STORM SURGES

Lecture delivered by Dr. A. T. Doodson, F.R.S.

Director of the Observatory and Tidal Institute, Liverpool, at the Vth International Hydrographic Conference.

The study of meteorological disturbances of sea level and tides has been actively pursued in many countries, with some measure of success. The earliest methods simply tabulated the storm effect in terms of barometric pressure, wind velocity and direction, all at the place where the effect was observed, and this is still a common practice. Such methods are largely statistical in kind and require large numbers of observations to give any kind of precise average effect, and large enough to include all variations in direction and velocity of wind. An improvement upon this method was effected when local wind data were replaced by data from weather charts which were taken over a large area, and when the wind velocity and direction were expressed by barometric gradients to the north and east. The lack of accuracy due to the assumption that wind velocity varied with gradient instead of the square of gradient, was offset by the ease with which the calculations could be effected. In fact, by the use of this method, quite valuable results could be obtained from short lengths of records. Fig 1 shows the results obtained from a method of this type, from a month's observations at each of a number of places round the British Isles. It gives the direction of the wind that is most effective in raising sea level. In some places the off-shore wind is most effective, but in other places the common idea that the off-shore wind is the important one has to be greatly modified. This diagram reveals the necessity for a detailed examination of the mode of generation of the effects, whether local or afar off. This is one of the major points to which we shall refer later.

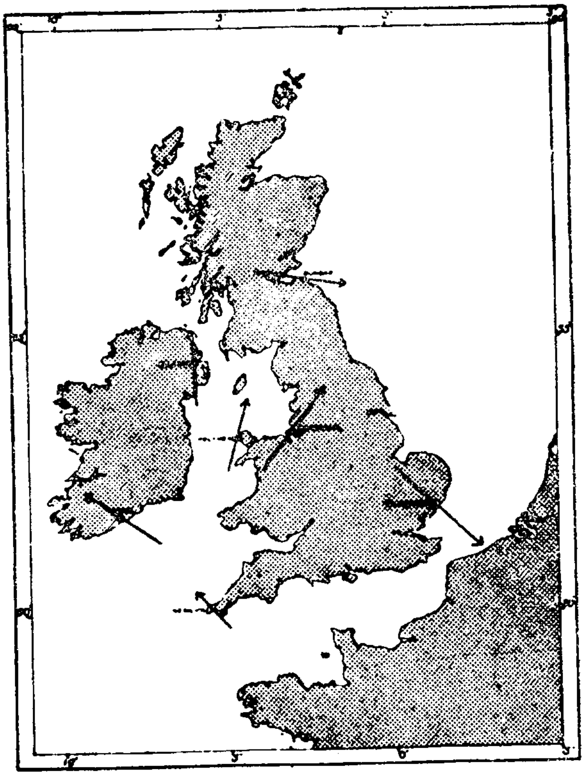


Fig. 1

The most effective winds for raising sea-level at places on the British Coasts.

The same method is very flexible in that the barometric data some hours prior to the observed effects can be rapidly studied for a series of hours, and so an estimate of time-lags can be obtained. The statistical results for Liverpool are shown in fig. 2, from which it is evident that the effects of the pressure and of the north-gradient are almost instantaneous but the effect of the east gradient is greatest some hours later. Obviously this is a matter of great importance and we can readily offer a simple explanation. A north-gradient of pressure corresponds with a westerly wind while the east-gradient of pressure corresponds with a southerly wind. A westerly wind across the narrow Irish Sea is quickly effective but a southerly wind affects the water of the whole of the approaches from the Atlantic Ocean, between Land's End and Ireland. This amount of water has greater inertia.

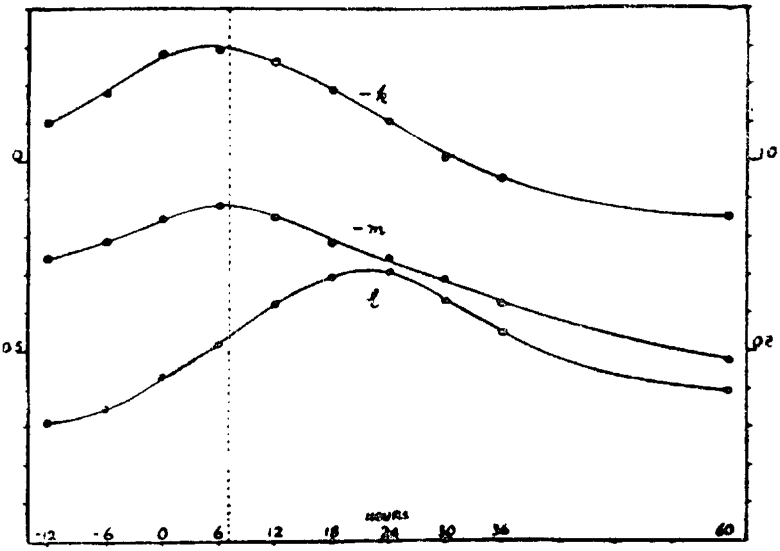


Fig. 2

Values of — k, + l, — m for Liverpool.

A further investigation of this kind amplified the formula used by expressing the effect in terms of local pressure, local gradients, and gradients south of Ireland, and very interesting results were obtained showing that the wind blowing south of Ireland was more effective than the same wind blowing at Liverpool. That is, the major part of the larger disturbances at Liverpool was more highly correlated with winds over the Atlantic than with winds over the Irish Sea.

These statistical investigations, while of very great value, suffer from all such methods. They give average results for the masses but fail to account for the individuals. The criticisms drawn at that time are stated in a paper by A.T. Doodson, *Meteorological Perturbations of Sea Level and Tides*, Monthly Notices, Royal Astronomical Society, Geophysical Supplement, Vol. I, 1924.

These relate to three things as follows :—

(1) When a disturbance occurs it tends to oscillate on its own account whatever the wind system does; that is, we cannot assume that the local effect varies exactly in phase with the generating causes. If a wind dies suddenly, the water will rock to-and-fro according to the configuration of the basin.

(2) It is hardly to be expected that a southerly wind will have exactly an opposite effect to a northerly wind.

(3) It may be necessary to take account of the rapidity of change of the pressure system.

We may sum up the conclusions by saying that we must not regard the sea-level as taking up an equilibrium position as though the water had no inertia, just as the equilibrium tide is not a true representation of oceanic tides. The problem is essentially a dynamical problem.

An important contribution to the theory was made in a paper on *Tide Relations in meteorological effects on the sea* by Proudman and Doodson, Proceedings of the London Mathematical Society, February 1924, and the conclusions are illustrated in fig. 3. Supposing that a wind begins to blow steadily it was found that the sea-level rose steadily to a maximum and thereafter oscillated with diminishing range until a steady state was reached. The period of the oscillation and its rate of decay depend upon the physical characteristics of the sea. Here we have a mathematical explanation of the time-lag such as was experienced in the case of the southerly wind over the Irish Sea. If, after blowing for a short time, it suddenly stopped then this could be represented by imposing a wind of the same strength in the opposite direction.

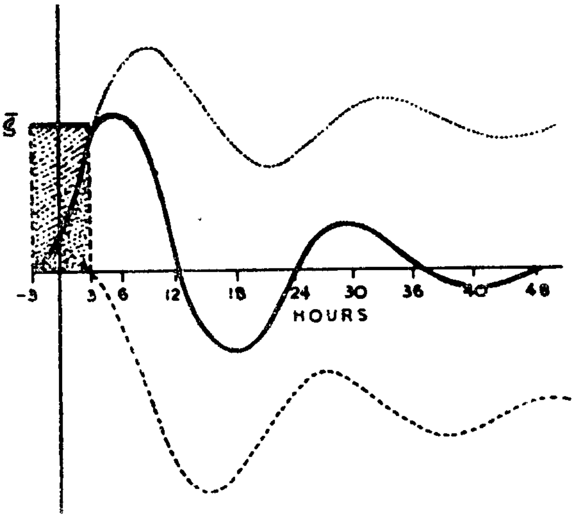


Fig. 3

Meteorological perturbation of sea-level.

.... Contribution from $\bar{g}$ suddenly commencing at — 3 hours and later remaining constant.
- - - - - - Contribution from — $\bar{g}$ suddenly commencing at + 3 hours and later remaining constant.
———— Resulting contribution for $\bar{g}$ acting from — 3 hours to + 3 hours.

The effect of this wind would be to give an opposing oscillation and the final results would be the sum of the two oscillations. The effect of a wind blowing with a steady velocity for a short time only is then seen to be a decaying oscillation of sea level about its mean value. We could then obtain results for any given wind by taking a number of such elements. For example, we could take the average wind from zero hour to one hour as x knots and describe the effects by a curve, starting at zero hour. From one hour to two hours we could similarly get a curve corresponding to the average velocity of y knots, starting at hour one, and so on. By adding up these contributions we could then obtain the final result for any given wind.

This method has been studied for the North Sea but it is found that that sea is so shallow that the oscillation decays very rapidly and in effect we are concerned only with the first oscillation, and its time-lag.

A very remarkable investigation has just been brought to a conclusion by Mr. R. H. Corkan of the Tidal Institute, and a brief account of some of his conclusions will now be given. The work was done at the request of the London County Council and the Port of London Authority who were interested in storm surges in the Thames, following an investigation by A.T. Doodson in the year 1928, when many deaths occurred due to a sudden surge overflowing the river walls in London. Mr. Corkan's investigation has amplified the earlier one but has done much more, for he has gone very carefully and systematically into an analysis of every large surge for many years. He has taken account of the principles expounded above, and has dealt with the effect as derivable from three main sources (see fig. 4).

(1) A local pressure system in the Flemish Bight, centred on point A ;
(2) A North-Sea pressure system centred on point B ;
(3) An external effect.

There are, of course, minor sources of flooding, such as the fresh-water in the river itself, and also the effect of disturbances in the English Channel which enter the North Sea through the Straits of Dover. It is beyond all question that these are of small importance compared with the sources given above. It is known that if a barrier were placed across the Straits of Dover then the tides in the North Sea would not be appreciably affected.

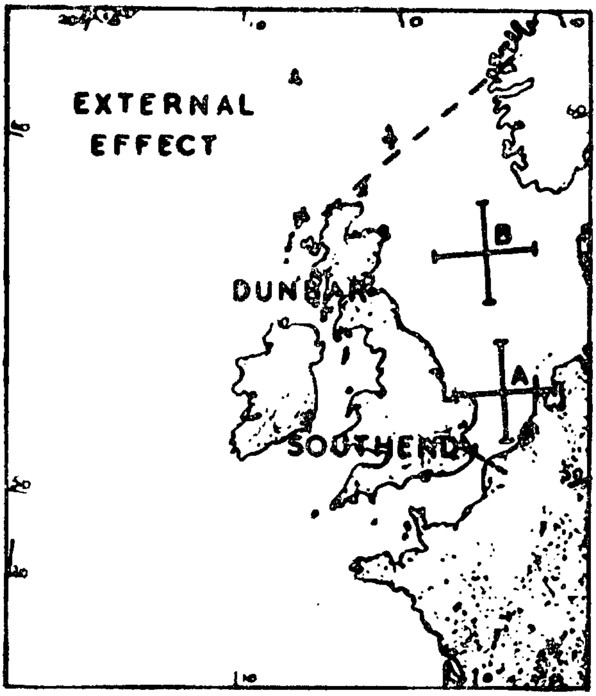


Fig. 4

After examining a large number of surges, Mr. Corkan has found none whose origin to any notable extent could be attributed to effects propagated through the Straits of Dover.

The effects of the barometric pressure systems have been expressed by the following formula :—

B = Barometric pressure (difference from the mean) ;
E = Easterly gradient of pressure (difference from the mean) ;
N = Northerly gradient of pressure (difference from the mean).

Assuming the tractive force varying as the wind-velocity,

$$\text{Effect} = f_1 B + f_2 E + f_3 N$$

where f_1, f_2, f_3 are constants.

But since the tractive force varies more nearly as the square of the wind velocity, a more exact formula is to take :—

$$\text{Effect} = f_1 B + (f'_2 E + f'_3 N) \sqrt{E^2 + N^2}$$

where f_1, f'_2, f'_3 are constants.

An approximation to this latter formula was used by Mr. Corkan. It was assumed that the local wind was instantaneous in its effects, as was shown by Doodson's earlier investigation, and that the North Sea effect would be delayed by a time-lag depending upon the depth of the sea, this time-lag being approximately one-quarter of the free-period of oscillation of the sea as a whole, and it was assumed in both cases that the oscillations decayed so rapidly that only the first one needed to be considered. But care was taken to ascertain by actual trial the validity of the general assumptions; the actual time-lag of the North Sea effect and the time of travel of waves from Dunbar to Southend were obtained by the examination of particular cases.

The external effect was not studied in the same way, but it was assumed that the effect of the external pressure system, to reach the Thames at all, must travel southward, and could be observed at a station in Scotland. A great deal of evidence for such travelling waves had already been obtained by Doodson. For example, the storm surge of January 5-8, 1928, which proved so disastrous at London, apparently travelled round the Flemish Bight, as shown by fig. 6, where it gets progressively later at Flushing, Hook of Holland, and Ymuiden, and later, as is seen in fig. 7 at Norderney, Cuxhaven, and Esbjerg. Evidence had also been accumulated by Doodson to show that there were similar progressions from Dunbar to Southend, but some of his conclusions needed to be revised in the light of Mr. Corkan's more elaborate investigations.

It is impossible to emphasise too much the patient skill with which these effects were disentangled, for it must be remembered that the North Sea pressure system does not exist by itself but is highly correlated with the external system and the Flemish Bight system. Nevertheless, occasions do occur when quiet conditions at Dunbar, in Scotland, exist during a disturbance at Southend, so that the effects of local pressure system could thus be isolated. Similarly occasions existed when the external effect predominated, and the effects of the North Sea pressure system and those of the Flemish Bight system were small. By a process of approximation it was thus possible to obtain the constants required for the formulae.

Doodson's earlier investigation had shown that if there was a travelling disturbance, its rate of travel from Dunbar to Southend was at the same rate as that of the tide itself. This is understandable if we recognise that both phenomena are governed by the same law of travel, in that the rate depends upon the depth of the sea. Corkan amply confirmed this, and showed also that the external effect which passed Dunbar and reached Southend about nine hours later did so without any appreciable loss in amplitude. This means that such a wave travels along the coast and is not dissipated over the whole sea. A depression of sea level travels south in exactly the same way.

It is necessary now to be quite clear that what is observed at Dunbar may be due either to

(a) an incoming oscillation generated externally ;
or
(b) the local effects of the North-Sea pressure system.

While these could be separated to some extent by further analysis, the immediate problem was to describe the effect at Southend in terms of

(a) The local pressure system ;
(b) The wind effect at Dunbar ;
(c) The residual effect of the North-Sea pressure system, some of which had already been incorporated in the Dunbar effect.

After correcting both Southend and Dunbar predictions for the simple direct effects of pressure at each place we could write

$$\text{(residual at Southend)} - \text{(residual at Dunbar 9 hours earlier)}$$
$$= (\alpha N + \beta E) + (\gamma n + \delta e)$$

where the gradients N, E are taken at point A in fig. 3 at the same time as the observed effect at Southend, and the gradients n, e are taken at B six hours earlier. (This formula can be improved, and in practice was improved so as to allow for the tractive forces varying as the square of the velocity). The lag of six hours for the wind effect was found to be the best average.

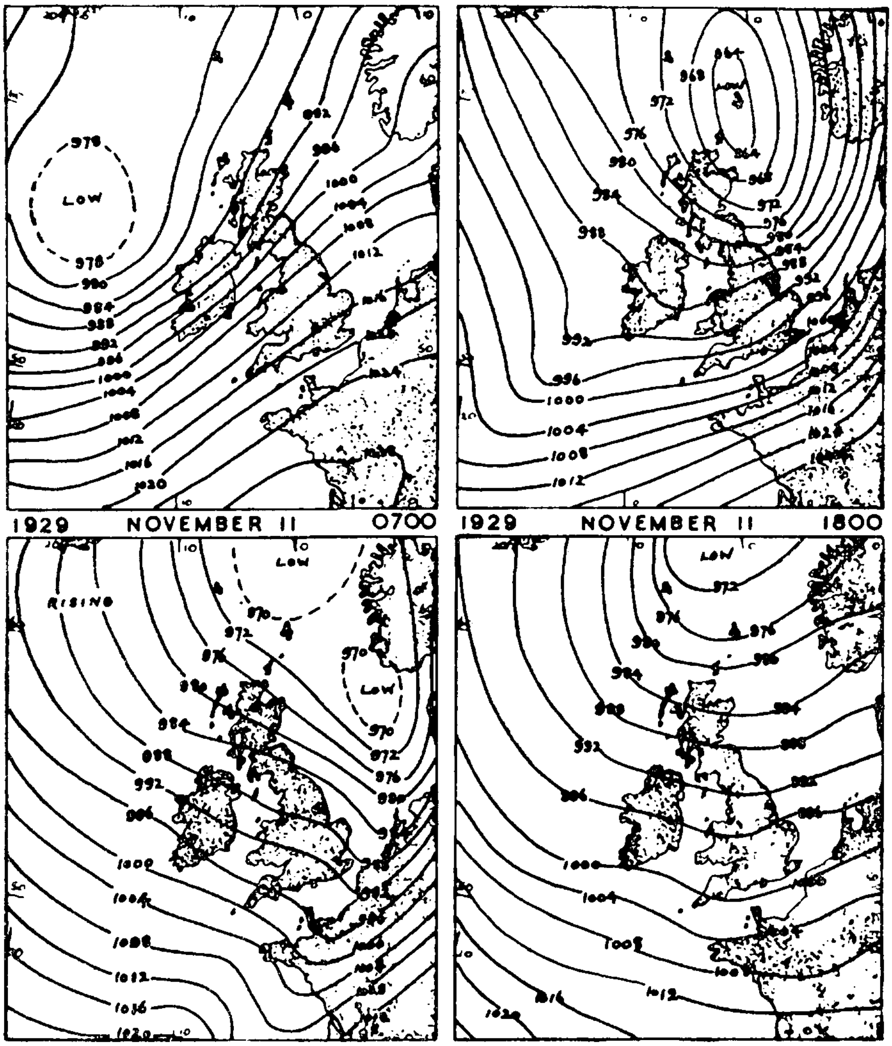
A few typical cases will now be considered out of the wealth of material provided by Mr. Corkan so as to illustrate the principal types of oscillation. In each case, the charts show the meteorological situation, together with :—

(a) Surge curves at Dunbar,
  (1) the original surge curve ;
  (2) DCT, the Dunbar corrected curve, corrected by BT (the local barometric tide, due to local pressure).
(b) Surge curves for Southend,
  (1) the original surge curve ;
  (2) the curve corrected by BT (the local barometric tide, due to the local pressure at Southend) ;
  (3) the curve as further corrected by DCT when this is taken 9 hours later than at Dunbar.
(c) The calculations from the formulae for the metreorological tide,
  (1) the local effect from the Flemish Bight (A) assumed instantaneously ;
  (2) the North Sea effect from point B, taken 6 hours later than the meteorological observations ;
  (3) the combined effect, the calculated meteorological tide.

Curve b(3) is assumed to be the residual tide due to wind which has to be expressed in terms of the wind in the Flemish Bight and in the North Sea so that c (3) should be a representation of b (3). The accuracy with which this is accomplished is a measure of the value of the method. We must not lose sight of the fact that the accurate representation of the curve b (3) is tantamount to the accurate representation of the whole of the original surge. A brief description of the six cases now follows.

Case 1.—*Surge of November* 10-13, 1929. (Fig. 8.)

This is a simple case of lowering of level (a "negative surge") followed by a small after-raising. It is noteworthy for being the occasion of the lowest high water (two feet below MTL) observed since 1916. The earlier lowering of level at Dunbar in this case was largely a result of the local winds at Dunbar, and was not due appreciably to external effect.



1929 NOVEMBER 11 0700

1929 NOVEMBER 11 1800

1929 NOVEMBER 12 0700

1929 NOVEMBER 12 1800

Fig. 8 a

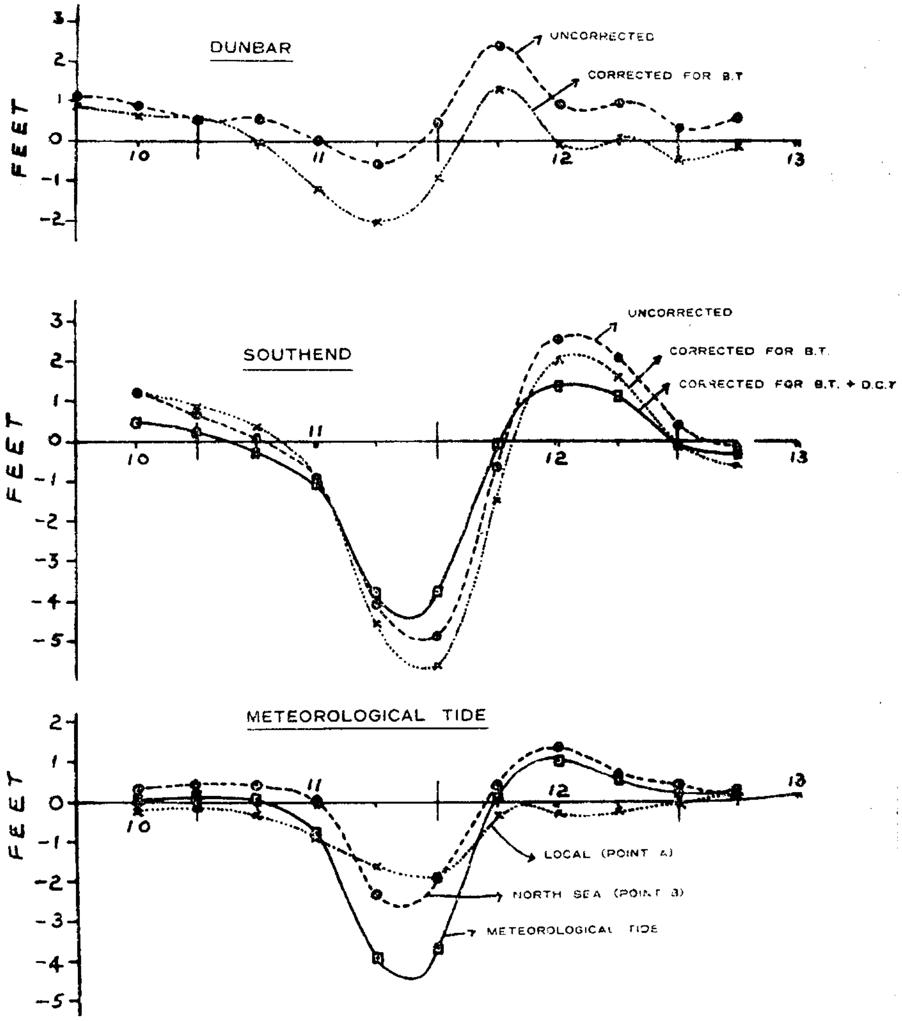
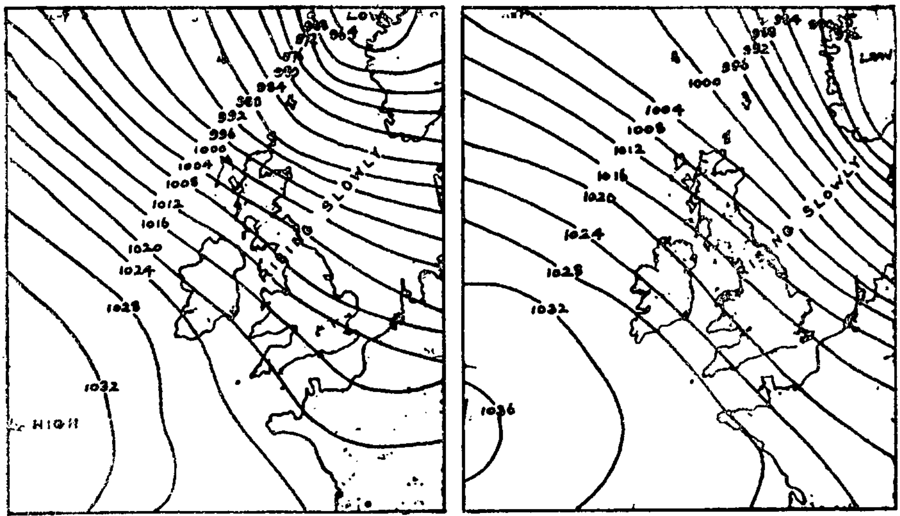

DUNBAR
UNCORRECTED
CORRECTED FOR B.T
FEET
3
2
1
0
-1
-2
10
11
12
13
SOUTHEND
UNCORRECTED
CORRECTED FOR B.T.
CORRECTED FOR B.T. + D.C.T
FEET
3
2
1
0
-1
-2
-3
-4
-5
10
11
12
13
METEOROLOGICAL TIDE
FEET
2
1
0
-1
-2
-3
-4
-5
10
11
12
13
LOCAL (POINT A)
NORTH SEA (POINT B)
METEOROLOGICAL TIDE

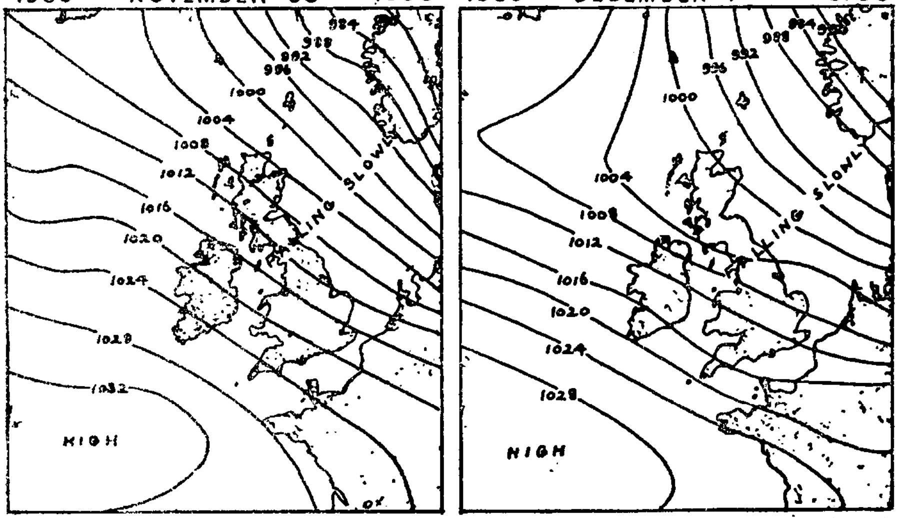
Fig. 8 b

Case 2.—*Surge of November 30-December 2, 1936.* (Fig. 9.)

This is a case of simple raising of level at Southend (a "positive surge"). In this case it is likely that the Dunbar effect was mainly externally generated, by the North Winds to the north of the North Sea, and the Southend local effects were small. This is a very common type of disturbance, with a depression usually centred over Scandinavia or the Baltic.



1936 NOVEMBER 30 1800 1936 DECEMBER 1 0700



1936 DECEMBER 1 1800 1936 DECEMBER 2 0700

Fig. 9 a

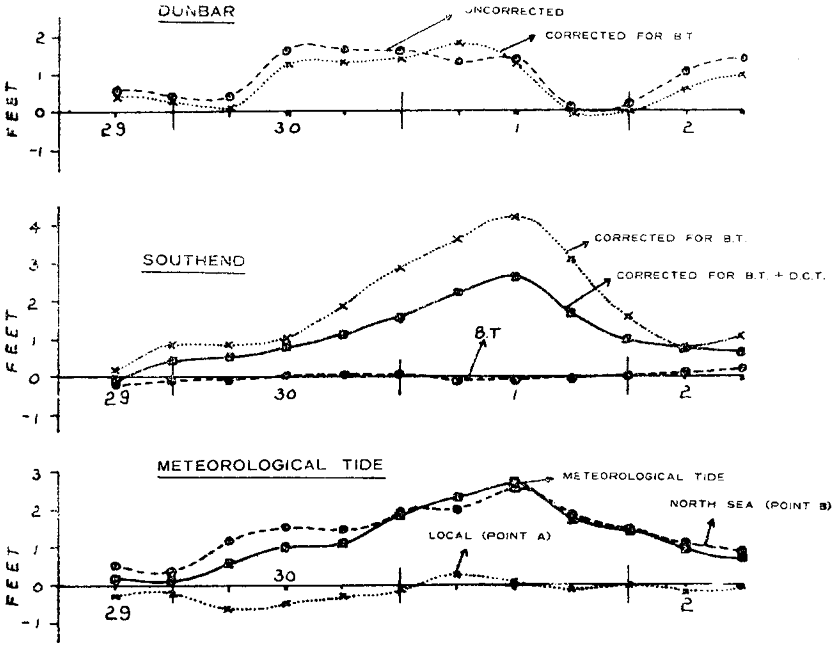
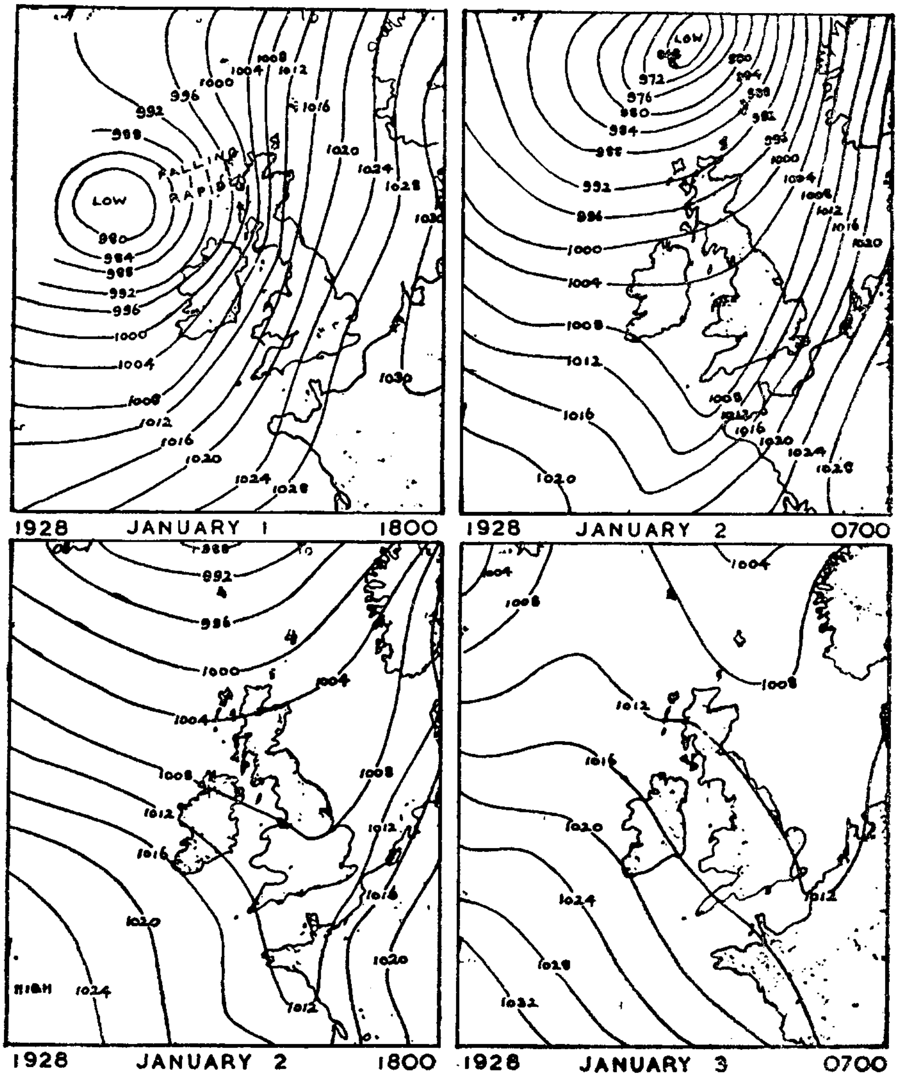

DUNBAR
UNCORRECTED
CORRECTED FOR B.T.
FEET
2
1
0
-1
29
30
1
2
SOUTHEND
CORRECTED FOR B.T.
CORRECTED FOR B.T. + D.C.T.
B.T
FEET
4
3
2
1
0
-1
29
30
1
2
METEOROLOGICAL TIDE
METEOROLOGICAL TIDE
NORTH SEA (POINT B)
LOCAL (POINT A)
FEET
3
2
1
0
-1
29
30
2

Fig. 9 b

Case 3.—*Surge of January* 1-3, 1928. (Fig. 10.)

This gives firstly a large lowering of level (as in case 1) but followed by a large raising of level, at a time when the winds inside the North Sea were negligible, so that it is a true externally generated surge.



1928 JANUARY 1 1800

1928 JANUARY 2 0700

1928 JANUARY 2 1800

1928 JANUARY 3 0700

Fig. 10 a

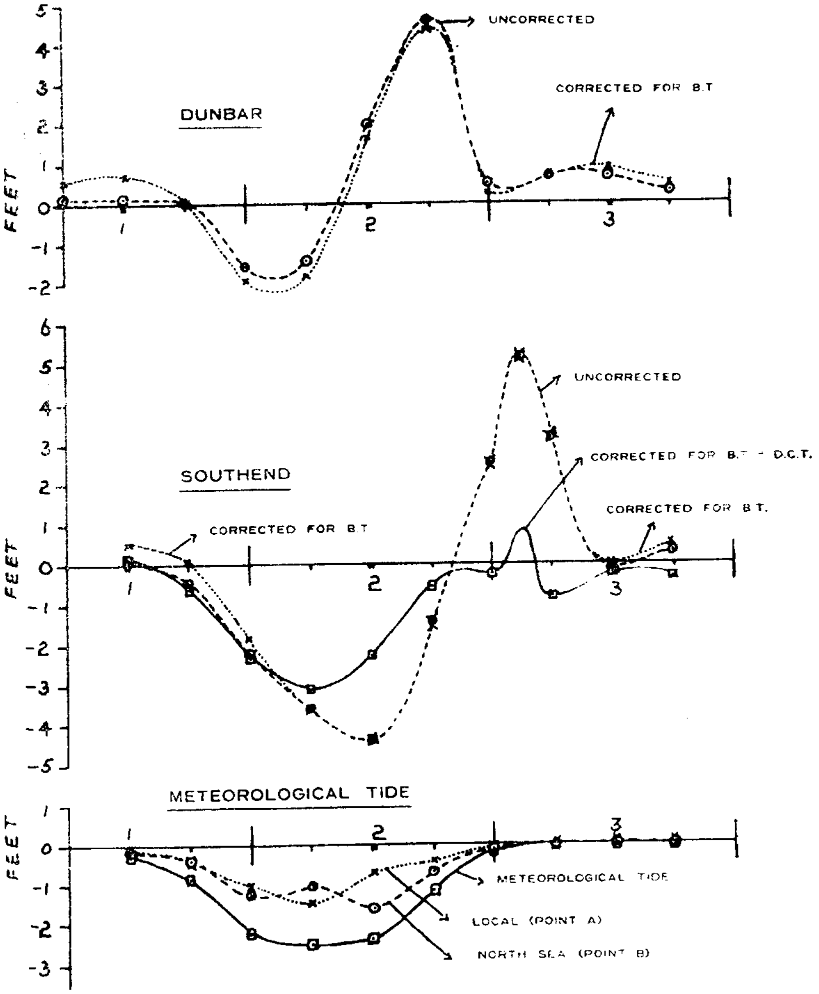
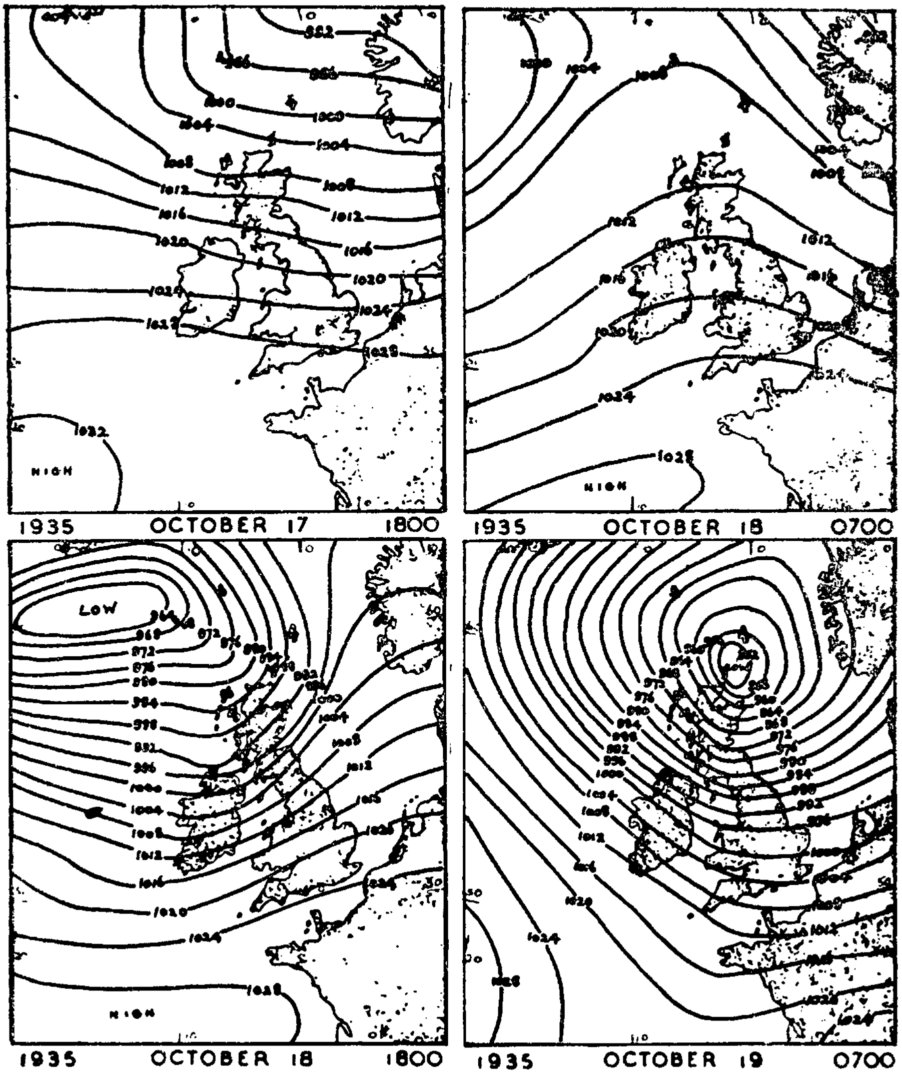

DUNBAR
UNCORRECTED
CORRECTED FOR B.T
FEET
5
4
3
2
1
0
-1
-2
1
2
3
SOUTHEND
UNCORRECTED
CORRECTED FOR B.T + D.C.T.
CORRECTED FOR B.T.
CORRECTED FOR B.T
FEET
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
1
2
3
METEOROLOGICAL TIDE
FEET
1
0
-1
-2
-3
1
2
3
METEOROLOGICAL TIDE
LOCAL (POINT A)
NORTH SEA (POINT B)

Fig. 10 b

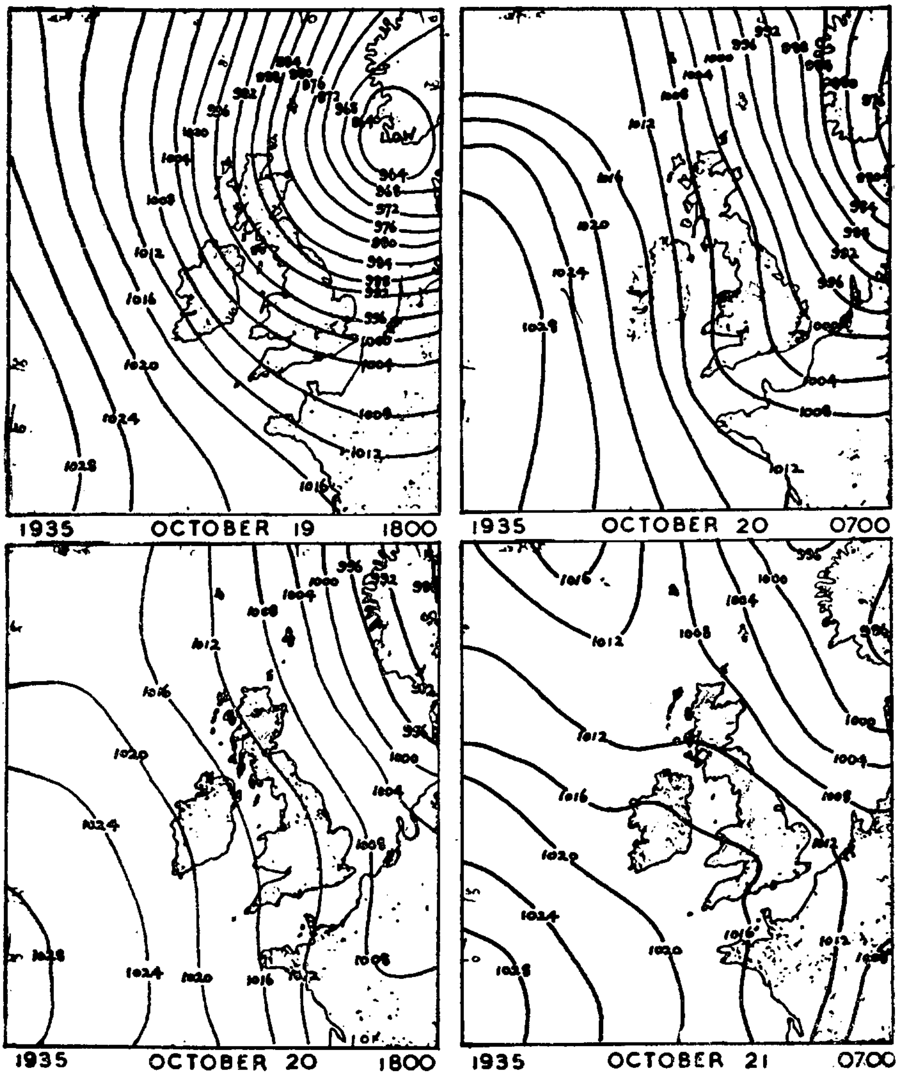
Case 4.—*Surge of October* 17-21, 1935. (Fig. 11.)

This is a very important type in which the centre of a large depression passed eastwards near the northern entrance to the North Sea, in earlier stages like case 1, with a large lowering of level. As the centre passes across the northern entrance to the sea, strong northerly winds in the SW quadrant depression cause a large inflow of water, which passes Dunbar and travels to Southend.



1935 OCTOBER 17 1800
1935 OCTOBER 18 0700
1935 OCTOBER 18 1800
1935 OCTOBER 19 0700

Fig. 11 a



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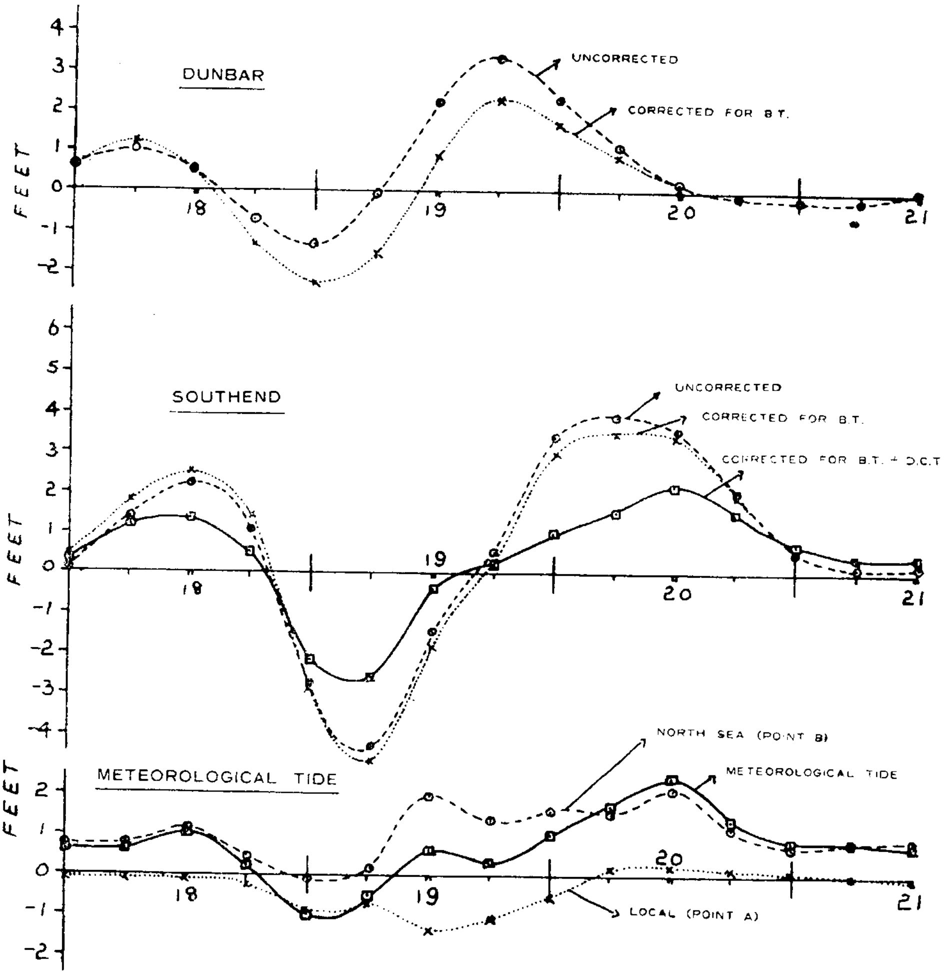
1935 OCTOBER 20 0700

1935 OCTOBER 20 1800

1935 OCTOBER 21 0700

Fig. 11 b


DUNBAR
FEET
4
3
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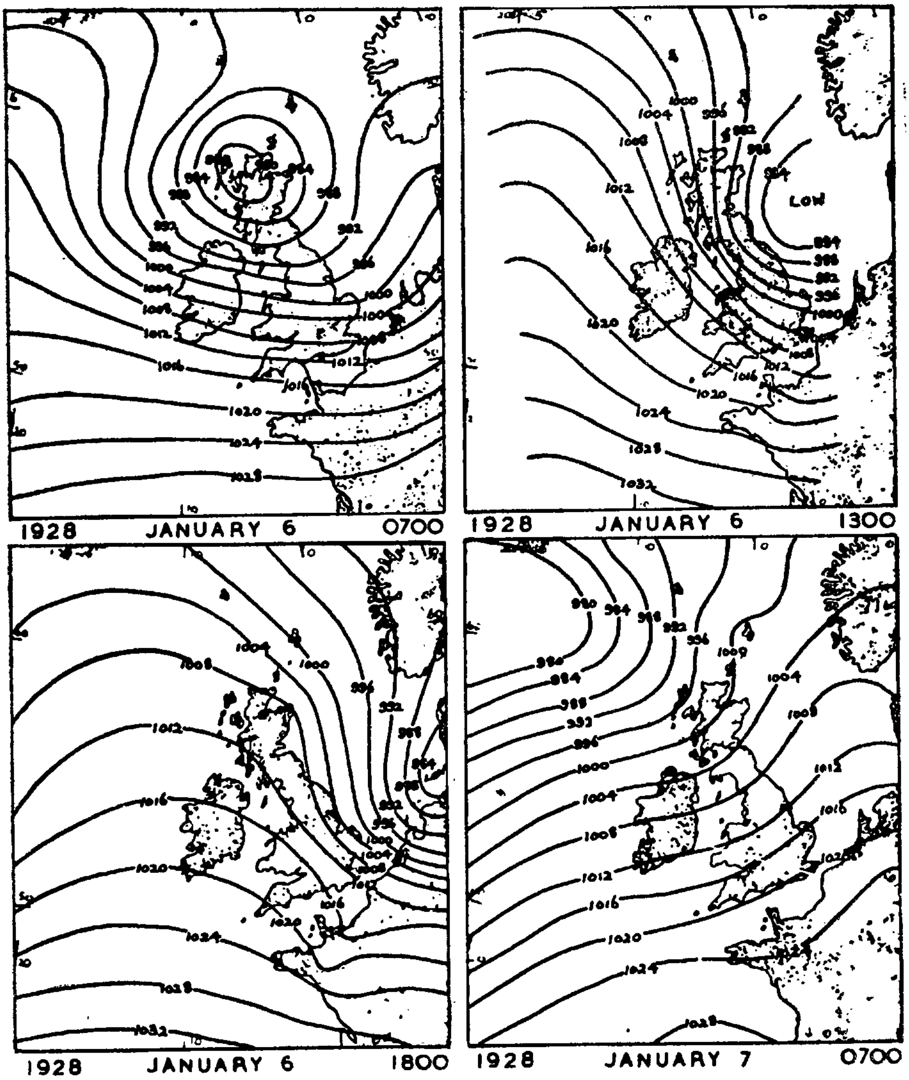
0
-1
-2
UNCORRECTED
CORRECTED FOR B.T.
18
19
20
21
SOUTHEND
FEET
6
5
4
3
2
1
0
-1
-2
-3
-4
UNCORRECTED
CORRECTED FOR B.T.
CORRECTED FOR B.T. + D.C.T
19
18
20
21
METEOROLOGICAL TIDE
FEET
2
1
0
-1
-2
NORTH SEA (POINT B)
METEOROLOGICAL TIDE
20
18
19
21
LOCAL (POINT A)

Fig. 11 c

Case 5.—*Surge of January* 6-7, 1928. (Fig. 12).

This is the surge which produced flooding in 1928. Most of the meteorological tide came from winds in the North Sea and not from local winds. The latter winds were strong but came from a direction which produced little effect at Southend. An investigation of the effects at Dunbar showed that there was in this case no surge generated externally.



1928 JANUARY 6 0700

1928 JANUARY 6 1300

1928 JANUARY 6 1800

1928 JANUARY 7 0700

Fig. 12 a

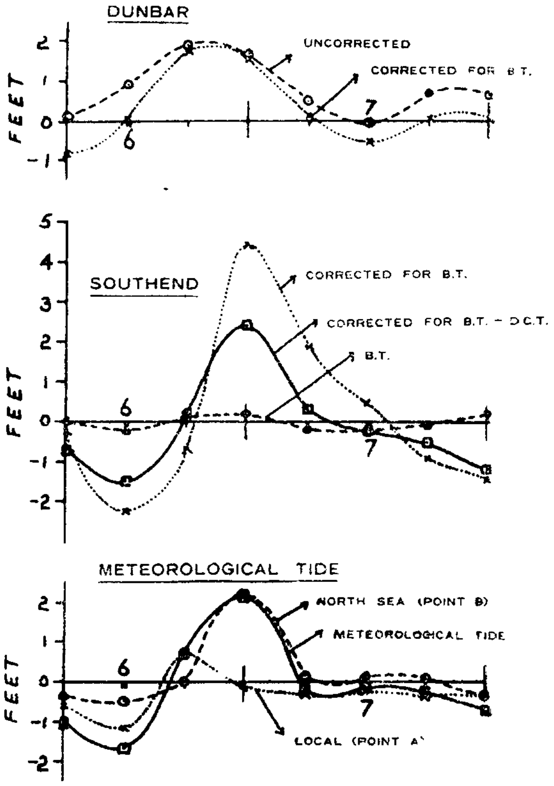
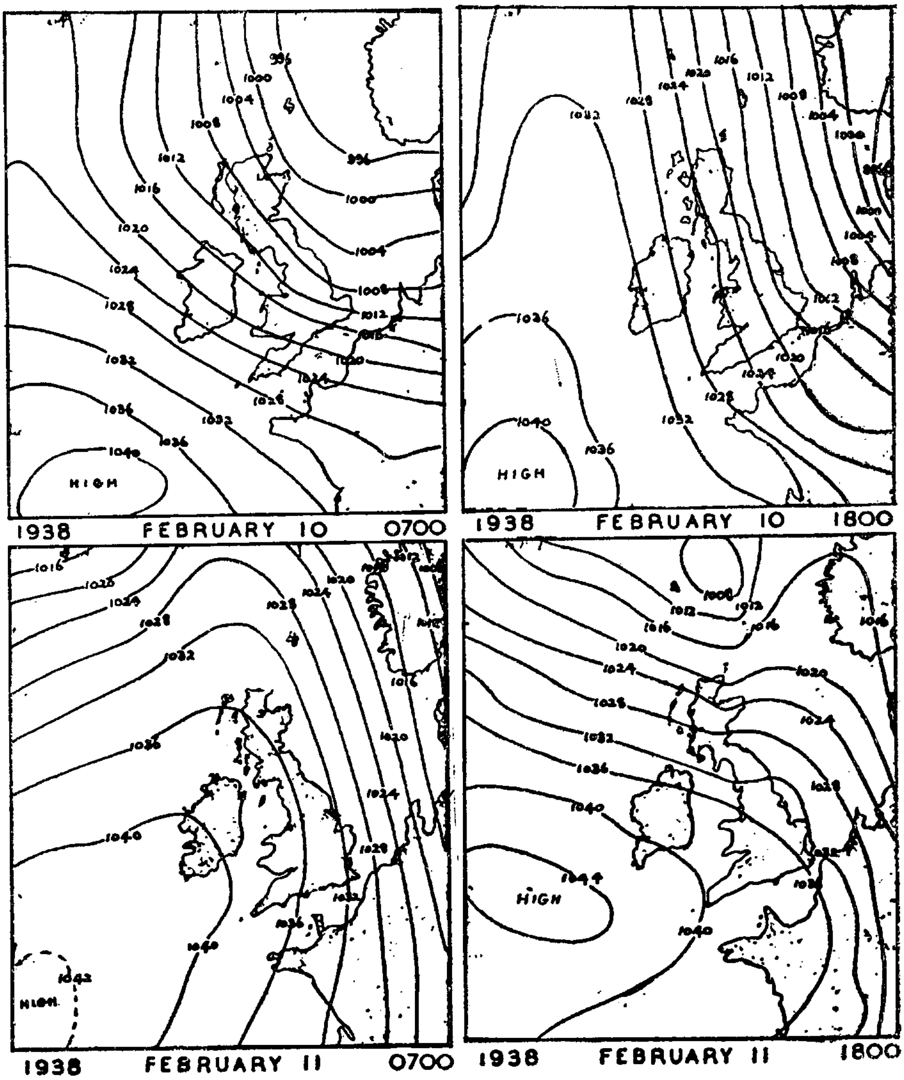

DUNBAR
2
1
0
-1
FEET
6
7
UNCORRECTED
CORRECTED FOR B.T.
SOUTHEND
5
4
3
2
1
0
-1
-2
FEET
6
7
CORRECTED FOR B.T.
CORRECTED FOR B.T. – D.C.T.
B.T.
METEOROLOGICAL TIDE
2
1
0
-1
-2
FEET
6
7
NORTH SEA (POINT B)
METEOROLOGICAL TIDE
LOCAL (POINT A)

Fig. 12 b

Case 6.—*Surge of February* 10-13, 1938. (Fig. 13.)

This surge produced the flooding at Horsey. The first surge coincided with low water and attracted no special attention. The second surge had passed its maximum at the time of high water but was still high. The first surge was an example of case 2, and the change in level was due entirely to the change in wind intensities and not to changes in direction. A large portion was generated in the Norwegian Sea and in the North Sea.

The second surge was produced by a travelling depression which passed down the east side of the North Sea. A lowering of level of the order of two feet which preceded the rise has not been explained, as winds in the North Sea were always of a type which produce a raising of level.

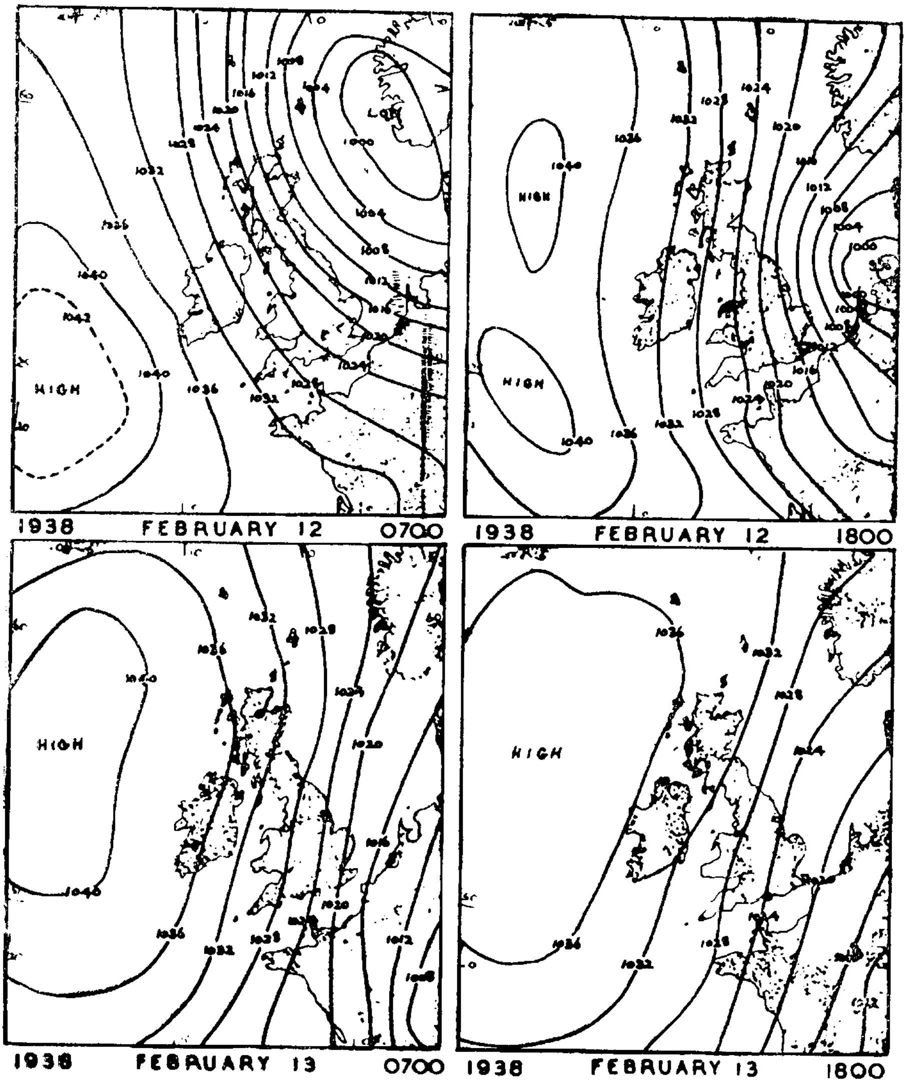

1938 FEBRUARY 10 0700

1938 FEBRUARY 10 1800

1938 FEBRUARY 11 0700

1938 FEBRUARY 11 1800

Fig. 13 a



1938 FEBRUARY 12 0700

1938 FEBRUARY 12 1800

1938 FEBRUARY 13 0700

1938 FEBRUARY 13 1800

Fig. 13 b

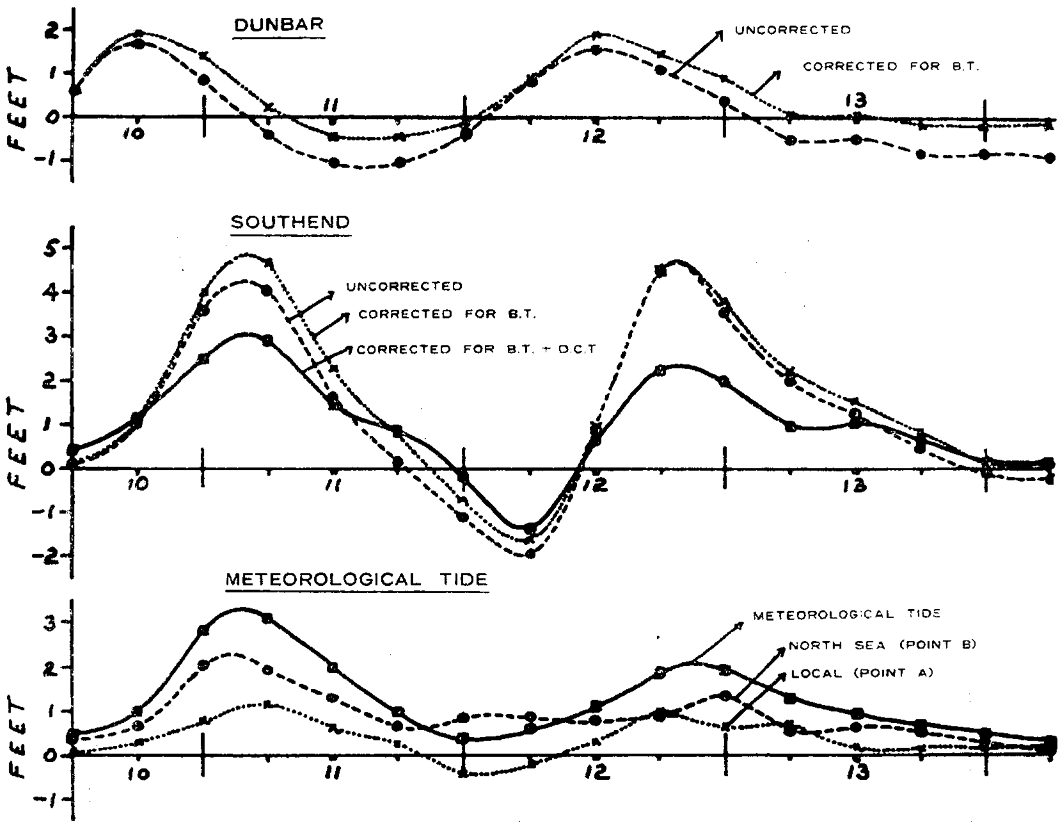


Fig. 13 c

It is evident that Mr. Corkan has produced a very satisfactory analysis of storm surges in the Thames, so much so that very satisfactory forecasts could be obtained, given accurate meteorological forecasts. There are a few anomalies which cannot be explained by the simplified formulae, but it will be evident that the theory explained earlier has not been fully used, for example, the decaying oscillaitons have not been utilised after the first ones and no account has yet been taken of the speed of travel of pressure disturbances, both of which are contributing factors in a full dynamical explanation.

The internal mechanism by which these surges are propagated (that is, the movements of the sea-water) have played no part in the investigation, but obviously a full explanation, to be looked for in due course, we hope, will cover the whole dynamical problem.

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