VERIFICATION OF A PROGRESSIVE WAVE IN THE SOUTHERN NORTH SEA

by Dr. G. Tomczak
German Hydrographic Institute, Hamburg

(Author's summary of an article published in the
Deutsche Hydrographische Zeitschrift, Hamburg, Jahrgang 11, Heft 3, 1958, p. 97)

On November 4, 1957, a disturbance of the tide that could not be explained as ordinary *wind effect* was observed on the coasts of the southern North Sea (Netherlands, German Bight). At some places the mean sea level was raised by several metres although the winds were offshore and reached gale force (Beaufort 8-10). Comparing the predicted tide at Cuxhaven with the observed levels, as is continually done by the storm surge warning service of the German Hydrographic Institute, one must conclude that the disturbance was caused by a progressive wave. In the North Sea such waves have been observed frequently. They especially influence the water levels of the coast of England, where they are called *external surges*. Therefore English authors have investigated them (Doodson, 1929, Corkan, 1948, Rossiter, 1954, Darbyshire, 1956), and methods have been developed for predicting their influence on the storm surges at the southern part of the coast between The Wash and the Thames estuary. The external surges originate in the Atlantic Ocean, where observations of the meteorological elements are rare and observations of the water level are missing. It is hoped that the observations of the IGY 1957/58, made with special tide gauges for long waves, can give us an explanation. Meanwhile the wave of November 4, 1957, may serve us as an example. This wave originated, as can be shown, in the southern portion of the North Sea, where sufficient observations of weather and sea conditions were available.

Tide gauge observations

Fig. 1 shows the tide gauge records of 4 stations on the Netherlands coast and of 10 stations on the coast of the German Bight for the period 4 and 5 November 1957. The records of 5 November correspond nearly to the tide predictions; the ones of 4 November are obviously disturbed by a piling up of water. Usually such deformations are produced by onshore

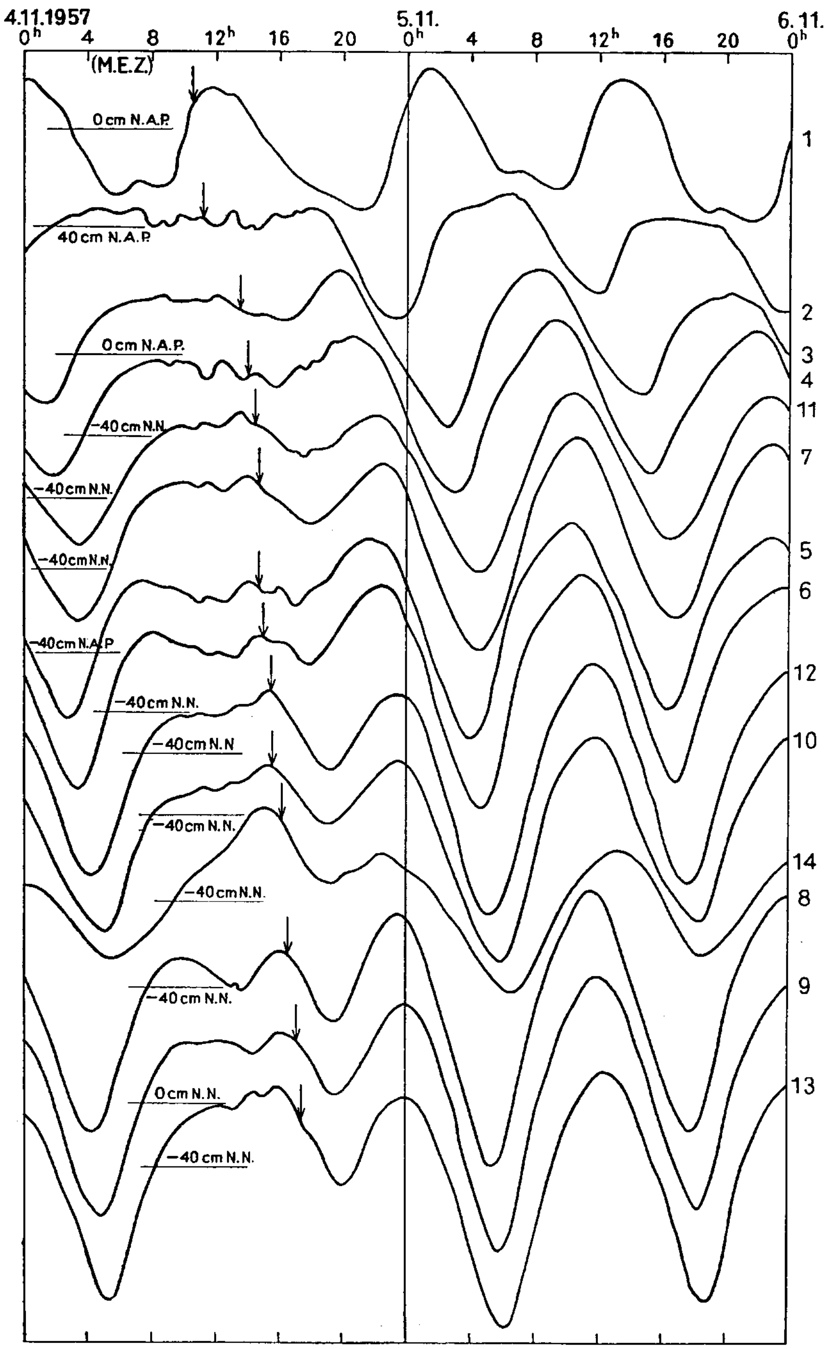

FIG. 1. — Observed water levels (4 to 5 November 1957)

1 = Hoek van Holland.	8 = Wilhelmshaven.
2 = Den Helder.	9 = Bremerhaven.
3 = Harlingen.	10 = Helgoland.
4 = Borkum.	11 = Cuxhaven.
5 = Delfzijl.	12 = Büsum.
6 = Emden.	13 = Husum.
7 = Roter Sand — Leuchtturm.	14 = List a.Sylt.

(Scale for all curves 1/52 approx.)

storms; in the winter time they occur frequently along the North Sea coast. But on 4 November a storm associated with offshore winds was dominant with directions from SSE to SSW and forces between 8 and 10 Beaufort; therefore the piling up must have been produced by a superposition of the tide and the wind effect with a wave of fairly large amplitude.

As shown by an analysis of the tide gauge records, the amplitudes reached 88 cm at Hoek van Holland as a minimum, and 282 cm at Wilhelmshaven as a maximum value. The method of analyzing the curves is described in detail by a former investigation (TOMCZAK, 1955*a*). For each station hourly values of the tide and the wind effect were computed, using for the latter the wind observations of the Netherlands and German lightvessels and the tables given by SCHALKWIJK (1947), POSTMA (1953) and VERPLOEGH and GROEN (1955) for the Netherlands stations, and by the storm surge warning service of the German Hydrographic Institute. The influence of the variable water depths during a tide interval, especially considerable in the shallow water area of the German coast, was borne in mind. The sum of the calculated time and the wind effect was compared hour by hour with the observed values of the water level. Residual curves thus obtained for each station have been plotted in fig. 2.

The peaks of the curves clearly indicate a progression from west to east in the southern North Sea. The similarity with the storm surge of 8 January 1949, as investigated by CORKAN (1950), is evident. CORKAN found that an external surge coming from the Atlantic Ocean was travelling around the North Sea.

In our case there was no external surge to be seen at the northern stations of the British Isles (Aberdeen, River Tyne Entrance), as can be concluded from the daily observations reported by teleprinter from the English warning service. Hence, taking arbitrarily the sea area off the East Anglian coast as origin area, we can compute the time of origin of the wave. Using sea charts we draw profiles between this coast (Great Yarmouth) and the 14 stations, at which the time of arrival of the wave is known. With the aid of Lagrange's formula $c = \sqrt{g \cdot h}$ (g = acceleration of gravity, h = water depth) we then calculate the travel times and from these the time of origin.

The result is given in table 1.

The mean time of origin is plausible with regard to the weather situation; it equals 07 22 h.

The weather situation

Three phases of the development of a cyclone travelling from south to north over the western part of the North Sea are given by fig. 3 *a-c*.

The cyclone is rapidly deepening until 10 00 h MET, having then a minimum pressure of 960 mb. A trough of low pressure extends from the centre in the middle of the North Sea to the Netherlands coast. During this phase the winds over the different areas of the North Sea are remarkable. Before the trough we find southerly, i.e. offshore winds at gale force. Behind the trough the wind directions are west to southwest, the velocities also reaching gale force. Hence the area of the trough represents a shearing

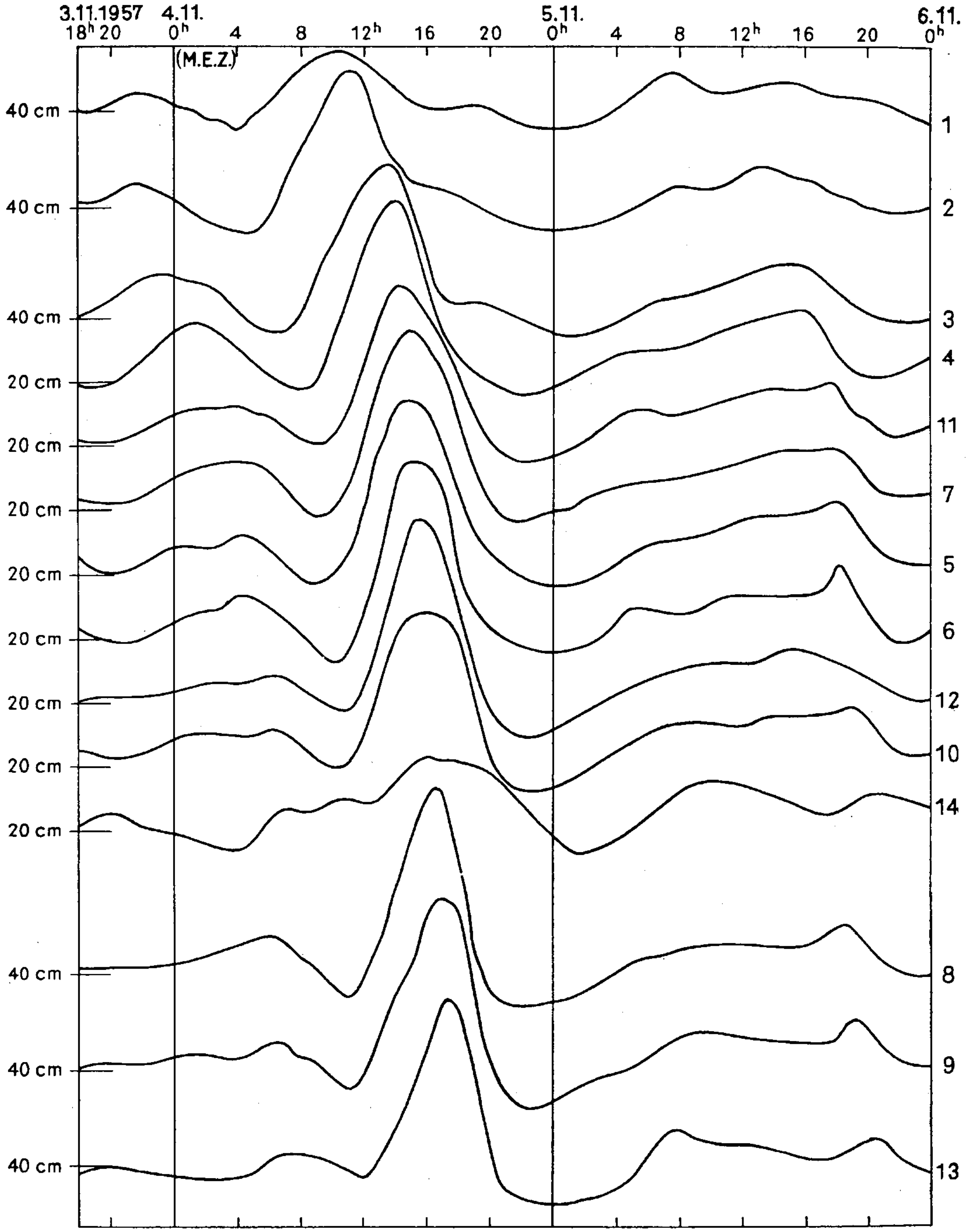

Fig. 2. — Disturbance of mean sea level, 4 to 5 November 1957.
(For the numbers see fig. 1; scale for all curves 1/40)

TABLE 1

Arrival times, travel times and time of origin of the progressive wave

Station	Distance from Gr. Yarm.	Observed arrival time	Computed travel time	Time of origin	Observed amplitude
	km	h min	min	h min	cm
Hoek van Holland	172	10 30	182	07 28	88
Den Helder	213	11 10	221	07 29	191
Harlingen	264	13 35	358	07 37	212
Borkum	356	14 00	413	07 07	237
Delfzijl	388	14 45	460	07 05	230
Emden	401	15 10	479	07 11	252
Roter Sand-Leuchtt.	458	14 50	464	07 06	235
Wilhelmshaven	499	16 35	534	07 41	282
Bremerhaven	509	17 10	562	07 48	240
Cuxhaven	508	15 45	512	07 13	195
Helgoland	452	14 25	439	07 06	202
Büsum	503	15 35	504	07 11	243
Husum	533	17 25	571	07 54	221
List a. Sylt	529	16 10	537	07 13	102
			Mean :	07 22	

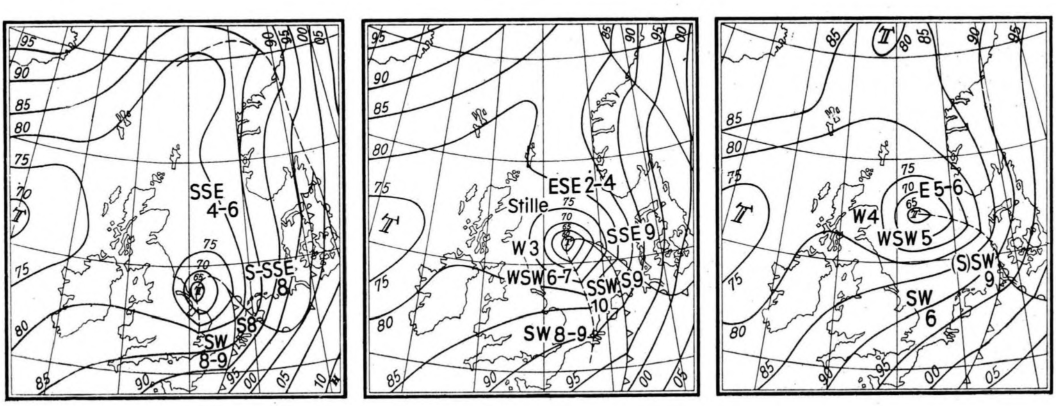

FIG. 3 *a-c*. — Weather situation over the North Sea.

a) Left : 07 h 00 MET
b) Centre : 10 h 00 MET
c) Right : 13 h 00 MET

zone, in which the winds are blowing against one another. Three hours earlier and three hours later the winds over the North Sea are directed more homogeneously : at 07 00 h the trough is still situated over the British Isles and the winds are blowing from southerly directions; at 13 00 h the winds have veered to west-southwest, and the trough has disappeared.

The second feature of the weather development is a very rapid change in air pressure over the area off the English coast. The fall in pressure before the trough over the British Isles reached values of 13 mb/3 hrs, the rise in pressure behind it even 18 mb/3 hrs and more.

Influence of pressure changes and winds on the origin of the wave

a) Influence of air pressure : according to statical law 1 mb of pressure change corresponds to about 1 cm change of sea level. In the case of rapid pressure changes the relation will certainly be more. This is verified by fig. 4.

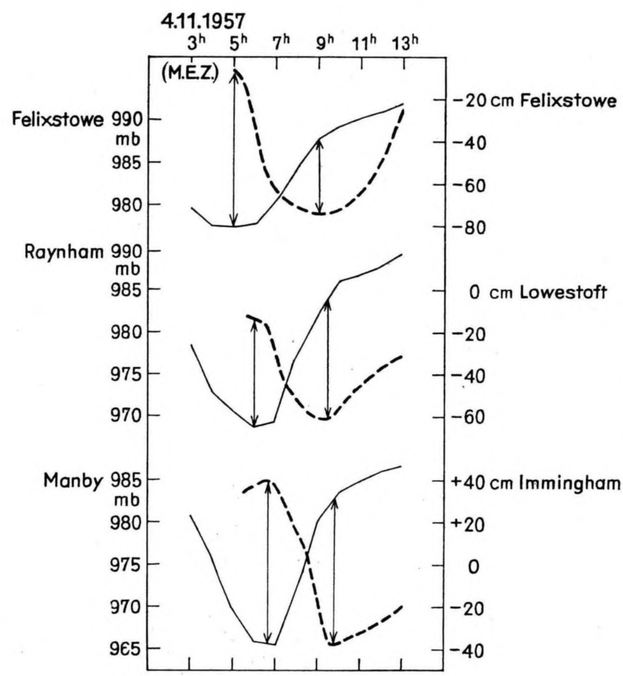

Fig. 4. — Changes of mean sea level (dashed lines) and air pressure (full lines).
Left : Air pressure stations
Right : Sea level stations

The dashed lines give the changes at Felixstowe, Lowestoft and Immingham, the full lines the air pressure changes at the left hand stations, situated in the vicinity of the coast stations. During the times indicated by arrows both curves run inversely, the amount of fall in sea level per mb rise in pressure being :

Felixstowe	6.5 cm/mb
Lowestoft	3.1 cm/mb
Immingham	5.1 cm/mb

Later on the sea level rises together with the rise in pressure. It is clear that the state of equilibrium must be restored after the pressure jump.

The unusually close relationship between pressure and sea-level changes may have been the cause of a progressive wave. But without the additional influence of the windfield it is not possible to interpret the observed amplitudes of 88 to 282 cm. Taking a relation of 5 to 6 cm/mb, one can compute an initial change of sea level of about 80 cm, because the rise in pressure was about 15 mb for the period 06 00 h to 10 00 h at the coast.

b) Influence of windfield : usually a trough of low pressure is characterized by the transition from falling to rising air pressure, by heavy and gusty winds, and possibly by meteorological events such as thunderstorms, hail, etc. Less frequently the winds suddenly veer. On 4 November, as we have seen from fig. 3*b*, the winds before and behind the trough were blowing against one another. Therefore the influence of the windfield consisted in the piling up of water masses in the shearing zone of the trough. According to the tables for the wind effect off the Netherlands coast, one can compute :

Area before the trough :	SSW 10 Bft =	60 cm
Area behind the trough :		
Northern part	WSW 7 Bft =	60 cm
Southern part	SW 8-9 Bft =	40 cm
	SSW 10 Bft =	

Hence the winds and air pressure together produced a piling up of water about 200 cm in height. This height was observed at Helgoland (202 cm), water depth there being 30 m, i.e. the same depth as in the area of origin in the southwestern portion of the North Sea.

In fig. 5 the observed amplitudes at the different stations are plotted against the water depths in the vicinity of the stations. Most of them correspond to the formula $A = A_0 \cdot \sqrt[4]{H_0/H}$, giving the relation between the amplitude of a long wave and the water depth. A_0 and H_0 have been taken as 200 cm and 30 m, the open-circle stations, which are situated behind

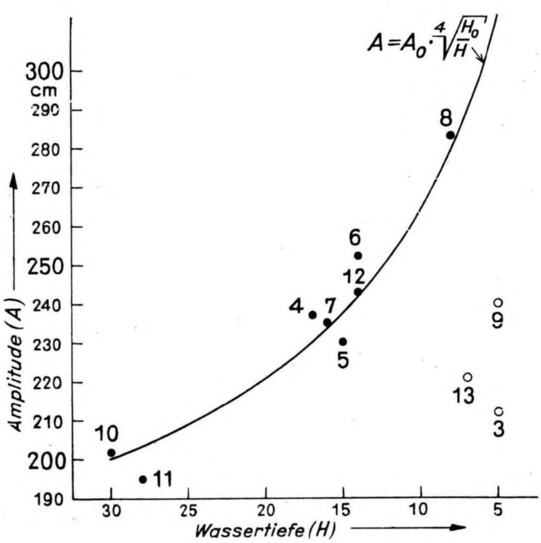

FIG. 5. — Relation between the amplitudes of the wave and the water depths.

large sand flat areas (Harlingen) or at the end of narrow channels (Husum, Bremerhaven), diminishing the energy of the wave.

In brief, one can evaluate the origin of the wave as follows : together with a rapidly deepening cyclone, a trough of low pressure entered the North Sea in the forenoon of 4 November. In the zone given by the moving trough, water was piled up by opposite windfields before and behind it. At the same time the piling up on the rear was increased by the influence of rapid pressure changes. The sea level, which was raised by a fall in pressure during the night, was suddenly lowered by an immediately following rapid rise in pressure. Both events led to a piling up of water in the area of the trough to a height of about 2 metres. Later on, at about 10 00 h to 11 00 h, the trough disappeared and the winds became homogeneous; the water masses could progress as a single wave similar to the solitary wave first investigated by Scott Russell.

Taking 10 30 h MET as time of origin, the progression of the wave is illustrated by fig. 6.

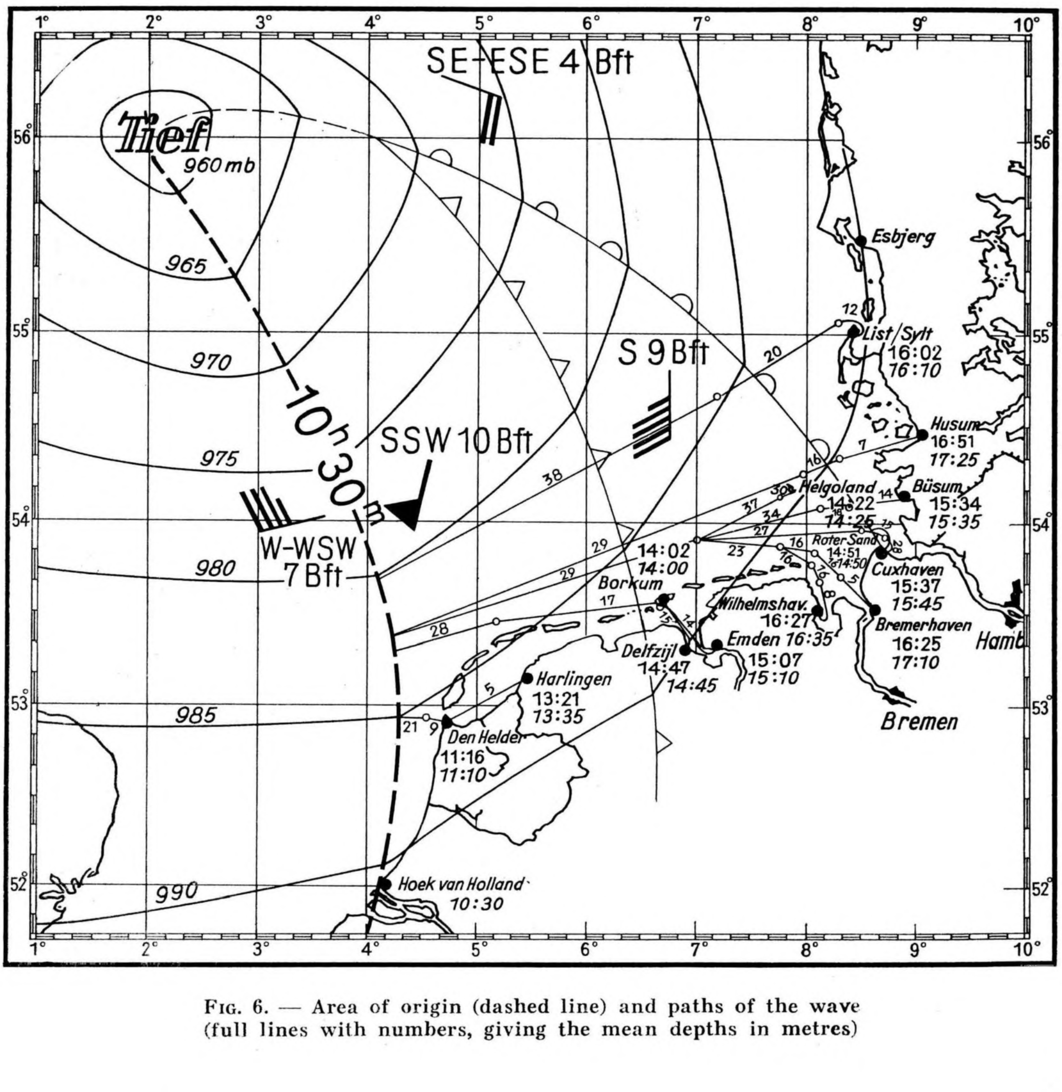

FIG. 6. — Area of origin (dashed line) and paths of the wave (full lines with numbers, giving the mean depths in metres)

The area of origin is given by the dashed line. At Hoek van Holland the maximum of the wave was observed at the same time. The amplitude there (88 cm) corresponds to the influence of the air pressure changes, winds having no influence in this southern area. For all other stations the profiles are drawn in with the mean depths used for the different sections. With the aid of these depths travel times were calculated by $c = \sqrt{g \cdot h}$. For each station two times are given : the upper number refers to the calculated time, the second number to the observed time of arrival of the wave. Table 2 summarizes these times.

TABLE 2

Comparison between the observed and the calculated times of arrival of the wave

	obs.	calc.
	h	h
Den Helder	11 10	11 16
Harlingen	13 35	13 21
Borkum	14 00	14 02
Delfzijl	14 45	14 47
Emden	15 10	15 07
Helgoland	14 25	14 22
Roter Sand-Ltt.	14 50	14 51
Wilhelmshaven	16 35	16 27
Bremerhaven	17 10	16 25
Cuxhaven	15 45	15 37
Büsum	15 35	15 34
Husum	17 25	16 51
List a. Sylt	16 10	16 02

The maximum of the wave, indicated by small arrows in fig. 1, arrived at all stations at or near low water. For this reason the water levels reached no dangerous heights. Nevertheless, in predicting storm surges it is necessary to take troughs into account. In former investigations the author has supplied two examples (TOMCZAK, 1950 and 1955*b*); the case of 4 November 1957 is new. In the southern North Sea it is even possible that external surges are combined with the progression of a trough, as was the case on 13 December 1956. Fig. 7 shows the shifting trough on that day. With the arrival of the trough at Cuxhaven the maximum of a wave 85 cm in height could be observed. During a conference on storm surges at the National Institute of Oceanography in Wormley, England, Cdr. C.T. Suthons from the British warning service submitted the same case of 13 December as a good example of an external surge. This opinion is endorsed by a short pamphlet by J. and M. DARBYSHIRE (1958). Referring to the case of 12 to

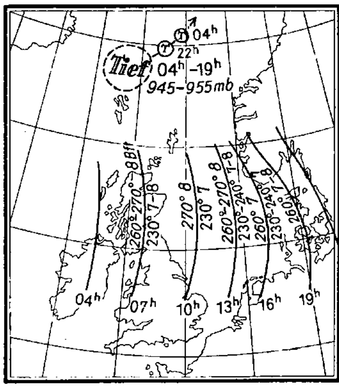

Fig. 7

14 December 1956 the authors say : « Some of the activity in this case could have been due to a storm which was *situated to the northwest of Scotland* ».

REFERENCES

Corkan, R., 1948 : Storm surges in the North Sea. *H.O. Misc. 15072.*

Corkan, R. H., 1950 : The levels in the North Sea associated with the storm disturbance of 8 January 1949. *Philos. Trans. Roy. Soc.*, London, Ser. A, Math. and Physic. Sci. *242,* No. 853.

Darbyshire, J. and M., 1956 : Storm surges in the North Sea during the winter 1953-54. *Proc. Roy. Soc.*, London, A, *235,* 260.

Darbyshire, J. and M., 1958 : Storm surges in the North Sea. *Dt. Hydrogr. Z., 11,* 124.

Doodson, A. T., 1929 : Report on Thames floods. *Geophys. Mem.* No. 47, Meteorol. Office, London.

Postma, K.R., 1953 : Storm- en stormvloedprognose. *De Ingenieur 65,* Nr. 32.

Rossiter, J. R., 1954 : The North Sea storm surge of 31 January and 1 February 1953. *Philos. Trans. Roy. Soc.*, London, Ser. A, Math. and Physic. Sci. *246,* No. 915.

Schalkwijk, W. F., 1947 : A contribution to the study of storm surges on the Dutch coast. *Kon Nederl. Meteorol. Inst. De Bilt* No. 125, Meded. en Merh. Ser. B, Deel 1, No. 7.

Tomczak, G., 1950 : Die Sturmfluten vom 9. und 10. Februar 1949 an der deutschen Nordseeküste. *Dt. Hydrogr. Z., 3,* 227.

Tomczak, G, 1955*a* : Die Sturmfluten vom 20. bis 24. Dezember 1954 bei Cuxhaven. *Dt. Hydrogr. Z., 8,* 145.

Tomczak, G., 1955*b* : Was lehrt uns dei Holland-Sturmflut 1953. *Die Küste 3,* 78.

Verploegh, G., en Groen, P., 1955 : De uitwerking van de wind over de Groningse Waddenzee op de hoogwaterstanden van Delfzijl. *Kon. Nederl. Meteorol. Inst. De Bilt, Wetensch. Rapp. W.R.* 55-009 (IV-010).