatest disturbance, the Thames Estuary, there was a lowering of over 2 ft.

Off north-east Scotland the level at 0000 hr. was rising, but there was no obvious explanation of how this rise originated, either in terms of the winds in the upper North Sea or those farther north.

The level of the North Sea as a whole was rising (see figure 6), and water which previously had been expelled out of it was returning.

There was no indication of any important change in level near the Norwegian coast or in the eastern half of the North Sea, so we must presume that the bulk of the returning water was proceeding down the western side, and this is confirmed by the levels 3 hr. later; the earth's rotation probably accounts for the deflexion of the returning water to the right and the hindering effect of the east coast of Scotland for the first rise in level.

In some respects this early rise resembles what has previously been termed an externally generated surge of unknown origin. Surges of this type are very important, and occasions are known when they have produced a raising of level at Southend of 5 to 6 ft. at a time when conditions over the North Sea have been comparatively quiet. They have been shown to be closely related to the pressure changes near the Wyville Thompson Ridge, and are a maximum at Dunbar 14 hr. after the time of minimum pressure at the Faroes. The possibility that they may originate in the manner indicated has not been previously considered; in the present example the effect was small, but further investigation of an example when the effect has been large seems worth while.

At 0600 hr. on 8 January the strong northerly winds in the rear of the depression were localized over the western North Sea and were obviously assisting the progression and growth of the rise in level which by now had spread well down the western half of the area. The two effects, one presumably owing to the returning water and the other to the internal wind

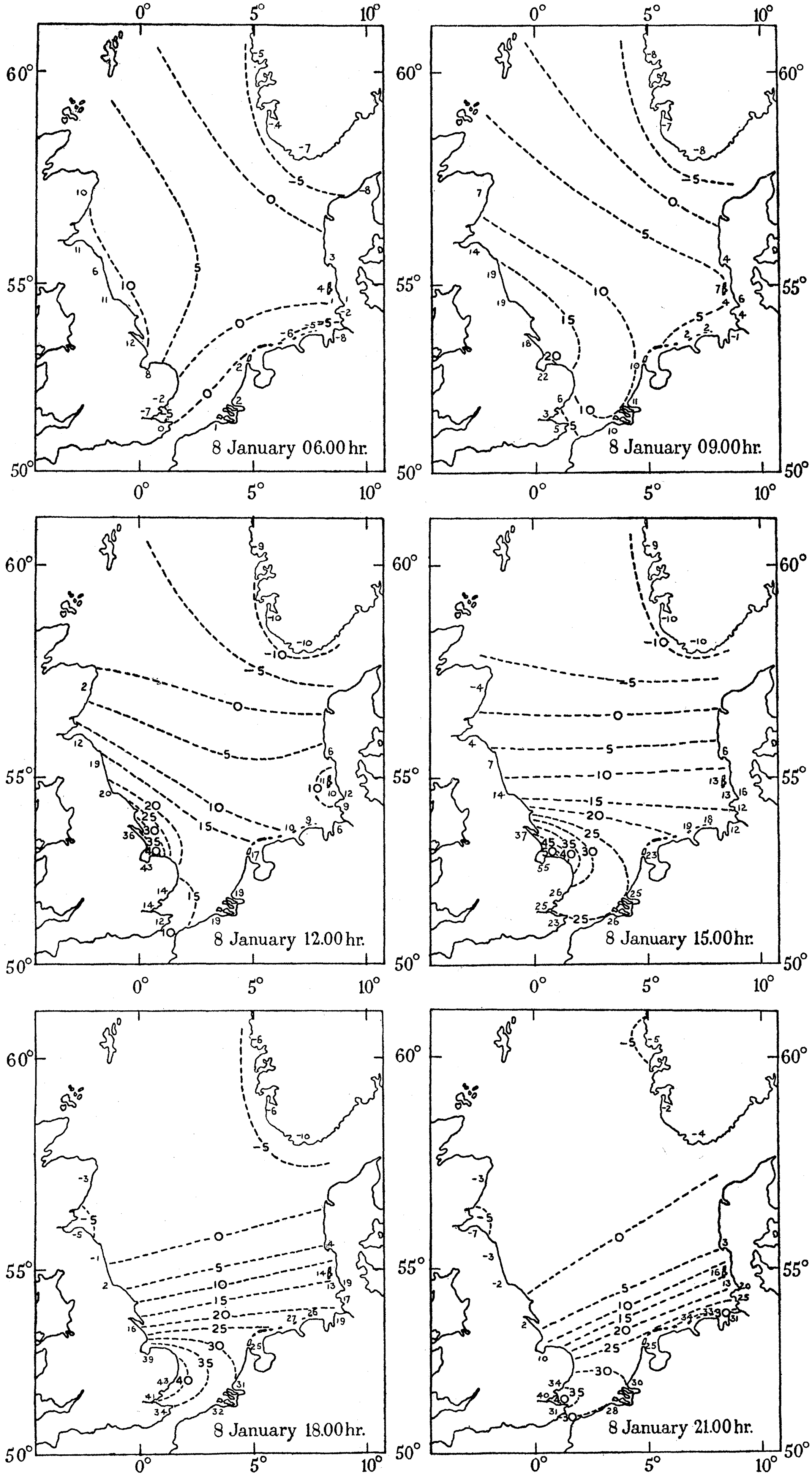

FIGURE 5*b*. Lines of equal disturbance, 8 January, 0600 hr. to 2100 hr.

effect, can be easily distinguished in the curves in figure 1*a* where the bump in the curves and the peaked effect, which were so prominent at places on the east coast of England, originated from the internal winds.

Along the east coast from Aberdeen to the Wash the level was approximately 1·0 ft. high. In the Flemish bight the earlier lowering had risen considerably, and the level along the southern coast of Norway was 0·5 ft. low.

At 0900 hr. the rise was still progressing southwards into the Flemish bight, and eastwards and southwards into the German bight. The water gradients over the whole area were taking up a more southerly direction at right angles to the pressure gradients, and these were becoming uniform and increasing in intensity.

The greatest raising of level, nearly 2 ft., was between Blyth and the Wash.

By 1200 hr. the northerly winds in the northern, north-eastern and central parts of the North Sea were nearly at their maximum, and their effect was shown by the large water gradients which were generated off the coast down the western North Sea. There was a considerable piling up of water near the Wash, and at King's Lynn the level was 4·3 ft. high. Changes in level over the eastern North Sea were still comparatively slight.

The North Sea as a whole was now 0·7 ft. high, the highest level it reached during the storm, and *the greater part of the water which had entered was in the western half*.

At 1500 hr. the meteorological distribution had not changed very appreciably from 3 hr. earlier, and the water gradients other than near the Flemish bight continued to take up directions at right angles to the pressure gradients. The disturbance near the Wash had increased, and at King's Lynn the level was 5·5 ft. high. There was also a progression southwards into the Flemish bight.

At 1800 hr. the line of zero disturbance stretched from near Blyth to northern Denmark, just north of the Dogger Bank, and except in the Flemish bight the lines of equal disturbance were nearly parallel to this direction. Along the Frisian Islands the level was approximately 2·5 ft. high.

The gradients north of the line of zero disturbance were much smaller than those south of the line, even though the winds over the two areas were not very different.

Figure 7 shows the depths in the North Sea, and it will be noted that the comparatively shallow parts are in line with and south of the Dogger Bank; north of the bank the depths are much greater.

These depths, since the water gradient is expected to vary inversely as the depth, partly explain the smaller gradients to the north but they are scarcely sufficient.

We note that the level of the North Sea as a whole was falling, so conditions were not steady; also because of the unlimited supply of water which is available from the ocean, we must expect the gradients near the northern entrance normally to be smaller than the theoretical gradients in a steady state.

In the Flemish bight the gradients were west to east, and the water which earlier had been piled up near the Wash had travelled south and was producing a maximum disturbance of over 4 ft. in the Thames Estuary.

The fact that a piling up of water on the east coast from winds well to the north can travel southwards as in the present example is a matter of some importance in the prediction of storm effects in the Thames Estuary.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

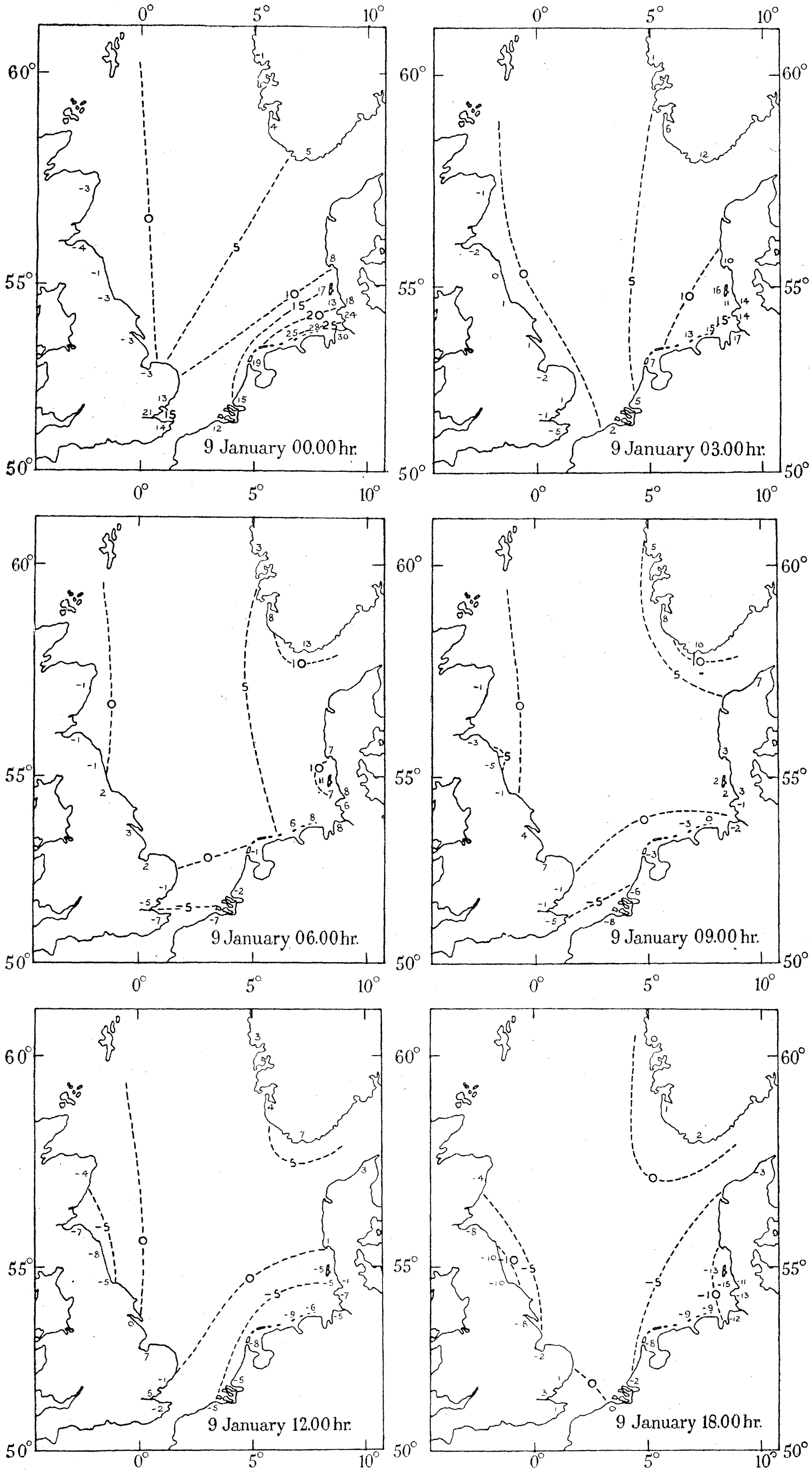

FIGURE 5*c*. Lines of equal disturbance, 9 January, 0000 hr. to 1800 hr.

In the remainder of the southern North Sea conditions approaching a steady state had probably been attained.

Figure 8 gives on the same chart the isobars and the lines of equal disturbance at this time, and it will be seen that the two sets of lines were approximately at right angles.

The free period of an oscillation in the North Sea in the direction with which we are now concerned is probably of the same order as the period of the present winds, so we must expect an appreciable lag of the order of 6 to 9 hr., in the response of the water to the wind. The weather maps, however, indicate that approximately steady conditions had prevailed over the North Sea during the previous 6 to 9 hr., so even though we may neglect the effect of an oscillatory approach to the steady state, a comparison of the winds and water gradients at 1800 hr. on the assumption that a steady state existed may be of some interest.

Using average values between Helder and the centre of the line of zero disturbance we have

$$\frac{\delta\zeta}{\delta L} = \frac{nk}{gh}\frac{\rho_a}{\rho}V^2,$$

$$\delta\zeta = 2\cdot5 \times 30\cdot5 \text{ cm.},$$

$$\delta L = 3\cdot2 \times 10^7 \text{ cm.},$$

$$h = 3\cdot5 \times 10^3 \text{ cm.},$$

$$\frac{\rho_a}{\rho} = 1\cdot2 \times 10^{-3},$$

$$\text{average gradient wind} = 2\cdot0 \times 10^3 \text{ cm./sec.},$$

$$\text{average surface wind} = 1\cdot33 \times 10^3 \text{ cm./sec.},$$

$$nk = \frac{2\cdot5 \times 30\cdot5 \times 981 \times 3\cdot5 \times 10^3}{1\cdot2 \times 10^{-3} \times 1\cdot33^2 \times 10^6 \times 3\cdot2 \times 10^7} = 0\cdot0039.$$

If

$$n = \tfrac{3}{2},$$

$$k = 0\cdot0026.$$

It seems unlikely in this particular case that the wind direction was very different from that of the isobars. The direction of the water gradient was only a few degrees to the right of the wind.

At 2100 hr. the lines of equal disturbance were still nearly parallel and crowded into the southern North Sea, though there had been a very definite anti-clockwise rotation of the lines in the previous 3 hr. In the Flemish bight the changes had been slight, but in the German bight the disturbance at Cuxhaven had increased to 3·0 ft. Over the western North Sea the winds were moderating and over the eastern half they were still strong.

At 0000 hr. on 9 January the disturbance, except in the German bight, was subsiding. The disturbed level at Southend had decreased from 4·0 to 2·1 ft. in 3 hr. Levels were rising along the Danish and Norwegian coasts, indicating a northwards transport of water up the eastern North Sea. In the German bight the levels were still the same as 3 hr. earlier, and it may be presumed that the water released from the Flemish bight was partly responsible for this stand, though also there were still strong northerly winds in the eastern North Sea.

At 0300 hr. on 9 January the winds were moderating over the whole area and continued to moderate until the end of the disturbance.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

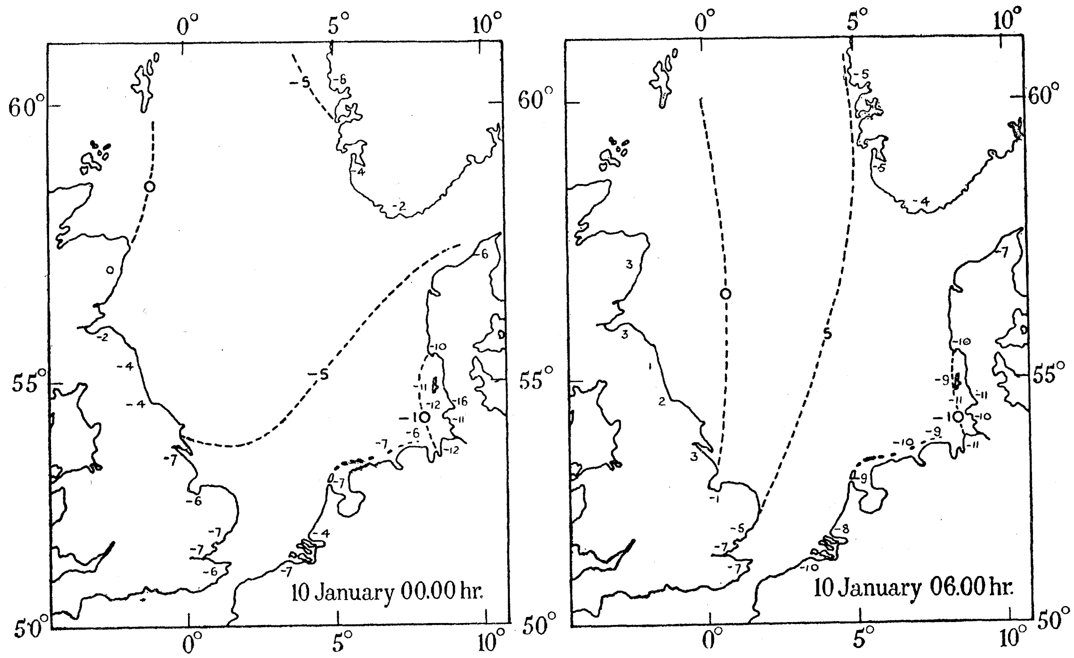

FIGURE 5*d*. Lines of equal disturbance, 10 January, 0000 hr. to 0600 hr.

(*c*) *Subsidence of the disturbance*

At 0300 hr. on 9 January, the line of zero disturbance was along the east coasts of Scotland and England.

In the Flemish bight levels were nearly normal, in the German bight the level had dropped 1·5 ft. in 3 hr. At Tregde in the extreme south of Norway the level was 1·2 ft. high, though the local winds were northerly and offshore, so there can be little doubt that as the levels fell in the southern North Sea, there was a northerly transport of water up the eastern half.

At 0600 hr. on 9 January, the level continued to fall in the Flemish and German bights and was still high along the Danish and Norwegian coasts. From the position of the line of zero disturbance there was also a partial reflexion of water on to the east coast of England and possibly into the Flemish bight.

The rise between Grimsby and King's Lynn at 0600 hr. and the further rise at 0900 hr. are definite.

The reflexion into the Thames Estuary is not so easily distinguished, but its existence may be seen from the oscillation in the curve of residuals.

The existence of what appears to be excessive damping in the curves at Southend has always been a matter of some concern, for it leads to an average value of eddy viscosity in the North Sea which is larger than that normally accepted.

The possibility that a reflexion from the German bight may reach Southend near the time when the lowest level is expected would explain the anomaly.

The later maps show the reflected rise slowly subsiding in the direction of the Norwegian coast and ultimately, at 0600 hr. on 10 January when the available data end, the lowest levels of the order of 1·0 ft. were in the German bight, and there were north-westerly surface gradients over the whole area.

The North Sea as a whole was one-third of a foot low and its level had only changed slightly in the preceding 12 hr.

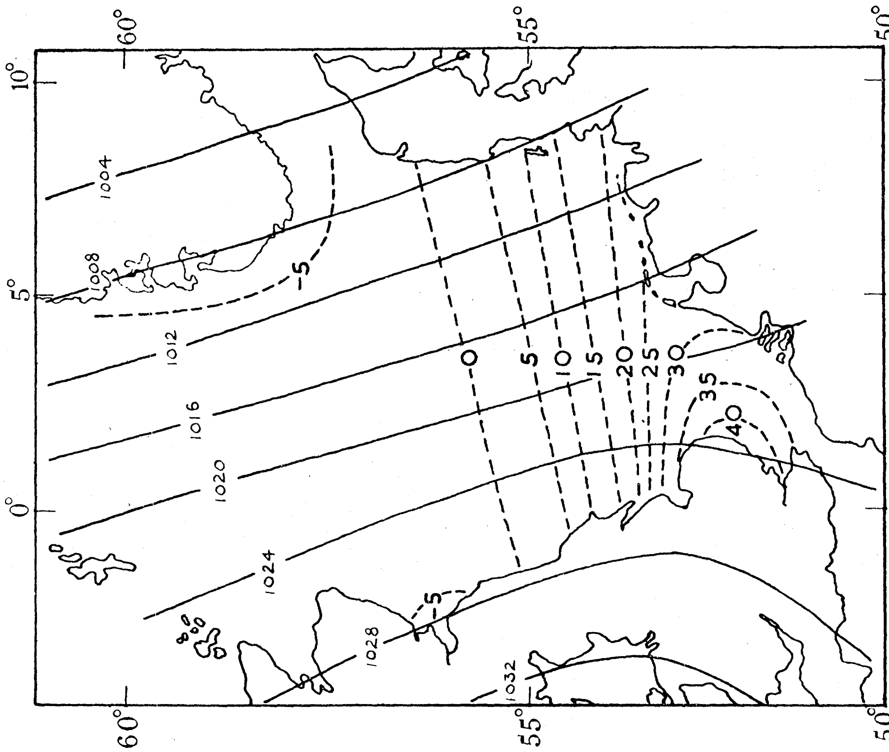

Figure 8. Co-disturbance lines and isobars at 1800 hr., 8 January 1949. —— isobars. - - - co-disturbance lines.

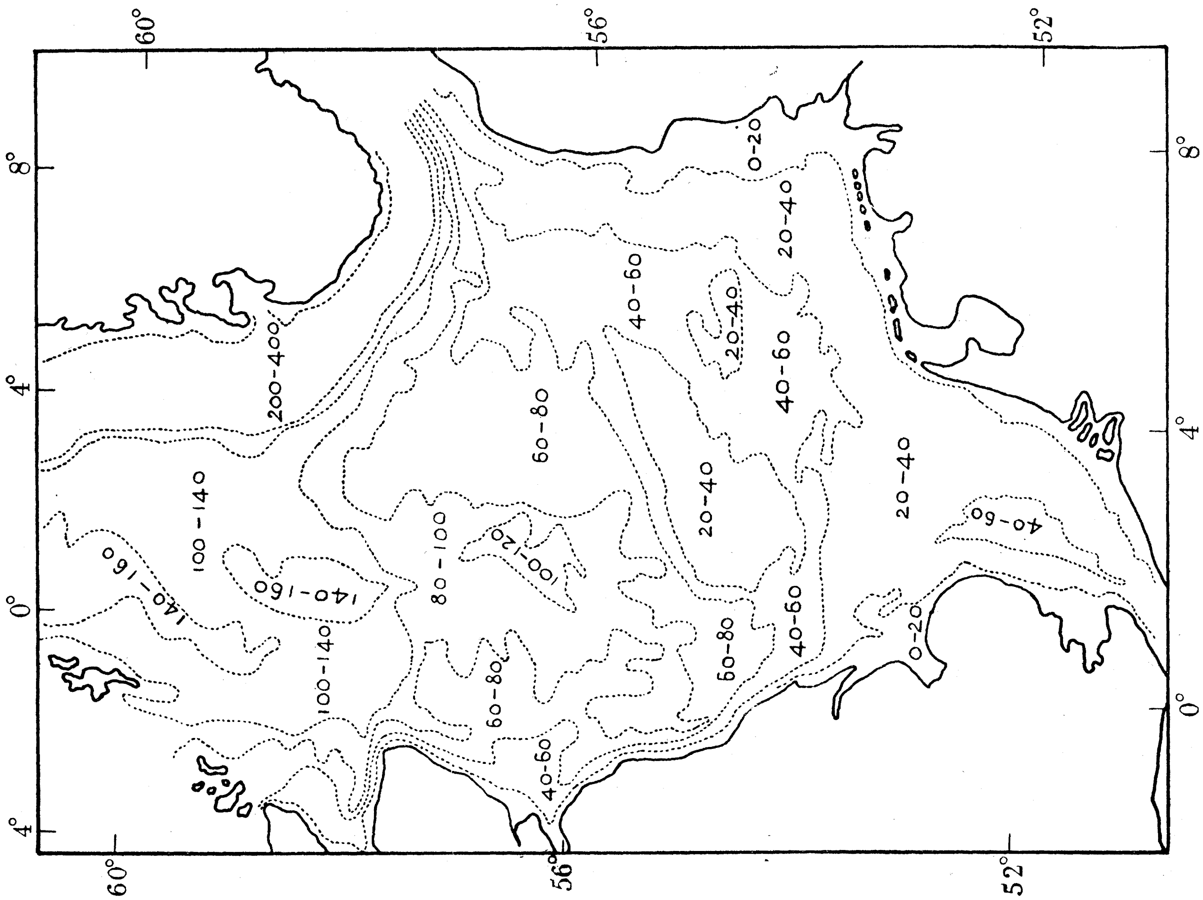

Figure 7. Depths in the North Sea in metres.

11. Prediction of the disturbance at Southend by the method previously established

In a paper by Corkan (1948) a numerical method has been developed for predicting the disturbance at Southend using the pressure gradients at points in the North Sea and the tidal disturbance observed at Dunbar 9 hr. earlier.

The Dunbar observations are necessary to allow for effects which originate outside the North Sea.

The prediction formula takes the form

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

where 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, 9 hr. earlier,

N and E are the north and east pressure gradients at a point A (figure 9) 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 9) between Scotland and Denmark, 6 hr. earlier.

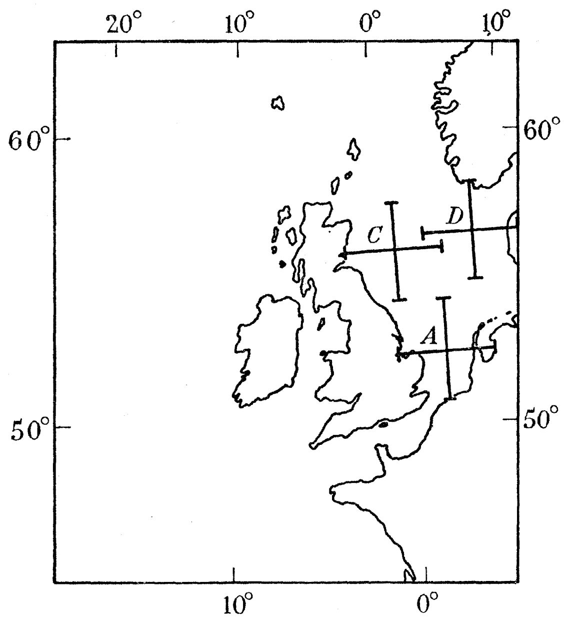

Figure 9. Positions of points A, C and D.

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

Theory indicated that the difference $(R_S - R_D)$ could be expressed most conveniently and yet very satisfactorily in the form chosen.

The constants and the time intervals were deduced numerically from the examination of a number of suitable storm surges, and the formula has been tested out on a large number of occasions.

One important assumption in the derivation of the formula was that storm effects produced by winds acting over the North Sea as a whole would be small at Dunbar as compared with at Southend. The general position of the nodal line during the present storm seems to uphold this assumption.

Table 6 gives for the period, 7 to 9 January 1949:

N, E, n and e, the pressure gradients defined as above,
$(R_S - R_D)$ the quantity predicted by application of the formula,
R_D defined as above,
B the barometric tide at Southend,
R'_S the predicted residuals at Southend including the barometric tide,
R''_S the observed residual at Southend before correction.

Figure 10 gives a comparison between R'_S and R''_S.

Table 6. Prediction of disturbance at Southend, 7 to 9 January 1949

		millibars				feet				
date	hours	N	E	n	e	(R_S-R_D)	R_D	B	R'_S (prediction)	R''_S (observed)
	18	.	.	−4	0	.	.	.	.	.
7 January	0	−5	−1	−3	−1	0·0	0·3	−0·6	−0·3	−0·5
	6	−7	3	−1	3	−0·2	0·8	−0·6	0·0	0·3
	12	−6	4	−8	7	−0·3	0·5	−0·4	−0·2	−0·5
	18	−9	7	−10	8	−0·7	−0·9	−0·3	−1·9	−2·1
8 January	0	−11	6	−6	2	−0·5	−1·5	−0·2	−2·2	−2·5
	6	−10	0	−4	−4	0·0	−0·5	−0·1	−0·6	−0·8
	9	−2	−5	0	−9	.	.	.	.	.
	12	−1	−6	0	−13	0·5	0·9	−0·2	1·2	1·2
	15	−3	−9	0	−13	1·2	1·1	−0·2	2·1	2·3
	18	0	−13	−4	−11	2·5	1·4	−0·3	3·6	3·8
	21	0	−11	−2	−8	2·3	1·2	−0·3	3·2	3·7
9 January	0	−1	−6	−3	−10	1·4	0·4	−0·3	1·5	1·8
	3	−3	−6	−2	−8	0·8	−0·5	−0·4	−0·1	−0·5
	6	−3	−4	−2	−8	1·1	−0·7	−0·4	0·0	−0·9
	9	−4	−6	−3	−7	0·7	−0·4	−0·4	−0·1	−0·5
	12	0	−4	−2	−4	0·7	−0·2	−0·4	0·1	0·1

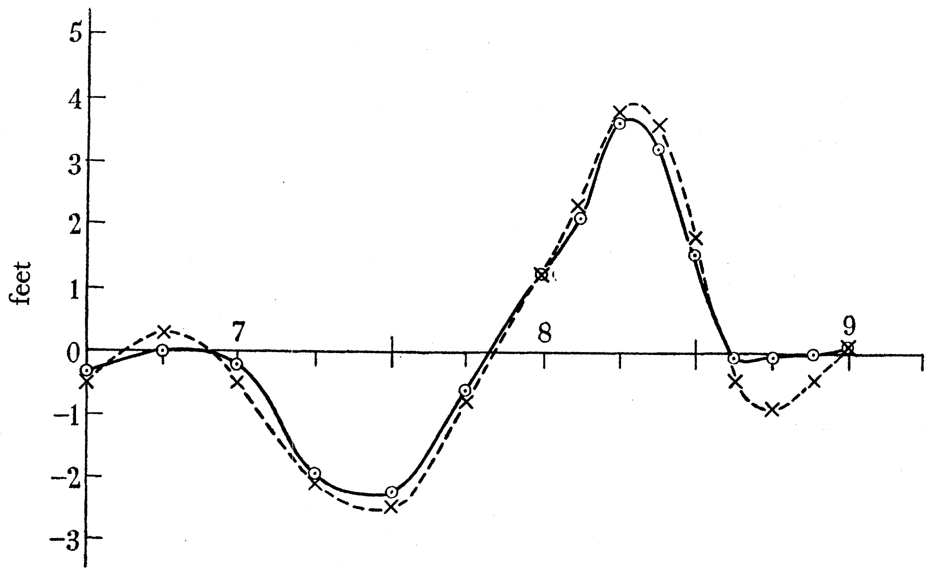

Figure 10. Observed and predicted disturbances at Southend.
—⊙— predicted. --×-- observed.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

12. Conclusion

We have seen that the sequence of changes in the co-disturbance lines and the associated pressure distribution in the course of a storm gives a good picture of the water movements inside the North Sea and the way in which these movements are produced, even though the exact positions of the co-disturbance lines may be at times a little uncertain.

The older methods of attack on the problem of storm surges have been either statistical, involving correlations between the residuals at a fixed station and the pressure and pressure gradients at chosen points, or numerical, and based on formulae derived from a simple mathematical solution like that by Proudman & Doodson (1924).

Both methods undoubtedly have their applications, but in the past they have been at a serious disadvantage through the absence of any clear picture of what happens. The probable positions of nodal lines, the important centres or areas of origin of disturbance, the resemblance of a disturbance under certain conditions to that in a non-rotating closed canal, the effect of the earth's rotation, have all been largely conjectural.

What we now require are investigations similar to the present one, of well-chosen examples of the various surge types. These types have been identified by Corkan (1948), who showed that practically all surges in the North Sea, both those in which the level is raised and those in which the level is lowered, can be expressed in terms of nine fundamental types, some of which are related in pairs. Three types produce a lowering of level and six types a raising of level, and each type has a distinctive meteorological distribution and produces a distinctive effect on sea-level.

When these have been completed, we shall be much better equipped to compare theory with observations, and to devise numerical methods which will provide satisfactory predictions of storm surges.

Acknowledgements

The writer would like to thank Dr Doodson for permission to undertake this investigation and for the facilities which he has provided and for his interest in the subject.

He would also like to thank the Director of the Meteorological Office who provided weather charts at three-hourly intervals.

Thanks are also tendered to the following who provided the tidal observations: Mr John Anderson, Harbour Engineer, Aberdeen; Mr G. L. Atkinson, General Manager and Secretary, Blyth Harbour Commission; Mr W. Mackenzie, Chief Engineer for Docks, Hull; Mr W. H. Haile, Engineer, River Trent Catchment Board; Mr T. A. Valentine, General Manager and Clerk, The King's Lynn Conservancy Board; Mr W. E. Doran, Chief Engineer, River Great Ouse Catchment Board; Commander D. V. Sutton, R.D., R.N.R., Harbour Master, Great Yarmouth Port and Haven Commissioners; Mr E. L. Snell, Engineer, Essex Rivers Catchment Board, Chelmsford; Director Ordnance Survey, Chessington, Surrey; River Superintendent and Chief Harbour Master, Port of London Authority; Harbour Master, Dover Harbour Board; Divisional Marine Manager and Harbour Master, Newhaven; Chief Engineer, Rykswaterstaat Directie Algemene Dienst, 's-Gravenhage; German Hydrographic Institute, Hamburg; Director, Det Danske Meteorologiske Institut, København; Hydrographer, Norges Sjøkartverk, Oslo; Director, Norges Geografiske Oppmaling, Oslo.

References

Association d'Océanographie Physique 1940 *Publication Scientifique*, no. 5.

Corkan, R. H. 1948 *Storm surges in the North Sea*, vols. 1 and 2. H.O. Misc. 15072, Washington, D.C. (Published by permission of the London County Council at whose request the investigation was undertaken.)

Doodson, A. T. 1929 *Geophys. Mem.* no. 47.

Doodson, A. T. & Warburg, H. D. 1936 *Admiralty tide tables*, Part III.

Egedal, J. 1934 Appendix to *Nautical meteorological annual*, København, 1933.

Egedal, J. 1946 Appendix to *Nautical meteorological annual*, København, 1945.

Ordnance Survey 1921 *The second geodetic levelling of England and Wales*, 1912–1921.

Proudman, J. & Doodson, A. T. 1924 *Proc. Lond. Math. Soc.* (2), **24**, 140.

Roberts, E. 1913 *Proc. Roy. Soc.* A, **88**, 230.

Schalkwijk, W. F. 1947 *Koninklijk Nederlandsch Meteorologisch Institutet De Bilt*, no. 125.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES