PRESSURE–GENERATED SURGES IN THE NORTH SEA

by

S. Ishiguro

Report No 35

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NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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Contents

This report is a part of the work described in Report 36. For the convenience of referring to this subject alone it has been arranged under a separate cover.

Abstract The characteristics of surges generated solely by a uniform atmospheric pressure field over the North Sea have been analysed by hydrodynamic computations. A set of curves showing the responses at 47 representative positions in the sea; a set of water-surface contour maps in two rectangled directions at five different stages of surge development; a set of diagrams showing the directional variations of surges; a set of diagrams showing the regional variations of the response time in the sea; and a diagram by which the highest pressure-generated surge under an arbitrary value of atmospheric pressure field can be estimated have been given, with their comparisons with wind-generated surges. Physical explanations for these characteristics have also been given. The results obtained have been applied to a method of highest resultant surge estimation (in another paper).

1. Introduction

It is understood that a surge in a shallow sea is generated by an atmospheric pressure field and wind field both at the sea surface. Since the wind field is induced by the pressure field, these two factors are always associated, and they are treated in combination in most theoretical investigations.

In this paper, the characteristics of surges in the North Sea, generated soley by an atmospheric pressure on the sea surface, (hereafter called 'pressure-generated surge') have been investigated hydrodynamically. This not only gives some idea of these types of surges, which are usually masked by 'wind-g enerated surges', but also supplies data for elaborating the method of highest surge estimation described in another paper (Ishiguro, 1976).

2. Method of computations

The analyses have been carried out by a depth-integrated single -layer two-dimensional electronic model which is based on a set of hydrodynamic equations, including the terms giving the effect of the earth's rotation. The mixed grid size of 50km and 100km has been used, with no time increments due to this particular technique. The model boundaries are terminated with conditions such that no reflections of long waves occur. The bottom friction is linearised with the coefficient of 0. 24 cm/s.

A uniform atmospheric pressure field (constant gradient) over the sea (within the modelled area) is instantaneously applied, in two rectangled directions. The atmospheric pressure outside the modelled area is kept undisturbed. Note that this creates a discontinuity in the pressure gradient on one of the boundaries.

After these basic dynamic solutions have been obtained, solutions for specific problems are carried out by vector computations. This procedure is outlined in Appendix 1.

A particular relationship between the x and y axes of the model and the indication of directions for a pressure field etc. , is used in this paper, in order to relate these factors with other papers. Details are explained in Appendix 2.

3. Sea-surface response to a uniform pressure field

Figures 1a and 1b show the computed responses of the sea level to an instantaneously applied uniform pressure field (constant gradient in westerly and northerly directions). Note that the direction (shown by an arrow) is taken towards the low pressure, for convenience of comparisons with a wind-generated surge. Figures 2a and 2b show the same data, but displayed in contour maps at the 5th, 10th, 20th and 40th hour (see the 248° map and 338° map in Figure 4 for those at the 30th hour.

In the westerly pressure field (Figures 1a and 2a), whose pressure is high along the British coast and low along the continental coast, water moves almost exclusively within the North Sea, although there is flow of water into the sea through the Straits of Dover, and also a small amount of water flows out through the northern boundary, during the transient state of surge development.

Since the amount of water associated with a surge is limited, and the distance moved by the water is short, the time taken to reach a steady state is generally short. The overall pattern of surface contours follows closely the atmospheric pressure field almost from the start to a steady state, with the undisturbed water level (zero contour) approximately on the long centre-axis of the sea, although a small amount of anticlockwise rotation can be seen in the general direction of the contours.

During the transient state of the development of a surge (say 10th to 20th hour), currents having direction west to east create, with the effect of the earth's rotation, a temporary rise (or a positive peak) of water level along the continental coast, before the whole sea reaches a steady state. The currents flowing into the sea through the Straits of Dover also increase this tendency. This peak can be seen clearly in Figure 1a, although it is not clear in Figure 2a unless values of contours are examined carefully.

A positive peak along the Norwegian coast and a negative peak around Aberdeen (also clearly seen only in Figure 1a), at approximately the 5th hour, seems to be a reflection of waves from the two coasts, which is emphasised by the instantaneously applied pressure field (this is unlikely to happen in the natural sea whose pressure field never changes so suddenly).

In the northerly pressure field (Figures 1b and 2b), a large amount of water flows into the North Sea through its northern boundary during a transient state, in order to balance the atmospheric pressure at the sea surface. The effect of the earth's rotation on these currents makes the sea level along the British coast high, and that along the continental coast low. The general direction of the contours at the 5th hour shows this clearly, with a high point off Hartlepool. Some irregularity of the contours at this stage is due to the variation in currents associated with local topographies. As the development of a surge progresses, the general direction of the contours rotates anti-clockwise, and the maximum moves towards the Straits of Dover.

At a steady state (say the 40th hour), all the contours are very uniform and follow, almost exactly, the atmospheric pressure at the sea surface, showing little effect of local sea-bottom topography (compare these with the contour maps for a wind-generated surge; e.g. Figures 10 and 12 of Ref. 2). The maximum surge is developed in the German Bite, because this is a closed corner of the sea, in addition to its very shallow water depth.

Currents still flow out through the Straits of Dover, even after the sea has reached a steady state (see chapter 2 for the boundary condition of this part), and these make the surface contour exceptional here, compared with the rest of the sea. Currents which compensate these currents flow into the sea through its northern boundary, but their amount is small compared with the section of the northern boundary, and little effect can be seen on the contour around there.

The undisturbed water level (zero contour) stays around Bergen all the time, because the water level outside the North Sea is not affected by the pressure field in this model condition.

Although Figures 1a and 2a show the responses of water to the westerly direction of pressure fields, and Figures 1b and 2b show those for the northerly direction, the responses to the easterly and southerly pressure fields can be obtained by reversing the direction and signs of values in the two sets of diagrams respectively. All the values for surge heights in these diagrams are given in the unit of cm/(mb/100km) so that a surge height for an arbitrary pressure gradient can be obtained by multiplying the gradient by a value on the diagrams.

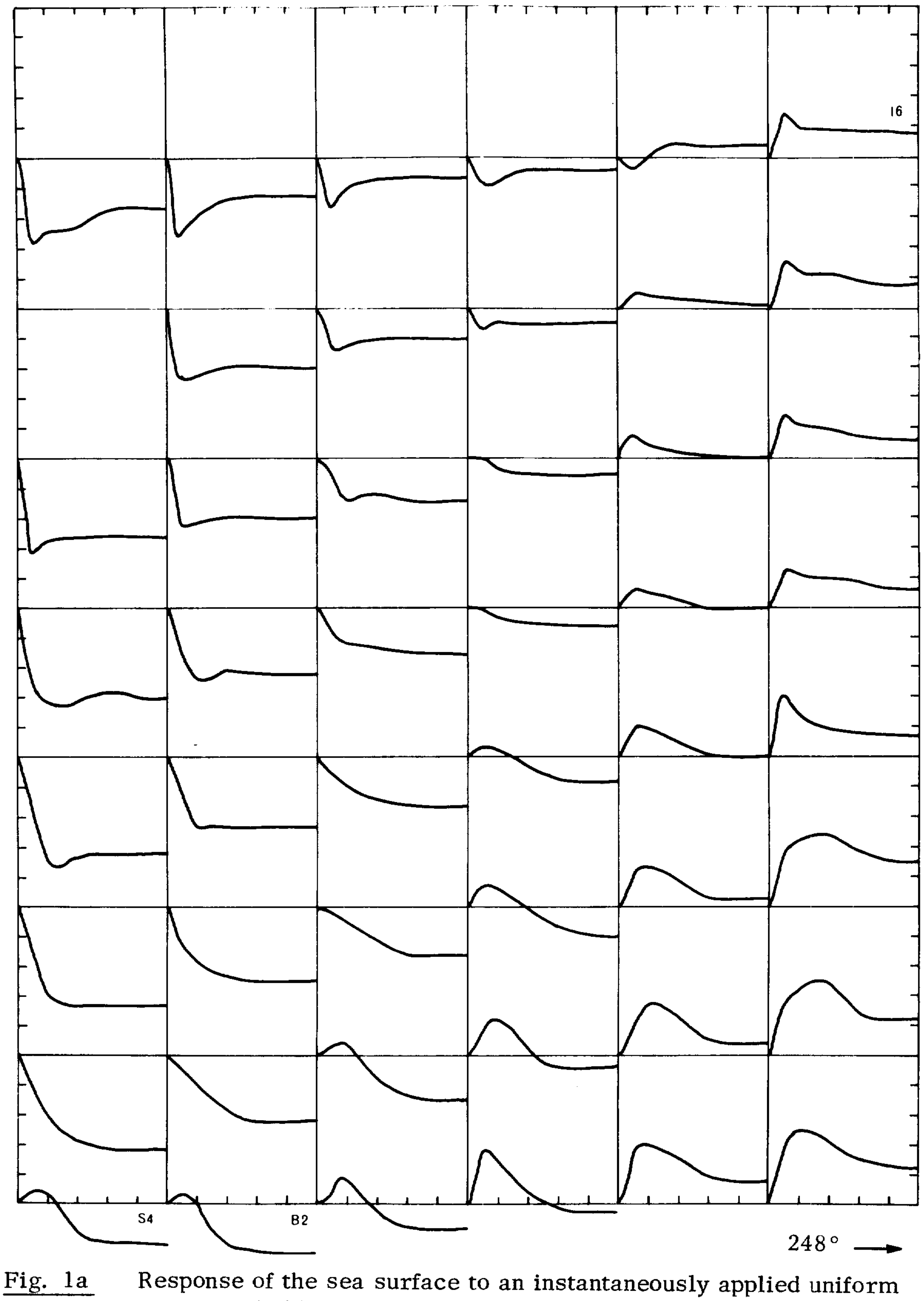
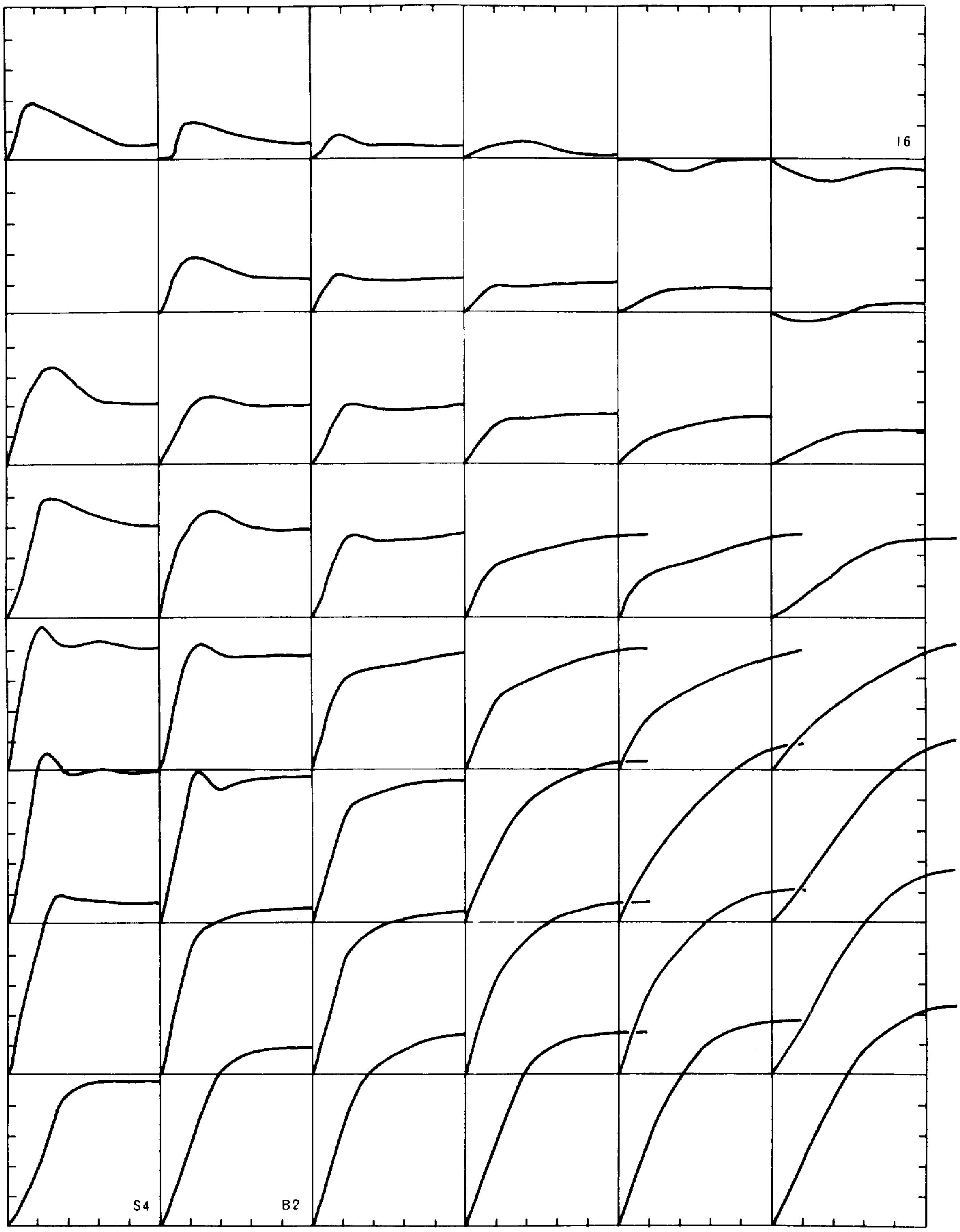


Fig. 1a Response of the sea surface to an instantaneously applied uniform pressure field (constant gradient) over the North Sea, the westerly direction.

Response curves for 47 representative positions in the sea are shown in square frames. Within each frame, the surge height per pressure gradient, in cm/(mb/100km) is taken as one division of the vertical axis; and time, in 10 hours, is one division of the horizontal axis. The representative positions are shown in the key map on the next page. The arrow points to the direction of low atmospheric pressure on the sea surface.



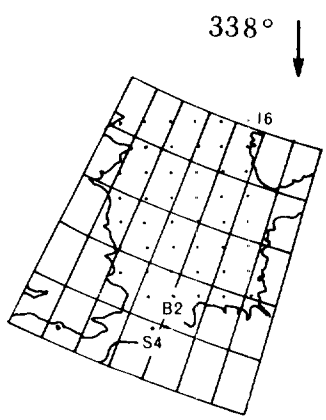


Fig. 1b The same as Fig. 1a,
but for the northerly direction

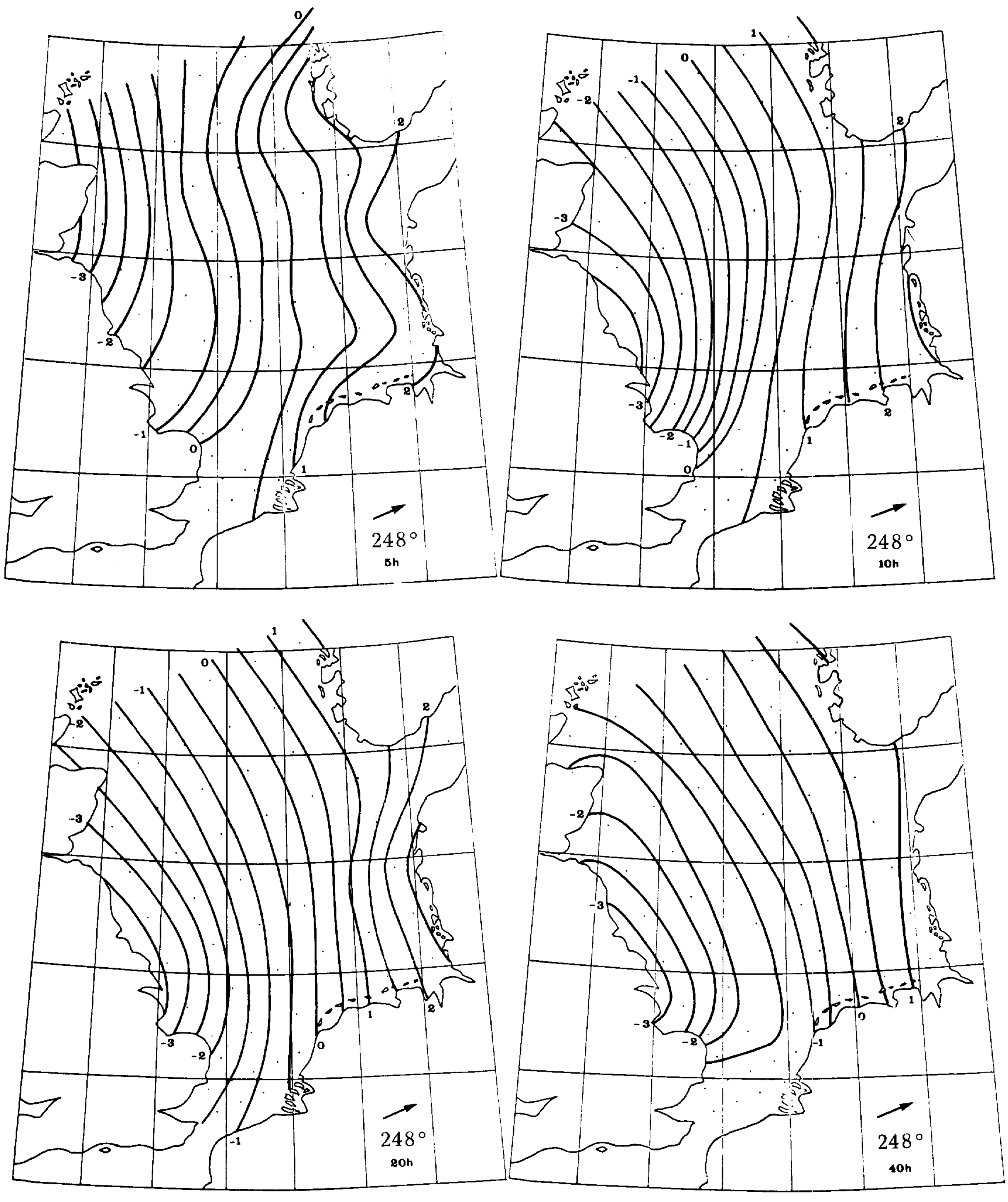


Fig. 2a Response of the sea surface to an instantaneously applied uniform pressure field (constant gradient) over the North Sea, the westerly direction.

Values for a contour are in cm/(mb/100km); the negative sign indicates a water level below an undisturbed surface, and the positive sign above it. Arrow points to the direction of low atmospheric pressure at the sea surface. Time is given in hours referred to the start of application of the pressure field.

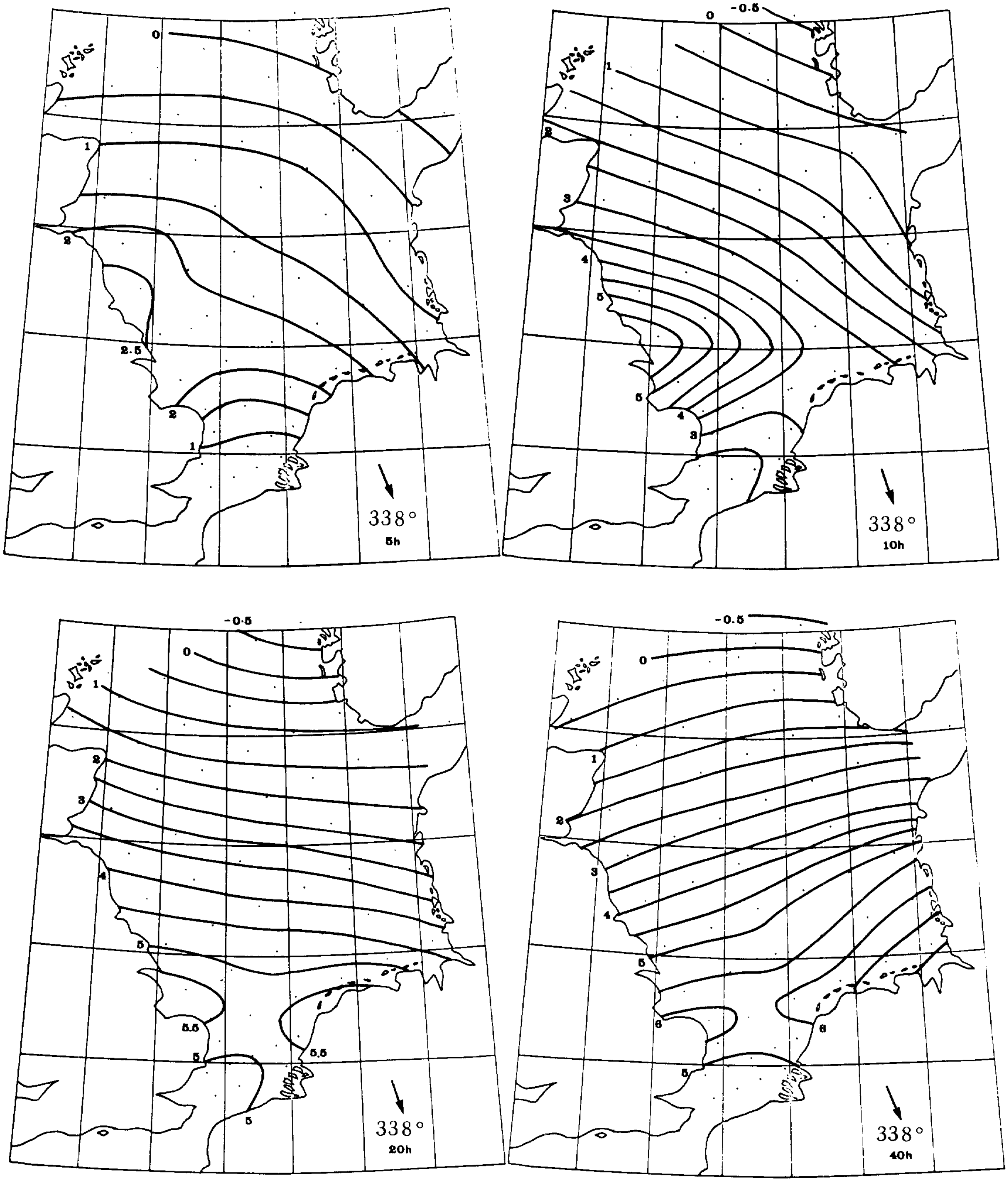


Fig. 2b The same as Fig. 2a, but for the northerly direction.

4. Response time

The response time of the sea surface, even to a uniform external force covering it, varies with the position and direction of the force. This is due to the fact that disturbances generated at various parts of the sea reach a certain position with different delay times and different magnitudes which are affected by the topography of the sea and the earth's rotation.

Figure 3 shows the computed response time of a surge to an instantaneously applied uniform pressure field (constant gradient) over the North Sea, in the westerly and northerly directions. The response time is defined here as a period between the start of application of the field and time when the surge height reaches 90% of its equilibrium value, or 90% of a peak value, if there is any peak before the equilibrium value. An equilibrium value could be above or below an undisturbed water level. In some cases, a peak value, referred to as an undisturbed water level, is greater than an equilibrium level (see Figure 1a).

In the diagram for the westerly pressure field (Figure 3a), a response time whose equilibrium value (or a peak value) is below an undisturbed level is shown by a solid line, and that for above an undisturbed level by a dotted line. The dashed straight line across the middle of the North Sea shows an approximate boundary at which the polarity of equilibrium values (or peak values) changes. In the rectangular area bounded by dashed lines, a positive peak is generated before a negative equilibrium value.

In the diagram for the northerly pressure field (Figure 3b), the area of negative equilibrium level is not significant (off Bergen).

Comparing the diagrams for the two directions (Figures 3a and 3b), a resemblance in their patterns, except for the values of the lines, is immediately recognisable. The response time is minimum along the Scottish coast, and maximum around the Danish coast. In Figure 3a, the maximum for the negative equilibrium value would be at the same position as that in all other cases, if these curves were extrapolated. The reason for this can be explained as follows:

Any disturbance entering the North Sea through its northern boundary propagates, as a free wave under the influence of the earth's rotation, along the coasts in an anticlockwise direction from Aberdeen coast to Bergen coast, crossing the Straits of Dover and the Skagerrak. This is the longest possible distance which a wave can travel, and it determines the largest response time of the sea. In practice, however, the height of such a wave is reduced sharply when it enters the Skagerrak, whose water depth is great (more than 400m) compared with that of the German and Danish coasts (say 40m); in addition, the wave height is already decreasing before it arrives here. In fact, the wave height is hardly distinguishable from other disturbances, after it has entered the Skagerrak. Consequently, the largest response time of the sea appears to be along the Danish coast of the Skagerrak.

The maximum response time of the positive peak (dotted lines in Figure 3a) appears approximately at the same place as the others, and this can be explained in the same way. The maximum value of the response time of this peak is much shorter than others, because it enters into the North Sea through the Straits of Dover.

The response time in this treatment is independent of the polarities of water level or currents, since the whole system is linearized.

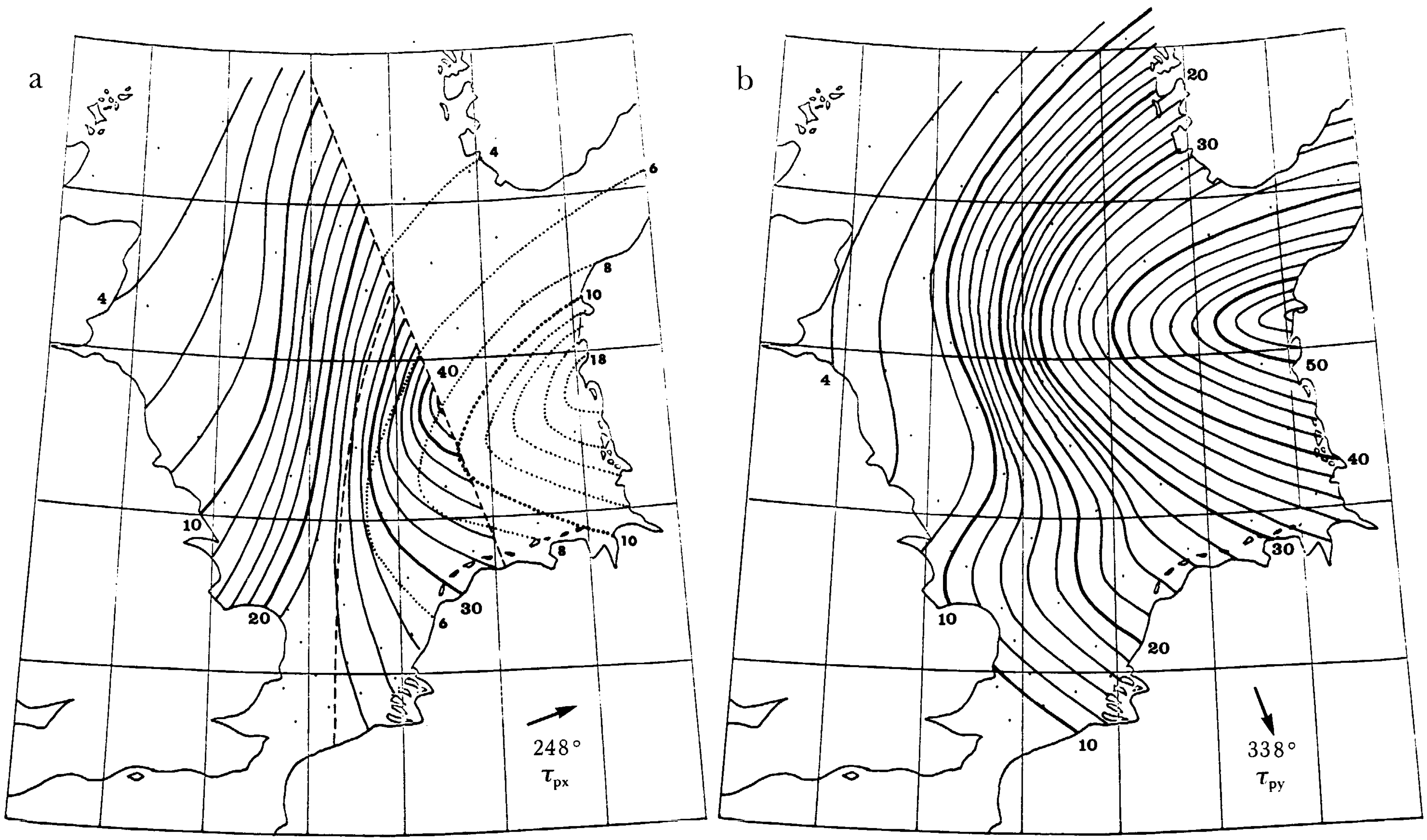


Fig. 3 Response time to an instantaneously applied uniform pressure field (constant gradient) over the North Sea. See the text for details.

5. Directional Variations

Figure 4 shows a set of water surface contour maps which are similar to those in Figure 2, but sampled at the 30th hour only, and for different directions of a uniform pressure field (constant gradient), with 30° intervals (38°, 8°, 338°, 308°, 278° and 248°). Each of the diagrams for 218°, 188°, 158°, 128°, 98°, and 68° can be obtained from the set shown in Figure 4 by using a diagram whose direction differs from a direction in question by 180°, and by reversing the polarities of all the values for its contours. The oddity of these angles is due to the relationship between geographical north and geometrical long axis of the sea (see Appendix 2).

Note that in the comparisons of these diagrams, the degree of approach to a steady state is different in each diagram. It is recognisable, however, that the sea surface contours almost follow those of the atmospheric pressure field in any direction of the field.

The effect of the existence of the Straits of Dover can clearly be seen in some cases where the direction of the pressure field is similar to the long axis of the sea. Note that this effect would not be seen if the pressure field (with an equally uniform gradient) was extended towards the English Channel and the open sea.

The values for contours are in the unit of mb/(cm/100km) so that they can be used for an arbitrary pressure gradient.

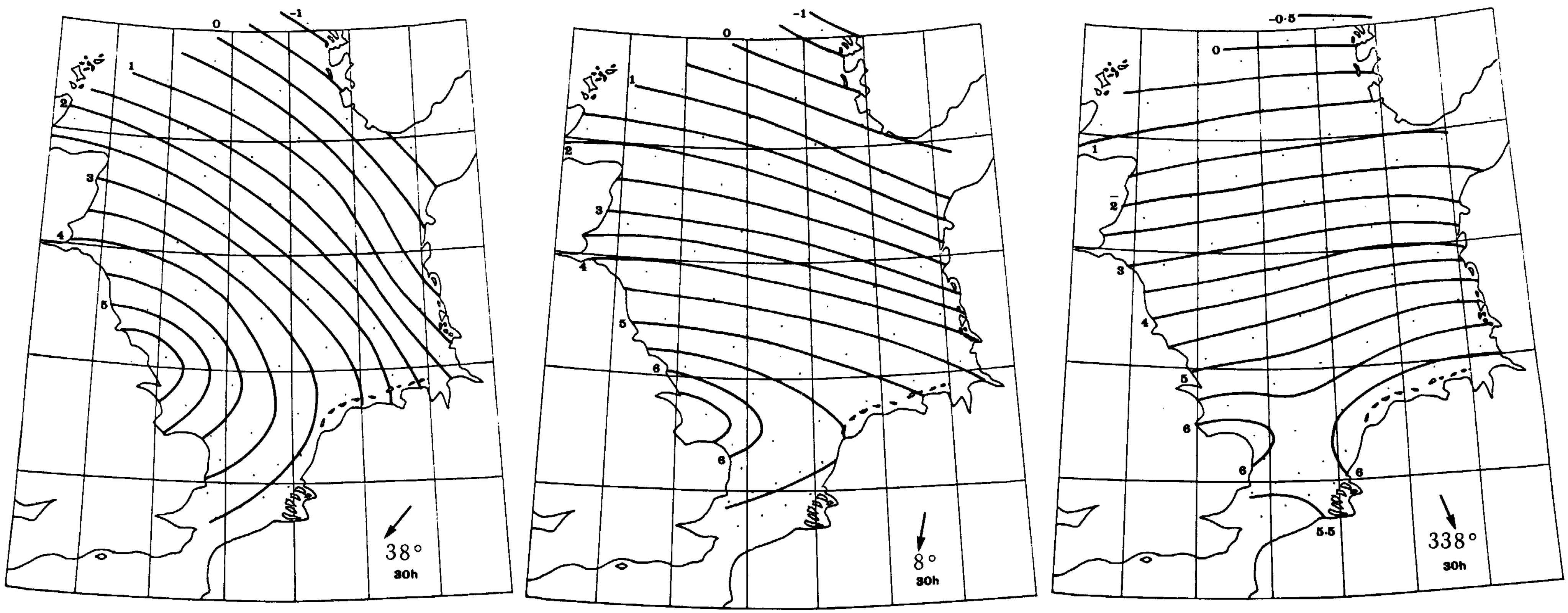


Fig. 4 Directional variations of the water surface response to an instantaneously applied uniform pressure field (constant gradient) over the North Sea, at the 30th hour.

Arrow points to the direction of low pressure. Value for a contour is in cm/(mb/100km), referred to an undisturbed sea surface.

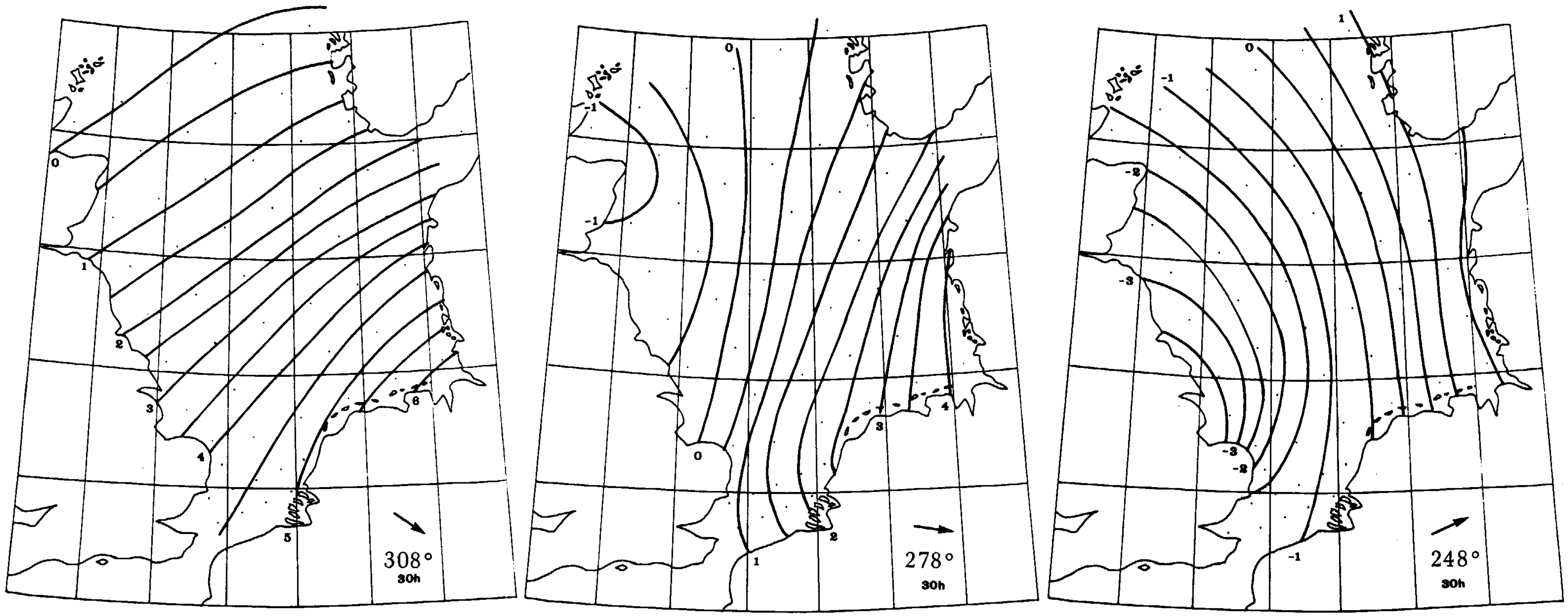


Fig. 4 (continued)

6. Highest (or lowest) pressure-generated surges

Figure 5 shows a diagram by which the highest (or lowest) pressure-generated surge in the North Sea can be estimated for an arbitrary position in it, assuming that the water height of any part of the sea reaches a steady state at the 30th hour (in fact, a longer time is required for the continental coasts; see Figure 3b).

The procedure of an estimation is as follows:

(1) Choose a certain position of the sea for which an estimation is required,

(2) read the values of a surge height and angle on this position, say 4cm and 20° for a position off Aberdeen,

(3) adjust the read surge height for a given pressure gradient, say 5 mb/100km, by:

$$\text{Highest surge} = 4 \text{ cm} \times \frac{5 \text{ mb/100km}}{1 \text{ mb/100km}} = 20 \text{ cm}$$

(4) then the final answer is:

'the highest water level off Aberdeen, under a uniform pressure field with the constant gradient of 5 mb/100km over the North Sea, will be 20 cm higher than a predicted tidal level, and the direction of such a pressure field (low pressure) will be 20° referred to geographical north.

The lowest surge can be estimated by the same procedure, but the sign of the final height must be reversed, and 180° must be added to the read value of the angle.

There is a particular point, off Bergen, where the amplitude of a pressure-generated surge becomes minimum for any direction of atmospheric pressure gradient at the water surface. The exact position of this point in this analysis, however, depends on the accuracy of the boundary of the model, particularly its position in the modelled area. Although the position of the boundary in this model is reasonable, it is ideal to set such a boundary further north, say 200 km from the present one, where the continental slope makes a great discontinuity of the dynamic characteristics of the sea.

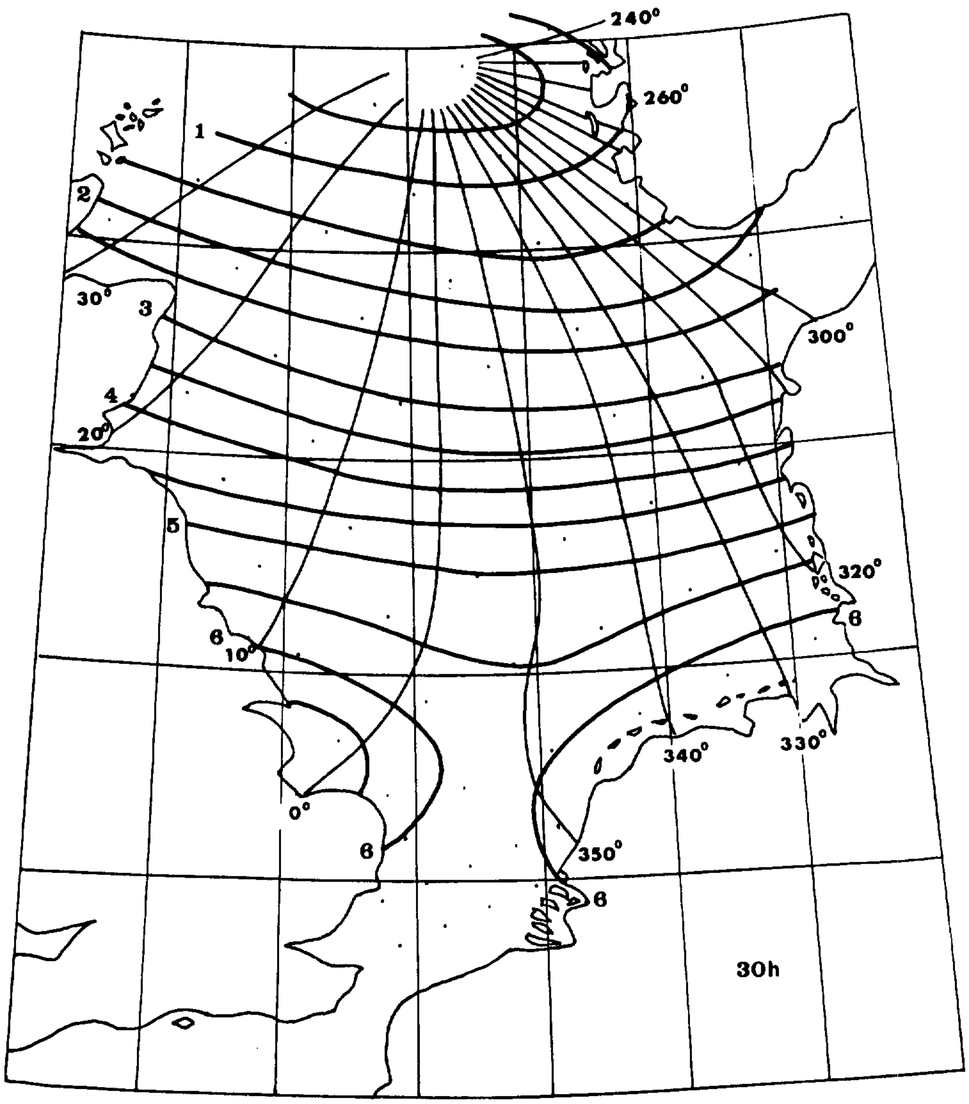


Fig. 5 Diagram for estimating the highest pressure-generated surge and direction of the pressure field, in the North Sea.

The value for thin line shows the direction of a pressure field, in degrees, referred to as geographical north (e. g. 0° indicates that pressure increases towards north). The value for a thick line shows the surge height per pressure gradient in cm/(mb/100km). See the text for details.

7. Comparisons with wind-generated surges

A similar set of analyses to those in this paper, but for wind-generated surges in the North Sea, has been described in chapter 5 of another paper (Ishiguro, 1966), and this set can be used for comparisons (See Appendix 4 for its extract).

An obvious difference between a pressure-generated surge and a wind-generated surge is the pattern of their water surface contours. The former has fairly uniform contours which are affected only by a large-scale bottom topography of the sea, while the latter has contours which are clearly affected by local bottom topography as well as that of the whole sea, showing sharp rises of the surface towards shallow waters.

When a surge, in the North Sea, generated by a uniform pressure field over the sea and that by a uniform wind field, both in the northerly (or southerly) direction in a steady state, are compared, a clear difference can be seen in the distribution of positive and negative water -level areas, and therefore also in the patterns of zero contours. In a pressure-generated surge, almost the whole sea surface rises (or falls), while in the wind-generated surge, the water in about half of the sea area rises (or falls) and the rest falls (or rises). This is due to the fact that a far larger amount of water moves into (or out of) a shallow part of the sea in a wind-generated surge than a pressure-generated surge.

When absolute amounts of water levels (or currents) in a pressure-generated surge and those in a wind-generated surge are compared, all the values have to be adjusted so that the pressure field and wind field satisfy a single meteorological situation. Among several possible ways of relating a pressure field and wind field for this purpose, the application of a set of statistical data given by Dietrich et al (1952) would be the most appropriate one. They have found, from a large number of observational data in the North Sea covering a period of 47 years, that the deflection of wind from the direction of an atmospheric pressure gradient is 77.5°, and the pressure gradient of 1 mb/100km produces the wind speed of 4.5 m/s over most of the sea.

Approximate comparisons of a pressure-generated surge and a wind-generated surge, under related conditions, for a particular position in the North Sea are shown in Table 1. The procedure of calculating these data is shown in Appendix 3.

We understand that the pressure-generated surge will not exceed 40 cm even in extreme meteorological conditions in the North Sea, but the error due to ignoring the pressure-generated surge from the resultant of the two types of surge will range between approximately 6% and 70%, low wind speeds being large errors, within the range of wind speeds of 10 m/s and 40 m/s.

Note that the highest surges in the North Sea, and the direction of wind field or pressure field, cannot be estimated by adding the two highest values obtained in the two diagrams (such as Figure 5 in this paper for pressure-generated surges, and Figure 13 of Ref. 2 for wind-generated surges). A practical solution for this problem has been given in another paper (Ishiguro, 1976).

Table 1. Approximate comparisons of a pressure-generated surge and a wind-generated surge, at a particular position (off the Wash) in the North Sea, under different wind speeds.

Wind direction	Wind duration	Wind speeds	Pressure gradient	Pressure -generated surge, ζ_p	Wind -generated surge, ζ_w	ζ_p/ζ_w
degrees	hours	m/s	mb/100km	cm	cm	%
22	30	10	2.3	8	33	24
		20	4.5	16	130	12
		30	6.7	23	293	8
		40	9.0	32	520	6
112	10	10	2.3	10	15	67
		20	4.5	20	60	33
		30	6.4	30	135	22
		40	9.0	40	240	17

8. Conclusions

The characteristics of a surge, in the North Sea, generated solely by an instantaneously applied uniform pressure field over the sea, have been analysed by hydrodynamic computations.

Since this type of surge is less influenced by local topography of the sea, compared with wind-generated surges, the effect of its large scale topography and those of the earth's rotation on surges can be understood more easily.

A pressure-generated surge at a steady state has even surface contours with almost the same direction of gradient as that of the pressure field, in any direction. The existence of the Straits of Dover has a considerable effect on the response of the North Sea, both at transient and steady states. At a transient state under a certain direction of pressure field, currents flowing into the North Sea through the Straits of Dover create, under the influence of the earth's rotation, a peak surge whose height is greater than an equilibrium level, along the Dutch, German and Danish coasts.

The absolute values and the variations of the response time of the North Sea to an instantaneously applied uniform pressure field have been investigated. The maximum value of the response time occurs near the Danish side of the Skagerrak, in any direction of pressure field; the reason for this has been explained.

All the diagrams in this paper have been designed so that the height of a pressure-generated surge can be estimated for an arbitrary pressure gradient.

A diagram by which the highest pressure-generated surge under a given pressure gradient can be estimated, together with the direction of such a field, has been given. The heights of pressure-generated surges and wind-generated surges in the North Sea have been compared.

The results obtained from this paper have been applied to a method by which the highest resultant surge in the North Sea can be estimated, in a different paper (Ishiguro, 1976).

The accuracy of these analyses mainly depends on that of the basic hydrodynamic computations carried out by the electronic model. The accuracy of the model has been proven to be reasonable,by comparing its output with observational data obtained in the North Sea (Ishiguro, 1972). Further improvements of the accuracy of this kind of analysis are expected by using the newly-built electronic model.

References

(1) Dietrich, G. , et al (1952):
Wind conditions over the sea around Britain during 1900-1946, The German Hydrographic Institute, Hanburg, pp38.

(2) Ishiguro, S. , (1966):
Storm surges in the North Sea, Advisory Committee on Oceanographic and Meteorological Research, Paper 25 (iii), pp57.

(3) Ishiguro, S. (1967):
Storm surges in the North Sea, Advisory Committee on Oceanographic and Meteorological Research, Paper 27 (iii), pp97.

(4) Ishiguro, S. , (1972):
An electronic model for tides and storm surges in the North Sea, IOS Internal Report, pp234.

(5) Ishiguro, S. , (1976):
Highest surge in the North Sea, IOS Internal Report No. 36, pp. 31

Appendix 1 Outline of computing procedure

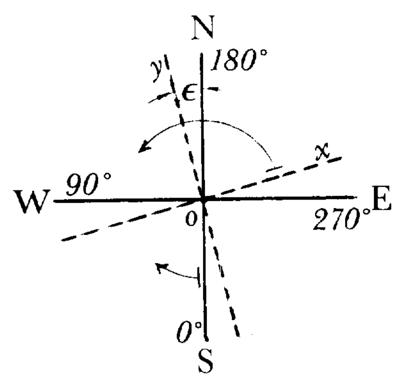
(1) A set of step-function responses of water height in the North Sea, 7442 solutions in all, has been obtained by the electronic model which is based on a set of hydrodynamic equations, including the terms for the earth's rotation. Values of this output have been stored as a set of numerical table and punched cards. Some of them are selected for this application.

(2) 14 representative positions in the North Sea are chosen first. Resultants of surges each of which is generated at another 40 positions in the sea are computed for each of the 14 positions,in the x and y directions, from the above mentioned set. Then the values given for the 14 positions are interpolated for the 40 positions, with five different sampling times.

(3) From these data, response curves, contour maps of water surface, and response time diagrams have been made. In order to obtain solutions in other than x and y directions, interpolation operations in vector quantities have been carried out. In order to estimate the maximum value of a surge, the maximum of a set of vectors has been computed.

Appendix 2 Indication of directions

The wind direction is customarily specified as that direction from which the wind is blowing. When this is indicated by an angle, this increases clockwise, referred to geographical north. For a mathematical expression, the right-hand rectangular cartesian co-ordinate system, in which an angle increases anticlockwise, referred to as its positive x-axis, is commonly used. Each axis of the model grids covering a large area has a different angle referred to geographical north. In order to combine these systems, a rather complex relationship as shown in the figure, has to be accepted, throughout this paper, and another paper (ref. 5). Full information is given for ϵ in Ref. 3.



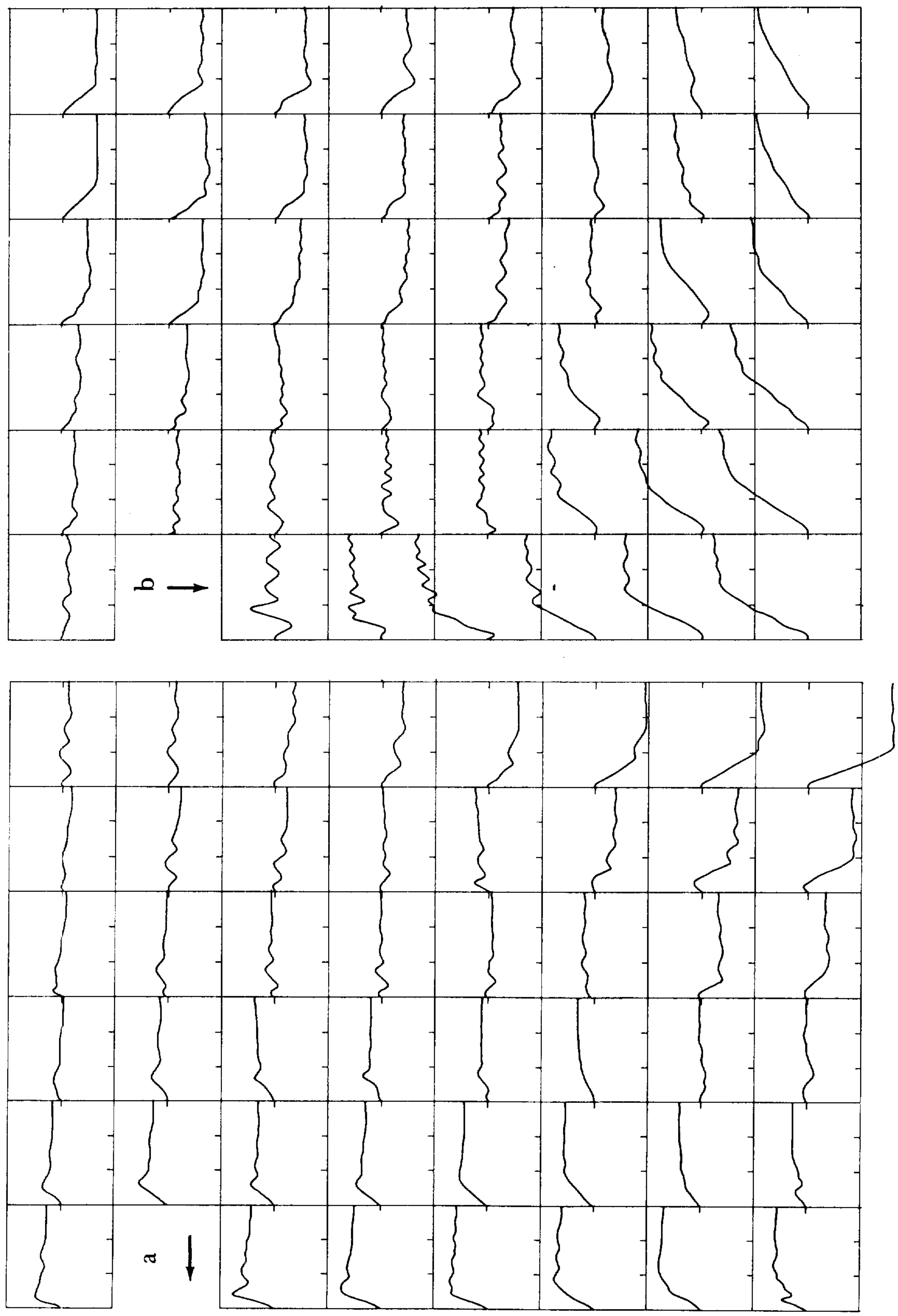
ϵ = 22° at the centre of the North Sea

Appendix 3 Procedure of calculating the data in Table 1

The wind duration of 30 hours is used for the northerly wind field, and that of 10 hours for the easterly wind field, because of their response times. The Wash is chosen as an example, since this is one of the positions in the sea where high surges have often been experienced. A wind-generated surge given in Ref. 2 (page 25) has been designed so that surge heights for the wind speed of 20 m/s can be read directly. Therefore, the conversion factor of $(S/20)^2$ has been used for making data in Table 1. The wind field and pressure field used in this calculation are related by a set of factors given in Ref. 1. For relating the angles of the wind field and pressure field, the nearest values available are used, instead of the exact value. Therefore, the results in the table are approximations.

Appendix 4 Wind-generated surges.

Extract from Ref. 2 (Ishiguro, 1966). The number and caption of each figure is different from the original.



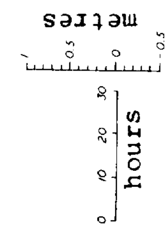


Fig.6 Response of the sea surface to an instantaneously applied uniform wind field (constant speed of 20m/s) over the North Sea. (a) Easterly wind direction (68° at the centre of the sea). (b) Northerly wind direction (338°). Response curves for 47 representative positions in the sea are shown in square frames (see Fig.1b for the key map). Within each frame. the vertical axis shows the surge height. and the horizontal axis time. The scale for each axis is shown separately. For the comparison of Fig.1a and Fig.6a, the polarity of each surge height in one of the figures should be reversed.

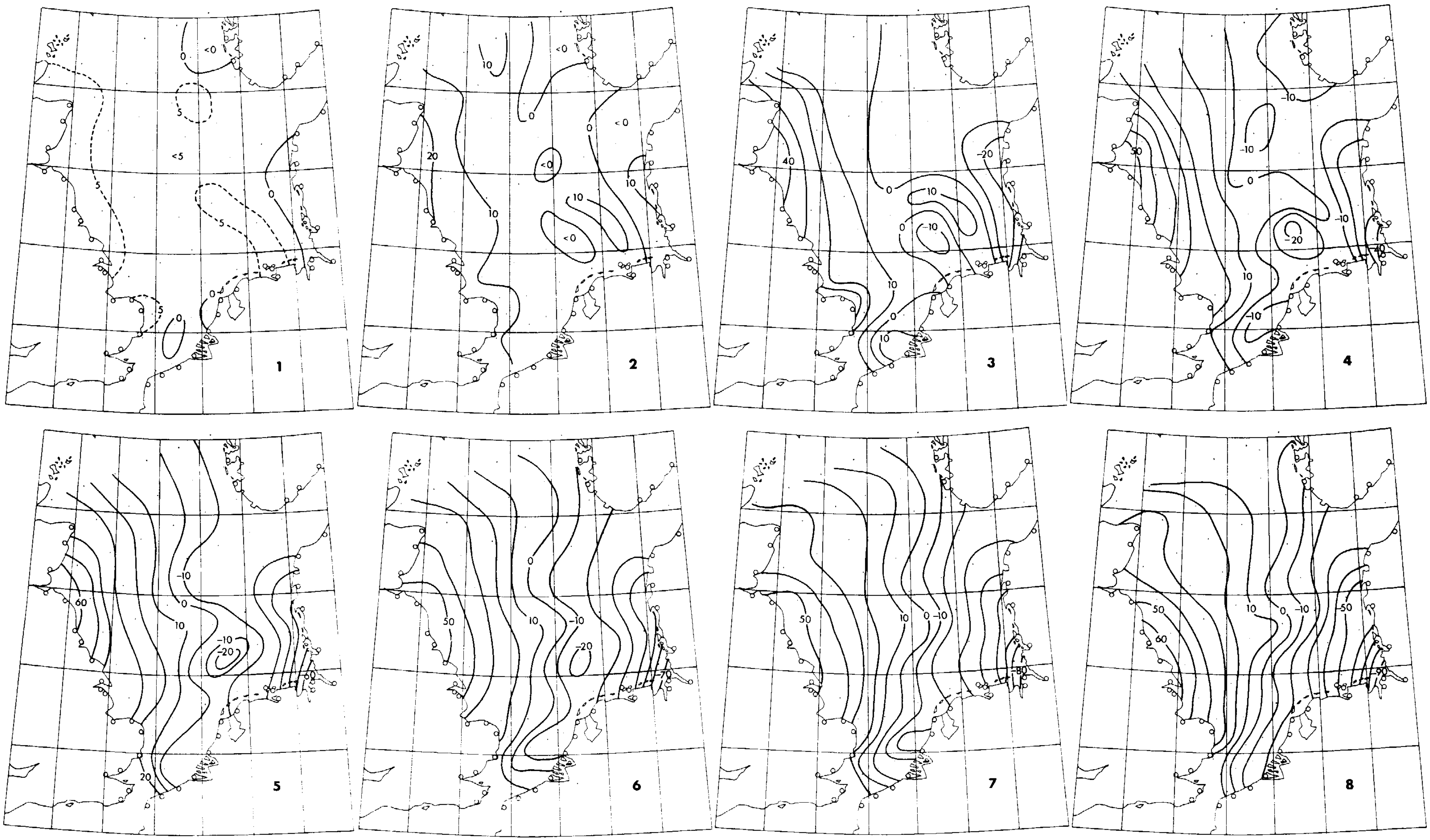
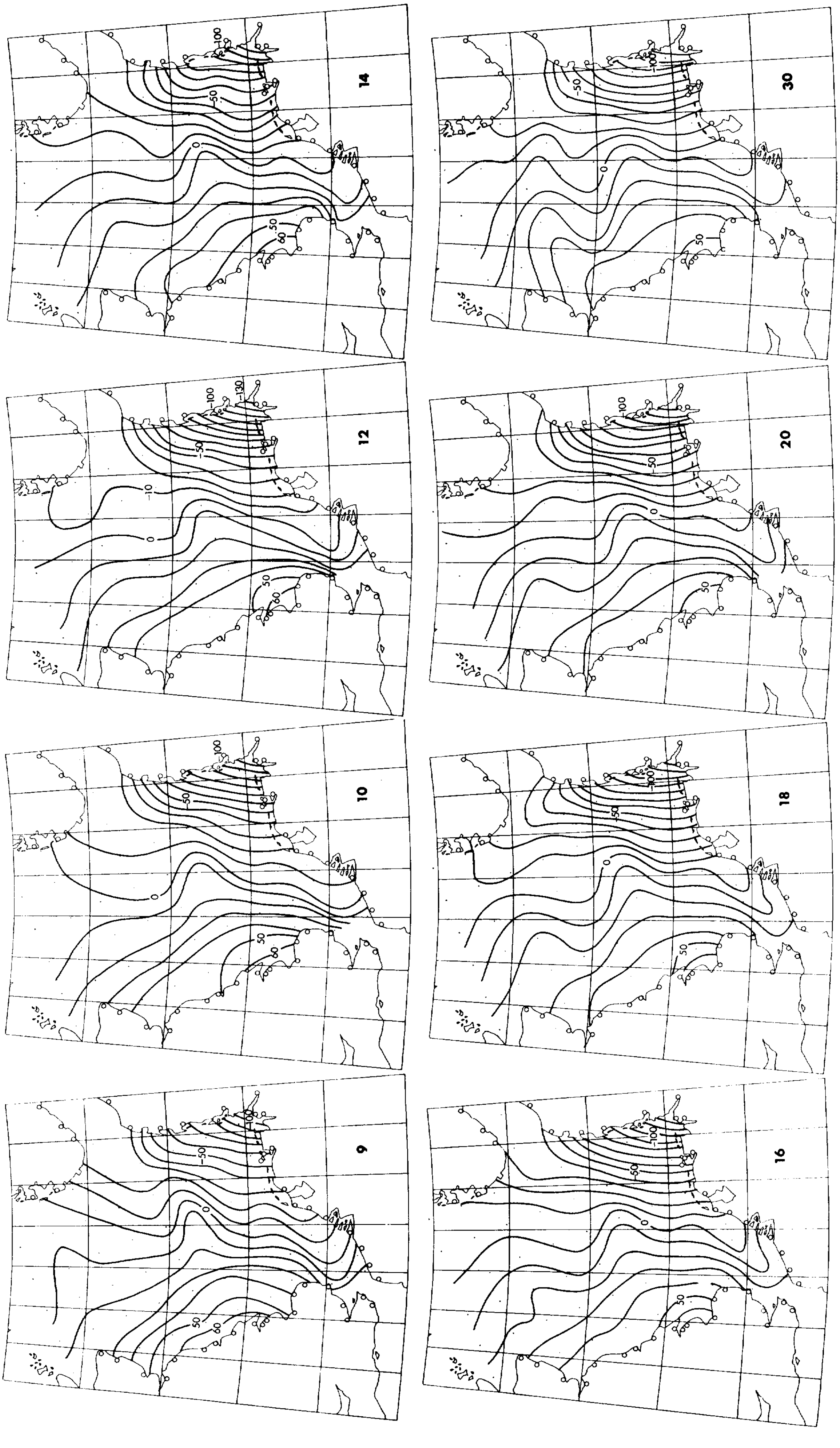


Fig. 7a Response of sea surface to an instantaneously applied uniform wind field (constant speed of 20m/s) over the North Sea. Easterly wind direction (68° at the centre of the sea). Line value is surge height in cm. The negative sign indicates a water level below an undisturbed surface, and the positive sign above it. The number in the bottom right-hand corner of each diagram shows the time in hours and refers to the start of the application of the field.


14
12
10
9
30
20
18
16
-100
-50
0
50
60
-130
-10

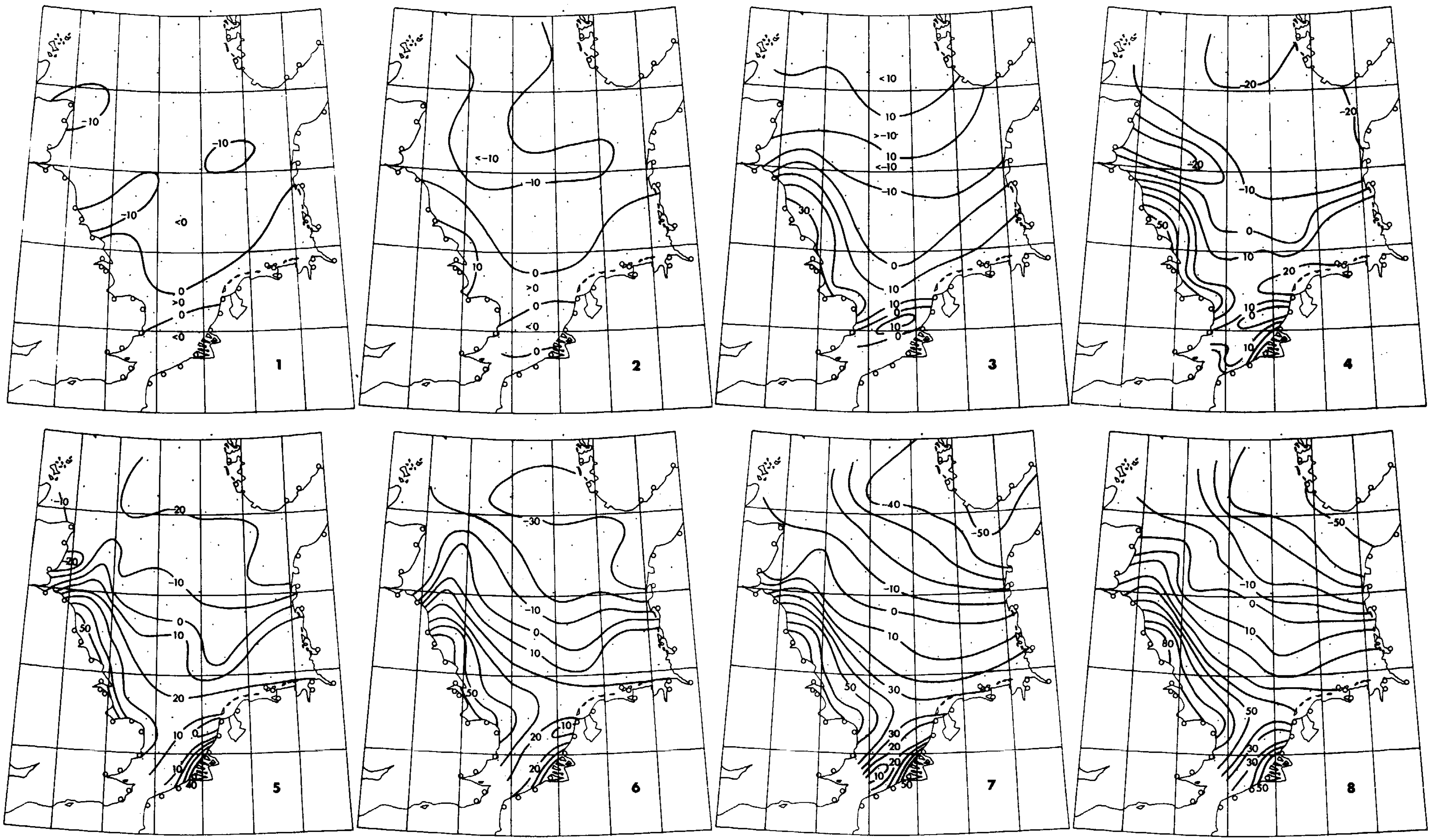
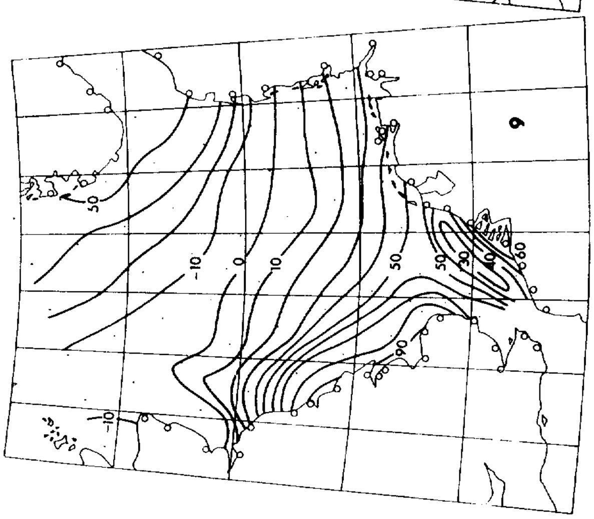
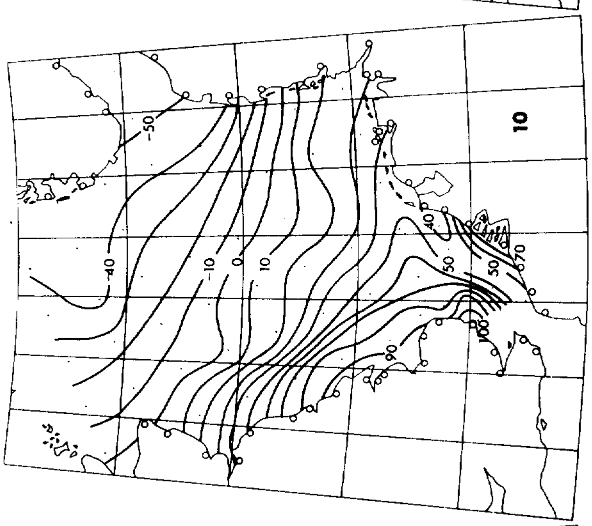


Fig.7b The same as Fig.7a, but in the northerly wind direction (338°).


9
50
-10
0
10
50
30
40
60
90
-10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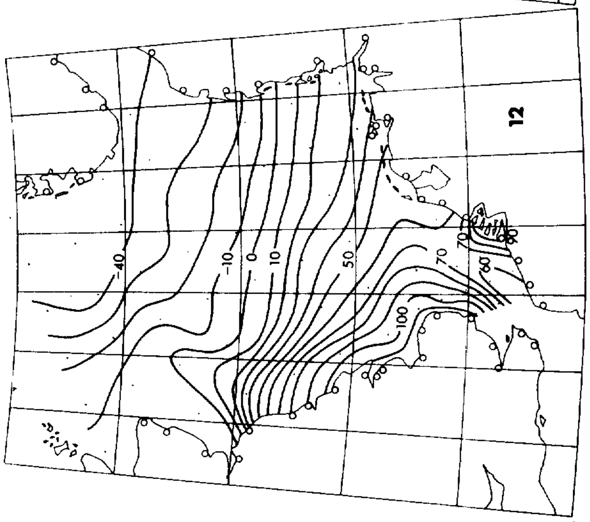
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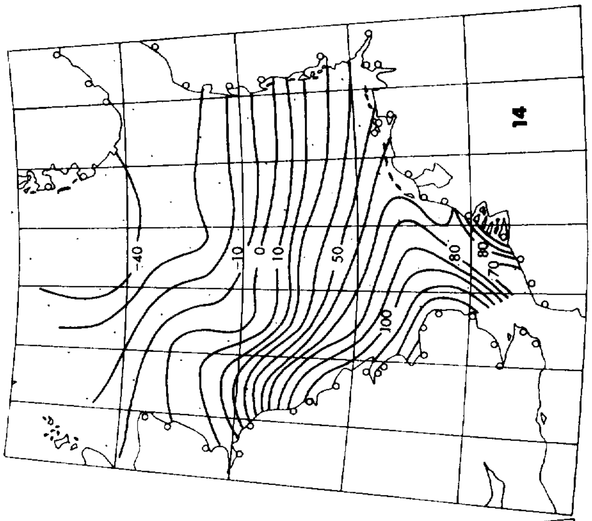
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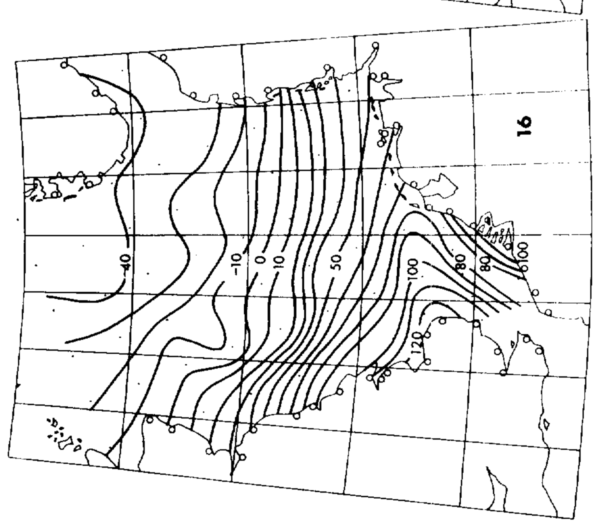
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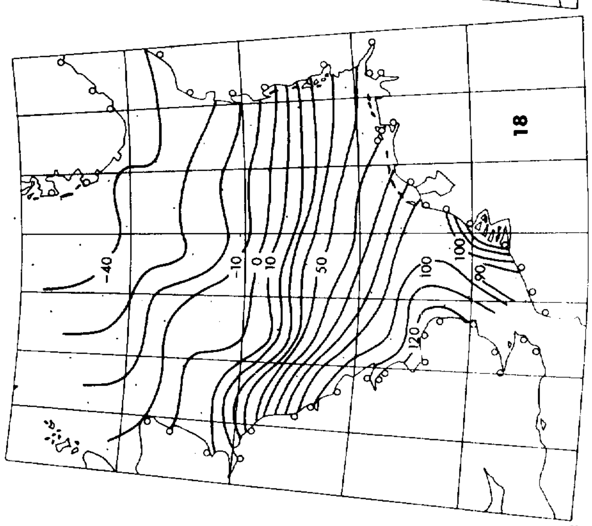
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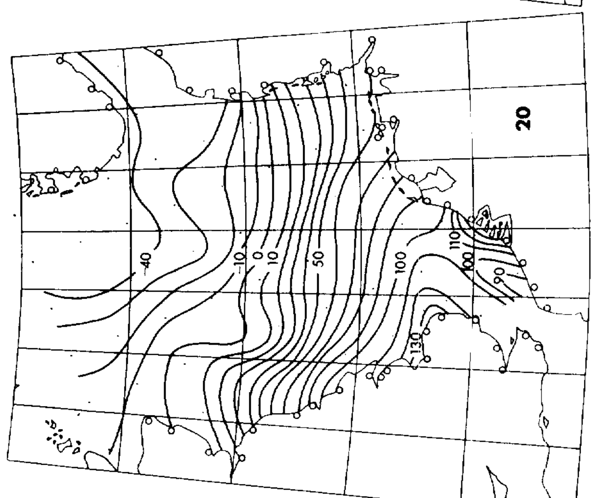
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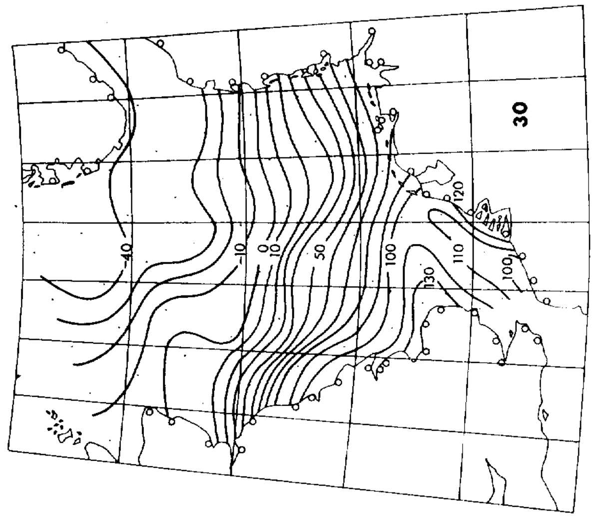
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130
100

a

b

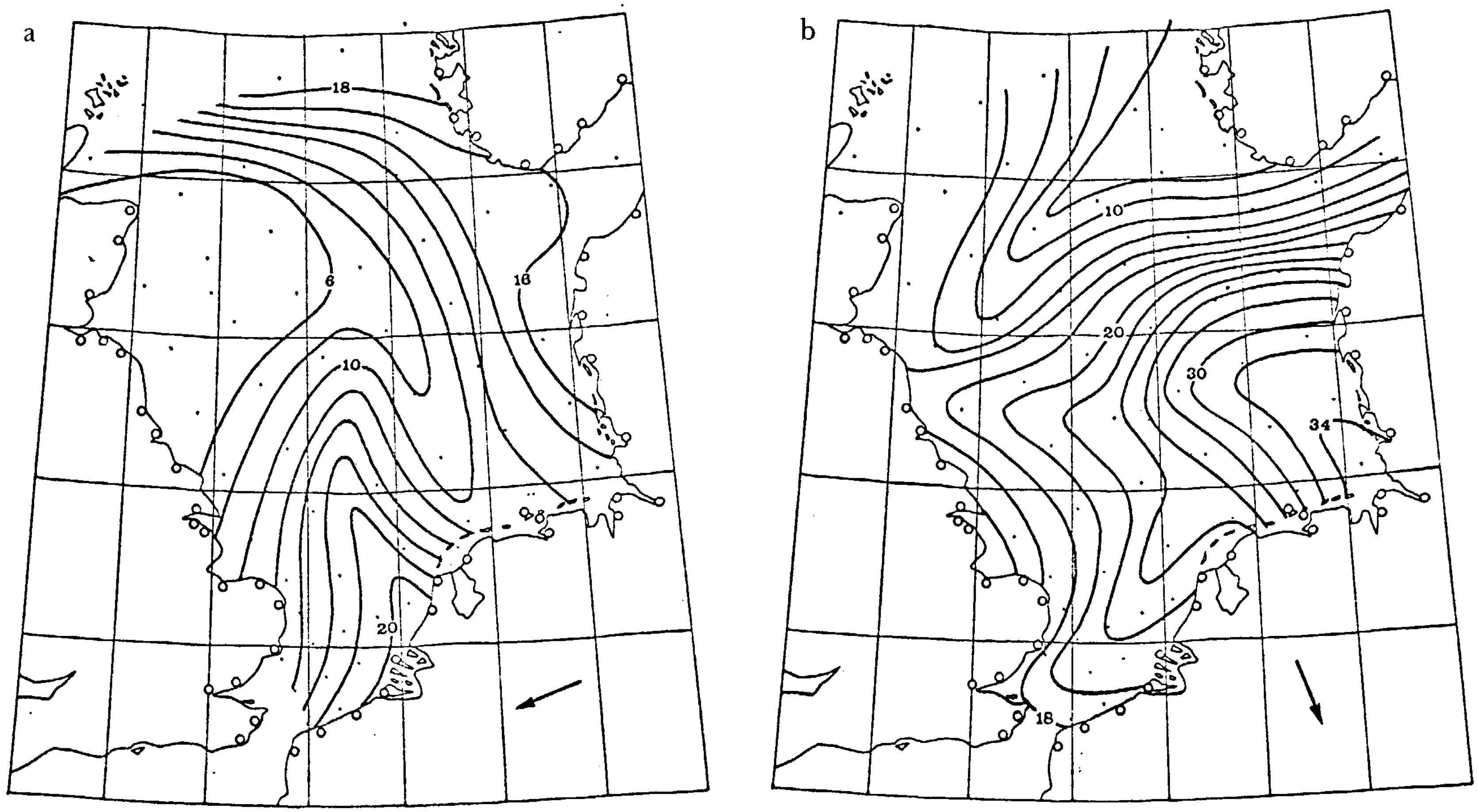

Fig.8 Response time of the sea surface to an instantaneously applied uniform wind field (constant speed of 20m/s) over the North Sea. (a) Easterly wind direction (68^{o} at the centre of the sea) or westerly wind direction (248^{o}). (b) Northerly (338^{o}) or southerly (158^{o}). Line value is the time in hours and refers to the start of the application of the wind field.

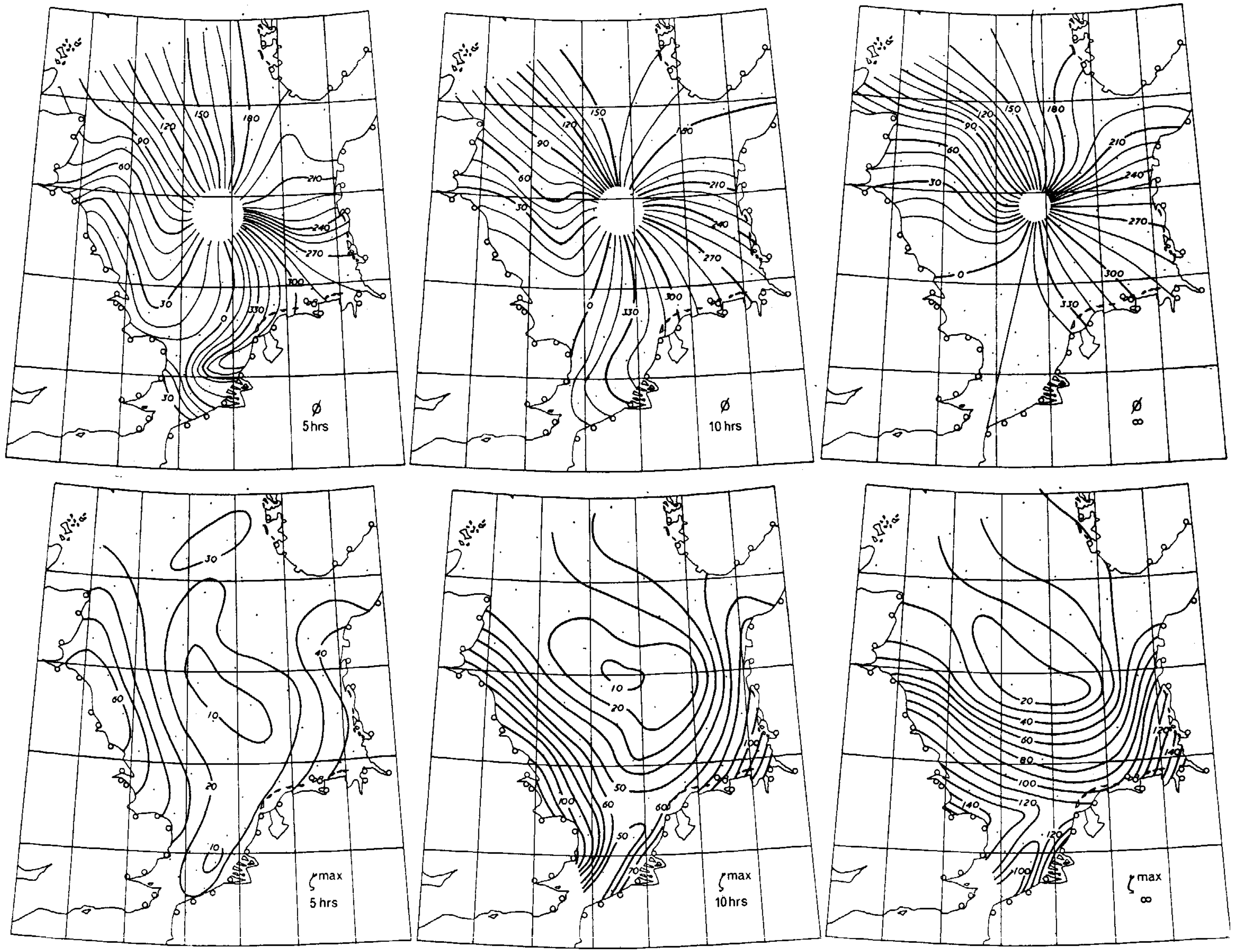

Fig.9 Diagrams for estimating the highest surge at an arbitrary position in the North Sea, for the wind speed of 20m/s averaged over its duration of 5 hours, 10 hours and inifinity respectively. The three lower diagrams show surge height in cm. The three top diagrams show wind direction, in degrees, by which such a surge is generated. The surge height for the wind speed of S m/s can be obtained by multiplying $(S/20)^2$ to the line value.