SVENSKA GEOFYSISKA FÖRENINGEN

VOLUME 5, NUMBER 2 **Tellus** MAY 1953

A QUARTERLY JOURNAL OF GEOPHYSICS

Comparison of Microseisms in Greenland, Iceland, and Scandinavia

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(Manuscript received February 16, 1953)

Abstract

Microseismic amplitudes and periods recorded at Scoresby-Sund, Reykjavik, Bergen, and Uppsala in seven different cases from the years 1949—1950 are studied. At all stations the polar air is of essential importance for the generation of microseisms, whereas there is in general no close connection with the cyclone centres themselves. A coast effect is of importance for Scandinavia, whereas the source for microseisms recorded at Scoresby-Sund is located over the open ocean within the polar air. Standing ocean waves may be of importance at the Norwegian coast but in many cases not on the open ocean. The microseismic waves propagate much farther over the continent than along the ocean bottom. The microseismic periods in Scandinavia vary generally in parallelism with the amplitudes, in Iceland and Greenland generally not. Period minima and rapid amplitude increases are observed in Scandinavia when cold fronts cross the Norwegian coast. There is no sign of microseismic barriers in the Atlantic outside Scandinavia. The microseisms at Scoresby-Sund have a regular, group character; at the other stations they are generally continuous.

Introduction

In a previous paper (Båth, 1949, p. 145) I expressed the idea that the main source of microseismic energy may be different in different parts of the world. This result was based on the fact that in Scandinavia some kind of coast effect was the dominant source, whereas in many other parts of the world a cyclone effect seems to be of greatest importance. Later I discussed these problems more thoroughly (Båth, 1951 c) and inferred a difference with regard to microseisms between east and west coasts of the continents. The reason would be differences in the properties of air masses blowing on-shore in cyclones—warm air blowing on-shore on an east coast, but cold air on a west coast. With a view to investigate these and related problems more closely as well as to get some basic data for possible judgment between various theories, a comparison of microseisms in a number of cases has been made between Scoresby-Sund (Greenland), Reykjavik (Iceland), Bergen, and Uppsala (Scandinavia).

The microseisms on Greenland have been studied by Lehmann (1949, 1951); the microseisms at Reykjavik have not earlier been studied in detail, but some data are given by Gutenberg (1932); the microseisms in Scandinavia have earlier been studied by the present author. Copenhagen and Helsinki were not included in this study, as it is already known that the microseisms at these stations are very closely related to those at Bergen and Uppsala (see my papers 1952).

Methods and materials used

The microseisms studied are those in the usual period range of 4—8 sec.

Data about the stations and instruments used:

Station	Lat.	Long.	Height	Ground	Instrument
Scoresby-Sund...	70° 29′ N	21° 57′ W	69 m	Gneiss	Galitzin E, N, Z
Reykjavik.......	64° 08′ N	21° 54′ W	44 m	Doleritic rock	Mainka E, N
Bergen..........	60° 24′ N	5° 18′ E	20 m	Gneiss	Wiechert E, N
Uppsala.........	59° 51′ N	17° 38′ E	14 m	Granite	Wiechert E, N

The mean values of the seismograph constants for the seven cases studied from the years 1949 and 1950 are as follows:

Constant	Reykjavik (Mainka) E	Reykjavik (Mainka) N	Bergen (Wiechert) E	Bergen (Wiechert) N	Uppsala (Wiechert) E	Uppsala (Wiechert) N
Free period of pendulum.............	5.8	7.6	8.4	9.2	9.3	9.1 sec
Static magnification..................	92	58	191	180	188	193
Damping ratio.......................	4.5	6.5	2.3	2.2	3.9	3.8
Deviation due to friction.............	0.3	0.3	1.0	2.2	0.9	0.7 mm

Constant	Scoresby-Sund (Galitzin) E	Scoresby-Sund (Galitzin) N	Scoresby-Sund (Galitzin) Z	
Seismometer period.....	11.8	11.7	9.4	sec
Galvanometer period...	12.0	11.9	10.0	sec
Seismometer damping...	appr. aperiodic			
Galvanometer damping..	aperiodic			
Transference factor.....	107	100	99	sec^{-1}
Reduced pendulum length	12.0	12.0	14.9	cm
Distance galvanometer to record...........	100	100	100	cm

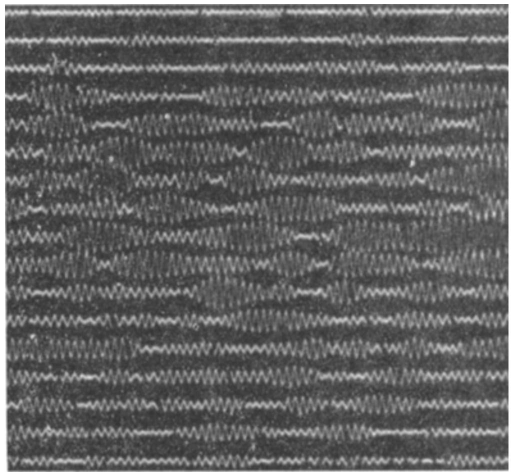
In computing the ground amplitudes naturally the values of the constants for each separate case were used. The Z-records of Bergen were often faulty (obviously too large friction) and were therefore not measured.

Of the seven cases studied each comprises in general four days. Representative values of the maximum amplitudes and the corresponding periods were measured on all records mentioned for every full hour ± about 15 minutes.

There are various methods of measuring microseisms. The amplitude given should be a measure of the microseismic activity at the given time. It is not sufficient to give only the absolute maximum amplitude. In one case there may be a practically continuous train of waves with a certain amplitude, and in another case there may be only one or two waves within a 30-minute interval with the same amplitude as in the former case. If the absolute maxima were given, clearly the same values would be obtained in these two cases, but obviously the microseismic activity is larger in the former case than in the latter. The author has here used the same method as earlier, i.e. a representative maximum is obtained by eye inspection of a 30-minute interval (method I). Another way is to measure for instance the five largest amplitudes within 30 minutes and compute their mean value (method II). Theoretically this would be better than method I, but practically there is no difference in reliability between these two methods. By increasing the number of measurements used in calculating a mean value, we could get a more representative measure of the microseismic activity. The author has therefore tried a third method (method III), measuring the maximum amplitudes for every minute within ± 20 minutes of a full hour. Successive mean values, $\frac{1}{2}(A_{+1}+A_{-1})$, $\frac{1}{4}(A_{+1}+A_{+2}+A_{-1}+A_{-2})$, etc. are formed ($A_{+i}$ is the maximum amplitude for the i-th minute after the full hour, and A_{-i} for the i-th minute before). The successive mean values are plotted against i. The mean amplitudes converge rapidly towards a final value. In general ± 7 minutes are sufficient to get a mean value agreeing within ± 0.01 mm (paper amplitude) with the ± 20-minute mean value. For weak, regular microseisms only ± 4 minutes are sufficient, for large, irregular microseisms ± 10 minutes may be required for the same result. However, even the measurement of ± 7 minutes (14 measurements) is quite lengthy. But it is possible to get mean values that agree within a few hundredths of a mm with the 20-minute mean value by shorter methods, e.g. by computing $^1/_6\ (A_{+1} + A_{+4} + A_{+7} + A_{-1} + A_{-4} + A_{-7})$ (method IV). The following table contains a comparison of the results of the different methods in three cases, measured on the Uppsala Wiechert records. As the periods were the same in each case, the paper amplitudes may be immediately compared. Columns (a) contain the results by the various methods, (b) give values obtained by multiplying (a) with certain factors so as to bring the amplitude for case A equal to 1.00.

Case	Method I a mm	Method I b mm	Method II a mm	Method II b mm	Method III a mm	Method III b mm	Method IV a mm	Method IV b mm
A	1.00	1.00	0.92	1.00	0.59	1.00	0.64	1.00
B	0.40	0.40	0.37	0.40	0.28	0.47	0.27	0.42
C	0.75	0.75	0.67	0.73	0.43	0.73	0.42	0.66

The values for methods II and especially III and IV (columns a) are naturally lower than for I. But the ratios between the amplitudes (columns b) are in perfect agreement in I and II. In III case B has got a somewhat higher value in relation to the other cases. This is due to the fact that the microseisms are continuous in this case with only small variations, and then the activity is actually somewhat higher than shown by methods I or II. On the whole, it may be said that it is just a matter of convention which method should be used. The method I used here is for our purpose as good as any other method and in addition it has the advantage of being a quick method.



a. Regular, group microseisms (Scoresby-Sund, May 13—14, 1949).

b. Less regular, continuous microseisms (Uppsala, October 3, 1949).

Fig. 1. Characteristic types of microseisms.

Discussion of the separate cases

Two characteristic types of microseisms are shown in Fig. 1. Fig. 1 a shows regular, group microseisms, typical for Scoresby-Sund, Fig. 1 b shows less regular, continuous microseisms, typical for Scandinavia and Iceland.

The ground amplitudes and the corresponding periods are given in Figs. 5—11. In order to avoid confusion it was necessary to displace the zero points of the scales for the different stations. The scale used is always the same. The scales as well as the amplitude curves have been marked by S = Scoresby-Sund, R = Reykjavik, B = Bergen, and U = Uppsala.

There were some obvious inconsistencies or variations of the constants for the E component at Reykjavik. In case 1 $A_N \simeq A_E$ at Reykjavik, in cases 2—4, $A_N < A_E$, and in cases 5—7, $A_N > A_E$. There is no explanation for this behaviour except instrumental. The computed A_E of Reykjavik have been multiplied by factors, in each case determined so as to give the same mean value of A_E as of A_N for each interval investigated. The A_E for Reykjavik given in Figs. 5—11 have been obtained in this way. The factors are 0.60 in case 2; 0.53 in 3; 0.39 in 4; 1.49 in 5; 1.18 in 6; and 1.92 in case 7. A_N and A_E for Reykjavik are naturally not comparable if their magnitudes are concerned, but their variations are comparable.

The periods given in Figs. 5—11 are the arithmetic means of the periods on the two horizontal components. Exceptions occur where only one of the horizontal components has been in operation, when the period of this component only is given.

The interruptions of the curves in Figs. 5—11, occurring in a few cases, are due to instrumental failures, unless otherwise mentioned under the separate cases.

The observations of ocean surface waves (mean maximum height H, period T, and direction of propagation) for every third hour made at the weather ship "Polar Front" (61° N, 2° E) are given in Fig. 4 for all our cases. These observations have been published by the Norwegian Meteorological Office, Oslo. There is a very clear parallelism between the periods and the heights of the ocean waves.

The ratios between the microseismic periods (T_x) and the simultaneous ocean wave periods (T) have been computed in all cases. For the microseisms the mean horizontal period is used. The following table gives the percentage frequency distribution of these ratios, comprising all cases studied.

Station	T_x/T												
	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
U	2	10	37	19	16	8	2	1	1	3	1		
B	4	16	40	18	10	4	4	1	1	1		1	
R	5	24	28	18	9	8	4		2		2		
S	1	6	30	10	27	7	11	3				1	4
Total	3	14	34	16	15	7	5	1	1	1	1	1	1

The number of observations used in computing this table were 224 for U, 221 for B, 223 for R, and 213 for S. The frequency maximum lies around 0.6 and is significantly higher than 0.5. This is not only statistically valid but is repeated in every case for every station. The higher ratios (> 1.0) occur for shorter ocean wave periods and are almost exclusively due to cases 2 and 5. On the standing ocean wave theory for microseisms (LONGUET-HIGGINS, 1950) the period ratio should be 0.5. It could be said that the ocean wave phenomena are too complex to be represented by only one period value. However, the wave observations refer to the mean maximum waves, and these should show the best relation to the microseisms. It can also be argued that the ocean wave observations do not refer to the point of origin of the microseisms. However, this does not seem to give a complete and satisfactory explanation. They could be expected to be valid at least for microseismic storms in Scandinavia originating on the south-west coast of Norway. But also in these cases significantly higher ratios than 0.5 are generally obtained.

For reasons of space the following discussions of the separate cases will be made as brief as possible and only the essential points will be emphasized. For a more complete survey of the weather development the reader is referred to the official weather maps. In this study I used weather maps for every third hour. One typical weather map for each case is given in Figs. 2 and 3. All times given are GMT.

Case 1: January 5—8, 1949 (Fig. 5)

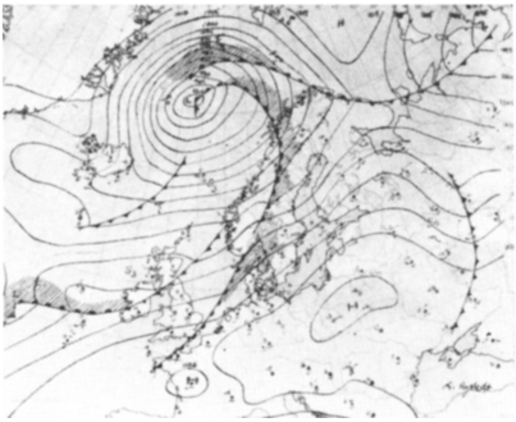
Weather (Fig. 2 a)

The weather development consists essentially of the motion of an intense cyclone from immediately south of Iceland (06^h 5/1) towards NE. At 06^h 8/1 its centre is over northern Scandinavia.

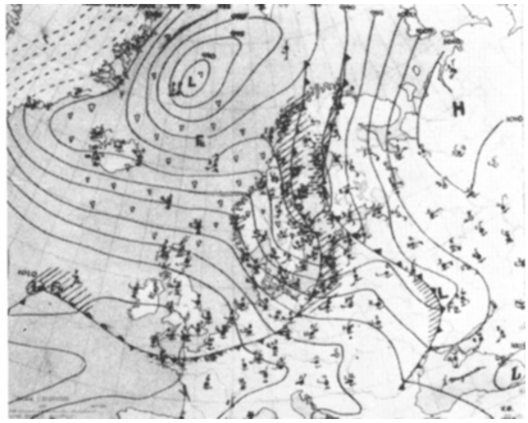
Amplitudes

R has a very large amplitude maximum. Both the increase and the decrease are very rapid, and much more rapid than at S. This indicates that only a very special situation is favourable for large microseisms at R, and when the cyclone moves quickly as in this case, the microseismic storm is of short duration. This situation with a rapidly moving low (mean velocity 50 km/hour 06^h 5/1—06^h 6/1 and 30 km/hour 06^h 6/1—06^h 7/1) could be expected to be favourable for the generation of standing surface waves on the ocean.

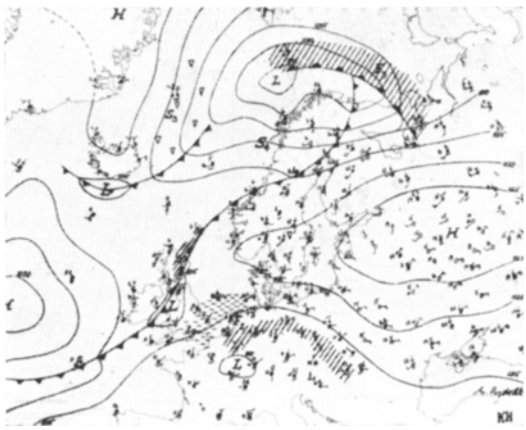
R's amplitudes begin to increase rapidly at 02^h 5/1 and reach a maximum around



a. January 6, 1949, 06^h (case 1).



b. April 20, 1949, 06^h (case 2).



c. May 14, 1949, 06^h (case 3).

Fig. 2. Weather maps for cases 1—3.

20^h—22^h 5/1. It seems to be a double maximum (16^h 5/1 and 02^h—03^h 6/1) on both components. The amplitudes at R begin to increase rapidly when the low is south of Iceland, but the maxima are not reached until the low is NE of Iceland and at a greater distance from R. The intensity of the low has increased slightly in the meantime. A possible reason for the rapid increase at 02^h 5/1 are standing sea waves on the east side of the cyclone between 4/1 and 5/1; a rapid change of wind direction has taken place there. The increase cannot in this case be ascribed to polar air, but the double maximum may be due to the approach of polar air (a cold front of smaller extent passes over Iceland at 18^h 5/1; after that time it is situated over the ocean immediately to the south of Iceland).

The amplitudes at S begin to increase at 02^h 5/1, i.e. simultaneously with R, but considerably slower. The maximum is reached about 06^h 6/1, i.e. later than at R. The microseisms at S were too large to be measured around the maximum. We have in case 1 an intense cyclone of relatively limited horizontal extent. There is no coast effect at S; the wind is almost parallel to the east coast of Greenland. But at the maximum there is an intense inflow of polar air over the ocean between S and the cyclone centre. No definite conclusion about the importance of the polar air at S is possible only from this case. Considering the maximum at 06^h 6/1 we have to take the following facts into account:

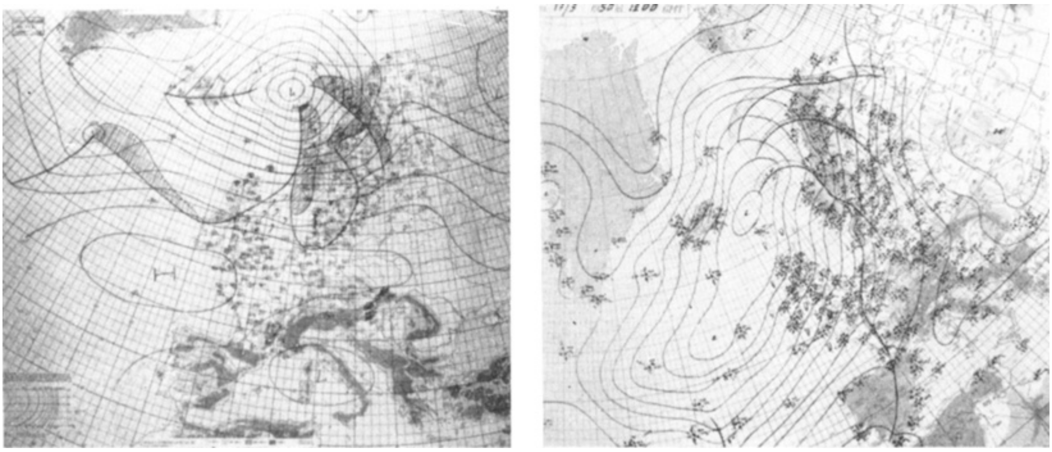
1. The distance from S to the cyclone centre is unchanged from 5/1 to 6/1.

2. The cyclone intensity has increased somewhat (960 mb at centre at 06^h 6/1 against 970 mb at 06^h 5/1). This could possibly explain part of the increase, but this change alone could hardly have such a large effect.

3. The essential difference between 6/1 and 5/1 is that on 6/1 the polar air has got large influence at S; that is not at all the case on 5/1.

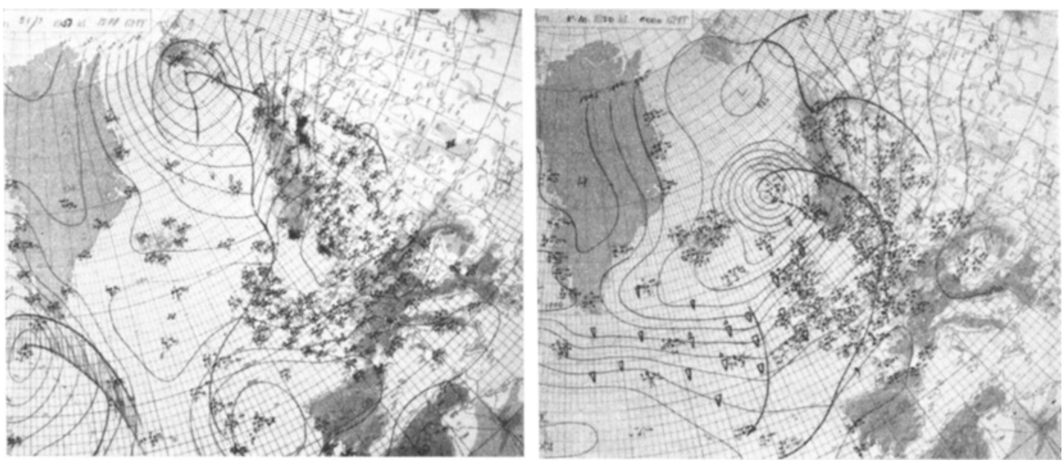
The origin of the microseisms at S is likely to be found in the polar air over the open ocean, just to the east of S.

Regarding the amplitudes at U and B we observe a rapid increase at B at 16^h 5/1; it occurs at U at the same time (UE 17^h 5/1),



a. October 2, 1949, 15^h (case 4).

b. March 17, 1950, 12^h (case 5).



c. March 26, 1950, 12^h (case 6).

d. October 8, 1950, 00^h (case 7).

Fig. 3. Weather maps for cases 4—7.

though less marked. Our earlier experience from the amplitudes at B and U leads us to suspect some effect localized to the coast around B (see my paper 1951 b). The increases coincide with the passages of fronts over the coast at B. The amplitudes are still unimportant, especially at U. There is a further increase at U at 08^h—09^h 6/1 (a cold front passes Kråkenes on the Norwegian coast at 06^h 6/1), and maximum is reached at U about 12^h 7/1, when the coast effect has been displaced to the central part of the Norwegian coast. $A_N > A_E$ for U and still more pronounced for B. It is to be observed that the maximum amplitudes at U (and B) are not reached until now, when the cyclone intensity is decreasing but when the coast effect is fully developed:

Time	Distance LU km	Distance LB km	Central pressure of cyclone (L) mb	Coast effect
06^h 5/1	2,000	1,400	970	minimal
06^h 6/1	1,600	1,300	960	increasing
06^h 7/1	1,400	1,400	980	considerable

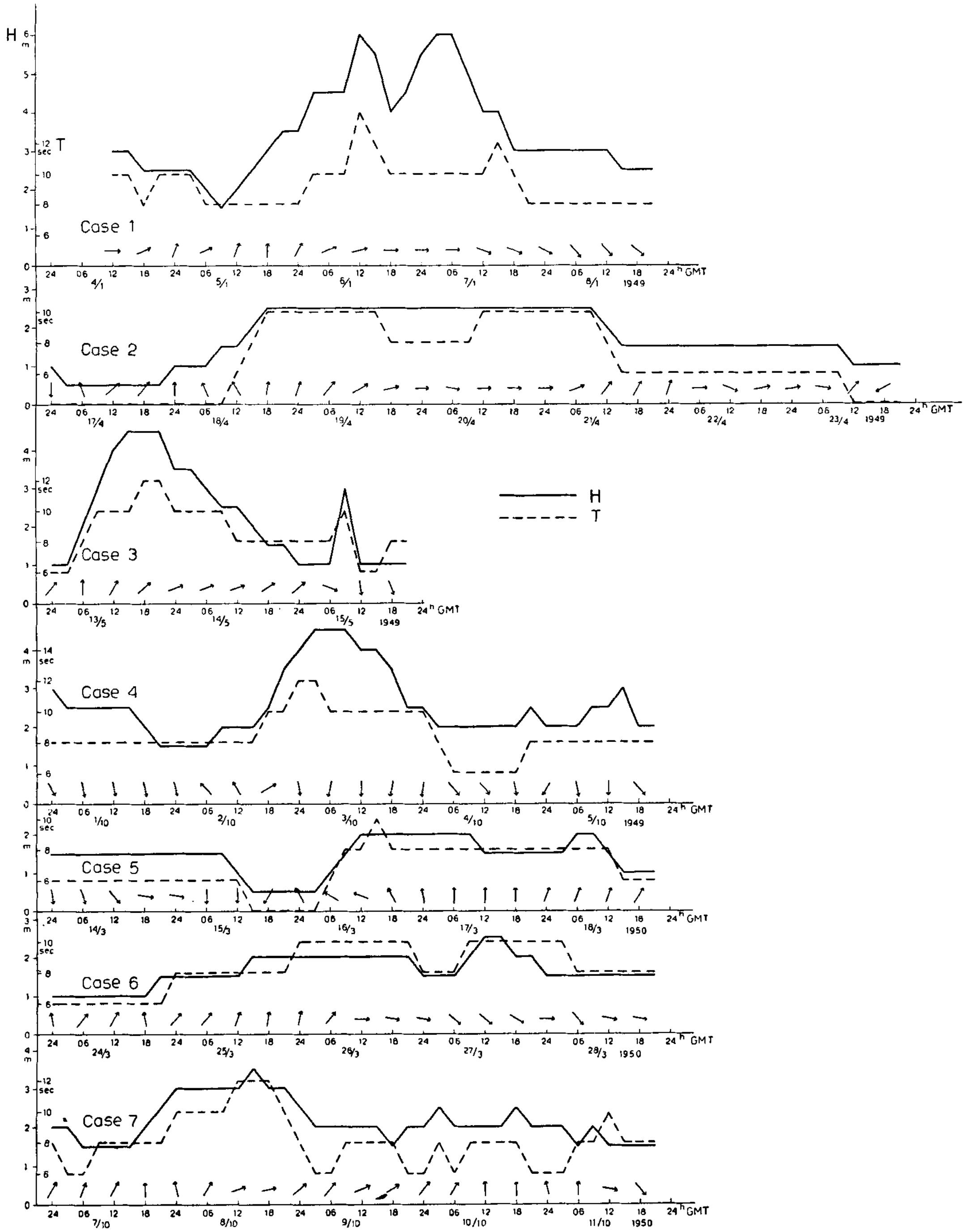


Fig. 4. Observations of mean maximum height (*H*), periods (*T*), and direction of propagation (arrows) of ocean surface waves at 61°N, 2°E.

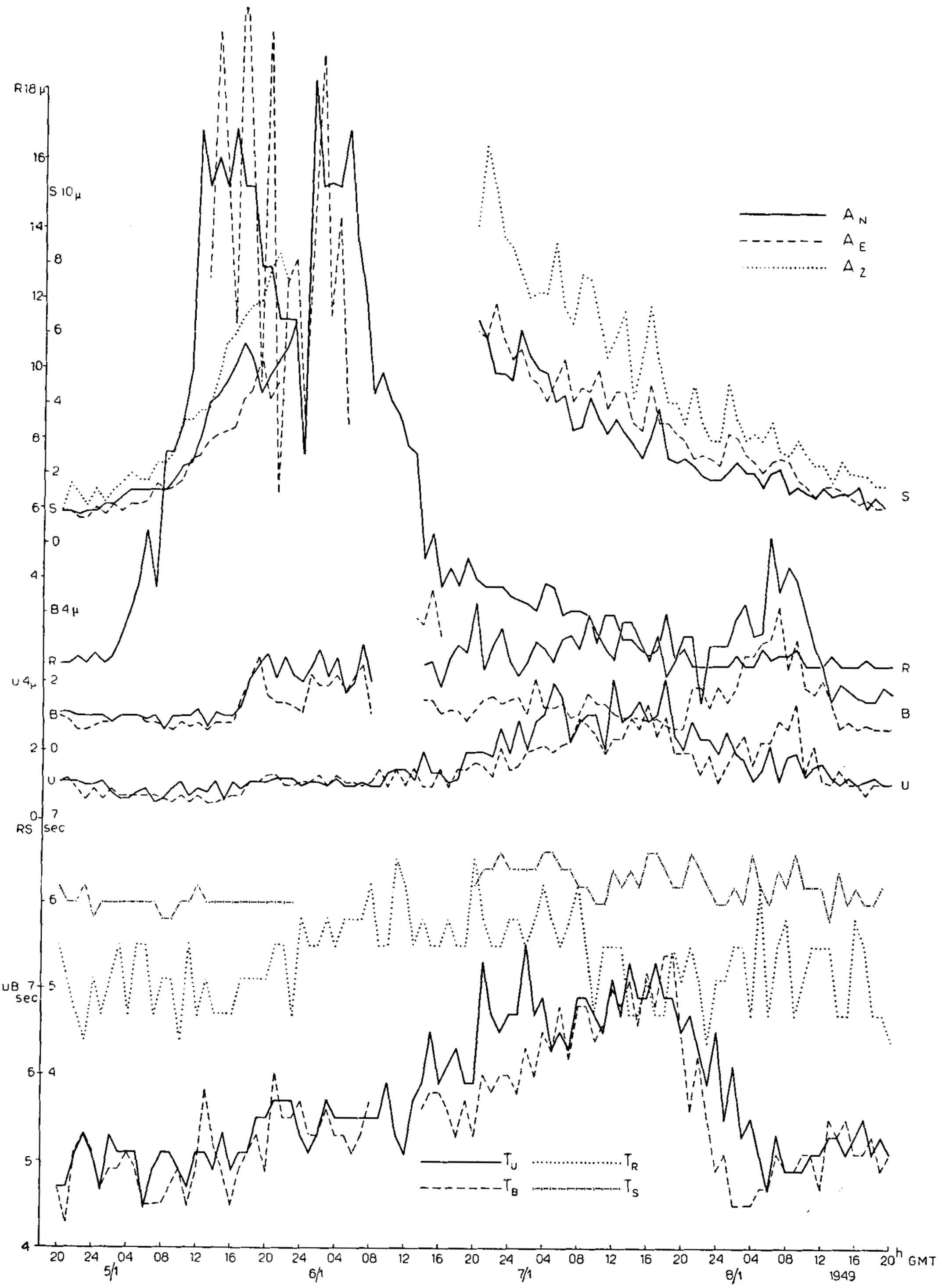


Fig. 5. Case 1: January 5—8, 1949.
U = Uppsala, B = Bergen, R = Reykjavik, S = Scoresby-Sund. A = amplitudes, T = periods of microseisms.

The coast effect is unimportant up to 03^h 6/1, increasing from 03^h 6/1 to 03^h—06^h 7/1, and maximum is reached about 06^h 7/1. There seems to be no doubt that the microseisms at U, B depend upon a coast effect (within the polar air).

Towards the end of case 1 there is another storm at U, B, apparently closer to the stations:

Station and component	Increase starts at	Maximum at
BE	20^h 7/1	07^h 8/1
BN..........	23^h 7/1	06^h 8/1
UE..........	24^h 7/1	09^h 8/1

UN is completely unaffected. There is no trace of this storm at R, S. The reason seems to be two smaller cyclones over the North Sea—Skager Rack, which may possibly give rise to standing ocean waves. There is no effect on the B coast, but rather on the Swedish west coast.

The ocean wave heights (Fig. 4) have a maximum from about 12^h 6/1 to 06^h 7/1, i.e. later than the amplitude maxima at S and especially at R, but earlier than at U and B. The general run is similar to the microseisms at S.

Periods

The periods of the microseisms are remarkably constant at S (6.0—6.4 sec), whereas the periods at U, B vary considerably. T_U, T_B increase from about 4.8 sec to 7 sec from the beginning up to 19^h 7/1. What is the reason for this period increase? Various possibilities will be considered:

1. The source moves away:

a) The cyclone centre does not move away (see above).

b) The effective coast is displaced from the B coast to the central part of the Norwegian coast. This may contribute to the period increase, but can hardly explain the increase after 06^h 7/1.

c) The polar air is closest at 06^h 7/1.

2. The increase of intensity of the coast effect (not of the cyclone) seems to be of essential importance for the period increase.

3. Displacement of the source in accordance with Press and Ewing (1948 and later personal communication):

a) The cyclone centre moves towards shallower water during 6/1—8/1.

b) Effective coast: no explanation possible in this way.

c) Polar air: no explanation possible.

The rapid decrease of T_U, T_B from 19^h 7/1 (7 sec to 4 ½—5 sec up to 8/1) is remarkable. It is hardly due to a decrease of intensity of the source, as the amplitudes at B increase. The reason is instead a new source close by. It is significant that T_B decreases more rapidly than T_U. After the period minimum at 02^h—04^h 8/1 for T_B and at 06^h 8/1 for T_U they increase again somewhat.

We observe that there is no maximum of T_R simultaneous with the maximum amplitudes at R. At R, S the periods seem to be more independent of the intensity of the source and vary mostly with the distance to the source. In every case $T_R < T_S$ almost without exception.

Types of microseisms

In case 1 the microseisms at U are typically continuous, slightly irregular, during 6/1—7/1; there is some indication of groups on E in the morning of 8/1. At B the microseisms are continuous up to about 02^h—03^h 8/1, after which there are clear group microseisms; on BZ the groups are clear already from about 19^h 7/1. There are no pronounced group microseisms at R, whereas S has in this case as almost always beautifully developed regular group microseisms.

Case 2: April 17—23, 1949 (Fig. 6)

Weather (Fig. 2 b)

The weather development is similar to the preceding case and is dominated by a cyclone which first (up to 19/4) moves rapidly from south towards north of Iceland and then stays practically in the same position at about the same distance from Iceland, Greenland, and Norway.

Amplitudes

At R we distinguish a series of microseismic storms:

1. The amplitudes increase in the beginning to an unimportant maximum at 07^h 18/4, i.e. when the cyclone has its centre on Iceland.

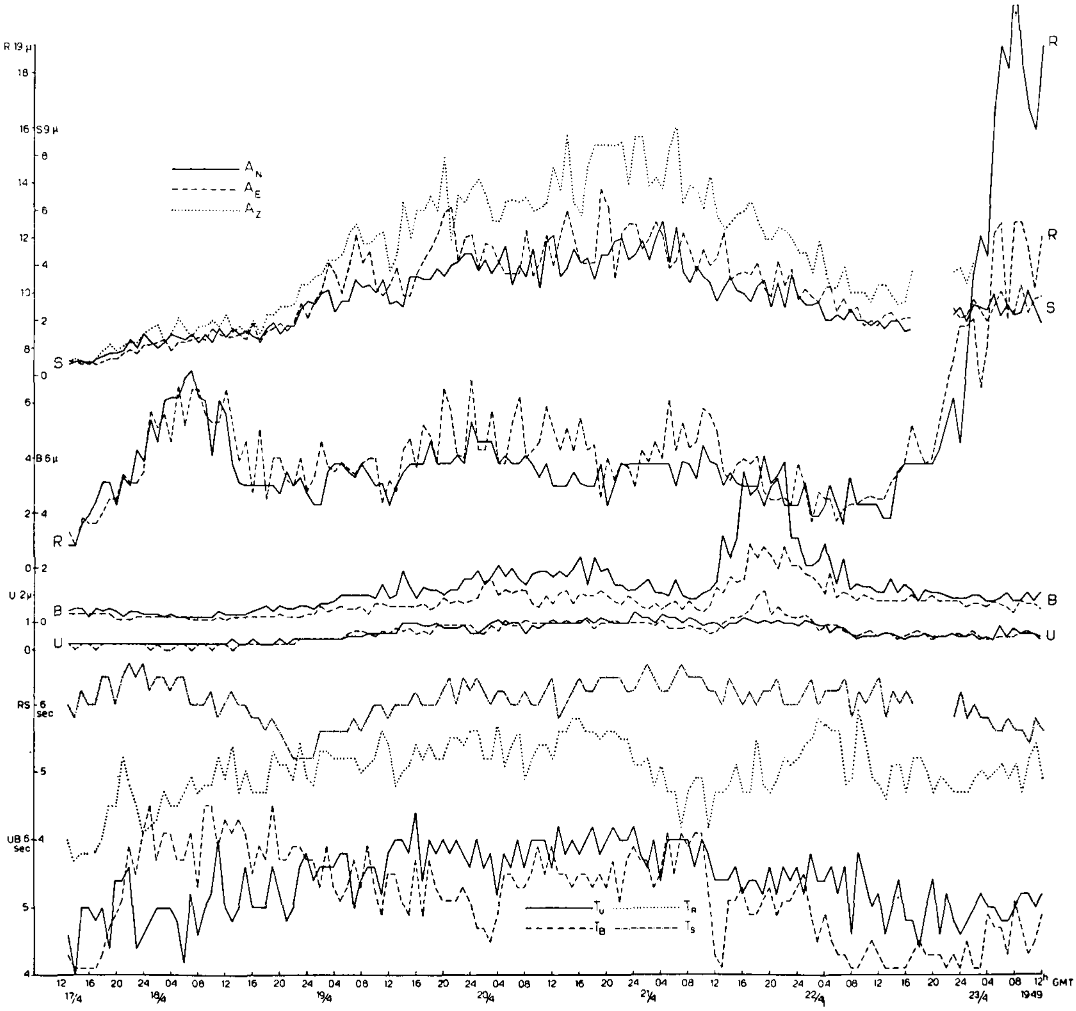


Fig. 6. Case 2: April 17—23, 1949.

This corresponds to case 1 with a rapid cyclone approaching Iceland from the south. Standing sea waves may be expected due to rapid changes of wind direction.

2. Most striking is the very rapid increase starting at 14^h 22/4 and reaching a very large maximum around 08^h 23/4. This storm ceased about 23^h—24^h 23/4. It is very important that this storm occurs not until the cyclone has moved away from R and when its intensity is decreasing, but, on the other hand, just when the stream of polar air straight from the north towards Iceland is most fully developed. In other words, the cyclone has reached its critical position. However, the possible importance of standing sea waves to be expected to the SE of Iceland cannot be excluded. Still more so, as at S there is only a slight increase of the amplitudes at the time of the large storm at R.

3. There are two smaller maxima at R at about 24^h 19/4 and 10^h 21/4, probably due to the approach of polar air.

The amplitude variations at S are again slower than at R. A more rapid increase starts at 17^h 18/4 and maximum is reached approximately at 20^h 20/4. If L denotes the cyclone centre, we have:

Time	Distance SL km	L mb
18^h 18/4	700	970
06^h 19/4	800	970
18^h 19/4	750	970
06^h 20/4	700	970
18^h 20/4	700	975

The polar air off the S coast is best developed on 20/4. This is obviously the reason for the microseisms at S. It does not seem possible to ascribe these microseisms to standing sea waves.

The amplitudes at U and B are on the whole rather unimportant in this case. This is also to be expected from earlier experience for cyclones with centres in the Atlantic. They never give rise to large microseisms in Scandinavia. There are two well marked amplitude increases (I and II):

The ocean wave heights (Fig. 4) have only one maximum of relatively long duration. The variation is similar to the microseismic amplitude variation only at S, but not at the other three stations.

Periods

With regard to periods we observe that T_U varies on the whole in good parallelism with the amplitudes at U. That is not the case at B, probably due to relatively greater importance of near-by parts of the coast around B. There are minima of T_B at 03^h 20/4 and 12^h—13^h 21/4. The last minimum is especially clearly marked and is also observable as a decrease of T_U. This period minimum is simultaneous with the onset of the storm on 21/4, i.e. the same phenomenon as was found in case 1 and in several other cases. The period minimum simultaneous with the onset of a storm is due to a new source of microseisms situated close to the station and which begins to dominate the situation. This source is here located at the B coast. After the minimum T_B increases again and reaches a maximum at about the same time as the maximum amplitude. This shows that at the coast effect the period depends also on the amplitudes.

	Increase starts at	Maximum	Remarks
I. U	21^h 18/4 and 05^h 19/4; 13^h 19/4	poorly developed	Cold front passes the B coast about 15^h 18/4
B	about the same time as U, but more gradual	poorly developed	
II. U	11^h 21/4 (only E)	19^h 21/4	This maximum is the largest for the whole interval studied for UE, BN, and BE. The coast activity is limited to the B coast. Cold fronts are coming in over the B coast after 18^h 21/4
B	11^h 21/4 (especially N)	19^h 21/4	

The following table gives the distances to the cyclone centre (L) and the pressure of the isobar closest to the centre, given on the maps.

Time	Distance BL km	Distance UL km	L mb
06^h 18/4	1,400	2,000	980
06^h 19/4	1,500	1,700	970
06^h 20/4	1,600	1,800	970
06^h 21/4	1,400	1,600	985
06^h 22/4	1,200	1,400	980

It is obvious that the second storm (II above) has no relation to the distance to the cyclone centre, nor to the central pressure, but just occurs when the coast effect around B has reached its maximum. It is to be observed that during the second storm the cyclone centre is all the time over the Atlantic far outside the continental shelf.

Concerning T_R it is remarkable that it does not change during the large amplitude maximum towards the end of the interval. This fact is not in favour for an explanation by means of standing sea waves.

T_S is as usual remarkably constant $\simeq$ 6 sec. But in the beginning of the interval T_S decreases from 6 sec to a minimum (5.2 sec) at 22^h 18/4—01^h 19/4 and then increases again, whereas T_R at the same time increases from about 4 sec and reaches 5.2 sec at the time of minimum T_S. It is essential to note that the T_S minimum coincides in time with the more rapid amplitude increase, i.e. a completely analogous behaviour to what we just found for B. The explanation is also for S very probably that a near-by source (polar air) begins to dominate the situation. During 19/4 T_S is again increasing, while the source does not move away but the amplitudes increase.

Types of microseisms

The microseisms are continuous on the U records. There is some indication of group formation on the E component at U in the storm on 21/4. Also at B there are continuous microseisms up to the storm on 21/4, when there are clear group microseisms. The groups are especially clear on the Z component at B and last approximately from 13^h 21/4 to 03^h 22/4. The microseisms at R are typically continuous, especially 18/4—20/4. On the other hand, during the storm on 23/4 they are group microseisms.

Case 3: May 13—15, 1949 (Fig. 7)

Weather (Fig. 2 c)

A cyclone moves rapidly in the direction from SW towards NE straight across Iceland or just to the SE of Iceland.

Amplitudes

The amplitudes are on the whole relatively unimportant, even at R; only S has a more important microseismic storm.

The storm at S is of short duration. An extremely sharp increase begins at 17^h 13/5; see Fig. 1 a. Maximum is reached about 23^h—24^h 13/5. The decrease is slower than the increase, which is a general property for the microseismic storms at S. The distances to the cyclone centre (L) and central pressures are as follows:

Time	Distance SL km	L mb
06^h 13/5	800	990
09^h 13/5	800	990
12^h 13/5	950	990
15^h 13/5	1,000	985
18^h 13/5	1,000	990
03^h 14/5	1,350	990
06^h 14/5	1,600	995

The very rapid amplitude increase at S obviously cannot be ascribed to some mechanism localized to the centre itself. But the polar air outside the coast of S begins to be well developed about 12^h 13/5. The maximum at S can hardly depend upon standing sea waves. There is no coast effect; the wind blows parallel to the coast. The short duration of the storm is due to a corresponding short duration of the conditions favourable for large microseisms (the polar air stream between S and L). An anticyclone over Greenland spreads out over the adjacent ocean at S and contributes to the disappearance of the microseismic storm.

At R there is a more unimportant amplitude maximum at about the same time as at S (00^h—02^h 14/5 at R), probably also depending on the polar air. It is interesting to see that the maximum does not occur earlier when the cyclone is nearest to R (06^h 13/5), but later when it has moved away towards NE and

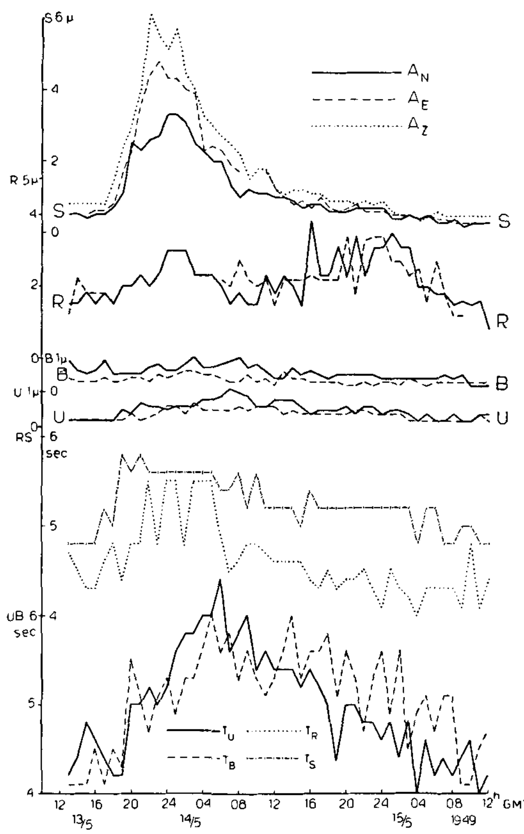


Fig. 7. Case 3: May 13—15, 1949.

reached a position most favourable for a polar air effect over the ocean to the north of Iceland. There is another also unimportant maximum at R about 23^h 14/5, of which there is no trace at the other stations.

The amplitudes at U and B are again very small. The coast effect is limited to the northern part of the west coast of Norway. This explains why the variations are larger at U, and that the amplitudes at U are larger on the N component than on the E component (see my paper 1951 b). The U amplitudes start to increase at 18^h 13/5 and have maxima at 07^h 14/5. BN has a maximum at about the same time. There is a cold front along the central part of the Norwegian coast at 18^h 13/5, coincident with the amplitude increase at U. There is no effect at the B coast in this case.

There is a very striking similarity between the variation of ocean wave heights (Fig. 4) and the amplitudes at S, but not at the other stations. But the rapid increase of wave heights occurs about 14 hours before the rapid amplitude rise. The maximum wave height (about 18^h 13/5) is reached 5—6 hours before the microseismic amplitude maximum at S. These time differences are due to the different localities. Whatever the mechanism is, there seems to be no doubt that the microseisms must be ascribed to ocean surface waves.

Periods

T_S increases considerably from 16^h 13/5 on, and it is probable that T_S has a minimum at the time of the approach of the polar air. T_S is very much lower in this case than in all other cases. This may be due to the season of the year (annual variation of periods; see my paper 1949, pp. 23—24). Still we have $T_S > T_R$ without exception as in all other cases studied. The variation of T_S resembles to a certain degree the variations of the amplitudes at S. The periods T_U, T_B follow each other on the whole with an obvious variation parallel to the variation of the amplitudes; the maxima of T_U, T_B coincide with the corresponding amplitude maxima. The variations of the periods are much more pronounced in relation to the corresponding amplitude variations at U and at B than they are at S. Also at R there is a period maximum at the time of the first storm, but not at the second.

Types of microseisms

There are no clear group microseisms at any time at B and U in this case. The microseisms are continuous also at R. The microseisms at S have a very regular group character (Fig. 1 a).

Case 4: October 1—5, 1949 (Fig. 8)

Weather (Fig. 3 a)

Three lows follow each other in a west-easterly motion from the SE coast of Greenland to Russia (along the northern edge of an anticyclone over the British Isles and Central Europe). The lows move all the time very close to the latitude 65° N. Of the three lows the middlemost is of greatest importance with regard to microseisms. The third low of the series is only of limited extent. The lows will be denoted (a), (b), and (c) in the order of appearance.

Amplitudes

The amplitudes at B and U run parallel to each other, whereas the variations at R and S deviate completely from those of U and B as well as from each other. The following table gives the essential features of the variations at U and B.

Station and component	Increase at	Maximum at	Remarks
I. UE BE BN	21^h 2/10 18^h 2/10 21^h 2/10	10^h—12^h 3/10 10^h—12^h 3/10	Cold front passes over the B coast at 18^h 2/10
II. UE UN	05^h 5/10 06^h—07^h 5/10	—	Cold front touches Norwegian coast at Kråkenes at 03^h 5/10, moving towards land

It is significant that especially in I UE reacts much quicker than UN. This is typical for a coast effect localized to the coast around B (due west of U). The maxima at B and U in I are not reached while the cyclone is deepest but about half a day later. At that time the centre is already over land, while when the

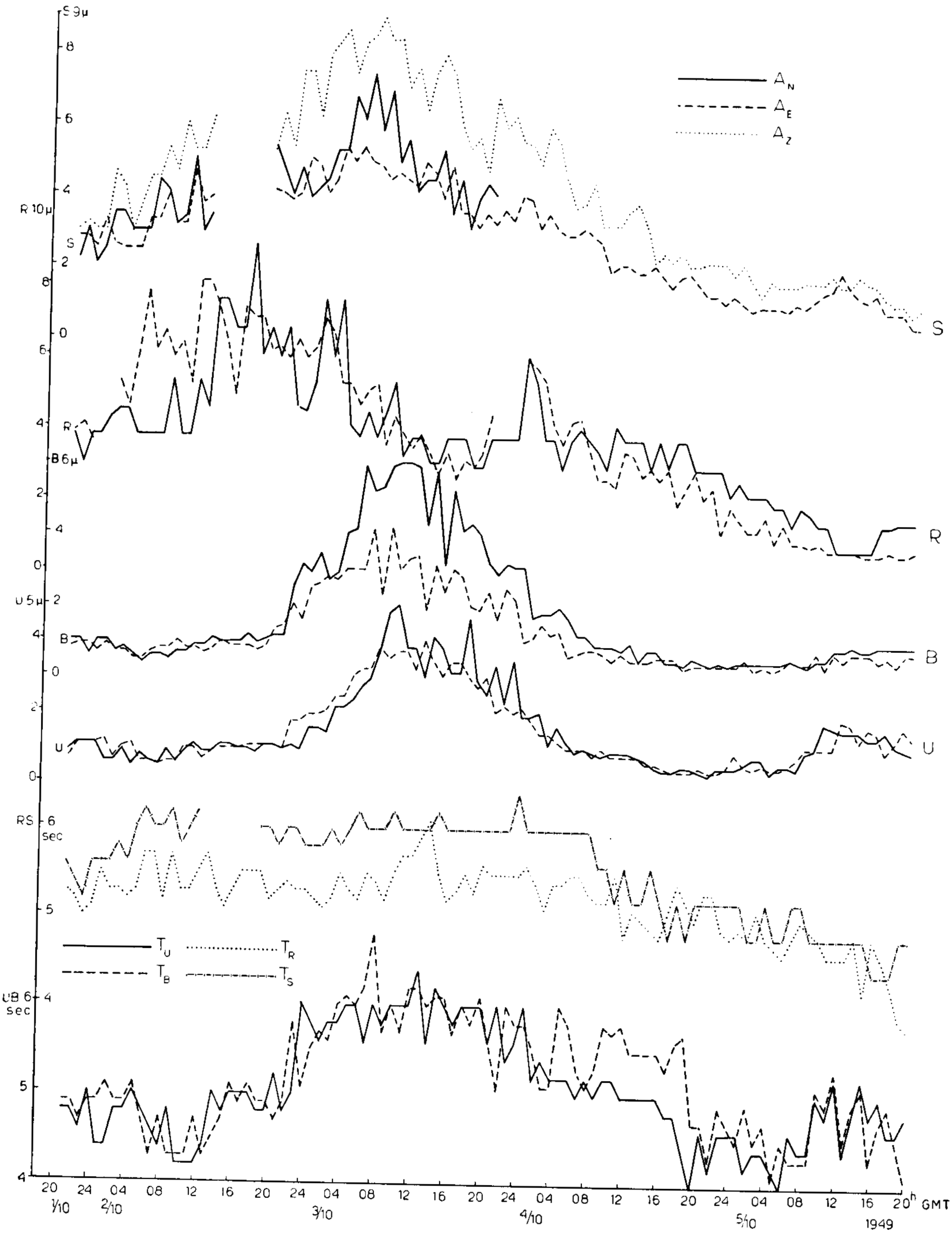


Fig. 8. Case 4: October 1—5, 1949.

sharp increase starts in I, the centre was far outside the continental edge. The increase II is not so clear at B as at U; it is due to cyclone (c). The second storm was finished at U (N) about 00^h—01^h 6/10.

The amplitudes at R have two maxima, one about 16^h 2/10 and another smaller one at 24^h 3/10. The E amplitudes at R begin to increase markedly already at 22^h 30/9; the N amplitudes have a marked increase about 12^h 1/10. The first maximum is caused by cyclone (a), the second by (c). At 15^h 2/10 the distances from the centre of (a) to R, B, U are approximately the same, but the amplitudes at B, U are considerably lower than at R. A cold front passes over Iceland at 15^h 2/10. The second maximum at R (24^h 3/10) seems remarkable; the cyclone (c) seems to be unimportant and is situated between Iceland and Greenland. It is possible that at R we have instead a maximum superimposed upon the general decrease. If this interpretation is correct, this maximum would be later, i.e. about 12^h 4/10, when the cyclone is closest to R.

The time difference of the amplitude maxima at R and U, B are for cyclone (a) about 20 hours, for cyclone (c) about 24 hours. The question arises if these time differences are an effect only of the different positions of the stations or if other factors dominate. The last explanation seems to be most probable for the following reasons:

1. The rapid increases at U, B could not be explained only by the very gradual approach of a cyclone, but are connected with the passages of cold fronts over the Norwegian coast.

2. If the mechanisms responsible for the microseisms were exactly the same for U, B as for R, we could expect similar variations of the periods; but there is no similarity.

3. The maximum amplitudes occur at U, B when the cyclone intensity is already decreasing, but not so at R in this case.

Obviously the coast effect at the Norwegian coast is observable only on the continental side and not on Iceland or Greenland. At R the oncoming of polar air from due north with long straight paths over the ocean to the north of Iceland seems to be of importance for large microseisms. Probably the source of the microseisms is located over the ocean but a contribution also from a coast effect along the northern coast of Iceland cannot be excluded.

At S there is a maximum about 06^h 3/10, due to cyclone (a). It is remarkable that there is no amplitude increase at U, B before the very rapid increases, whereas at S there is a gradual rise all the time. The maximum at S occurs about half a day after the time of the largest cyclone intensity, when the cyclone is moving away and its intensity decreasing, but just when the whole ocean between Greenland and Scandinavia to the north of Iceland is occupied by polar air. The microseisms at S have obviously no close connection with the cyclone centre itself. There is no coast effect either at S. There is another maximum at S (E) at 11^h 5/10, due to cyclone (c). The situation is completely the same as at the larger maximum.

The variation of ocean wave heights at 61° N, 2° E (Fig. 4) is similar to the amplitude variation at S and also at U and B. The maximum height occurs about 06^h 3/10, i.e. simultaneous with the amplitude maximum at S and slightly earlier than at U and B. Also the small storm towards the end of the interval occurs on all the records mentioned.

Periods

T_U and T_B follow each other, and the periods vary in an obvious parallelism with the amplitudes; this is valid also for the smaller storm towards the end of the interval. T_R and especially T_S are remarkably constant, except for a decrease from 08^h 4/10 onwards; this may be due to a new source, cyclone (c). T_R and T_S show no obvious connection with the amplitudes. There is no increase or any change at all of T_R when cyclone (a) passes over the largest ocean depths of the whole region to the NE of Iceland at 12^h—15^h 2/10.

Types of microseisms

At U there are in both storms (I and II above) a certain group formation but not very pronounced or regular (Fig. 1 b). Also at B there are no regular group microseisms at any time in case 4. The microseisms at R are mostly continuous.

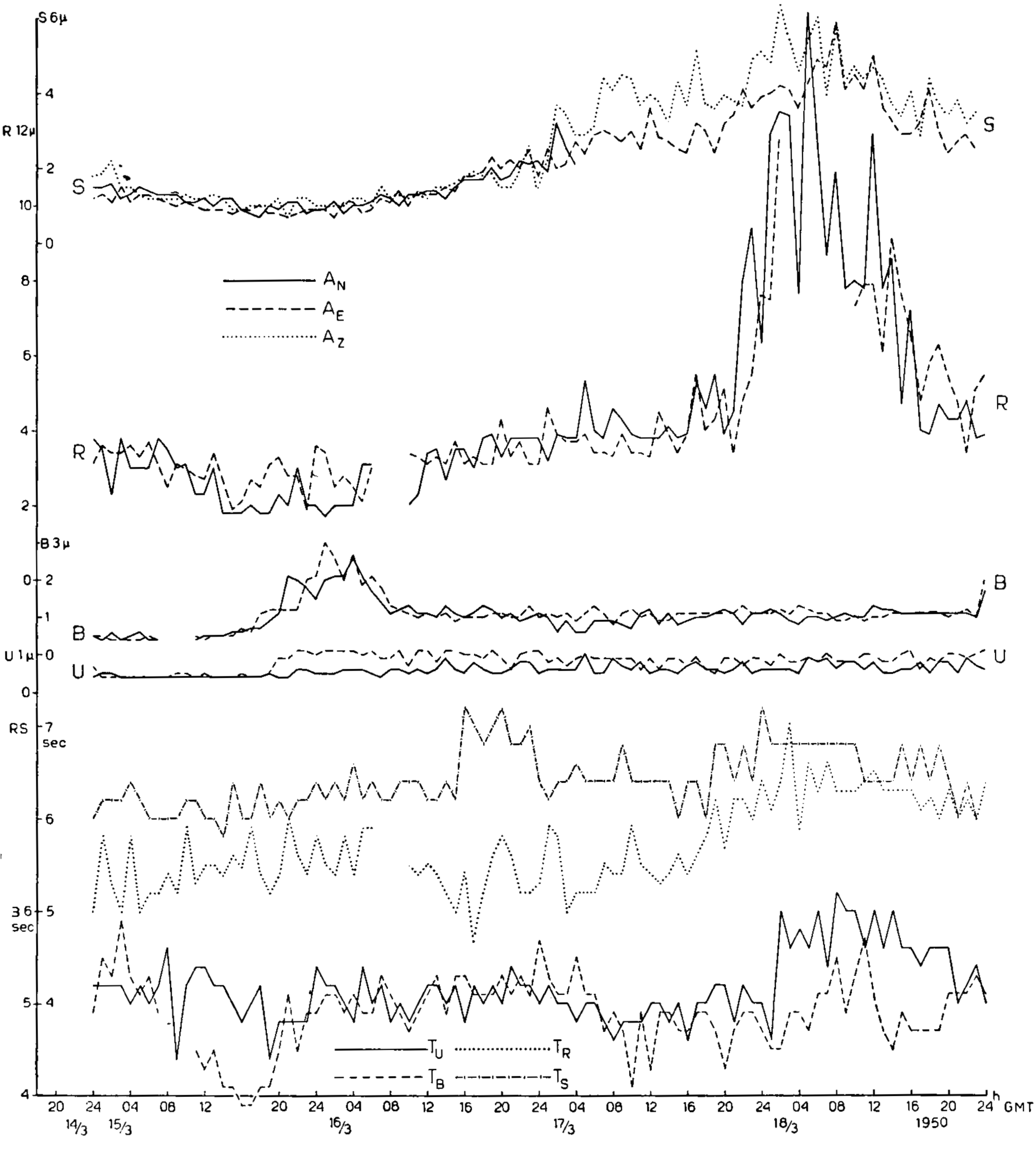


Fig. 9. Case 5: March 14—18, 1950.

Case 5: March 14—18, 1950 (Fig. 9)

Weather (Fig. 3 b)

On the whole the weather is dominated by a single, large low pressure area which is first lying practically immovable around 50° N, 23° W and then (from the morning of 17/3) moves slowly towards NE between Iceland and Norway.

Amplitudes

The amplitudes at U, B are quite unimportant as always in cases with SW winds over Scandinavia. The main variations are summarized in the following table.

Station and component	Increase at	Maximum at	Remarks
I. UE	19^h 15/3	—	Increase sharp on UE; not so clear on UN
B	17^h 15/3	01^h 16/3	
II. B	23^h 18/3	—	Cold front from NW over south Norway

Storm I seems to be a typical case of a coast effect localized to the coast around B, to judge from the behaviour of the amplitudes. However, the weather maps used show only an increased wind velocity on the B coast from 15^h to 18^h 15/3 and that an occluded front passes the B coast about 21^h—22^h 15/3. It is remarkable that the B amplitudes later decrease again although the wind velocity continues to increase during 16/3 and then remains at a high value (5—6 Beaufort) up to at least 18/3. According to the experience of TODD and WIEGEL (1952) it is not always that a near-coastal storm is obvious from the isobaric pattern of a weather map alone.

The amplitudes at R show a very large maximum. A very rapid increase sets in at 21^h 17/3, and maximum is reached at 05^h 18/3. It is remarkable that the amplitude variations are completely different at R and at U, B. There is no trace at U, B of the large maximum at R in spite of the fact that the cyclone is situated between Iceland and Norway and the distance from R to the centre is about the same as the distance from B. One may believe that there is a microseismic barrier between the cyclone and Scandinavia. However, the study of other cases, especially case 7, makes this explanation improbable (see also the discussion in Conclusions).

It is important to note that both the increase and the maximum at R do not occur until the cyclone intensity is decreasing, whereas the distance from R to the centre is approximately unchanged all the time. Again it seems as if a certain position of the cyclone were of critical importance for large microseisms at R, just as the case is for every station. The critical position for R is evidently over the ocean to the E-NE of Iceland. But that is just the position when the stream of polar air from due north towards Iceland is most developed. This is in complete accord with most of the other cases. It could be believed that the delay of the microseisms behind the largest cyclone intensity was only due to the time it takes for the ocean surface waves to reach their full development. This circumstance certainly contributes but if it were the only explanation, large microseisms should be obtained also for other wind directions, if they have been blowing long enough over a sufficiently large body of water. However, this is definitely not the case. For instance the microseisms in Scandinavia are never large when the winds are coming from SW or W. It is only in connection with polar air from NW—N that large microseisms are obtained. And this is a common property for all four stations investigated.

The amplitudes at S vary on the whole, but not in detail, in parallelism with those at R. The maxima are approximately simultaneous. The variations at S are more gradual. The microseisms at S are most probably due to the polar air over the ocean to the west of the cyclone.

A question of great importance is how the microseisms originate in the polar air. The two main theories will be considered.

1. Standing sea waves (LONGUET-HIGGINS, 1950). They could be expected at a coast but there seems to be no possibility for their existence over the open ocean in case 5. The wind direction has been practically unchanged all the time, as the cyclone has moved only very slowly.

2. Organ-pipe theory (PRESS and EWING, 1948, and later personal communication). If the source for the microseisms at R and S were the same, the periods at R and S should vary in parallelism, the only difference being due to possibly different distance to the source. But the periods T_R and T_S behave quite differently.

Periods

T_B has a pronounced minimum at 16^h—17^h 15/3, i.e. at the same time as the amplitudes begin to increase. This is a further indication that the source of this storm is on the B coast.

The periods at U, B diminish from 01^h to 10^h 17/3, about 0.4 sec at U and about 0.8 sec at B. There is a marked increase of 0.8 sec of T_U at 01^h 18/3. These cases are examples of

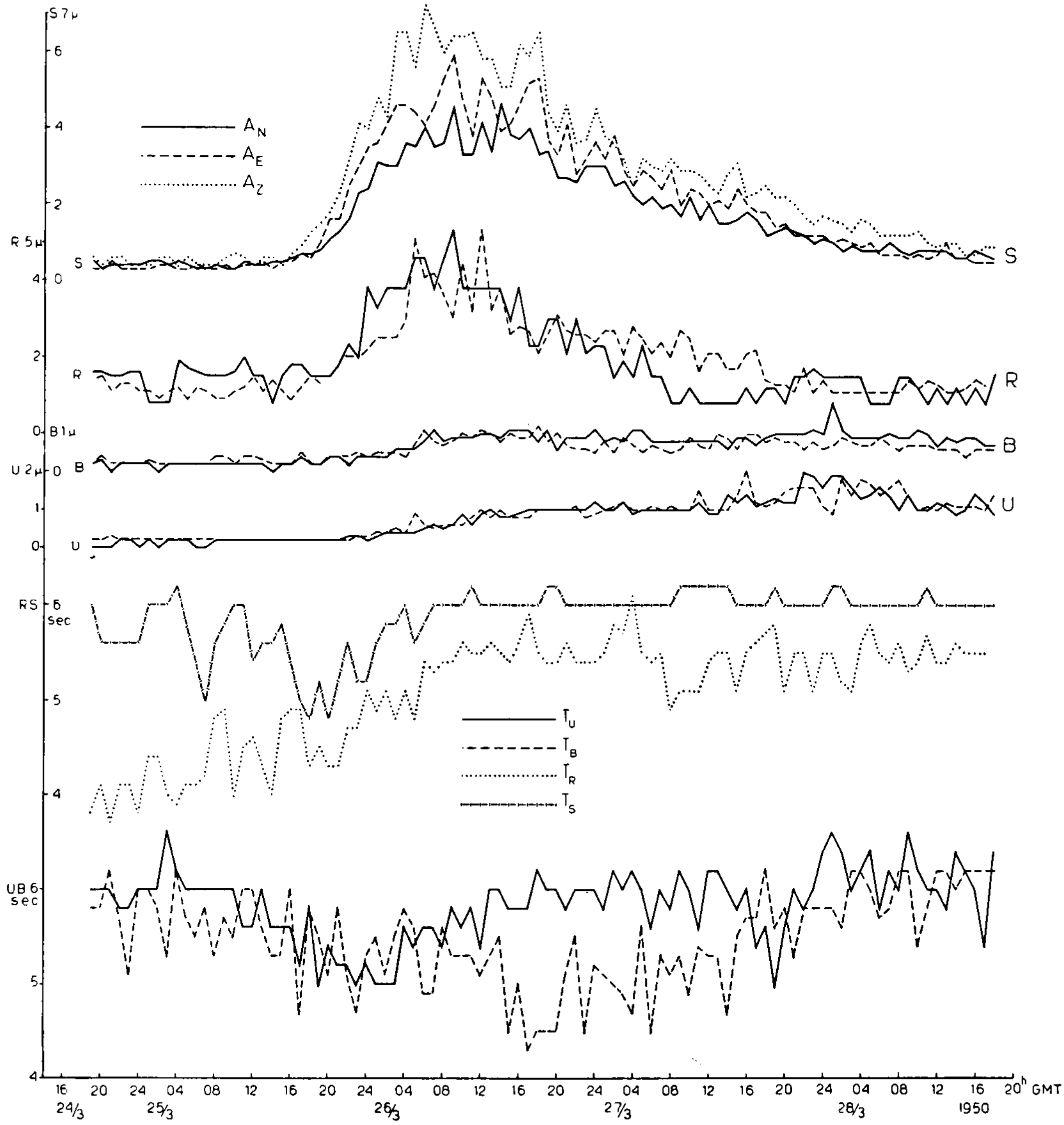


Fig. 10. Case 6: March 24—28, 1950.

period variations without corresponding amplitude variations. The reason is most probably that the position of the dominant source is variable without producing changes of amplitudes. For instance it is not excluded that the higher T_U from 01^h 18/3 on could be due to an origin from the cold air sector of the cyclone. It is known that U sometimes records microseisms with small amplitude ($\leq 1\,\mu$) but large period (8—9 sec). In addition to the cases mentioned in (1949) the following are typical: January 12, 1951; September 12, 1951; December 22—23, 1951; January 7, 1952. These microseisms may be due to a source further out on the open ocean and not at the Norwegian coast (for a fuller discussion see my paper 1949, pp. 140—141). The microseisms from the Atlantic have always small amplitudes at U.

As in every other case T_S is larger than the periods at the other three stations. In both this case and case 4, T_R is on the whole larger than T_U and T_B.

Types of microseisms

The microseisms at U are continuous. In the morning of 18/3 at the time of the period increase, they become irregular, especially on the E component. There is no clear group formation at any time at B either. The same is true at R, also for the storm towards the end. At S the group microseisms (on 16/3) are not so regular as in many other cases.

Case 6: March 24—28, 1950 (Fig. 10)

Weather (Fig. 3 c)

During the interval investigated a cyclone moves slowly from south Greenland via Iceland towards the region to the north of northern Norway.

Amplitudes

The main amplitude variations at U, B are as follows.

Station	Increase at	Remarks
I. U	21^h 25/3—17^h 26/3	
B	around 02^h 26/3	
II. U	10^h 27/3	Cold front over central and northern part of Norwegian coast
III. UN	21^h 27/3	

It is significant that in II the increase is much clearer at U than at B; this is characteristic for a coast effect localized to the central and northern parts of the Norwegian coast (see my paper 1951 b). The same is true for storm I. A cold front passes U about 20^h 27/3; if this front has something to do with the approximately simultaneous increase remains uncertain, because if this were true, it is a rather unique case. The amplitudes at U, B have no maxima during the interval investigated; they do not return to the original values, whereas the amplitudes at R, S do. The amplitudes at U, B are on the whole relatively unimportant. The wind velocity at and outside the Norwegian coast is also small. The cyclone is not very intense, except for a shorter time on 27/3.

The amplitudes at R start to increase at 20^h 25/3 and reach their maximum at 09^h—10^h 26/3. It is obvious that the increase first starts when the cyclone is situated over the ocean to the NE of Iceland and not when it is nearest to Iceland. The reason cannot be varying cyclone intensity, as this is practically unchanged the whole time. It is clear that there is no close relation between the microseisms and the cyclone centre itself. The large microseisms at R are obtained when the cyclone has reached such a position that the polar air stream north of Iceland is most fully developed. From about 12^h 26/3 the area of polar air moves away from Iceland and an anticyclone south of Iceland increases in importance; the microseisms at R are then decreasing.

The amplitudes at S are on the whole in good parallelism with those at R. There is a very marked increase at S at 16^h—18^h 25/3, i.e. somewhat earlier than at R, and the maximum is about 10^h 26/3, i.e. about the same time as at R. It is evident that the marked increase at S occurs when the wind changes to a northerly direction and the polar air is coming down over the ocean to the east of S. The increase cannot be explained by the distance to the centre, which is about the same all the time before maximum, nor can it be explained by variations of cyclone intensity. There is no coast effect at S; the wind is parallel to the coast at S during the amplitude maximum.

After the maxima the amplitudes at R, S decrease slowly, but at U, B the amplitudes are unchanged or increasing. The distance from the centre to U, B and R are about equal, while the distance to S is smaller. The stations U, B are not nearer to the cold air sector than are R, S. In spite of this the amplitudes decrease at R, S, but not at U, B. This is an indication of the importance of the Norwegian coast for Scandinavian microseisms.

At the beginning of this case there is a cyclone around southeast Greenland with on-shore winds to the north of the centre. There is no microseismic effect at S, i.e. no coast effect. The on-shore winds are not polar air, but more stable, warm air.

Periods

There are clear minima of T_U at 23^h 25/3—01^h 26/3 and at 19^h 27/3, in both cases at the same time as the amplitudes increase or begin to increase (I and II above). T_U is larger than in the two preceding cases.

T_B has a minimum about 18^h—20^h 26/3; a cold front passes B about 16^h 26/3 from NW to SE. After the minimum T_B increases all the time towards the end of the interval. The cold front at the time of minimum T_B had no observable effect on amplitudes at B or on amplitudes or periods at U (compare my paper 1951 a). The connection between period minima and cold fronts is indisputable, and is a further support for the microseismic importance of polar air.

T_R increases up to the time of maximum amplitudes from 4 to 5 ½ sec and then remains approximately constant. There is some similarity between this variation and the variation of the periods of the ocean surface waves (Fig. 4).

T_S decreases from the beginning up to 18^h—20^h 25/3 and then runs parallel to T_R. The behaviour of T_R and T_S resembles very much case 2. Also for T_S the minimum is coincident with the largest amplitude increase.

Types of microseisms

The microseisms have a typically continuous character at U, B, and R. At S they have generally a regular group appearance.

Case 7: October 7—11, 1950 (Fig. 11)

Weather (Fig. 3 d)

A whole series of cyclones moves rapidly towards NE between Iceland and the British Isles. From the microseismic point of view the weather development is more complicated than in all the preceding cases. For ease of reference the cyclones will be denoted (a), (b), (c), (d) in the order they appear. For more exact definition the following data are given:

Cyclone	Time	Position of centre
(a)	06^h 7/10	72° N, 3° E
(b)	06^h 8/10	68° N, 1° E
(c)	06^h 9/10	58° N, 25° W
(d)	06^h 11/10	57° N, 34° W

Amplitudes

Due to the complicated weather development the amplitude variations are more difficult to explain than in the preceding cases.

The R amplitudes are at first decreasing from a maximum on 6/10—7/10 (RE maximum about 14^h—24^h 7/10). At 06^h 6/10 there is a cyclone (a) with a central pressure of 975 mb NE of Iceland and polar air is coming from the north over Iceland. This is the only obvious reason for this microseismic storm at R. The maximum does not occur earlier when the cyclone was much closer to Iceland and its intensity larger, but first when the critical position NE of Iceland has been reached. The next cyclone (b) has no greater effect at R, the probable reason being that the cyclone, when the critical position is reached, is only of limited extent and produces no important inflow of polar air. Polar air is coming in later, but then the whole system has moved away too much to be of greater significance, and also the cyclone (c) disturbs the conditions around Iceland. At R there is only a small maximum around 20^h 9/10, superimposed on the general decrease. Cyclone (d) is the probable reason for an amplitude increase at R in the morning of 12/10 (cyclone effect).

The amplitudes at S seem to be simpler to explain, as only cyclone (b) is of importance. A very rapid increase starts at 14^h—16^h 8/10 (before that the amplitudes were slightly decreasing from a maximum corresponding to cyclone (a); maximum is reached about 07^h 9/10. As in general at S the increase is much more rapid than the decrease. Some details of the development are given in the following table.

Time	Distance SL km	L mb	Distribution of polar air
00^h 8/10	1,100	955	no
06^h 8/10	1,100	955	no
12^h 8/10	1,100	965	slight beginning over the ocean outside Greenland;
00^h 9/10	1,050	975	well developed off the coast of S;
06^h 9/10	1,000	975	very well developed off S;
12^h 9/10	900	975	well developed;
00^h 10/10	1,000	980	decreasing

The microseismic storm at S cannot simply be explained by variations of the distance or the intensity of cyclone (b). Again clearly the polar air is of decisive importance. But there

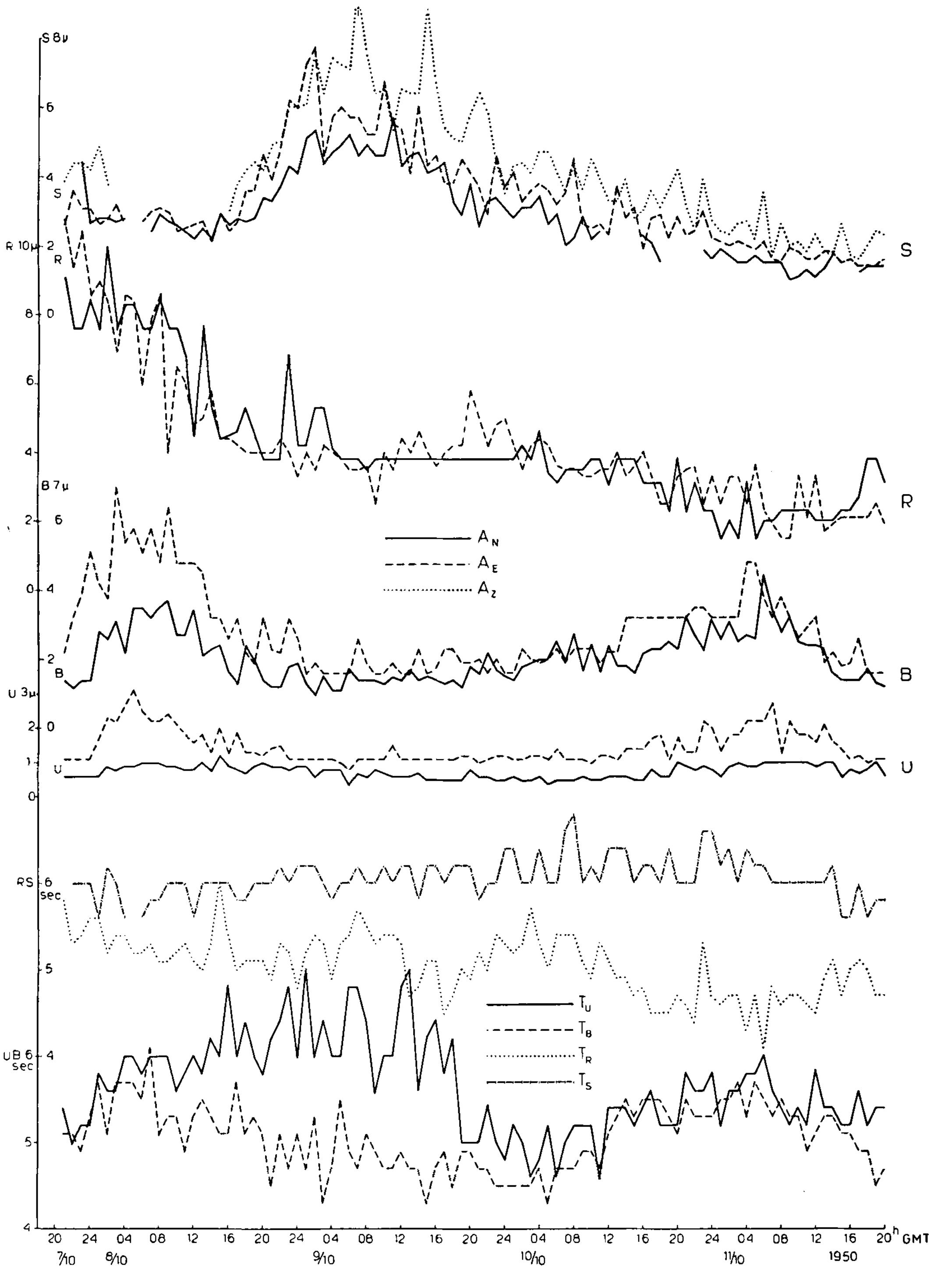


Fig. 11. Case 7: October 7—11, 1950.

is no coast effect at S, as the wind is approximately parallel to the coast. At least in wintertime also ice along the Greenland coast prevents a coast effect.

The variation of the amplitudes at U, B deviates completely from S. The cyclone (b) which was of great importance at S is of very little significance in Scandinavia. It gives SW winds over Scandinavia. The amplitudes at U, B indicate a clear coast effect localized to the B coast:

1. The amplitudes at B are considerably higher than at U.

2. $A_E > A_N$ without exception at U.

3. The increase is earlier and more rapid for A_E than for A_N at U.

There are two storms (I and II) at U and B.

Station and component	Increase at	Maximum at	Remarks
I. UE	24^h 7/10	05^h 8/10	cyclone (b); cold fronts pass the B coast about 15^h 7/10 and 24^h 7/10;
UN	01^h 8/10		
BE	beginning of interval (21^h 7/10)	06^h—07^h 8/10	
BN	24^h 7/10		
II. UE	about 13^h 10/10	about 06^h 11/10	cyclone (c)
UN	16^h 10/10		
BE	13^h 10/10	04^h—06^h 11/10	
BN	not clear		

At 00^h 8/10 the cyclone centre (b) lies in the direction W 40° N from U, but the E component of the amplitudes is considerably larger than the N component. This happens always at U when cold fronts pass the B coast. This excludes the cyclone centre as source of the microseisms. The question remains if the source is located at the B coast or further out on the open ocean within the polar air. The last-mentioned possibility is excluded for the reason that the storms I and II are observed only in Scandinavia, and not at R, S. This is easily explained for a source at the B coast, as the distance to R is then too great. But it can hardly be explained by an origin within the polar air over the ocean, as the distance from R to the polar air sector is just about the same as from U, B. On the other hand, for R, S the polar air over the open ocean, especially with straight wind paths over a large body of water (large fetch), is of greatest microseismic importance. The special rôle of the coast will be discussed in the Conclusions below.

At 00^h 8/10 there is a cyclone (b) between Iceland and Norway; there is no microseismic storm at R, but there is one at U, B. It is interesting to compare this situation with case 5, where there was also a cyclone at about the same place between Iceland and Norway, but accompanied by a microseismic storm at R and not at U, B, i.e. just the reversed situation. The difference lies in the different form of the isobars. In case 5 there were SW winds over Scandinavia and polar air only over Iceland and over a large body of water to the north of Iceland. On the other hand, in case 7 polar air is coming in over the B coast, but there is no pronounced inflow of polar air north of Iceland, at any rate only a small fetch. That completely different microseismic situations are obtained for a cyclone with its centre in about the same place shows clearly that the source cannot be located at the cyclone centre. The different conditions could only be explained from differences in the distribution of different air masses. We also note that the idea of a source in the centre and a microseismic barrier, e.g. along the continental edge outside Norway, is untenable. The cyclone centre (b) in case 7 is far outside the continental edge at 00^h 8/10, and the idea mentioned could not explain why in one case we get a microseismic storm only in Scandinavia, in another case only on Iceland. The conditions are simply explained by the distribution of the polar air without using the hypothetical explanation by means of a microseismic barrier, the existence of which is by no means proved.

That $A_E > A_N$ at U at 06^h 9/10 as all the time can only be explained by a coast effect at the B coast. At 06^h 9/10 the centre (b) lies in the direction W 60° N from U and the polar air over the ocean to the W of (b) is in approximately the same direction. The coast effect is limited to the B coast.

There is some similarity only between the microseisms at S and the ocean wave heights (Fig. 4). The increase and the maximum of the waves occur earlier than of the microseisms at S.

Periods

T_S is as always remarkably constant ($\cong$ 6 sec) and has no variation in parallelism with the amplitudes. The period variations are much larger at R, U, B.

T_B, T_U, especially T_U, show some remarkable variations. T_U has one maximum at about 01^h 9/10 ($\cong$ 6.4 sec) and another maximum at 04^h 11/10 ($\cong$ 5.6 sec) with a minimum between, about 06^h 10/10 ($\cong$ 4.8 sec). The period variations are quite considerable and no doubt significant. T_B deviates from T_U in not showing the first maximum. There is a pronounced parallelism of T_U, T_B with the amplitudes only in the second maximum. We have to observe that the amplitudes UE and UN behave rather differently, and that the parallelism between T_U and UN is relatively good on the whole, but for UE it is good only for the last maximum. The amplitudes BN, BE, and UE are quite similar (due to the B coast), whereas UN deviates. UN is probably more dependent on conditions at the more northerly parts of the Norwegian coast, i.e. a more distant source and higher periods. This distance effect is certainly the essential reason that $T_U > T_B$ during the first part of the interval. A comparison of T_N and T_E for U clearly shows that during 8/10 $T_N > T_E$, whereas for 9/10—11/10 they are approximately equal. The minimum periods occur just when a new source, cyclone (c), comes to importance. The variations of T_U in case 7 cannot be explained by motion of the cyclone centre (b) or of the polar air over varying ocean depths.

Types of microseisms

The microseisms at U are irregular on 9/10, especially on the N component. The microseisms are continuous at U, B and also at R.

Conclusions

In the study of the special cases several questions have appeared which cannot be answered definitely due to the lack of sufficient meteorological and especially oceanographic data. But in addition a number of well-established general conclusions can be drawn. They will be summarized in this chapter.

1. Importance of polar air

For every station investigated there is a certain critical position in which a cyclone of given intensity produces the maximum microseismic amplitudes. I think that quite some progress towards solving the microseismic problems could be made if these positions were determined for every station within a larger area and also the situations studied which produce rapid amplitude increases. For Uppsala the maximum microseisms are obtained for a low with its centre in the region of northern Russia (see BÅTH 1949); for Bergen the critical position is outside the central part of the Norwegian coast (on-shore winds and waves at the coast around Bergen; see BÅTH 1951 b). For both stations rapid amplitude increases are generally obtained when cold fronts pass the Norwegian coast in the direction sea to land (see BÅTH 1951 a). In the present paper it has been shown that maximum amplitudes occur at Reykjavik when a low is over the ocean to the NE of Iceland and polar air is coming down from the north across Iceland along straight paths over a large body of water; and the critical position for Scoresby-Sund is over the ocean to the east of the station and when the area between Scoresby-Sund and the centre is occupied by polar air. All four stations have in common that the microseisms show no close relation to the cyclone centres themselves, but that they are at all stations closely related to the approach of polar, unstable air. This circumstance cannot simply be explained as a time lag between winds and ocean waves, but must be due to some special property of the polar air (see discussion of case 5). In general it seems difficult to explain this as an effect of standing ocean waves, especially when the wind has been blowing in about the same direction for several days and not against a steep coast.

Indications of some kind of cyclone effect with a closer connection to the cyclone itself has earlier been obtained for Uppsala in cases with a minimum coast effect (BÅTH, 1949). At Reykjavik a cyclone effect, possibly due to standing ocean waves, is obtained when a rapidly moving low is in the near vicinity of Iceland.

In several cases there are greater similarities between the ocean wave observations at 61° N, 2° E and the microseisms at Scoresby-

Sund than at any other of the stations investigated. The reason may be that the ocean wave observations correspond better to the conditions on the open ocean, whereas the microseisms at least in Scandinavia are dominated by a coast effect. There seems to be no doubt that the ocean surface waves are of essential importance, whatever the mechanism is.

2. Coast effect

Recognizing the common microseismic importance of the polar air for Scoresby-Sund, Reykjavik, Bergen, and Uppsala, the question arises what importance the Norwegian coast has in the case of Scandinavia, in other words what is the nature of the coast effect. There is no coast effect in Scoresby-Sund in the cases studied; at Reykjavik the coast effect may contribute, but for both stations the main source is probably located over the open ocean within the polar air. Some kind of coast effect on the Norwegian coast, especially within the polar air, is the main source of microseisms in Scandinavia. For a full discussion of the evidences for this, see BÅTH (1951 c).

The coast effect at a steep coast could be due to one or both of the following possibilities.

Pressure fluctuations on the ocean bottom below standing sea waves, formed by reflection from a steep coast (LONGUET-HIGGINS, 1950). In this case standing sea waves can naturally be expected. This idea is supported by the behaviour of the periods (see below). The special importance of the polar wind would then be its property of producing higher ocean waves than within warm, stable air of the same wind velocity (see BÅTH, 1951 a, pp. 295—303). Concerning ocean wave phenomena of importance for formation of standing waves at a coast, reference is made to an investigation by WILLIAMS and ISAACS (1952).

The importance of surf at a steep coast still deserves further attention.

The continental layers serve as a waveguide for the microseismic waves, whereas the ocean bottom does not. It was shown by GUTENBERG (1932) that the microseisms originating at the Norwegian coast are observed in Russia and far into Siberia, whereas in this paper it is shown that even at such relatively near places as Reykjavik and Bergen the microseisms behave quite differently. EWING (1951) found from theoretical and empirical considerations that Rayleigh waves of the same period as the microseisms could not travel very far over an oceanic structure. He proposed the hypothesis that microseisms instead were body waves (P and SV), for which different absorption would not be expected. However, the empirical result, obtained here, does not seem to require the introduction of body waves, but could be explained by the hypothesis of Rayleigh waves or a combination of these and other surface waves. At any rate, if the microseisms were only body waves, I cannot see how the range could be so much larger over the continent than over the ocean.

When this result had already been found for our region, I found that CARDER (1952) had got the same results for other parts of the Atlantic Ocean and for parts of the Pacific Ocean. The condition may be general and, as stated by CARDER, microseisms which are well recorded on land would hardly be expected to originate from great distances at sea. It is not excluded that the continental channel is the same as for the short-period surface waves *Lg* and *Rg*, observed in earthquake records when the path is purely continental. See also a recent paper by GUTENBERG (1951).

3. Periods of microseisms

On the whole, it is more difficult to explain the observed period variations than the amplitude variations. But for every theory of microseisms it is essential that also the behaviour of the periods can be explained. The period at Scoresby-Sund is remarkably constant and shows no obvious connections with the amplitude variations. The period variations are larger at Reykjavik but also here there are in general no very obvious connections between the variations of period and amplitude. At Bergen and Uppsala, on the other hand, there are often large period variations, and the periods vary in obvious parallelism with the amplitudes. In addition the periods vary with the distance to the source of microseisms (for a full discussion of this problem for the Scandinavian region see BÅTH, 1952 b).

It is characteristic with a period minimum coincident with a rapid amplitude increase and the passage of a cold front over the Norwegian coast around Bergen. Similar observations have been made in New Zealand by JONES (1949). There is a very striking resemblance between this behaviour of the microseisms and the behaviour of periods and amplitudes in near-coastal storms, the latter demonstrated by TODD and WIEGEL (1952); see especially fig. 3 in that paper. They found that in near-coastal storms, the periods of the ocean waves dropped rapidly while breaker heights increased. There is no doubt that the microseisms at Bergen and Uppsala in these cases are due to ocean surface waves in near-coastal storms. Similar period minima are observed at Scoresby-Sund, apparently simultaneous with the approach of polar air over the ocean outside Scoresby-Sund.

Apparently due to varying distance to the source there are period variations sometimes observed at Bergen and Uppsala, with no simultaneous amplitude variations.

If the standing ocean wave theory is valid, we should expect a parallelism between periods and amplitudes, for the organ-pipe theory not. As mentioned above, standing waves may be expected at the Norwegian coast, but often not over the open ocean in the cases studied. This means that standing ocean waves may be of importance for Scandinavian microseisms, and some other mechanism is the main reason for the microseisms on Iceland and Greenland. However, I have in no case succeeded in correlating the period variations at any place with varying depths of ocean and underlying sediments, as required by the organ-pipe theory. The ocean depths are well known (see STOCKS, 1950), whereas there are no measurements at hand of sediment thicknesses so far to the north as our region of the Atlantic Ocean. Some information for regions more to the south is obtained from results of the Albatross expedition, as well as from British and American investigations. The standing wave theory requires a ratio of 0.5 between the periods of microseisms and of ocean waves. Using the ocean wave observations at 61° N, 2° E, we found this ratio to be significantly greater than 0.5 at all stations investigated.

The periods at Scoresby-Sund are practically without exception larger than at the other three stations.

4. *Microseismic barriers*

The fact that cyclones in the Atlantic are of relatively little microseismic importance in Scandinavia, whereas the effect on Iceland and Greenland may be large, could lead us to suspect a microseismic barrier west of Scandinavia. In a previous paper (BÅTH, 1952 a) I mentioned that no barrier effect was observed at the continental edge. It is also clear that it is not a sufficient reason for large microseisms that a cyclone has passed the continental edge. For instance a cyclone around north Russia has a far greater importance for Scandinavian microseisms than a cyclone situated over the North Sea, also within the continental edge, and moreover at a much shorter distance from Uppsala. Large increases occur in Scandinavia in several of the cases studied already when the cyclone is far outside the continental edge. The reversed behaviours of the microseisms in cases 5 and 7 (see discussion of these cases) also disproves the existence of a microseismic barrier. The microseismic amplitude variations at the different stations in our region can be explained by the distribution and approach of polar air without using the artificial explanation by means of microseismic barriers.

On the other hand, the apparently low ability of oceanic structures to transmit microseismic waves may be called a barrier effect. I have earlier offered a supplementary hypothesis (BÅTH, 1952 a) for the explanation of barriers. In addition to this hypothesis I would like to mention also the possibility that irregular distribution of microseisms (barrier effects) may be due to interchanging oceanic and continental structures.

5. *Types of microseisms*

The microseisms at Scoresby-Sund are in general much more regular than at the other three stations and show a clear group character. At Reykjavik as well as at Bergen and Uppsala the microseisms are usually continuous. Group microseisms are observed at Bergen and Uppsala in some cases with a coast effect limited to the southwest coast of Norway (around Bergen). In general the microseisms are likely to be more regular for a limited source, whereas they become irregular when several sources are active simultaneously or when there is one source of large extension.

Acknowledgments

The present investigation has been made at the Seismological Laboratory, Meteorological Institute, Uppsala.

The Directors of the Seismological Stations at Scoresby-Sund, Reykjavik, and Bergen have lent me their original records and given information on seismograph constants etc.

The Director of the Swedish Meteorological and Hydrological Institute, Stockholm, has permitted me to reproduce their weather maps (Figs. 2 and 3).

Mrs I. Thomasson, Uppsala, has assisted me in drawing the figures.

My best thanks for valuable help are due to all the above-mentioned persons.

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