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Long-term changes in hydrographic conditions in the North Atlantic and adjacent seas

by

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In this paper an attempt is made to describe in summary form some important hydrographic changes induced in the eastern Atlantic area by a recurrent atmospheric circulation pattern. A progress report on part of the work described here was presented at the SCOR Symposium on Variability in the Oceans, Rome 1966, (Dickson and Lee 1968) and a full account is at present in preparation for publication.

As part of a research programme relating long-term changes in hydrographic conditions to long-term changes in both atmospheric circulation and marine faunal distribution, a simple analysis of salinity data was carried out for all possible sea areas around the British Isles.

In attempting to delimit the underlying processes responsible for hydrographic change, salinity was chosen for analysis rather than temperature since not only is salinity less subject to local modification by external processes than is temperature (see, for example, Montgomery, 1955) and is therefore a more conservative property of a given watermass, but also, as pointed out by Dietrich (in Laevastu 1963), a much larger area of our shelf seas tends to be homohaline all year round than homothermal, so that surface estimates of salinity are more consistently representative of conditions in the whole water column than are similar estimates of temperature.

In analysing the 60-year salinity record (1905-65) for these shelf seas, it was found that during this century they have experienced a striking and fairly regular (but not cyclic) alternation between periods of low and periods of high salinity, these salinity fluctuations being roughly contemporaneous events in all areas of these seas. Figure 1, for example, illustrates the essential similarity of the interwar salinity-anomaly curves for 4 groups of sea areas in the English Channel and southern North Sea, and the same might be shown to be true for all areas of the shelf seas during all periods for which we have data. The question arose as to the cause of these inter-annual salinity fluctuations.

Seasonal change in the level of actual salinity in European waters (as illustrated by the seasonal advance and retreat of the 35 °/oo isohaline) is known to be largely a result of a seasonal variation in the strength of Atlantic water inflow to these seas. Therefore, since our 60-year salinity analysis showed each high salinity period to be the end-point of a continuous rise in the anomalies of salinity over a period of as long as four years, irrespective of season, it was immediately suspected that the cause was a gradual evolution in the anomalies of Atlantic water inflow strength over the same period. Indeed various factors appeared to confirm that these salinity fluctuations had an "Atlantic" origin, notably the fact that the actual size of the salinity anomalies encountered, and their phase lag, increased with increasing distance from the open Atlantic.

Unfortunately we have only a limited amount of direct evidence for this theory. The volume-transport data of Tait (1957) for the Faroe-Shetland Channel are too limited to enable us to distinguish such short-term changes, and while the data for the Varne lightvessel (Carruthers 1935, 1939, Carruthers, Lawford and Veley, 1949) certainly support the theory, the time span involved is an uncomfortably short one. Therefore since atmospheric processes are the only reasonable means by which our proposed acceleration of Atlantic inflow could be effected, an attempt was made to find out whether atmospheric conditions during these periods of rising salinity anomaly were capable of producing such an acceleration. It is clear that if the atmosphere is to be held responsible for an acceleration of inflow lasting for periods of a few years, two connected atmospheric processes must be in operation, the first responsible for initiating the acceleration and the second responsible for maintaining the acceleration over a period of years.

Namias (1965) has outlined the anomalous atmospheric processes which were responsible for causing an increased advection of warm water northwards along the western European seaboard in the period from late 1958 to 1960. Since this period of warming also corresponds to one of our periods of continuously rising salinity anomaly, it is thought that Namias has described an actual case of atmospherically-induced inflow acceleration.

Namias describes this anomalous warm water advection as an Ekman drift effect, owing its initiation to the establishment of a large low pressure anomaly cell over the western Atlantic and an equally large pressure-anomaly ridge over northwest Europe (Figure 2) whose combined effect was the generation of a southerly anomaly wind over the eastern Atlantic. Ocean/atmosphere feedback effects which became more and more important as the distribution of sea surface temperature became more and more abnormal, were responsible for maintaining and intensifying this initial pressure pattern, with the result that the warm water advection also tended to persist and intensify.

An attempt was then made to find out whether atmospheric conditions similar to those outlined by Namias were in operation during other periods of rising salinity anomaly in our shelf seas. Charts of 500 mb. height anomaly for the northern hemisphere were computed by the Meteorological Office, Bracknell, for each 6-month period between 1949 and 1964. In only eight 6-month periods out of 32 was the disposition of 500 mb. thickness conducive to increasing the southerly anomaly-wind component over the eastern Atlantic, and in only 4 cases was this pattern strongly developed. The dates are however of great significance. In the post-1948 period the salinity of our shelf seas rose to maximum values on only four occasions, 1949-50, 1953-early 1954, late 1958-early 1960, and 1963. In other words these years represent the end parts of our postulated Accelerated Inflow Periods, and in each case these salinity maxima were accompanied by the establishment of a "Namias-type" circulation over the North Atlantic, this circulation pattern being weakly developed in 1949-50 but strongly developed in the remaining three periods mentioned above, (Figures 3-7).

In view of the possibility that pressure-anomaly cells at sea level may be longitudinally displaced from the corresponding centres of pressure (or "thickness") anomaly at 500 mb. level an indirect check was made on the positional agreement of the cells at the two levels using various meteorological indices. In each case (Figure 8) the "peaking" of salinity anomalies in our seas was accompanied, or more strictly slightly preceded, by the increased anticyclonicity (decreased cyclonicity) over northwest Europe and by the increased southerly circulation over the eastern Atlantic which is characteristic of the circulation pattern described by Namias.

Four inherent aspects of this anomalous circulation could have brought about the observed progressive increase in the salinity of our seas. Of these, two (reduced precipitation and increased evaporation) were capable of effecting an <u>in situ</u> increase in salinity by reducing the freshwater accession to the shelf seas. The other two appeared capable of bringing about an <u>advective</u> increase in salinity by increasing the inward flux of salt to our seas:

(i) The "Namias-type" of atmospheric circulation may actually accelerate the inflowing current of Atlantic water such that a greater quantity of salt than normal will be brought in. Supporting evidence for this is to be found in Carruthers' Varne current measurements as well as in the fact that the deep inflow to the Baltic certainly appears to strengthen at these times (see below).

(ii) The abnormal southerliness of the atmospheric circulation during these periods means that a greater proportion of the inflowing water is derived from a more southerly source area than normal. Therefore on this account also the inward salt flux should increase since the inflowing stream will carry water with higher salinity than normal into our seas.

It is thought likely that the first two processes are of relatively minor importance in raising the salinity of our seas compared with the salinity rise due to salt brought in by the inflowing Atlantic current. (A conclusion opposed to that of Schott, 1966, who regards inter-annual fluctuations in precipitation as the major cause of salinity variation in our shelf seas).

The reasons for this belief are clear from Figures 1, 9 and 10. When one correlates the 20-year mean interwar curve of salinity anomaly for the Western Approaches Group of sea areas (curve G1) with similar curves for the Eastern Channel (G2), Southern Bight (G3) and German Bight (G4) Groups, it is found that the highest correlation is obtained by introducing a time-lag of 2 quarters between curves G1 and G2, 3 quarters between curves G1 and G3 and 4 quarters between curves G1 and G4. (All the correlation coefficients are highly significant). This fact - that the entire 20-year curve of salinity anomaly lags progressively up-Channel - clearly indicates the dominant influence of the advective factors in bringing about these salinity fluctuations, although it is not yet clear which of the two advective factors is the more important.

The two <u>in situ</u> factors (decreasing precipitation and increasing evaporation) may both however assist in the raising of salinity levels in our seas, especially during the end point of each salinification period when the "blocking" Grosswetterlage is most strongly developed.

It was mentioned earlier that over the 60-year period for which we have data, the pattern of salinity-anomaly fluctuations has been essentially similar in all areas of the European shelf seas which is to be expected in view of the large geographical scale of the processes responsible. However, if we confine our attention to the European shelf seas alone we are to some extent underestimating the importance of the "Namias-type" circulation and the advective streams which it generates, since there is evidence that the long-term hydrographic variations in two adjoining sea areas are largely brought about by the same processes:

1. The Transition Area and Baltic

A direct correlation between the mean salinity anomaly curve for sea areas in the Irish Sea group and the anomalies of salinity for the Lappegrund lightvessel (in the Sound between Zealand and south Sweden) at 12.5-15 m depth, yields a correlation coefficient of 0.3659 (see also Figure 11). This correlation applied to the period between the second quarter of 1939 and the third quarter of 1961. Since in this case "n" = 84, the significance of the correlation between these two very different areas is well beyond the 0.001 level. Further, since the Irish Sea data can be shown to mirror hydrographic conditions in the shelf seas as a whole, and since salinity fluctuations in the shelf seas are thought to be produced by southerly-wind-induced variations in oceanic inflow, it is hard to escape the conclusion that acceleration of Atlantic-water inflow to the shelf seas is accompanied by an acceleration of inflow to the Kattegat, Belts and Sound, this latter event being caused basically by the same anomalous atmospheric processes that gave rise to the former. (It is not suggested however that this boosting of the bottom-flow to the Kattegat is a mere inertial extension of accelerated inflow to the shelf seas. The special circumstances of the Transition Area demand that other factors be considered in addition; the volume of the Baltic compensation current for example may well increase under the conditions of relative drought attending the establishment of a persistent "blocking" anticyclone over Scandinavia).

Apart from the case of the Transition Area, a fairly clear concurrence of Accelerated Inflow Periods and major Baltic inflows may also be shown from the hydrographic records of the Baltic deep basins themselves. (Fonselius 1962, 1966, 1967), although in contrast with events in the shelf seas and even the Transition Area, these Baltic inflows tend to take the form of sudden, short-lived irruptions at the time of peak inflow to the North Sea, and do not build up gradually to peak strength over a period of time.

2. The Barents Sea

As shown in Figure 12 the curve of integrated 0-200 m temperature anomaly along the Kola Meidian section ($70\frac{1}{2}^{\circ}$N 33°E-$72\frac{1}{2}^{\circ}$N 33°E) shows a striking similarity to the post-war curve of salinity anomaly for the European shelf seas. Although events in the Barents Sea have not yet been examined in greater detail, it is thought likely that the southerly anomaly wind running from latitudes south of Britain across the Norwegian Sea to the Arctic, which tends to be characteristic of the "Namias-type" anomaly-circulation, is fully capable of bringing warmer conditions to the Barents Sea, both through advective processes and by lessening the loss of sensible and latent heat to the atmosphere (Lee 1961).

In conclusion it must be added that the above represents merely a very curtailed summary of the main conclusions resulting from a three year research programme. Much of the evidence for many of the conclusions described here has had to be omitted for reasons of space but will shortly appear in full in the Bulletins of Marine Ecology. It is hoped however that some idea has been given of the hydrographic importance of the periodic gradual changeover from the normal westerly atmospheric regime to one of extreme southerliness in the eastern Atlantic; this southerliness being generated at some point in the changeover by the establishment of the type of pressure anomaly pattern described by Namias. Perhaps the most important result is the suggestion that the annual Atlantic-water inflows to the European shelf seas are not separate unrelated units but that they are in fact related events connected by an atmospheric process capable of progressively accelerating (or decelerating) the anomalies of Atlantic inflow strength over a period of years.

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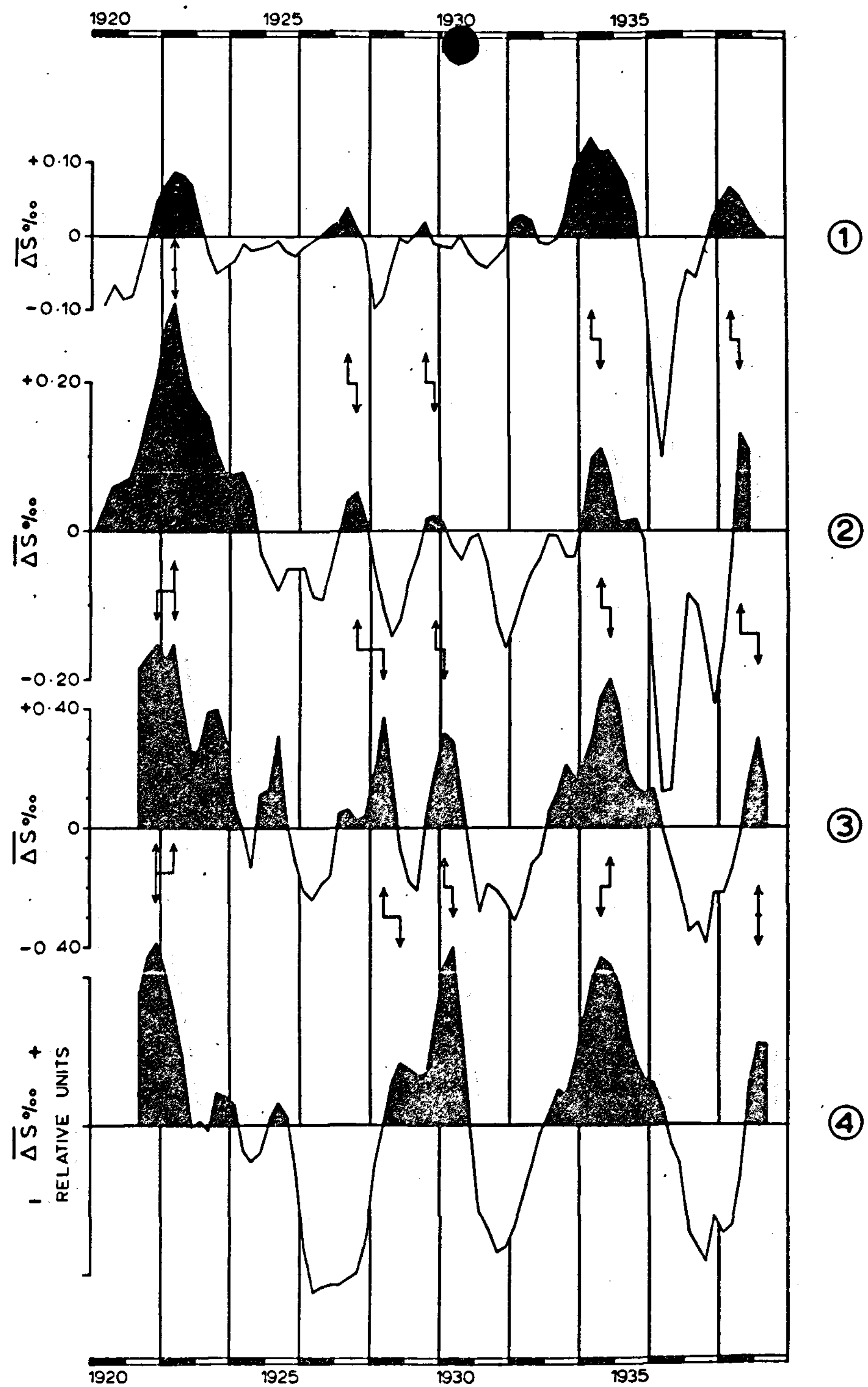
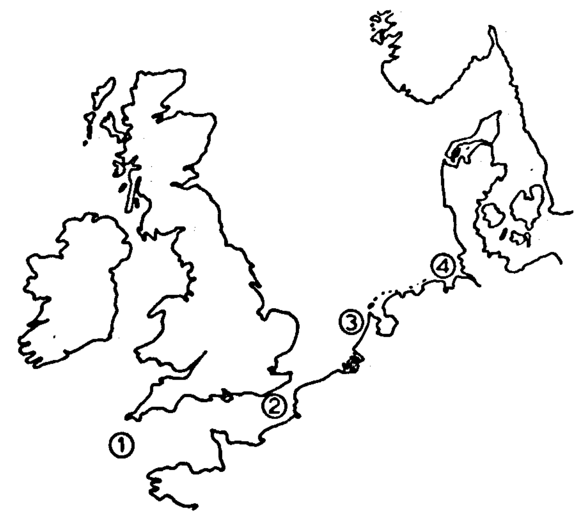




<u>TO SHOW THE ADVECTIVE TIME-LAG BETWEEN SEA AREAS ALONG THE CHANNEL INFLOW ROUTE</u>

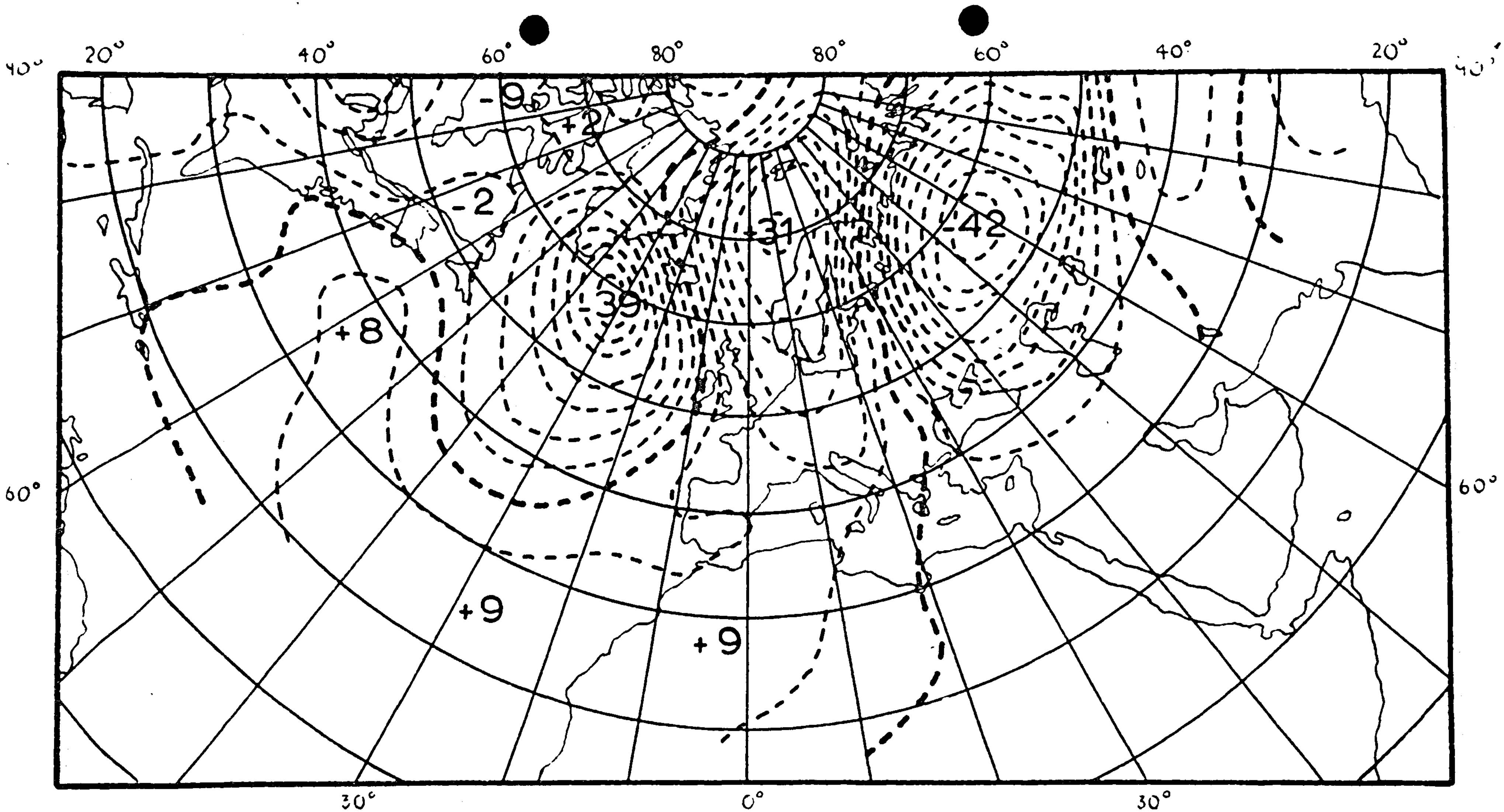
GRAPHS SHOW MEAN TREND OF SALINITY ANOMALY FOR ALL AREAS IN :

① WESTERN APPROACHES GROUP

② EASTERN CHANNEL GROUP

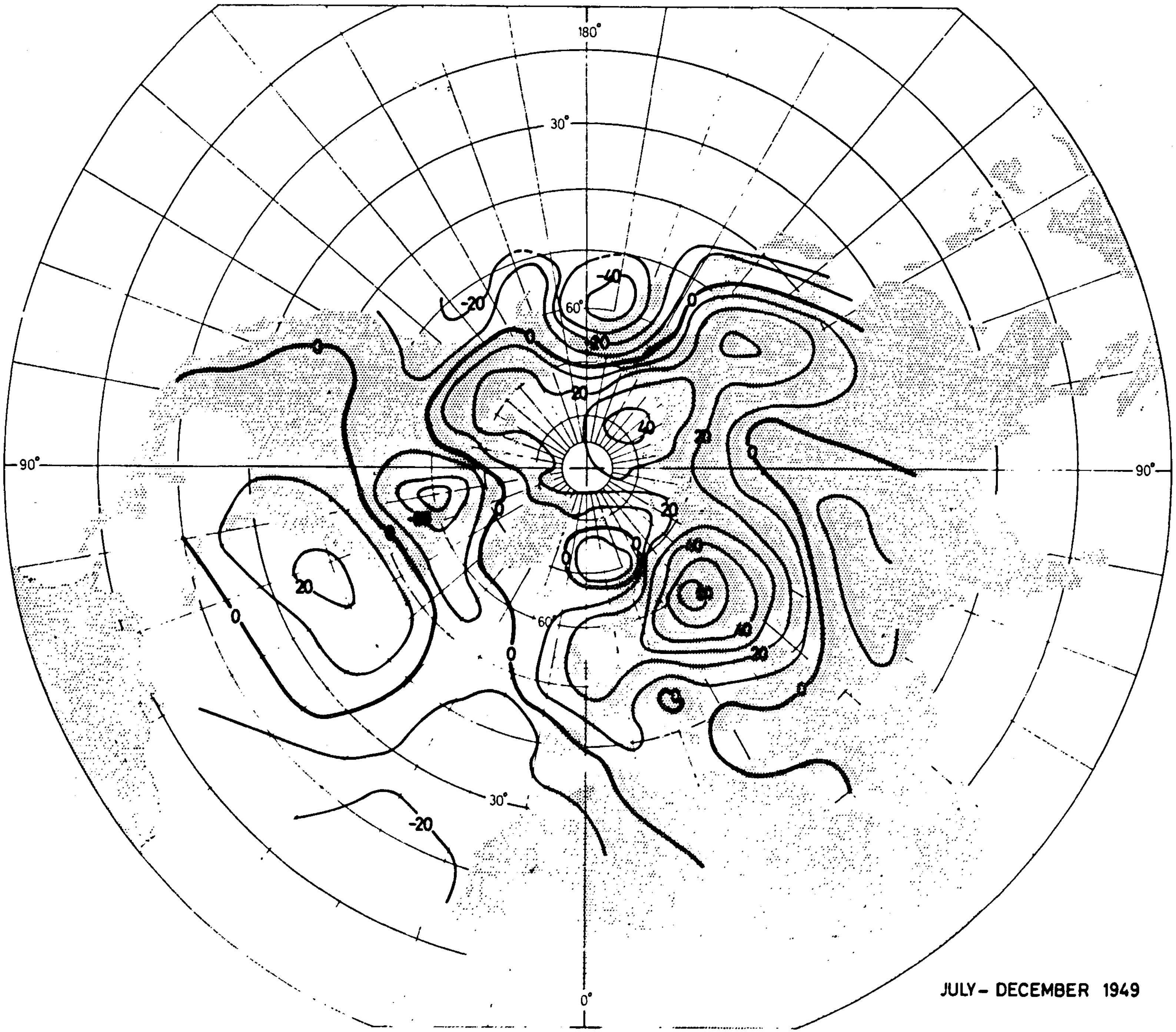
③ SOUTHERN BIGHT GROUP

④ GERMAN BIGHT GROUP



MEAN DISPOSITION OF 700-mb. HEIGHT ANOMALY—OCTOBER 1959

AFTER NAMIAS



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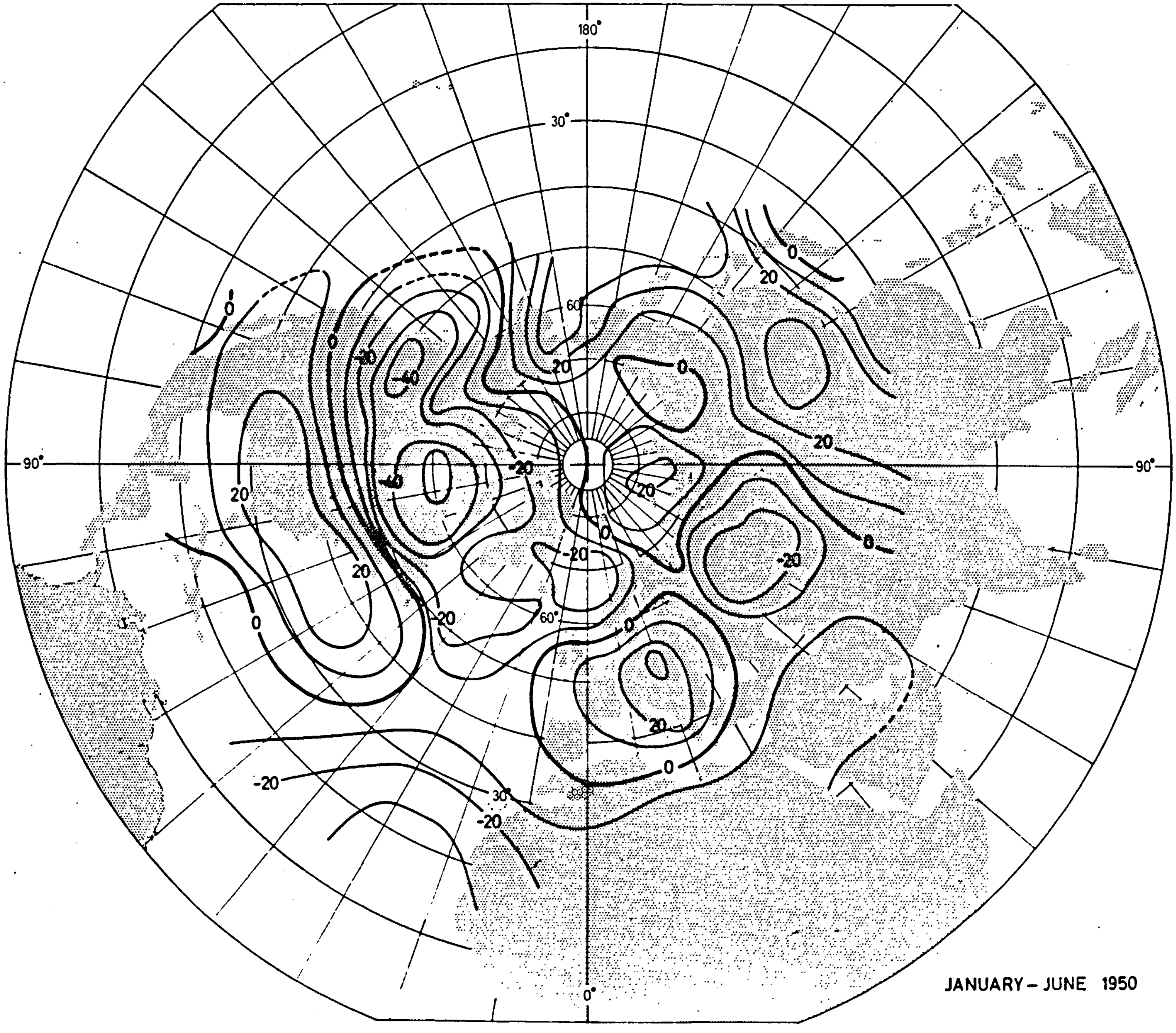

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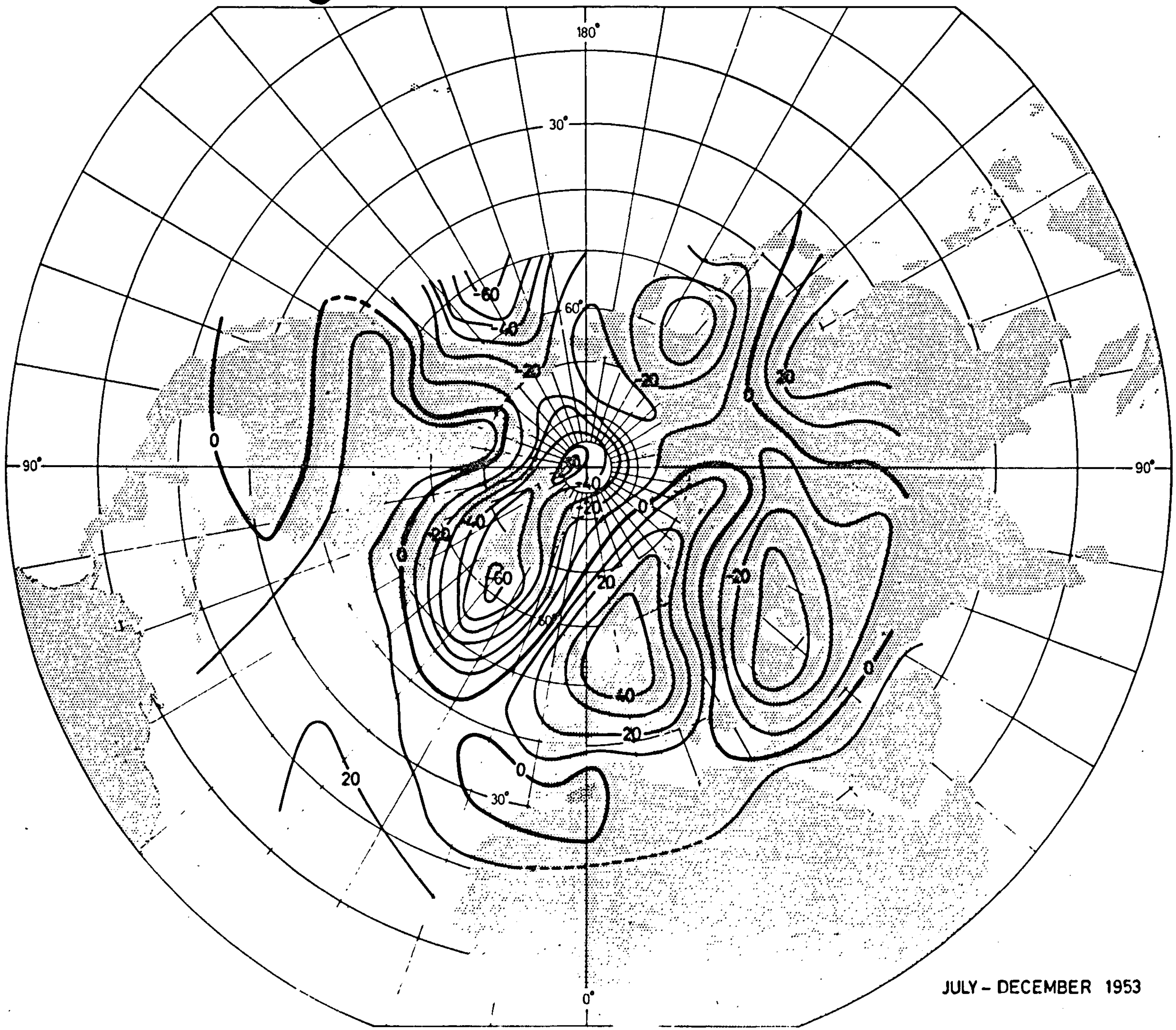

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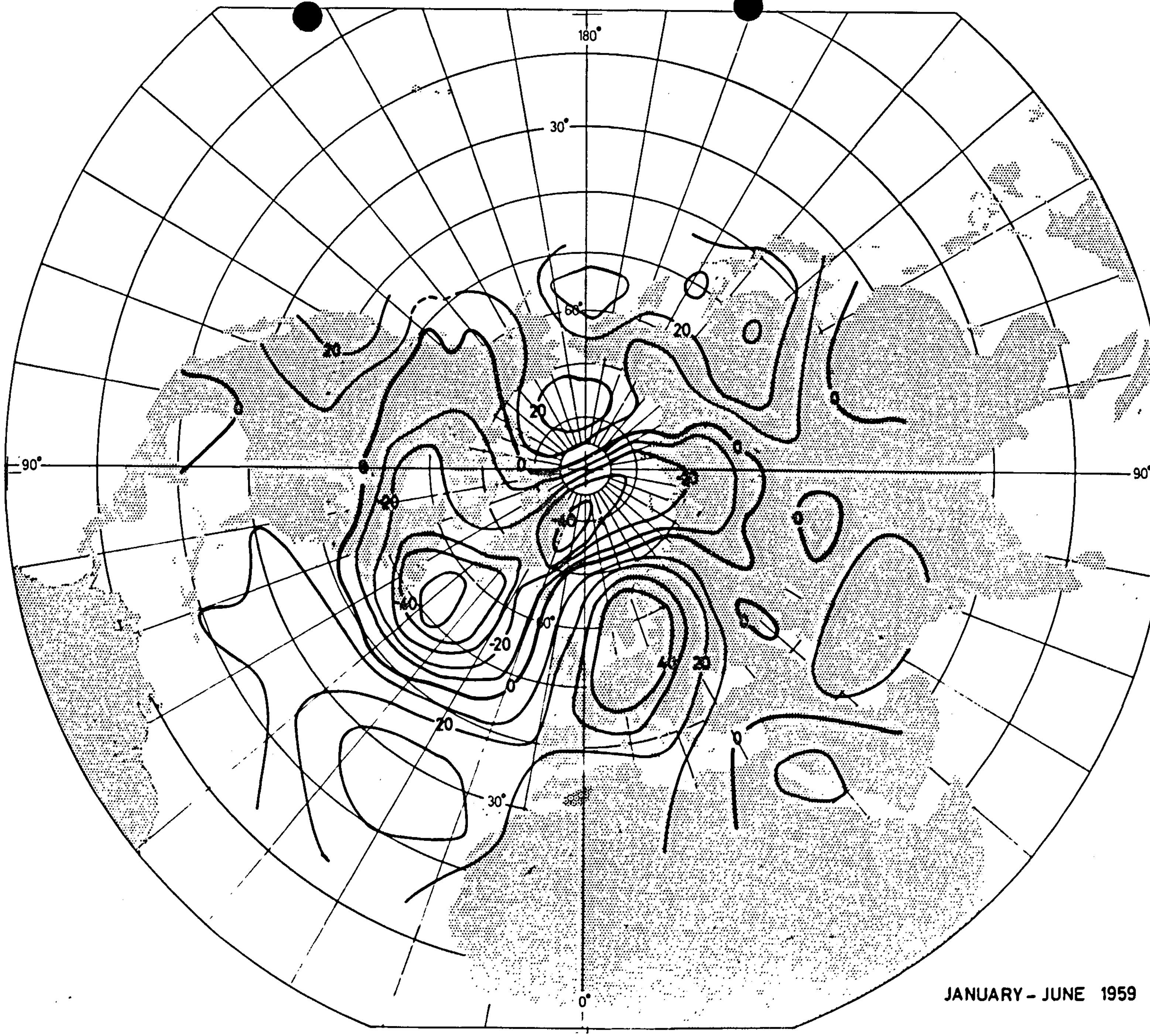

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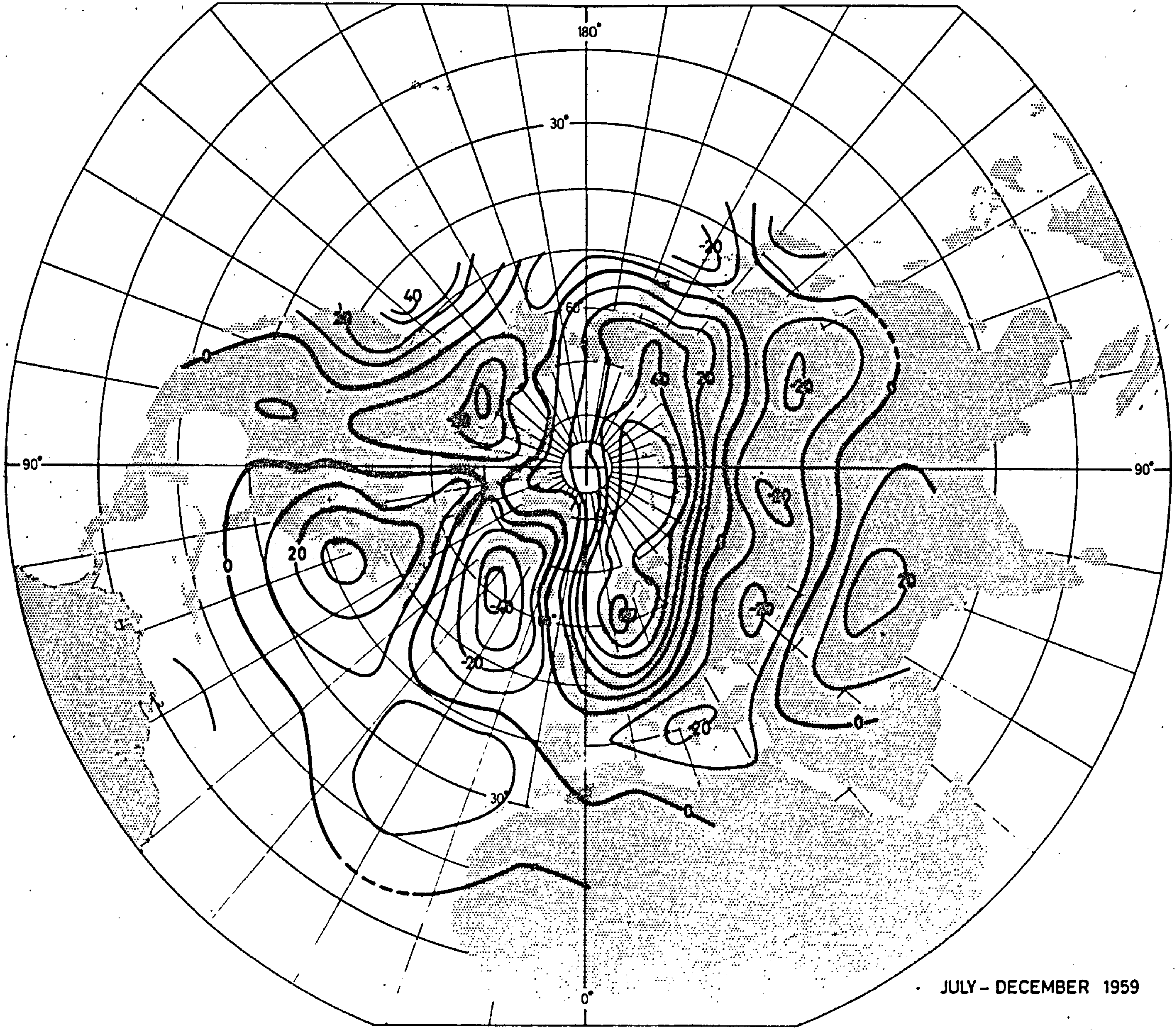

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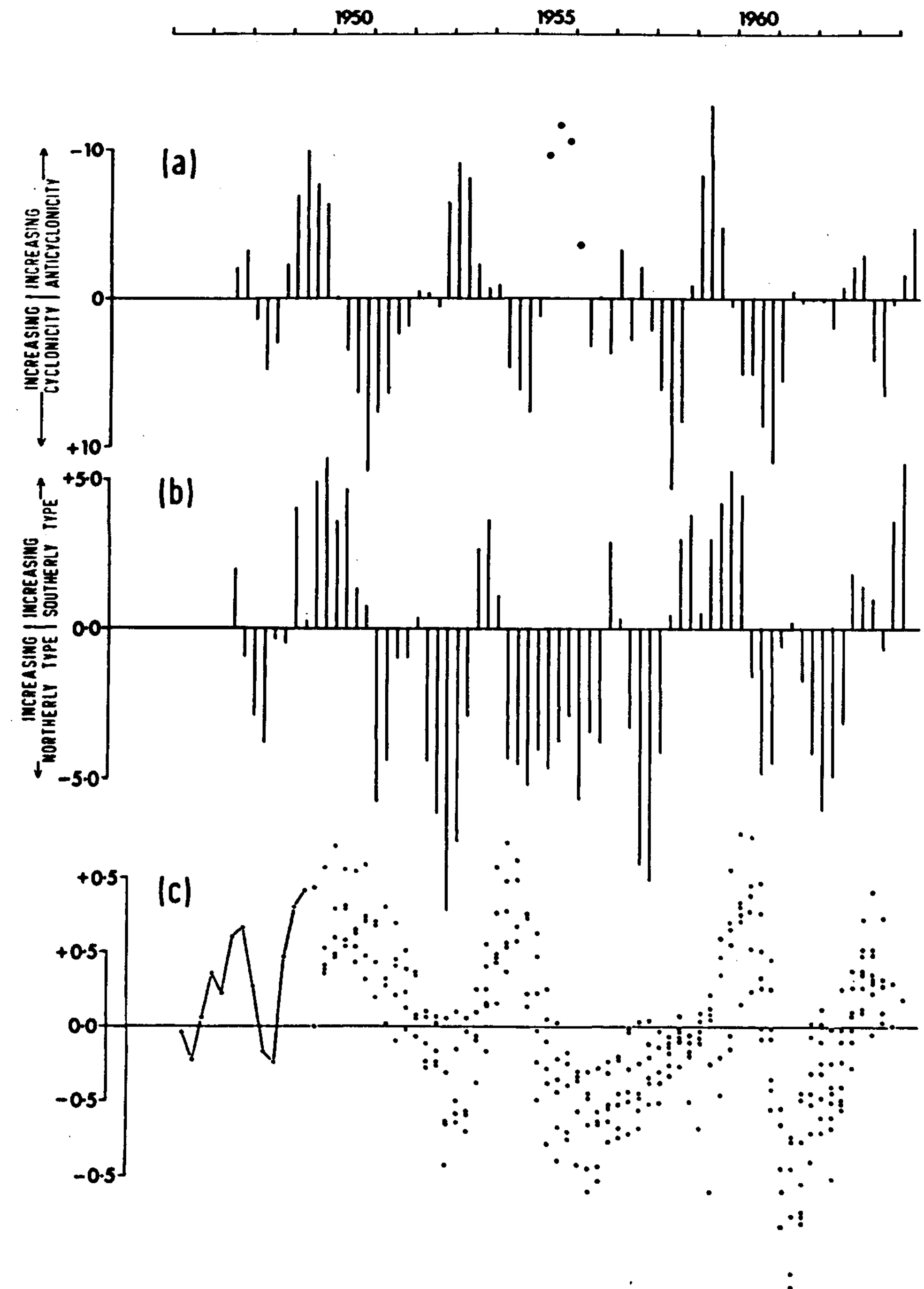
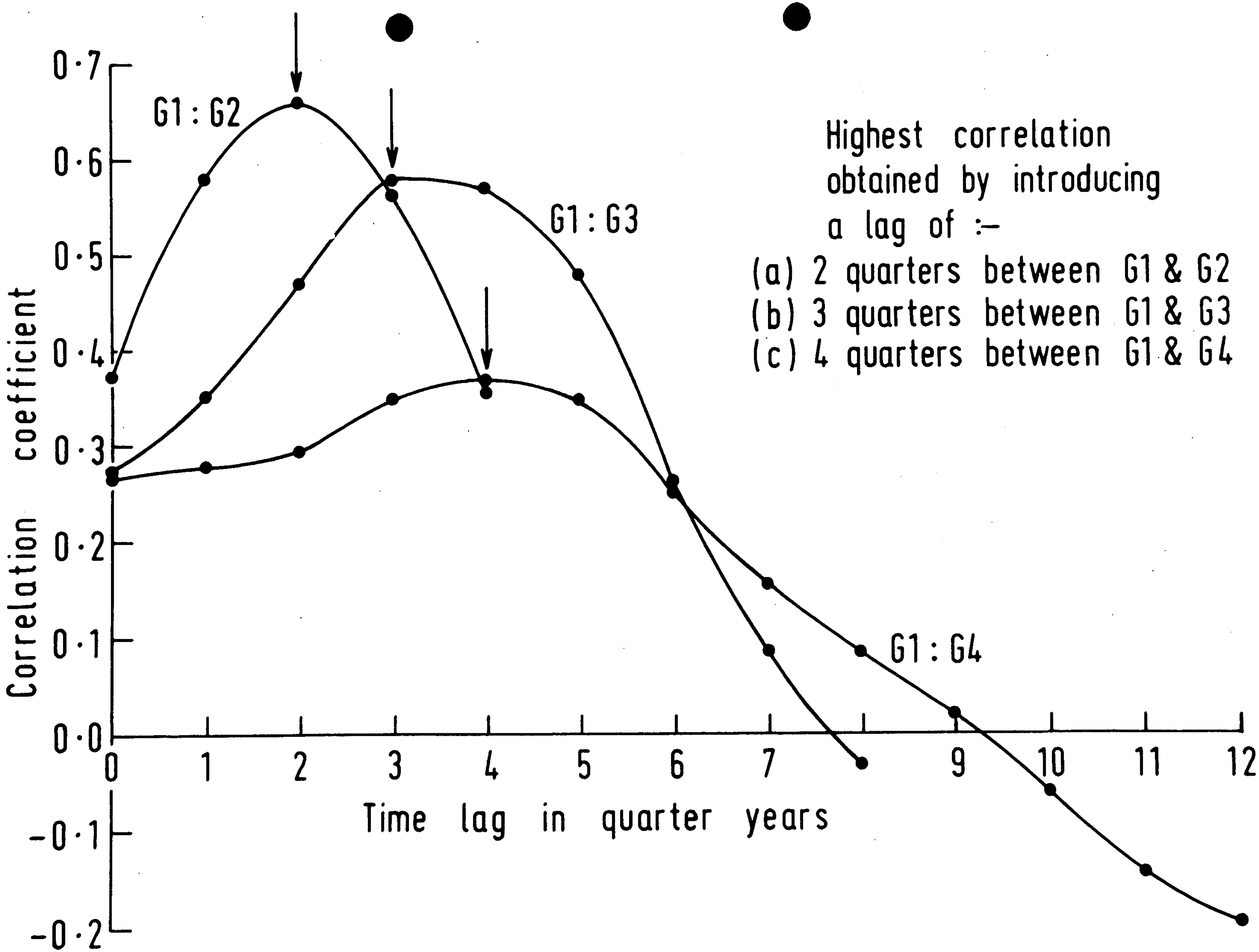


RUNNING NINE MONTHLY MEANS (POSTWAR PERIOD) OF:

(a) CYCLONIC INDEX ANOMALIES (CYCLONIC TYPES POSITIVE BUT GRAPH INVERTED) — BRITISH ISLES

(b) MERIDIONAL INDEX ANOMALY (SOUTHERLIES POSITIVE) — BRITISH ISLES

(c) SURFACE SALINITY ANOMALY — GERMAN BIGHT GROUP

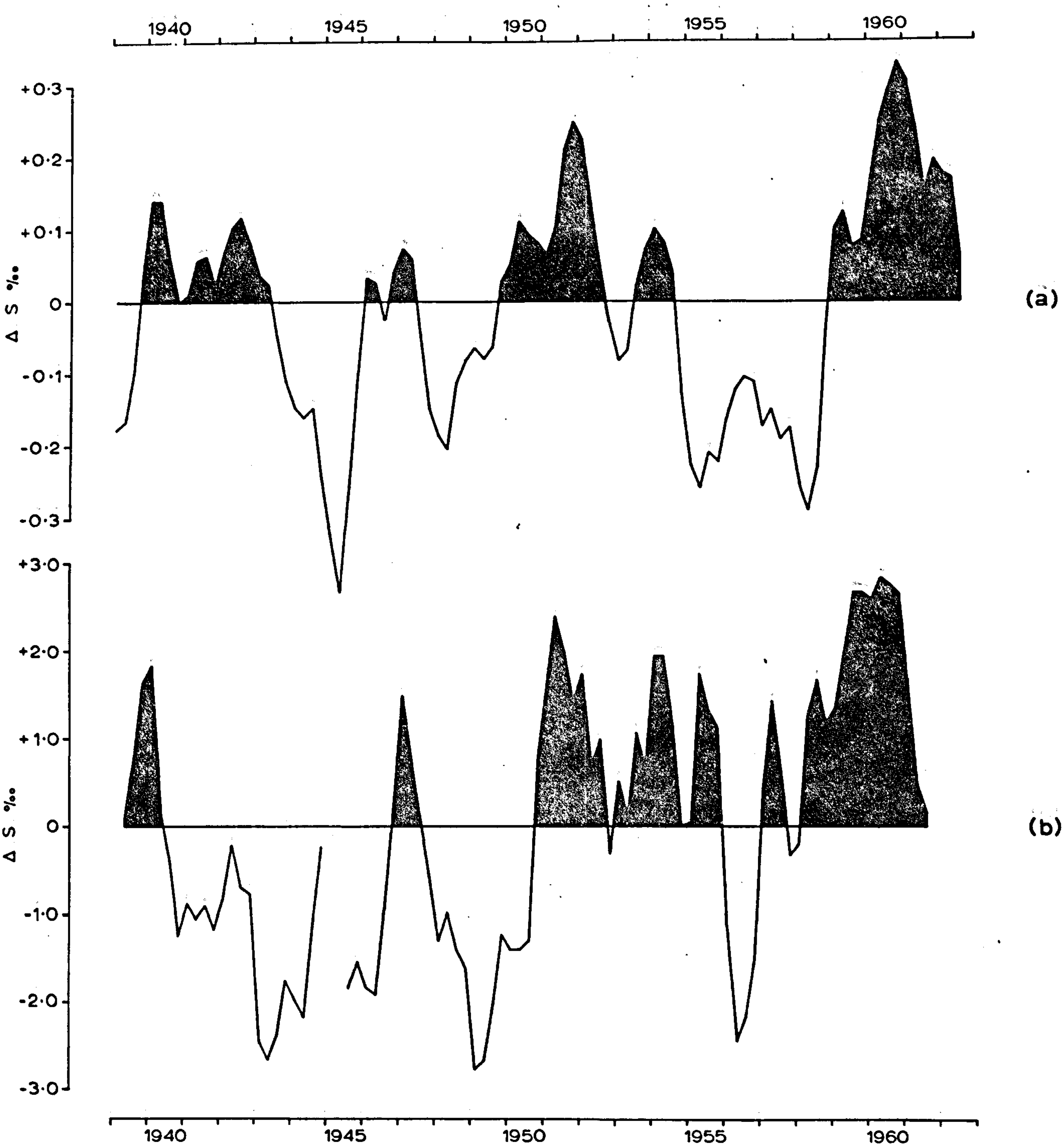

0·7
0·6
0·5
0·4
0·3
0·2
0·1
0·0
−0·1
−0·2
Correlation coefficient
0
1
2
3
4
5
6
7
9
10
11
12
Time lag in quarter years
G1 : G2
G1 : G3
G1 : G4
Highest correlation obtained by introducing a lag of :–
(a) 2 quarters between G1 & G2
(b) 3 quarters between G1 & G3
(c) 4 quarters between G1 & G4

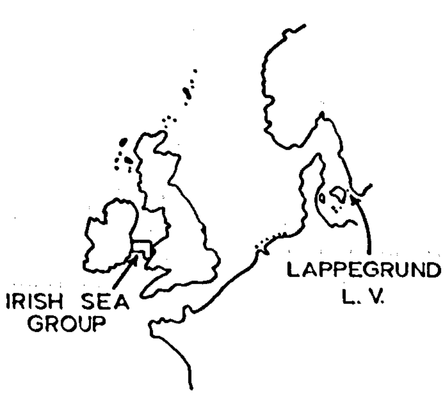
CORRELATED GROUPS / LAG	G1/G2	G1/G3	G1/G4
0	0·3743	0·2751	0·2670
1	0·5807	0·3529	0·2807
2	0·6602	0·4716	0·2961
3	0·5651	0·5805	0·3517
4	0·3557	0·5727	0·3692
5		0·4809	0·3498
6		0·2631	0·2513
7		0·0863	0·1552
8		−0·0320	0·0868
9			0·0206
10			−0·0618
11			−0·1430
12			−0·1936

Correlation series obtained by comparing the salinity anomaly data of group 1 with similar data from groups 2,3 & 4 after introducing various time-lags from 0 to 12 quarter-years. "n"= 59 in each case.

SIGNIFICANCE	CORRELATION COEFFICIENT
·1	0·2128
·05	0·2523
·02	0·2975
·01	0·3277
·001	0·4114

For "n"= 59

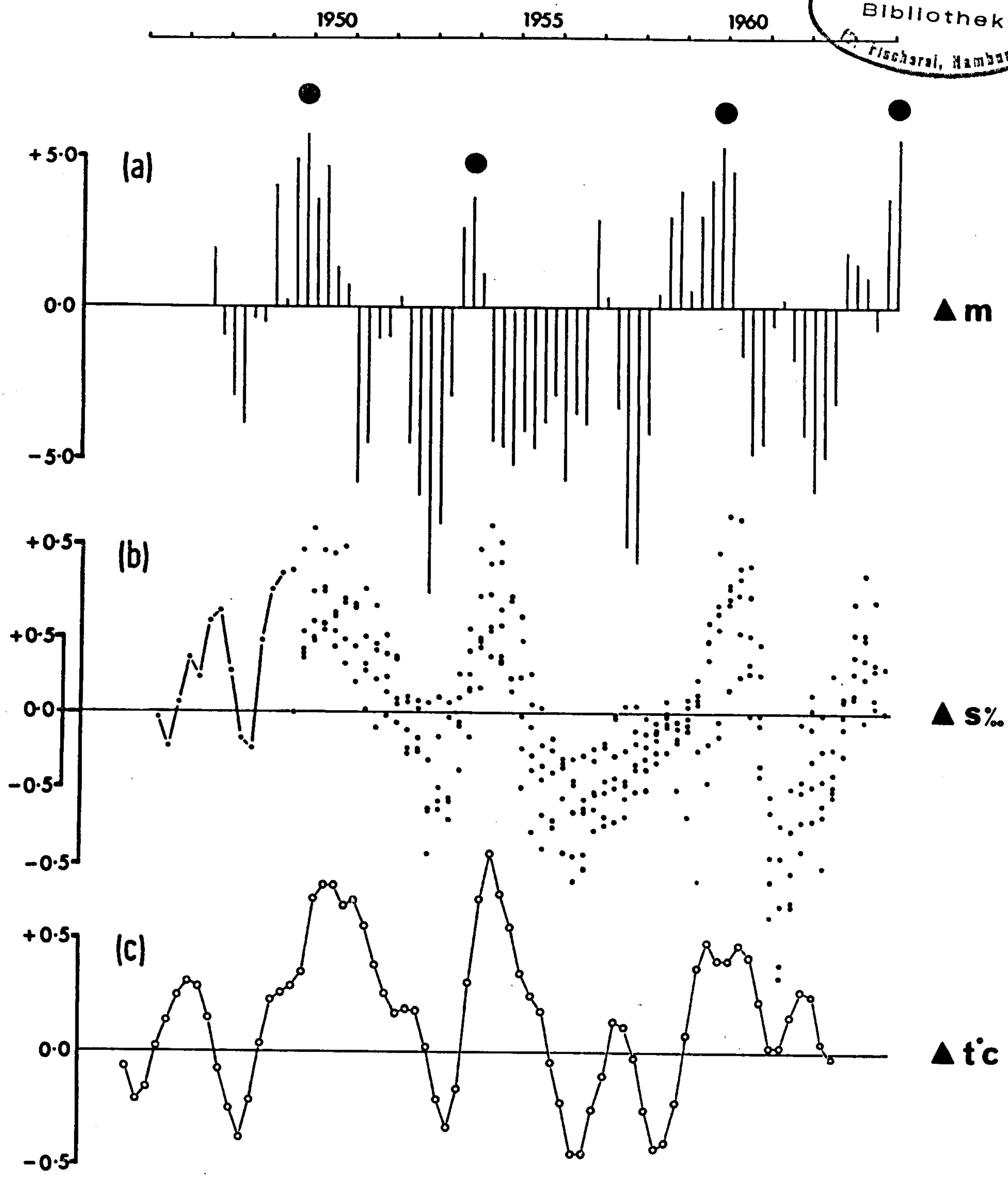




Running 3-Quarterly Means Of Salinity Anomaly (Post 1939) For:

(a) The Irish Sea Group — Mean Of Areas 141, 143, 145, 212. From Surface Salinity Observations

(b) Lappegrund Lightvessel — From Observations Made At 12·5-15m Depth



RUNNING NINE – MONTHLY MEANS (POSTWAR PERIOD) OF:

(a) MERIDIONAL INDEX ANOMALY (SOUTHERLIES POSITIVE) — BRITISH ISLES

(b) SURFACE SALINITY ANOMALY — GERMAN BIGHT GROUP

(c) 0 – 200 METRE TEMPERATURE ANOMALY — KOLA SECTION