The North Sea Storm Surge of February 1, 1953.

Its Origin and Development.

By Asger Lundbak.

While in former times eclipses of sun and moon were considered sinister omens, there were hardly many, who formed any conceptions of that kind, when late in the evening of Jan. 29, 1953, a dark brim appeared on the left edge of the full moon, preceding a total eclipse of the moon that reached its climax, when at 11,45 p. m. GMT the moon was standing in the centre of the shadow of the Earth. Nor would an atm. depression, which at the same time was situated south of Iceland in about 60° northern latitude and 20° western longitude, indicate that anything alarming was developing according to general experience. The depression was not very deep, barely a little less than 1000 millibars, and the common thing is that such a depression in the course of a few days passes over South Scandinavia and for instance in Denmark causes westerly winds.

Nobody could at that time imagine that one of the largest inundation catastrophies in history — in connection with the two abovementioned phenomena — would be a tragic fact in north-west Europe just a few days later, although it was known that a depression of the said kind might be the germ of a violent storm, and that particularly strong tides used to occur on the coasts of the North Sea a couple of days after full and new moon.

It was further known that a windswept sea could bring disastrous surprises at high water. Best known in Denmark is undoubtedly the storm surge of Nov. 12—14, 1872, when considerable territories around the western portion of the Baltic, including large stretches of the Danish island Lolland, were inundated with attendant loss of lives. Another storm surge, which has, however, got a legendary character, is the storm surge of October 10 and 11, 1634, when 6000 lives were lost and the rich German island Nordstrand was cut through by the roaring sea and divided into two smaller islands, later named Pellworm and Nordstrand, with a broad water between.

Catastrophies occurring with intervals of one or more centuries easily get the impress of unreality. Furthermore long stretches of coast, which were earlier exposed to attacks from the sea, have gradually become protected by dikes of varying heights; these are f. inst. 5 to 7 meters along many North Sea coasts.

Nevertheless, there is reason to stress that the three North Sea states England, Holland and Germany — considering the importance of extraordinary sea-level variations, for instance as regards navigation conditions of various harbours — in this century have established and used various kinds of warning service; in Holland they started to predict particularly high tides already in 1916. Besides, the Tidal Institute at Liverpool has made various sea-level variations the subject of especially thorough investigations, f. inst. "external surges", which will be dealt with in the following.

Two main causes of especially high or especially low waters have already been stated, namely the astronomical tide and the meteorological conditions. As to these two causes the astronomical tide is very regular and originates mainly in the oceans outside the North Sea area, while the latter cause is very irregular, and its influence on the sea-level in the North Sea appears mainly in the North Sea area itself.

Placed between these two causes are the socalled "external surges" in the North Sea; they are most probably of a meteorological origin and created outside the North Sea area. As far as we know, they are created when an eastward travelling depression passes over the Wyville Thomson-ridge north-west of Scotland. The general thing to happen is that the sea surface rises — 1 cm per mb decrease of the air pressure — in sea areas with low air pressure; such a rise of the sea surface can be considered a moving wave carried in a definite direction by the depression; this wave will furthermore — almost like a swell passing over a bar — be steeper and consequently higher by decreasing depth, f. inst. on account of a ridge.

The astronomical tide is composed of various oscillations called harmonic constituents; these travel independent of each other in the North Sea. The dominating constituent is the semi-diurnal M_2-tide; in most places by the English and the Scottish east coasts the amplitude of this constituent is 1—2 m; yet values of 2½ m occur in the Thames Estuary and in the Wash Bay, situated somewhat farther to the north. In the south-eastern part of the North Sea the M_2-amplitude increases from ¼ m at Thyborön (situated in the north-western part of Denmark) and ⅔ m at Esbjerg to 1½ m in the inmost part of the Bight of Heligoland, whereupon it decreases somewhat, namely to ⅔ m by the north-western corner of Holland. Farther south the amplitude increases again, namely to a little more than 1 m by the Dutch island group Zeeland, to a little less than 2 m by the Belgian coast and to 2½ m by Calais (Adm. Tide Tables, II, 1938).

The next most important harmonic constituent in the North Sea is the S_2-tide, the amplitude of which in the North Sea amounts to ⅓—¼ of the M_2-amplitude. The diurnal constituents, the K_1- and the O_1-tides, which are important in many places, have mainly amplitudes between 5 and 15 cm in the North Sea, and as a rule they do not contribute essentially to extreme tides. The periods of the M_2-, S_2-, K_1 and O_1-tides are respectively 12.42, 12.00, 23.93 and 25.82 hours.

Other harmonic constituents have still lesser influence. The decisive fact concerning the storm surge of Febr. 1, 1953, is already mentioned, namely the fact that the M_2- and the S_2-tides in the North Sea co-operate and cause spring tide two days and nights after full and new moon.

If from a certain water level we first subtract the astronomical tide and secondly subtract the part that is due to the difference between the local air pressure and the normal air pressure of the place, there remains a residual, which mainly originates from wind conditions, both in the place itself and in the neighbouring sea areas.

A very thorough analysis of the meteorological causes of the storm surge, which occurred on January 31 and February 1, 1953, has been made by J. R. Rossiter (1954), and from his work many figures in the following have been extracted. It appears from Rossiter's work, what a decisive role the winds in the North Sea area have played just before and during the storm surge dealt with, and Rossiter concludes, that no "external surge" contributed to the surge mentioned.

In a statement from an eye-witness on Smith's Knoll lightship, situated in the south-western part of the North Sea 35—40 km east of Great Yarmouth, it is said (A. L. Lawford, 1954, p. 69—70),

"— — — it was like hell let loose, but I am thankful that the cable and anchor held — — — it is the first time I have had to wipe up salt water in my cabin; the seas were so high and often that they found their way down the ventilators, and these are at least 20 feet above the sea-level — — — in my thirty-four years of life in lightships, I think this gale was the worst of all — — —"

The 24 hour-means of wind at 8 lightships, which were distributed in the south-western part of the North Sea, accordingly reached recordheights in the course of the two days of Jan. 31 and Feb. 1. The highest average for 24 hours was recorded on the 1st of February on the Goeree lightship, whose position is south-east of the above-mentioned lightship and just off Zeeland; It was 31 m/sec, i.e. strength 12 referring to the Beaufort scale, as strength 12 begins at 29 m/sec (A. L. Lawford, 1954). Yet, essentially higher speeds of wind occurred these two days during short periods in several places, which will be mentioned in the following.

These extreme winds were connected with the atm. depression already mentioned; this depression which came from a position south of Iceland, reached a position just north of Scotland at midnight between Jan. 30 and 31, and it was then considerably deepened, namely to 970 mb. It was further deepened — to about 965 mb — when it moved rapidly into the North Sea, and it gradually took a direction to south-east instead of east, as one should have expected.

Thus it was not the question of any extraordinarily deep depression. Neither can a high pressure of 1030—1035 mb. which in the course of the afternoon of January 31 and the following day travelled from the area west and north-west of Ireland and passed over Scotland and the more northerly island groups, be said to have been unusually high. As a comparison serves that the extreme low and high pressures, which have been recorded in Denmark in this century, are respectively 708 and 797 mm Hg corresponding to 944 and 1063 mb.

However, there was reason to be alarmed about the great speed of the depression in a south-easterly direction, reaching as far as Heligoland in the course of Jan. 31, and even without any essential filling. Something similar to that happened during the night between Jan. 6 and 7, 1928, when it was spring tide too, and when the water in the estuary of the Thames rose to 1½ m above the predicted spring tide level, causing inundation and loss of lives (K. F. Bowden, 1953).

Also the velocity of wind, prevailing on the western side of the depression in the morning of Jan. 31, 1953, must be regarded as very alarming. An electric anemometer placed shortly before on a hill in Orkney thus recorded winds of 45 m/sec with 55—60 m/sec in the gusts at about 8 o'clock that morning (R. F. M. Hay & J. Laing, 1954).

Undoubtedly winds of the same strengths roared during the following hours over great parts of the western and southern North Sea; these have only been measured or estimated in a few places, but they may be calculated approximately on the basis of the horizontal gradient of the atm. pressure; this gradient reached values of about 0.15 mb per km, which must be considered exceptional for north-west Europe. The corresponding socalled geostrophic winds, which are normally stronger than the winds just above the sea surface, were 60 m/sec at about 6 p. m. on Saturday night in a belt 100—150 miles wide. A slight decrease of wind speed seems to have taken place, whereupon a new culmination may have occurred off the Dutch coast on Sunday morning. Finally Sunday night the wind moderated considerably, and so the most exceptional by the situation was not only the extremely strong winds, but also the unusual duration of these winds. The predominant direction of wind was mainly NNW.

The primary effect of the gale was that huge volumes of water were dragged into the North Sea from the north, and in the course of Jan. 31 they were driven southwards along the English coast. By Aberdeen in Scotland the residual due to the wind reached a peak of little more than ½ m at 4—5 p. m. GMT on Jan. 31. By Grimsby the residual reached its peak at about 10 p. m. on the same day, and the height was a little more than 2 m. Farther to the south, in the Wash and along the coast of Norfolk, the peak of the residual was maximal for the English coast and reached 3 m, while the peak of the residual in the estuary of the Thames, where it occurred just about midnight, was 2—2½ m (cf. Fig. 1). The characteristic feature here was, however, the very steep rise — at London Bridge there was no rise of sea-level due to the wind at 9 p. m., and on account of the astronomical tide the sea-level was below mean sea-level till 10.45 p. m. GMT — and the unfortunate coincidence that the predicted astronomical high water (which was 30 % above the M_2-high water on account of spring tide) occurred a couple of hours later, before the residual had decreased essentially, and caused a total high water of 5 m, in a few places maybe even a little more. Concerning the air pressure it may be added that it was about its normal value, when the peaks of the residual occurred at the localities mentioned, and therefore it did not contribute particularly to the disturbances.

At the time of the flooding in the Thames Estuary the wind direction was here NNW, which may surprise somewhat, as such a wind is transverse to the funnelformed estuary, rather blowing offshore than inshore. That a considerable disturbance could occur after all, is due to the influence of the rotation of the Earth. This influence is of such nature that a wind-generated movement in the sea surface of the free and deep ocean on the northern hemisphere will be turned 45° to the right (clockwise) compared to the direction of wind. In deeper water the turn will be still larger, so that a current in a depth of 50 m, when it is indirectly wind-generated through the layers above, often runs at right angles to the wind: for the same reason the wind direction itself is turned almost 90° to the right in relation to the direction of the causing gradient of pressure. These facts do not only explain that a considerable residual must have occurred in the Thames Estuary, but also that the southward moving water in the North Sea in the afternoon and in the evening of Jan. 31 was literally flung towards the English coast. Furthermore, it is hereby explained that the sea-level by the coast of Norway was unusually low in the evening of Jan. 31; between Ålesund and Bergen it was 1 m below mean sea-level, and the local wind was then north-easterly.

A residual of about 2—2½ m in the Thames Estuary does not occur as seldom as one might think. One af the highest storm surges recorded in the Thames Estuary occurred on Jan. 1, 1922 (K. F. Bowden, 1953); its height was 3½ m, but it got no serious consequences here, as it occurred two hours after the time of ebb and had decayed considerably before the following flood. At the same time the record for high water was touched in several places along the Danish coasts. Thus the sea-level in the southern part of Kattegat was 1½ m, at Nyköbing Sj. even 2.2 m above mean sea-level (J. Egedal, 1949); simultaneously there was a severe gale from north-north-west.

Leaving the storm surge of Jan. 31 and Feb. 1, 1953, for a while a few remarks about the stress of wind shall be added. The stress of the wind was one of the things which were made the subject of investigation after the establishment of meteorological institutes in various countries after the middle of the 19th century. In the

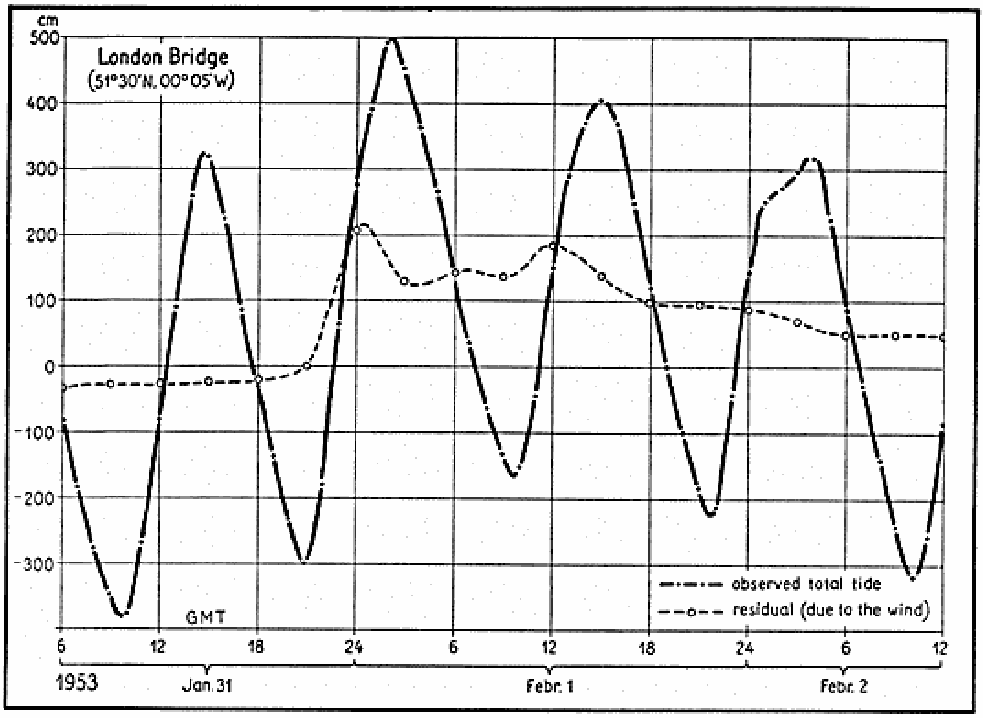

Fig. 1. The tide at London Bridge during the storm surge. The thin curve indicates the part of the tide, which is due to the wind solely (the effect of the air pressure is insignificant here). Beside subtraction of the astronomical tide some smoothing is also undertaken to obtain the thin curve.

seventies rather thorough theories were elaborated by the German meteorologist H. Lentz and the Danish meteorologist A. Colding. A formula elaborated by the latter (1881) was thus able to explain the sea-level conditions during the storm surge of Nov. 12—14, 1872, rather accurately. After transformation into modern units of measurement this formula looks as follows:

$$h = 0.049 \frac{L}{H} V^2 \cos^2 u,$$

h being the residual in cm (actually the difference between the heights of sea-level on opposite coasts), H and L respectively the depth in m and the extension in km of the sea area which the wind blows above, V the velocity of the wind in m/sec and u the angle between the direction of the sea area in question and the direction of the wind. It appears from this formula that besides velocity of wind, direction of wind and extension of the sea area, the depth of the sea area is a decisive factor too, as the residual is inversely proportional to the depth; this is partially owing to the fact that backgoing currents near the bottom are stronger when the depth is large. Colding's formula says nothing about the influence of the

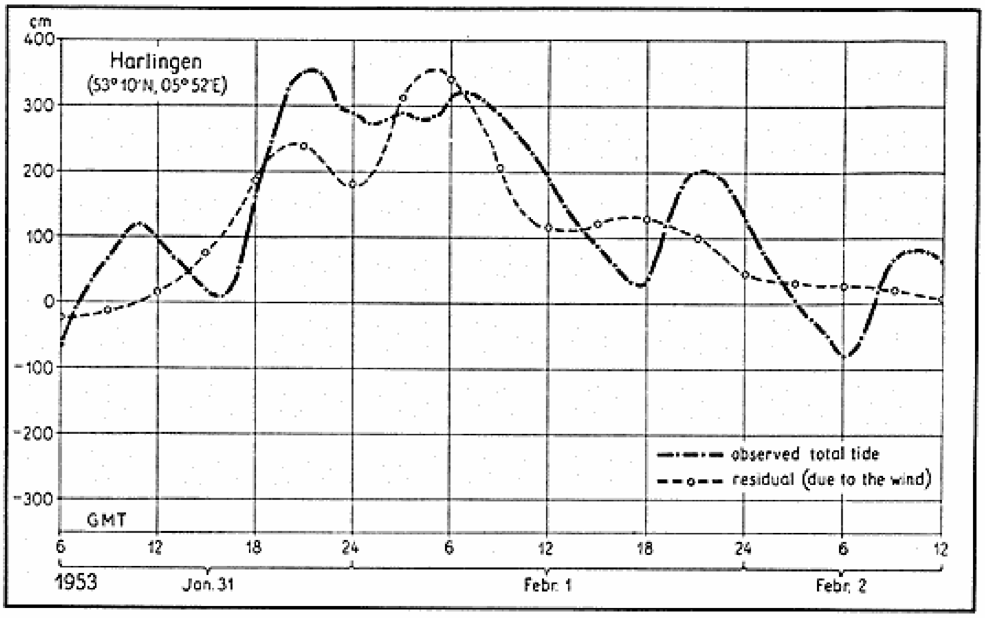

Fig. 2. The tide at Harlingen. The thin curve has been obtained by subtracting both astronomical tide and effect of air pressure from the recorded curve.

Earth rotation. This influence may be taken into consideration in the value of the angle u; however, the reflections, which are already made on this matter, cannot be transferred freely to a closed and rather shallow sea area as the Baltic.

More recent investigations of wind-stress have in principle confirmed Colding's formula; yet, the constant 0.049 appears to be somewhat too large; it should be fixed at 0.035—0.040 (B. Hellström, 1941; J. Egedal, 1949; J. R. Rossiter, 1954). The reason why Colding obtained so good conformity with observed tide-values, after all, may be due to a possible overestimation of these tide-values or to the fact that in the Baltic — as in any other closed sea area — there may arise socalled seiches, so that high water and low water slowly supersede each other in the two terminating parts of the Baltic. Finally, the power of V in Colding's formula is a little too high according to more recent investigations; the correct power in most cases is 1.7—1.8.

It may be stressed, that the best value of the wind speed to be used is the one, which exists in the sea area itself some hours before the hour on which the computed height of water is centered. This wind is not always known with sufficient accuracy, but can be computed approximately on the basis of the gradients of pressure. From such considerations R. H. Corkan brought forward a formula in the years before 1950 (R. H. Corkan, 1948); this formula

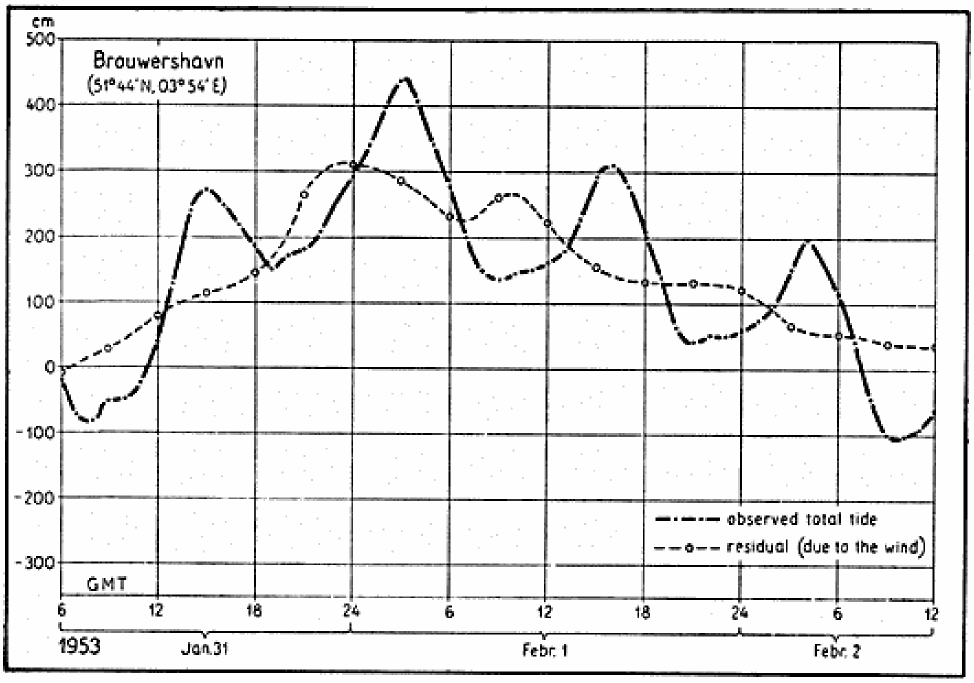

Fig. 3. The tide at Brouwershavn. It is seen that the peak of the total tide was almost 1 m higher than the peak at Harlingen, and it occurred about 6 hours later.

is rather different from Colding's formula. The residual at Southend in the Thames Estuary can be computed on the basis of Corkan's formula. For this purpose one must apply the observed residual at Dunbar (east of Edinburgh) in Scotland 9 hours before the hour for the residual at Southend and also the gradients of pressure at three chosen points in the North Sea, i. e. two points in the northern part and one point in the southern and narrow part; while the hour for the two gradients shall be six hours before the hour for the residual at Southend, the last-mentioned gradient shall be taken at the exact hour for the residual at Southend.

With an almost surprising accuracy it has been possible to predict the height of the sea-level in the Thames Estuary by means of the above-mentioned formula. Also the disastrous sea-level on the night before Feb. 1, 1953, could be predicted fairly accurate by the formula; yet the conformity does not seem to be quite as good as on previous occasions, as the predicted heights were mainly ½ m higher than the real ones. The cause of this seems to be that some of the pent-up water was forced out through the Channel shortly after the residual had reached its peak, still before the stress of the wind had moderated essentially.

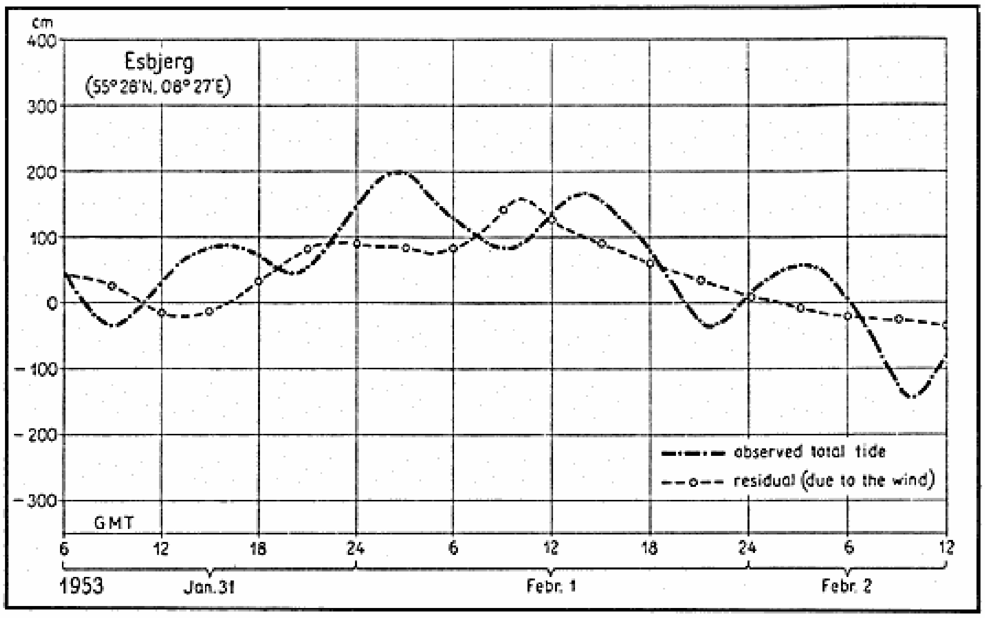

Fig. 4. The tide at Esbjerg. It appears that the peak of the total tide here was 2 m above mean sea level, but such a value is not exceptional at Esbjerg.

The role of the Channel as a kind of safety-valve for pent-up water in the southern part of the North Sea is unquestionable, a fact which manifested itself during and after this storm surge. While the average water-movement in the Channel is normally in-going (towards NE), it was SW-going from noon Jan. 31, and on Feb. 1 it was — with a speed sometimes exceeding 1 m/sec, averaged across the Channel — eight times stronger than the normal inflow, and not until at week after this storm surge did the water movement in the Channel get normal again. The total excess of water in the North Sea during the storm surge is by Rossiter (1954) calculated to 430 milliards of tons or 420 km^3, corresponding to a height of water of 65 cm above mean sea-level for the entire North Sea area.

The role of the Channel in the days immediately before the storm surge was unfortunately of the opposite character, as the in-going water movement was stronger than usual on account of winds from the right angle between south and west; the average water movement of Jan. 30 was f. inst. three times the usual (J. N. Carruthers and A. L. Lawford, 1954). Partly due to this and partly due to westerly winds over the Channel early in the morning of Jan. 31 some of the pent-up water was driven towards the centre of the south-western portion of the North Sea and later thrown towards the Dutch coast. Before considering the conditions here, a few remarks about the progress of the astr. tide in the North Sea shall be added.

Just like the disturbance mentioned before, the M_2-tide travels southwards along the English east coast, and consequently it may be of interest to compare the speed of movement in the two cases. The speed proves to have been almost equal for the disturbance and the M_2-tide along the northernmost ⅔ of the coast, while the speed of the disturbance along the remaining part of the coast has been almost three times larger than that of the M_2-tide; the M_2-tide has literally been overtaken by the disturbance off the coast of Suffolk between Great Yarmouth and Harwich. The rather slow movement of the M_2-tide along the southern part of the English east coast is due to the fact that it does not move as a free wave here; because of interference with a north-going M_2-tide from the Channel an anticlockwise-rotating amphidromie os built with its centre on 52½—53° northern latitude midway between the English and the Dutch coasts. A similar anticlockwise amphidromie exists NNE of the said position off the central part of the west coast of Jutland.

As amphidromies are caused by interfering tidal waves, one must conclude that the disturbance of Jan. 31 had no amphidromic nature in its first stage, as a corresponding and reverse wave did not exist. However, the right side of the disturbance struck the coast of Norfolk shortly before midnight, as already mentioned, and at the same time the left side of the disturbance — strengthened by the said inflowing water from the Channel — struck the Dutch coast. In both cases reflection was possible, so that back-going, or transverse disturbances could arise and to some extent create interferences in the nature of amphidromies.

The fact that the disturbances by the coasts of south-east England, Holland, north-west Germany and west Jutland in most cases had two peaks indicates interferences of this kind, although fluctuations in the weather conditions may have played a part. However, the disturbances by the coasts of Scotland, north-east England and Belgium had only one marked maximum. By the coast of Belgium, where the peak of the disturbance occurred simultaneously with the first and highest peak in the Thames Estuary, being almost of the same height, there may have been an effect of the said reflection during the rather slow decrease of the disturbance; but the slow decrease itself, which veiled this possible effect, was mainly due to the already mentioned outflow of water through the Channel.

Another fact has probably contributed to two or more peaks along the Dutch coast. From the formulas for wind-stress (cf. A. Colding, 1881) it appears that shallow water promotes the height of the disturbance.

That is to say that the residual on the coast, by the same velocity of wind, must be less at the time of flood in the sea area off the coast than at the time of ebb. For instance the predicted time of flood at Harlingen in the north-western corner of Holland was 10.33 p. m. GMT on Jan. 31 (Adm. Tide Tables for the year 1953), and so the residual should be comparatively small at this hour and during the following hours.

As a matter of fact it appears from the material collected by Rossiter (1954), that the residual (after subtraction of the astr. tide and the local effect of the air pressure) had a minimum at Harlingen just about midnight GMT (cf. Fig. 2); the residual was at that time 180 cm, being 240 cm three hours before and 310 cm three hours later. On the basis of the material available the highest residual at all along the North Sea coast occurred at Harlingen (cf. remarks below); it was 350 cm and occurred at 5 o'clock in the morning of Feb. 1. At the same time it was near ebb, and the actual height of the water was only 2¾ m.

For the sake of completeness it must be mentioned that the said effect of the astr. tide on the wind-residual is not solely responsible for the irregularities of the curve of residual at Harlingen, as the wind off the coast at Harlingen just about 5 a. m. was very strong. However, the said effect explains the peculiarity observed in several places along the Dutch coast that the ebb connected with the astr. tide was not very noticeable during the storm surge. Moreover, the effect itself is somewhat more complicated than stated above; in the formula for wind-residual the difference of speed between movement of air and water shall be used instead of absolute velocity of wind. A wind will consequently cause a comparatively smaller residual, if the water is already flowing towards the coast, f. inst. just before high water. An opposite effect, namely that the astr. tidal wave moves faster from place to place, when the wind has created a greater depth beforehand, may have manifested itself during the storm surge, but a complete separation of the different effects is hardly possible on the existing basis.

As regards Harlingen the maximal total tide during the storm surge occurred about 9.20 p. m. on Jan. 31, at which time the sea-level was 3½ m above mean sea-level; 80 cm were due to the astr.

tide and 30 cm were due to the local air pressure, this being 980—985 mb or about 30 mb below normal.

The tract of coast from Harlingen towards the Straits of Dover was hit by the storm surge during the following hours. At Ijmuiden off Amsterdam a disturbance of about 3 m (the effect of the local air pressure is included for the sake of simplicity here and in the following) remained almost unchanged from 11. p. m. Jan. 31 to 6 a. m. Febr. 1, and at Brouwershavn in the island group of Zeeland a distinct peak of disturbance of 3⅓ m occurred shortly before midnight GMT, whereupon the disturbance decreased to 3 m about 3 a. m. and to 2½ m about 6 a. m. (cf. Fig. 3 where residual — disturbance minus effect of local air pressure — is indicated by the thin curve). At Ostend the disturbance was 2½ m just after midnight GMT.

To this must be added, that the amplitudes of the tidal waves and consequently the heights of the spring flood are still greater southwards along the Dutch coast. While the height of the spring flood above mean sea-level at Harlingen is only about 0.8 m, it is respectively 0.85, 1.45 and 2.35 m at Ijmuiden, Brouwershavn and Ostend, and the predicted hours of high water on the night of the disaster were respectively 4.20, 3.29 and 1.29 a. m. GMT, as the tidal wave as already mentioned moves in the direction south-north along this coast. All things considered the absolute maximal high water at Ijmuiden occurred with 3.9 m above mean sea-level at about 4.30 a. m. GMT, at Brouwershavn with 4.4 m shortly after 3. a .m. GMT and at Ostend with 4.6 m (this height is a little inaccurate) shortly after 1.30 a. m. GMT.

In these three last-mentioned cases the absolute maximal high water occurred rather near the predicted time for astr. high water. At London Bridge and Harlingen the absolute maximal high water came, as we have seen, one hour before the predicted time for astr. high water; the cause is probably, as already indicated, that the astromical flood (which was the M_2-wave preceding the above-mentioned M_2-wave at Ostend, Brouwershavn and Ijmuiden) in this case moved faster than usual on account of the greater depths, caused by the residual.

The remarkable fact that the first peak of the disturbance of Jan. 31 reached Harlingen earlier than it reached the point on the English coast situated on the same latitude can most probably be explained by the same cause, as the depths are greater in the direction from Scotland to Harlingen than along the English coast.

The said values of the absolute maximal high water along the coasts of Holland and Belgium are among the most accurate ones known during this storm surge disaster. This fact does not exclude that greater heights of water may have occurred along certain parts of the coast and in the estuaries of the Meuse and the Scheldt. According to numerous available reports there is no doubt in fact, that the high water in certain places has exceeded 5 m. Furthermore it seems to be proved that the maximal height of water solely due to the meteorological conditions just touched 4 m, according to the said reports.

The height of many of the Dutch dikes were just 5 m above mean sea-level, but this does not infer that the maximal high waters must have exceeded 5 m to inundate the dikes, as the wash of the sea-waves has caused a greater effective height of water.

The lightships have given rather good information about the heights of the waves caused by the gale in the North Sea. Several of these lightships have reported heights of waves — from trough to peak — of 10 m about noon Feb. 1; the velocity of wind was at that time 10—12 according to the Beaufort scale. Such seas are not quite exceptional, as waves with heights up to 15 m can arise in the great oceans during similar conditions. Heights of 10 m are, however, rather exceptional for the North Sea, and as the waves in question were steeper than ordinary ocean waves, they were very dangerous to the navigation. Thanks to preceding gale warnings the disasters at sea did not get the same dimensions as the disasters in the inundated areas; yet, several shipwrecks with loss of lives were reported, f. inst. the 2700 tons ship Princess Victoria, which sank about 2 p. m. on Jan. 31 in the waters between Scotland and Ireland (the weather situation here was almost as in the North Sea during the following night) being a terrible omen of the horrors to follow in the course of the next night.

Wave-heights of 10 m, i. e. heights of 5 m above mean sea-level, do normally not occur near the coast, as the sea bed along most coasts rises near up to the level of the coastline and consequently breaks the waves. In the same way foreland outside the dikes and slightly rising dike slopes serve to break the waves during such conditions.

Considering the arrival of the disturbance along the coasts of northern Holland, north-west Germany and western Jutland, we see that its progress here appears to have occurred in the same way as the progress of the M_2-tide. It thus seems that the disturbance here has the nature of an amphidromie equal to the astr. tide; but it is also a fact that both a direct disturbance and a reflected disturbance from the south coast of the North Sea must have existed in this area, although the proportion between these two waves has probably not been the same as for the M_2-tide. It must be mentioned as a comparison that the "external surges" expand in the North Sea like the diurnal partial tides, and these tides do not progress in the North Sea exactly like the M_2-tide; the latter travels from Harlingen to Esbjerg in 5 hours, while the diurnal partial tides barely use about 3 hours for this distance.

The resemblance between the disturbance and the M_2-tide is particularly evident, if one considers the further expansion of the maximum of 350 cm (370 cm including the effect of the local air pressure), which occurred at Harlingen at 5 a. m. GMT, Feb. 1. The same wave reached Cuxhaven between 7 and 8 a. m. GMT with a maximum height of about 2½ m (the effect of air pressure is included in the values as usual, but not on Fig. 1—4). Shortly before 9 a. m. GMT it struck the bars outside the deeps leading to the Danish Wadden Sea, and about 10 a. m. GMT (11 MET) at Sunday noon, Feb. 1, the disturbance reached Esbjerg with a maximum of 1.8 m (cf. Fig. 4). However, conditions in the Danish Wadden Sea as well as by the coast of north-west Germany were almost as at Harlingen, with the peak of the disturbance coinciding with the time of astr. ebb (at Esbjerg the astr. ebb should occur at 9.25 a. m. GMT — 10.25 MET — according to the tide tables). Although the disturbance in question might very well be noticed along the German and the Danish coasts, it caused no damage worth mentioning.

Finally it must be mentioned that a small disturbance (maximum 1¼ m when effect of local air pressure is included) occurred at Esbjerg just about midnight Jan. 31. It is probably the direct disturbance coming from Scotland across the North Sea. The time difference from Harlingen is just as for the diurnal K_1-tide, and it cannot be excluded, that the disturbance mentioned contains an element of "external surge".

LITERATURE

The Admiralty Tide Tables. Part II. 1938.

The Admiralty Tide Tables for the year 1953. European Waters.

Bowden, K. F.: Storm Surges in the North Sea. Weather. March 1953, pp. 82—84.

Carruthers, J. N. & Lawford, A. L.: The Progress of the Storm Surge of January 31st/February 1st, 1953. Association d'Oceanographie Physique, UGGI. General Assembly at Rome, Sept. 1954. Reports and Abstracts of Communications.

Colding, A:. Nogle Undersøgelser over Stormen over Nord- og Mellemeuropa af 12te—14de November 1872 og over den derved fremkaldte Vandflod i Østersøen. Vidensk. Selsk. Skr., 6. Række, nat.-math. Afd. I, 4. Kjøbenhavn 1881.

Corkan, R. H.: Storm Surges in the North Sea, vols. 1 and 2. H. O. Misc. 15072, Washington, D.C. 1948.

Egedal, J.: Abnorme Vandstandsforhold i de danske Farvande, II. Publ. fra det Danske Met. Inst. Medd. Nr. 11. 1949.

Hay, R. F. M. & Laing, J.: The Storm Surge of 31st January—1st February, 1953. The Marine Observer. April 1954, pp. 87—91.

Hellström, B.: Vattenståndsvariationerna i Östersjöbäckenet. Särtryck ur Teknisk Tidsskrift, häfte 8. Norrköping 1941.

Lawford, A. L.: Currents in the North Sea during the 1953 gale. Weather. March 1954, pp. 67—72.

Rossiter, J. R.: The North Sea storm surge of 31 January and 1 February 1953. Phil. Trans. Roy. Soc. Series A. Vol. 246, pp. 371—400. 1954.