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VARIATIONS OF TROUGH POSITIONS AND PRECIPITATION PATTERNS IN THE MEDITERRANEAN AREA

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ABSTRACT

Recent variations of circulation and climate can be studied by investigating even rather short periods of time as far as they display different modes or anomalies which may also act on larger timescales as more persistent ones. Thus a period of 10 years (September 1966 to August 1976) which could be covered by daily sets of 500 hPa airflow data in the Atlantic–European region and of precipitation data at 101 Mediterranean stations was chosen to examine the variable distribution patterns of upper troughs in the Mediterranean area and their corresponding patterns of precipitation anomalies. After the outline of trough axis distribution to eight successive longitudinal bands and of the different percentages of trough precipitation at various trough axis positions for the whole period of 10 years a subdivision into individual years was made to show some of the operative deviations both of the upper trough distribution and of the corresponding precipitation pattern in relation to the overall mean situation. Together with some circulation indices (zonal index, geopotential anomaly, measure of the relative vorticity, specifications about the Westerlies' main branch) which have been calculated for the crucial upstream region of the North Atlantic, some basic tendencies concerning different circulation patterns and their consequences for the Mediterranean region could be outlined. Considering within-type changes and the variations of further cyclonic elements this might serve for estimating climatological effects on larger time-scales of more persistent anomalies of circulation.

KEY WORDS Airflow Trough Positions Precipitation

1. INTRODUCTION

The Mediterranean area with its alternating climate (Flohn, 1950) experiences at least a seasonally direct influence of cyclonic upper troughs which are characterized by cold subpolar air masses advancing far towards the equator; by high values of positive relative vorticity with resulting mass divergence aloft and upward movement at the leading edge; by generating frontal or instability precipitation; and by steering the induced low-level disturbances.

These upper troughs are highly variable in both their frequency of occurrence (both as a whole and in different areas of geographical longitude) and their particular qualities (amplitude, intensity, kind of drifting etc.) thus constituting a substantial part of climatic variability. Studying such changes even on shorter time scales (years to decades) allows one to get information about both climatic deviations resulting from such variabilities as well as an indication about changes to be expected during larger and more persistent anomalies of circulation.

As a contribution to this study a data base has been used comprising daily rainfall at 101 Mediterranean stations (see Figure 2) from September 1966 to August 1976 and daily specified 500 hPa elements of airflow for the same period of time (Jacobeit, 1985). These elements (linear, undulatory and cellular ones) have been obtained by several steps of computation:

(i) calculation of stream variables (geopotential anomaly, measures for strength of gradient, for strength and direction of upper geostrophic winds and for relative vorticity, composite wind fields) by using

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daily grid point values of 500 hPa heights between 20 and 70° N, 57·5° W and 62·5° E at distances of 5 or 7·5 degrees of latitude or longitude;

(ii) referring to a field of overlapping nine-grid-point-areas the combined distributions of the actual values of these stream variables allowed the identification of the elements of airflow for each day over the whole region mentioned above;

(iii) numerical characterization of these elements by means of parameters indicating position, dimension, structure and intensity.

In contrast to the paper mentioned above, in which a number of precipitation indices have been calculated to get a differentiating characterization of these elements as a basis for palaeoclimatic reasoning (Jacobeit, 1985), it is the striking feature of upper troughs that will be picked out in this paper, to investigate their variable frequencies of occurrence both in space and time and to examine the corresponding variability of precipitation distributions.

2. TROUGH POSITIONS AND PRECIPITATION PATTERNS FOR THE WHOLE PERIOD

Upper troughs of the 500 hPa level, which are of direct importance for the Mediterranean area, are taken as cyclonic waves, the amplitude of which extends over 20 degrees of latitude at least, and the extension of which stretches both to the north and to the south of the 10 degree zone around 45° N (as a transitional area between higher and lower mid-latitudes). Thus, what is not taken into account are both the upper troughs located more poleward, not directly reaching the Mediterranean area itself, and cyclonic waves which only develop south of 45° N as separate configurations of the lower mid-latitudes (cut-off products, and autonomous wave formations).

Figure 1 shows the frequencies of upper troughs during the whole period (September 1966 to August 1976) for the (extended) Mediterranean area (20° W–40° E) subdivided into eight bands each of 7·5° longitudinal extent. The maximum of trough axis positions between 17·5 and 32·5° E corresponds to the mean long-wave trough position (Flohn, 1952), the lower values in the western part correspond to the more frequent occurrence of anticyclonic elements there (Jacobeit, 1985, p. 85).

Figure 2 reveals in extracts how the patterns of trough precipitation differ for different trough axis positions. Displaying the percentages of trough precipitation related to the total amount of precipitation, it can be recognized first that highest percentages accumulate at the various trough fronts where positive

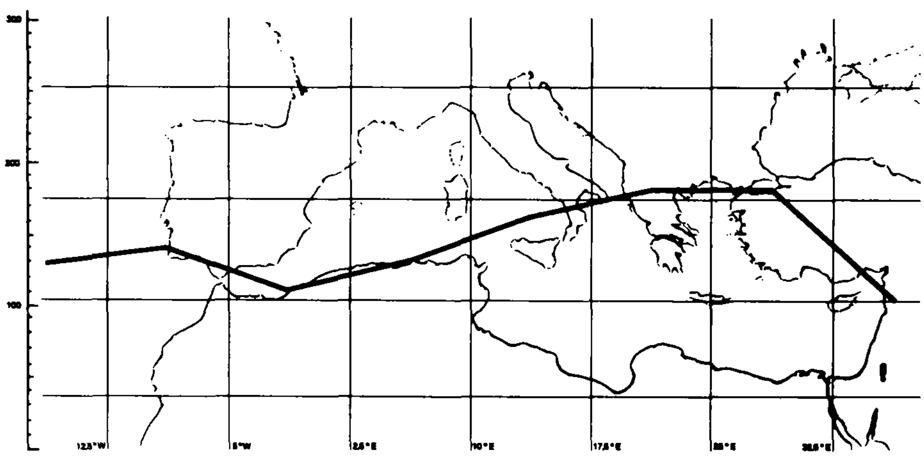

Figure 1. Frequencies of occurrence of upper trough axes (500 hPa level) in eight longitudinal bands during the period from September 1966 to August 1976

vorticity is strongly advected resulting in mass divergence aloft and cyclogenetic effects near to the ground; around the upper trough axes higher percentages appear in decreasing numbers whereas lower percentages dominate at the rear where there is decreasing relative vorticity, mass convergence aloft and downward vertical movement. Somewhat higher percentages in the eastern part of Figure 2a at extreme western trough axes positions (20–12·5° W) result both from secondary troughs at below-average wave lengths and from autonomous cyclonic elements of low amplitude bordering downstream on anticyclonic or neutral currents in advance of the western trough.

Secondly the modification of precipitation patterns through changing the trough axis position clearly comes out: Figure 2b (trough axis between 17·5 and 25° E) indicates a concentration of highest percentages in the Aegean Sea and the southern part of Turkey, whereas Figure 2c (trough axis between 10 and 17·5° E) shows a distribution with higher percentages predominantly above Italy (apart from the northwest), Yugoslavia and Greece (all stations in this area within the three highest classes); Figure 2d (trough axis further to the west between 2·5 and 10° E) finally reveals a shift into higher classes above northwest Italy, Corsica, Sardinia and the northern part of Tunisia, whereas above Greece there are lower percentages again (10 out of 15 stations within the two lowest classes). The different frequencies of trough axes in these three longitudinal bands (see Figure 1) affect the precipitation patterns in so far as in the range of trough axes and trough fronts the rate of percentage-values within the highest class related to percentage-values within the three highest classes distinctly decreases (from 66·7 to 43·3 to 8·3 per cent) while proceeding westward into regions of lower trough frequency.

Thirdly the precipitation changes to be expected at hypothetically supposed long-term trough axis displacements (assuming unchanged conditions for all other cyclonic elements) may be roughly estimated as a first-order approximation: complete displacements of troughs from one longitudinal band to an adjacent one (corresponding to a shifting of the mean trough axis by 7·5 degrees of longitude) would bring about some 5–10 per cent of total precipitation that directly affected stations might gain or lose in the mean. This is a common feature on the time-scale of interannual variability, but implies substantial significance on larger time-scales.

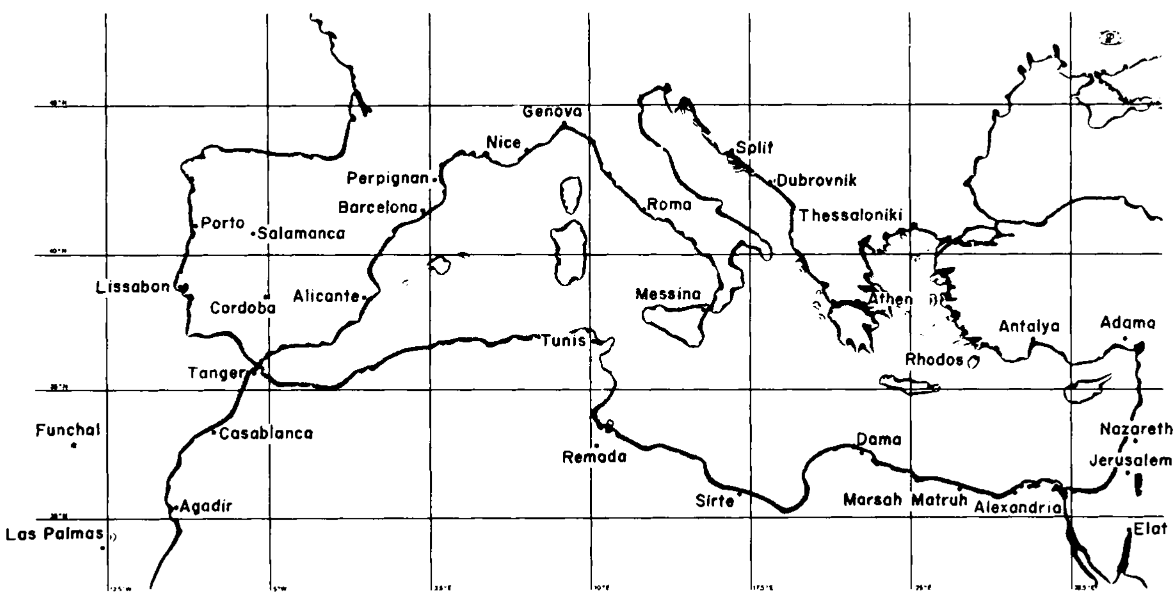

Figure 2. Location of stations used in this study and their percentages of trough precipitation related to the total amount of precipitation (September 1966 to August 1976) at different trough axis positions (⬇): (a) 20–12·5° W; (b) 17·5–25° E; (c) 10–17·5° E; (d) 2·5–10° E

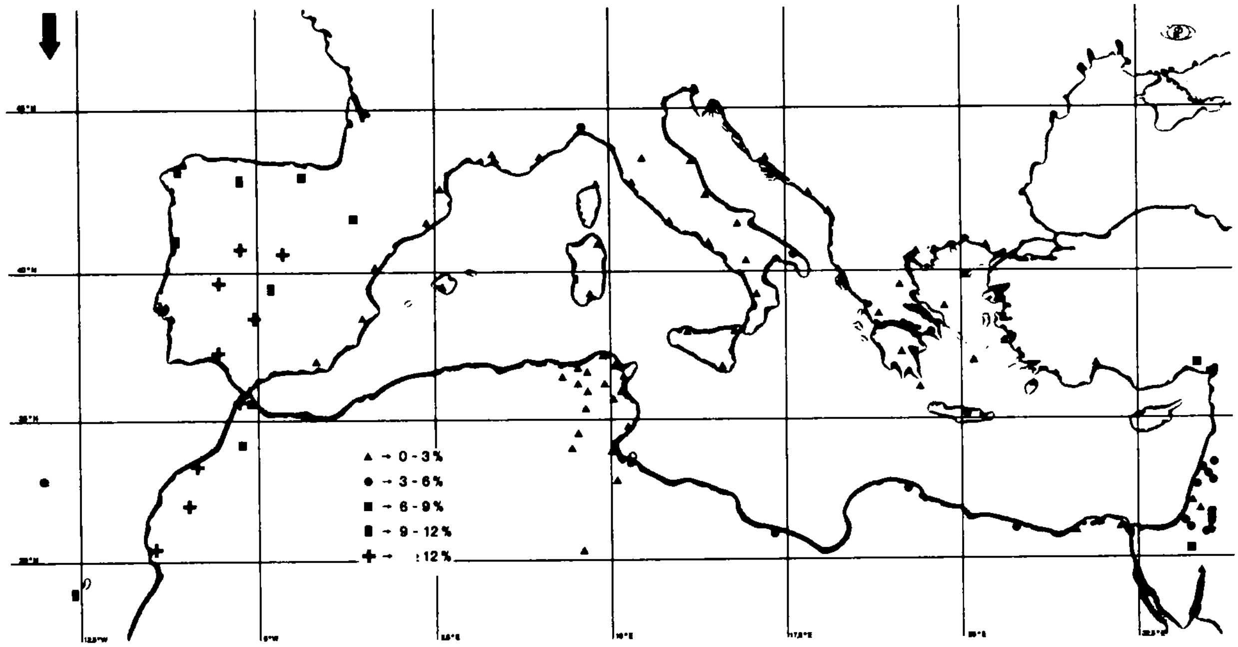

Figure 2(a)

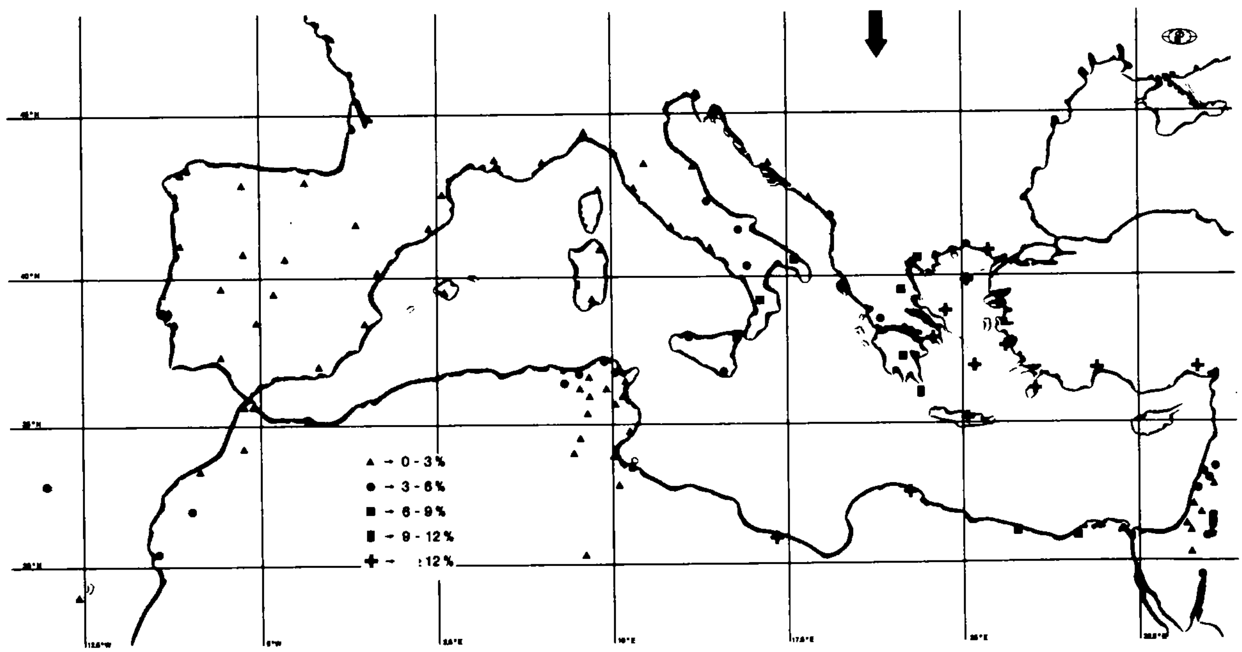

Figure 2(b)

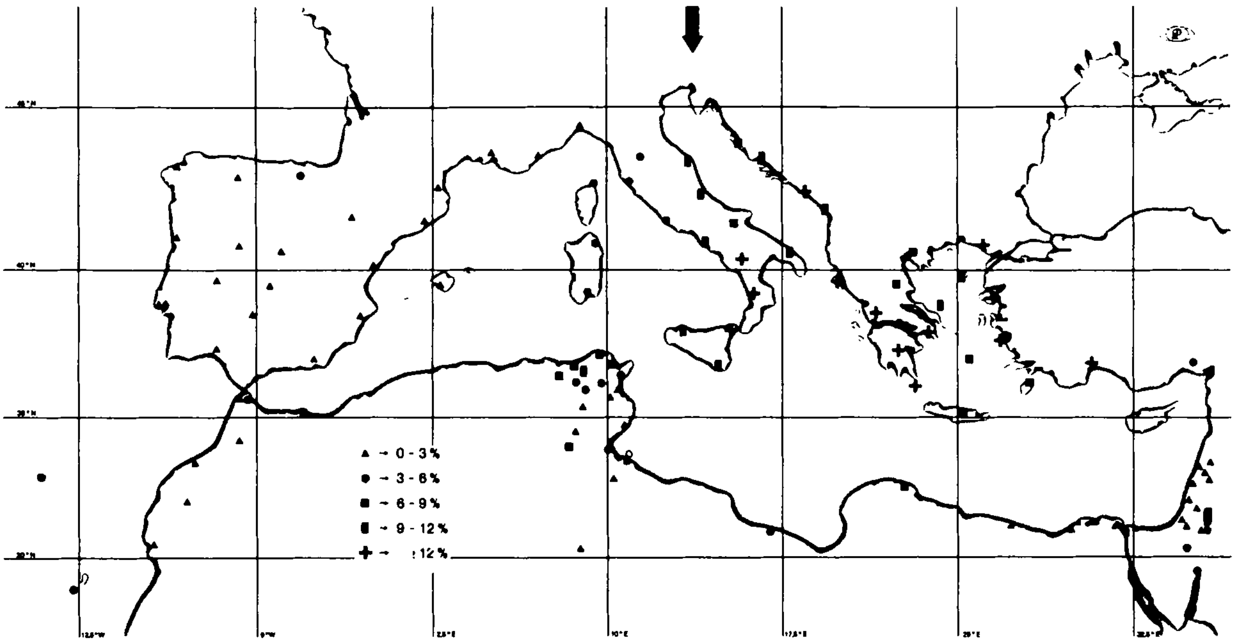

Figure 2(c)

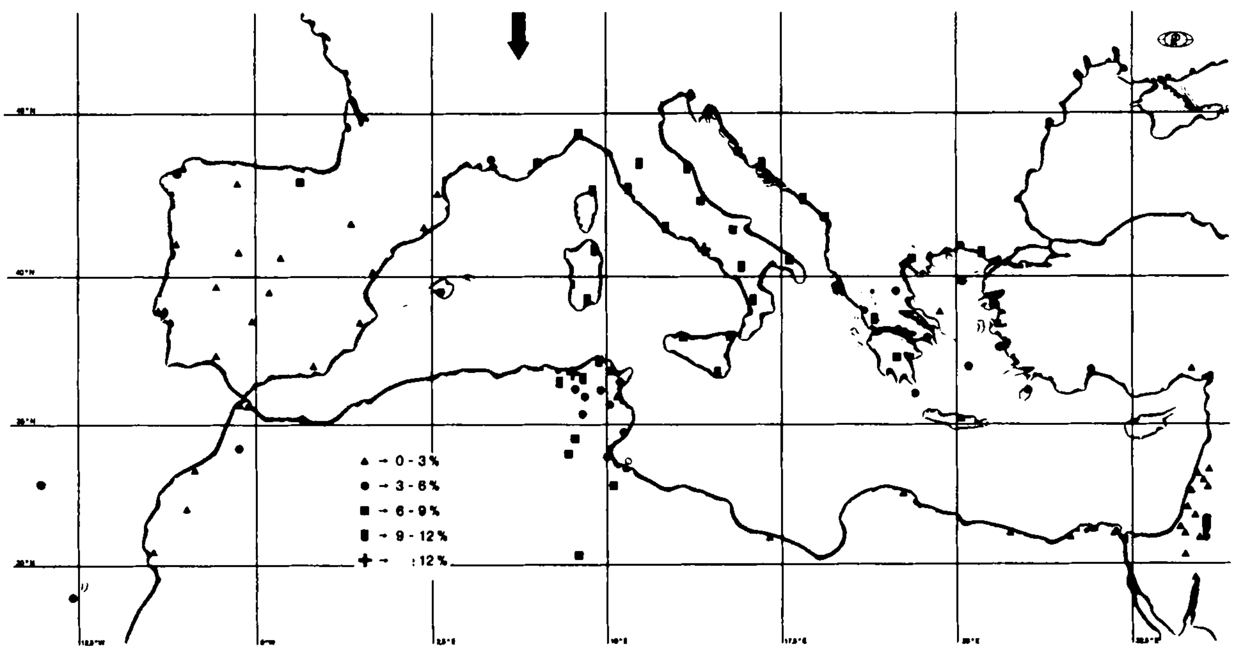

Figure 2(d)

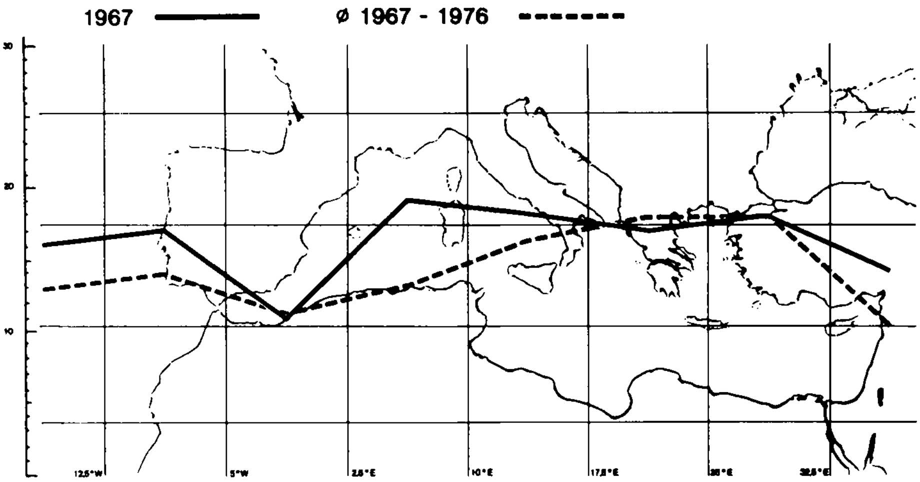

Figure 3(a)

Figure 3. Frequencies of occurrence of upper trough axes (500 hPa level) in eight longitudinal bands during periods of 1 year (September of the year before to August) reference graph: decade average 1967–76

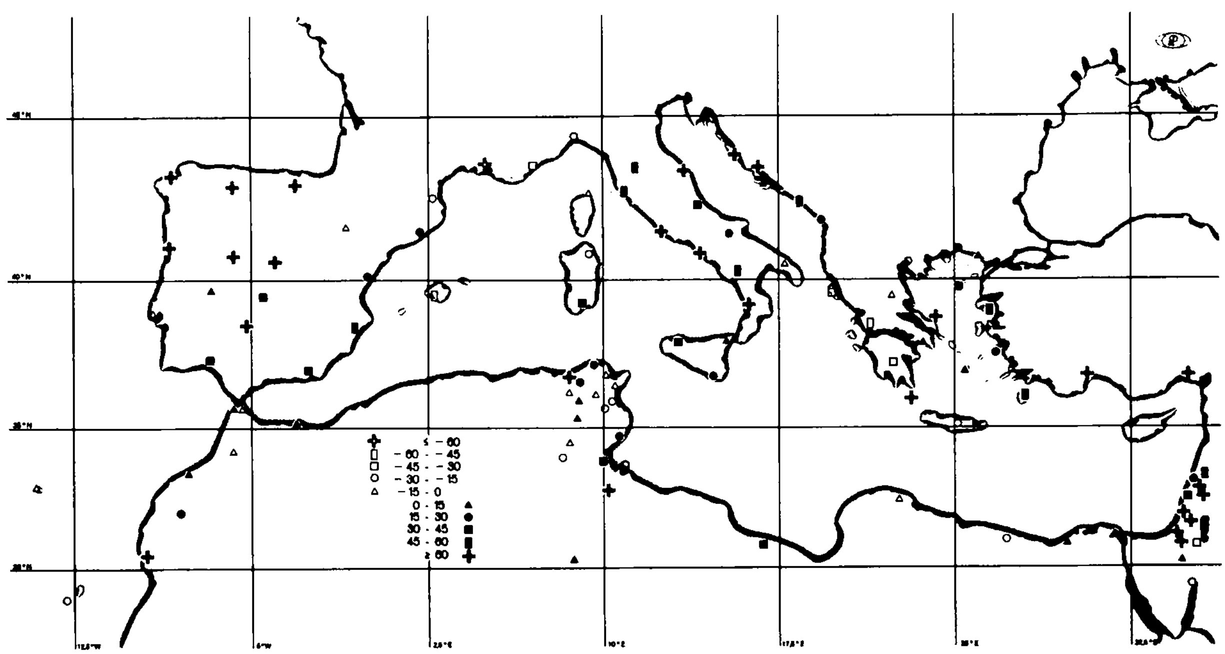

Figure 4(a)

Figure 4. Deviation of trough precipitation during periods of 1 year (September of the year before to August) from the decade average. The value mapped is a transformed quantity resulting from the product of the absolute mm deviation and a station-specific factor *F* (see text)

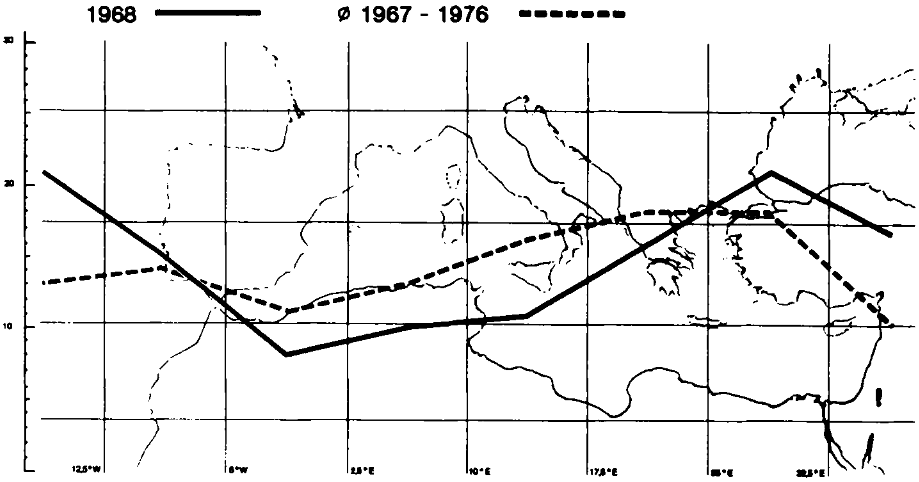

Figure 3(b)

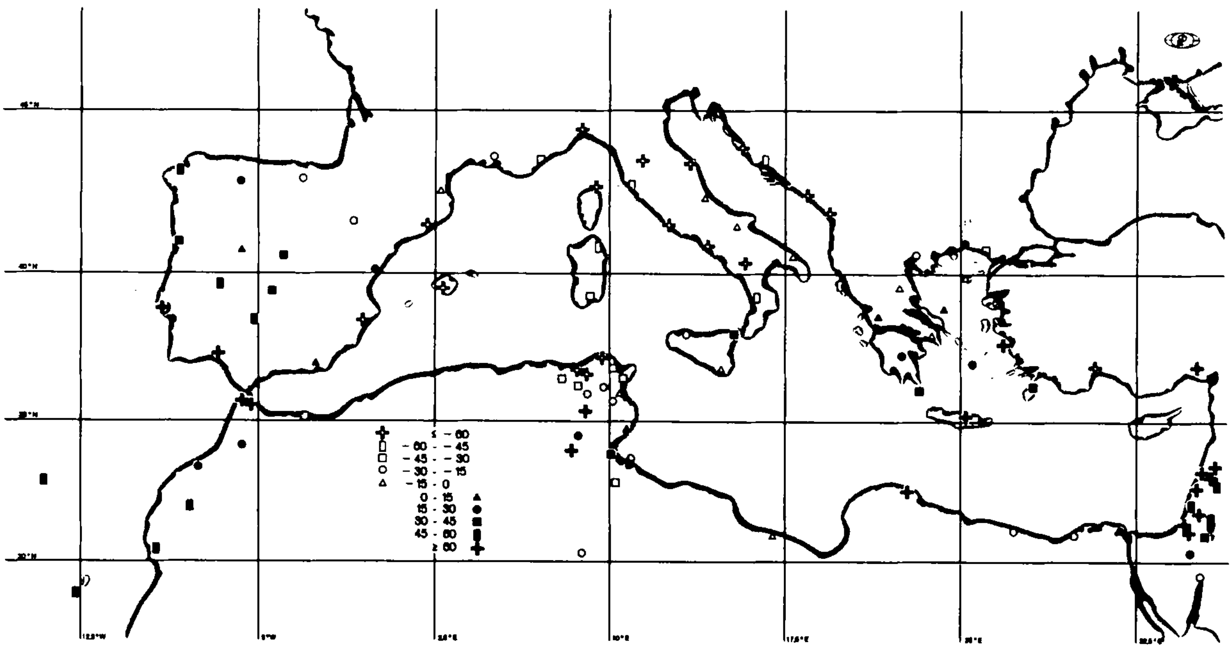

Figure 4(b)

3. DEVIATIONS OF TROUGH FREQUENCY AND PRECIPITATION PATTERNS FOR INDIVIDUAL YEARS

Temporal variations in trough frequency

To get an idea about the temporal variations of trough frequency and of the corresponding precipitation patterns the whole period has been divided into separative years (from September to August, identified by the year in which August falls). Figure 3 indicates the yearly frequencies of upper trough axes (divided into the same eight longitudinal bands) in relation to the decade average (corresponding to the summary version of

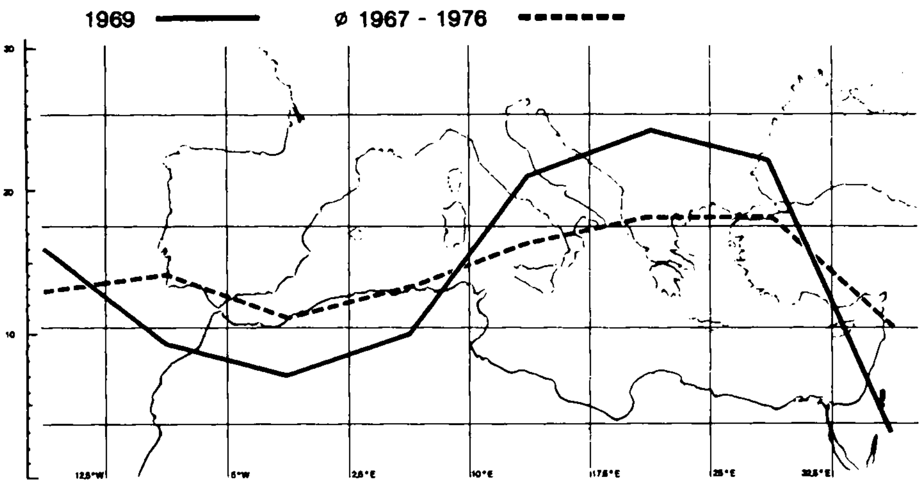

Figure 3(c)

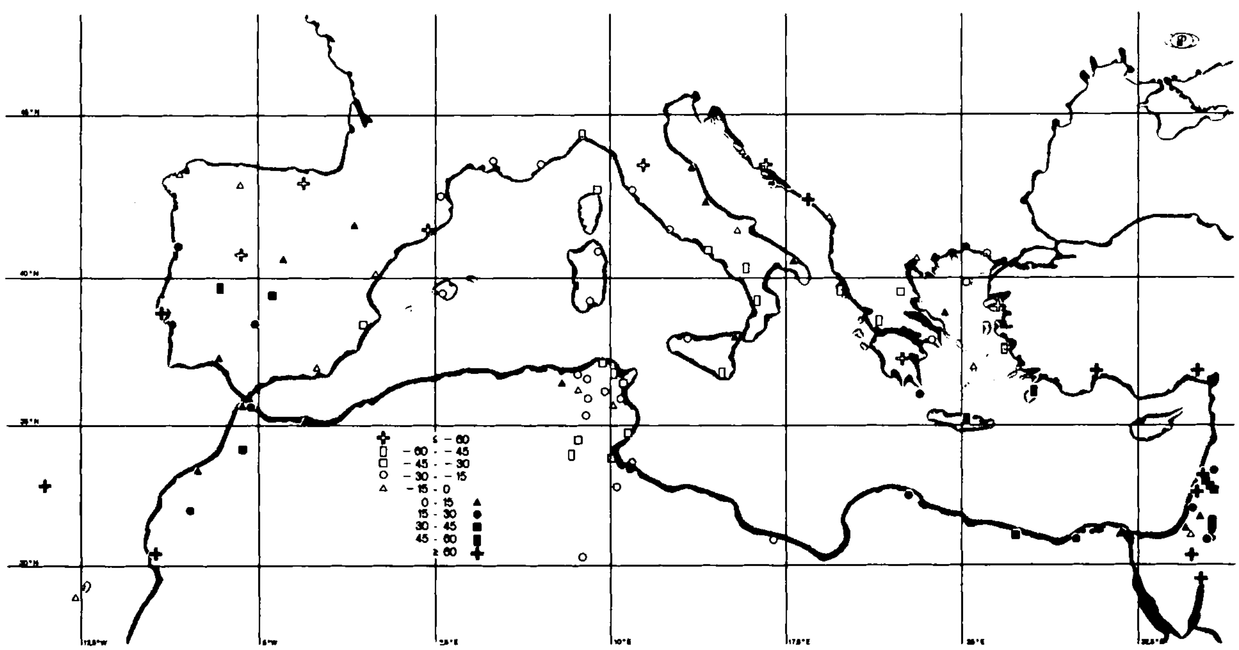

Figure 4(c)

Figure 1). Table I gives further information about these frequency distributions: the standard deviation of trough axis frequencies within a single year indicates the concentration of distribution in the various longitudinal bands, the sum of squares of differences of trough axis frequencies between a single year and the decade average yields a measure of deviation of the annual distribution from the average one.

Quite different kinds of distribution are revealed: more equally distributed than the decade average in 1967 and 1974 (see Table I), but with different absolute levels (highest number of trough days (130) in 1967, lowest (98) in 1974). This means that similarly high or higher frequencies than in the average long-wave area predominate in 1967, whereas below-average trough frequencies prevail in 1974 (see Figure 3).

1972 and 1976 only show weak maxima. Comparison with the decade average, however, yields more apparent characteristics. In 1972 both the higher number of trough days in the minimal-band of the average

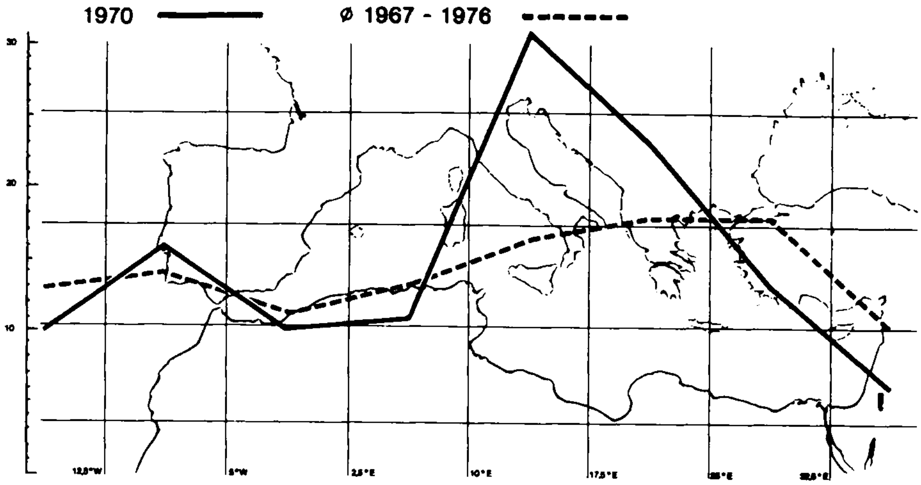

Figure 3(d)

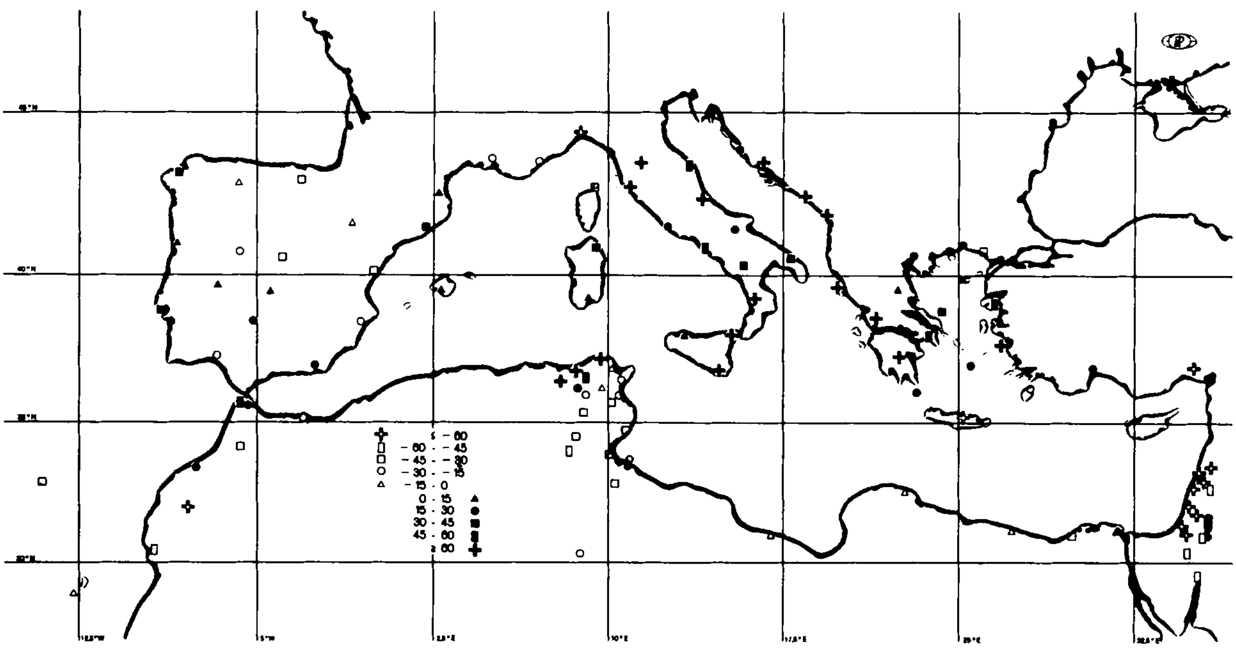

Figure 4(d)

Table I. Standard deviation σ of the annual distribution of trough axis frequencies and their sum of squares of differences Δ^2 from the decade averages

	σ	Δ^2		σ	Δ^2
1967	2·60	69·0	1972	3·37	120·6
1968	4·88	165·4	1973	5·68	109·6
1969	7·82	189·8	1974	2·31	93·2
1970	8·21	300·0	1975	6·89	207·2
1971	7·96	469·4	1976	4·40	171·8
			1967–1976	2·90	0·0

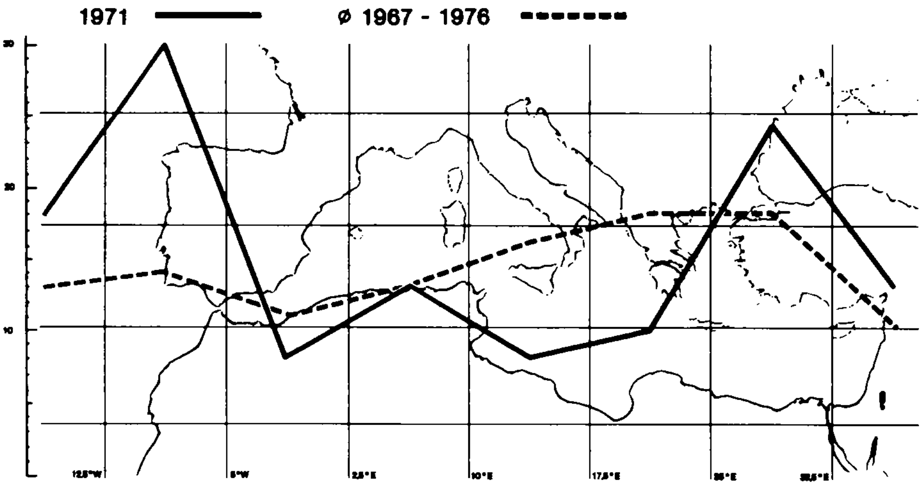

Figure 3(e)

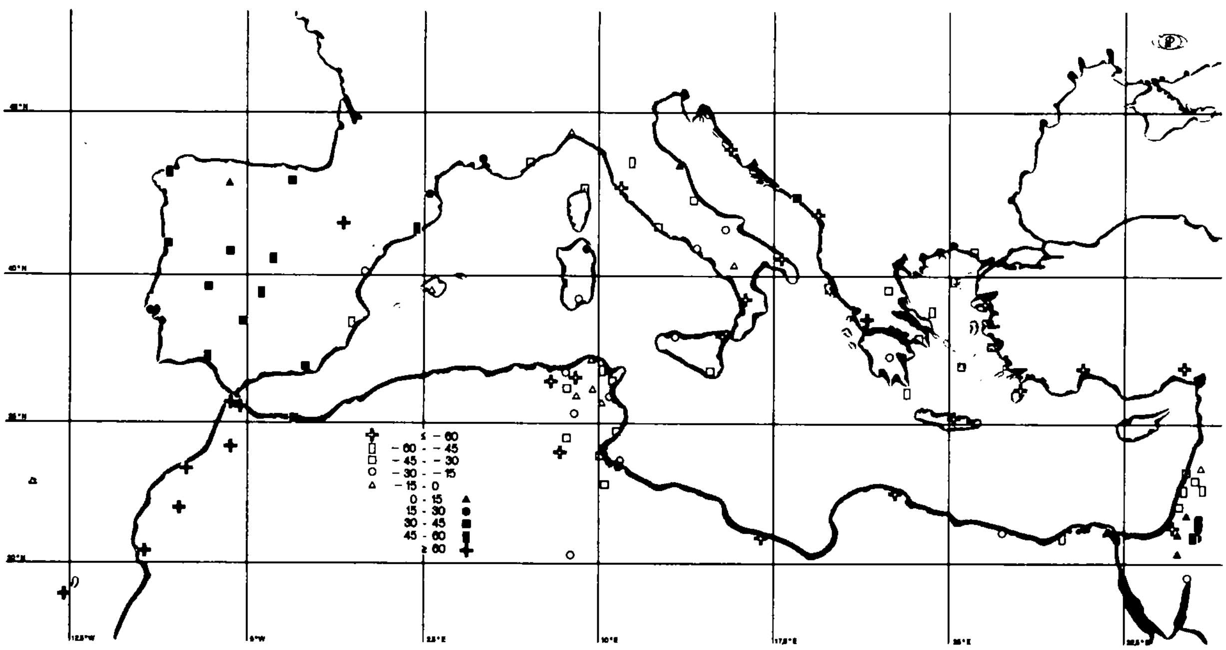

Figure 4(e)

(5° W–2·5° E) and the smaller number in the maximum-band of the average (17·5–32·5° E); in 1976 distinctly below-average frequencies in the 2nd and the 5th bands.

More accentuated distribution patterns can be seen in the remaining years with western longitudinal bands being represented above the average only in 1968 and, above all, in 1971, whereas the three bands between 10 and 32·5° E very often show maxima with different positions. The degree of variation related to the decade average can be very different (see Table I). In 1973, with a relatively small sum of squares of differences, the deviations concentrate on the range around the increased and westward shifted maximum. In 1975 the patterns in phase opposition in the western part also contribute to a generally higher degree of deviation. In 1968 the eastern maximum scarcely exceeds the decade average with a continuous series of four bands of

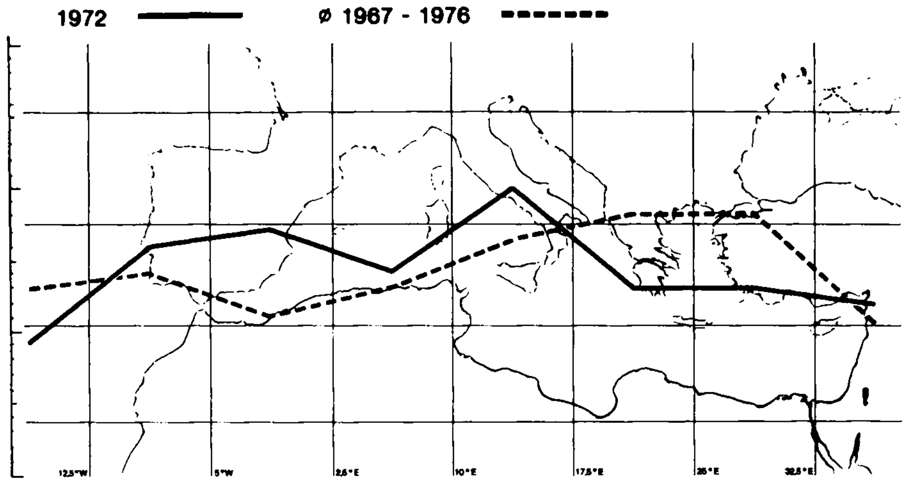

Figure 3(f)

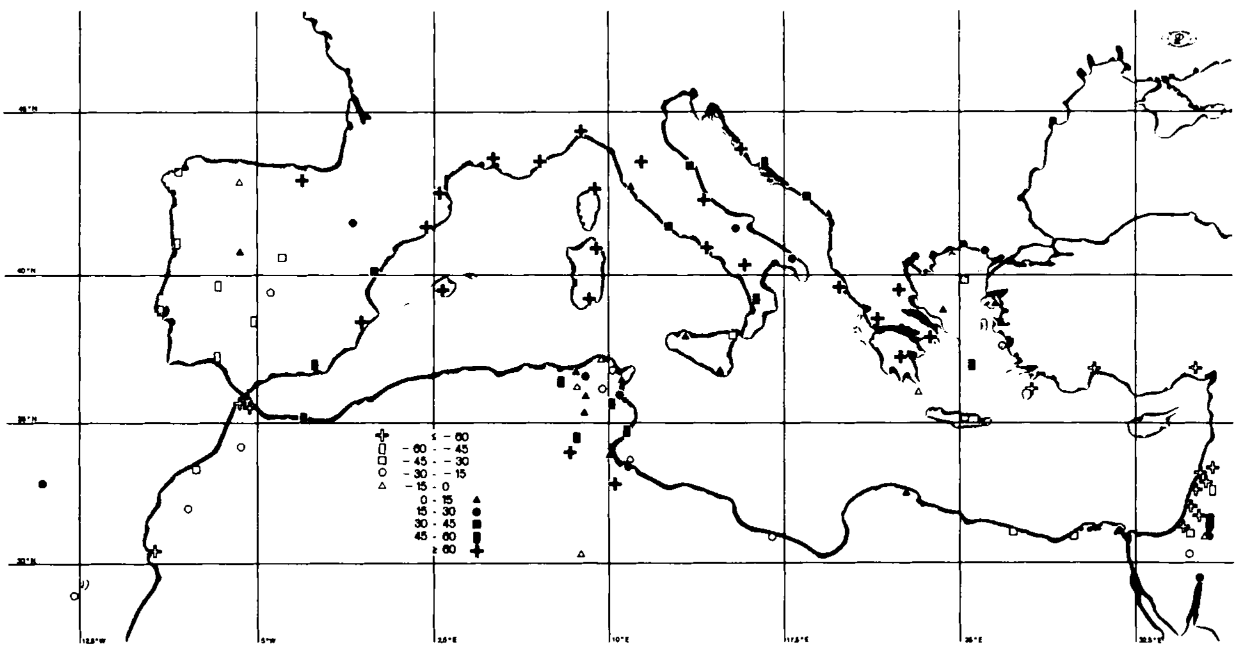

Figure 4(f)

moderately below-average values bordering to the west and an additional and even more distinct maximum follows in the extreme west. 1969 shows two deviations spatially connected which accentuate the pattern of above average in the maximum range 10–32·5° E, and below average at 12·5° W–10° E around the average minimum. In 1970 the sum of squares of differences considerably increases though only small deviations occur in the western part; more striking is the westward shifted maximum of band 5, from which a steep decline to the east beyond 25° E leads into areas below average. Finally 1971 shows the highest deviation, composed of a strong anomaly maximum in the west, values below average in bands 5 and 6, and another, (long-wave) maximum further east. Most striking is the sequence of the successively westward shifting of the eastern trough maximum from 1968 to 1970. This is accompanied by an increased deviation from the decade average and an increased accentuation of the distribution pattern (see Table I).

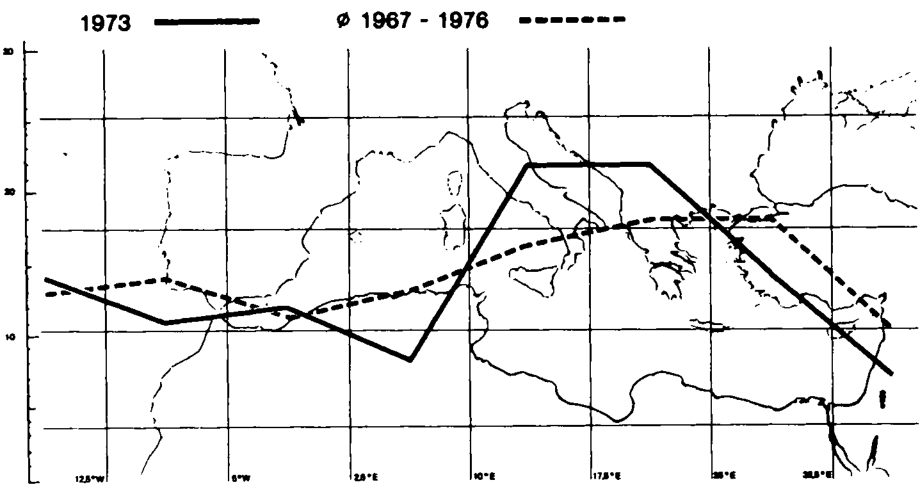

Figure 3(g)

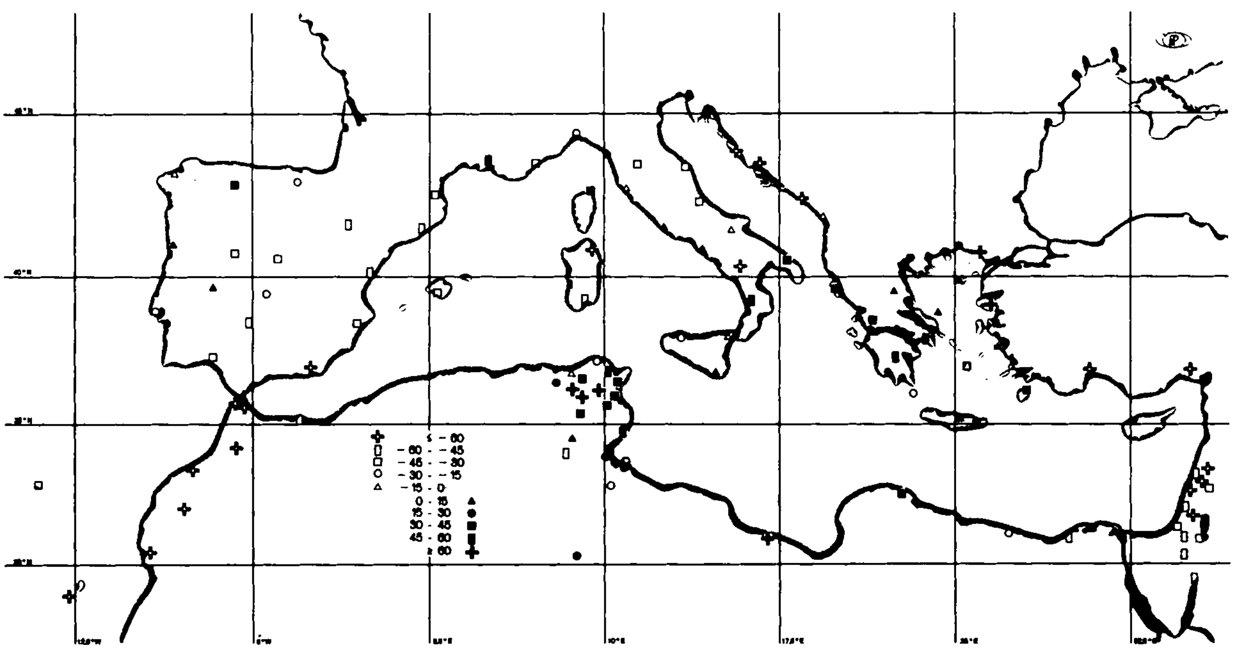

Figure 4(g)

Yearly precipitation patterns

To display the corresponding yearly deviations of trough precipitation for each of the 101 rainfall stations, those daily amounts of precipitation that fell on days with direct trough influence at the respective station were summed. This was brought about by using both the horizontal trough axis position and a rough evaluation of the trough's longitudinal extension considering the vertical trough axis inclination (see section 2) by a general westward shift of the range of upper trough influence by half a longitudinal band.

The yearly deviations of trough precipitation from the decade average would not be adequately expressed either in terms of absolute mm-deviations (at such a wide range of mean annual precipitation (MAP) as between 1384·5 mm (Ulcinj) and 38·6 mm (Elat)) or in terms of per cent of the corresponding MAP

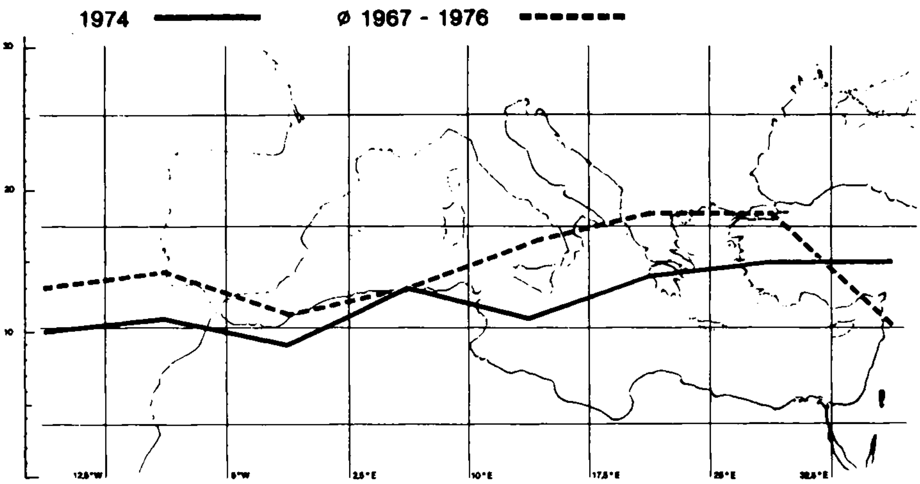

Figure 3(h)

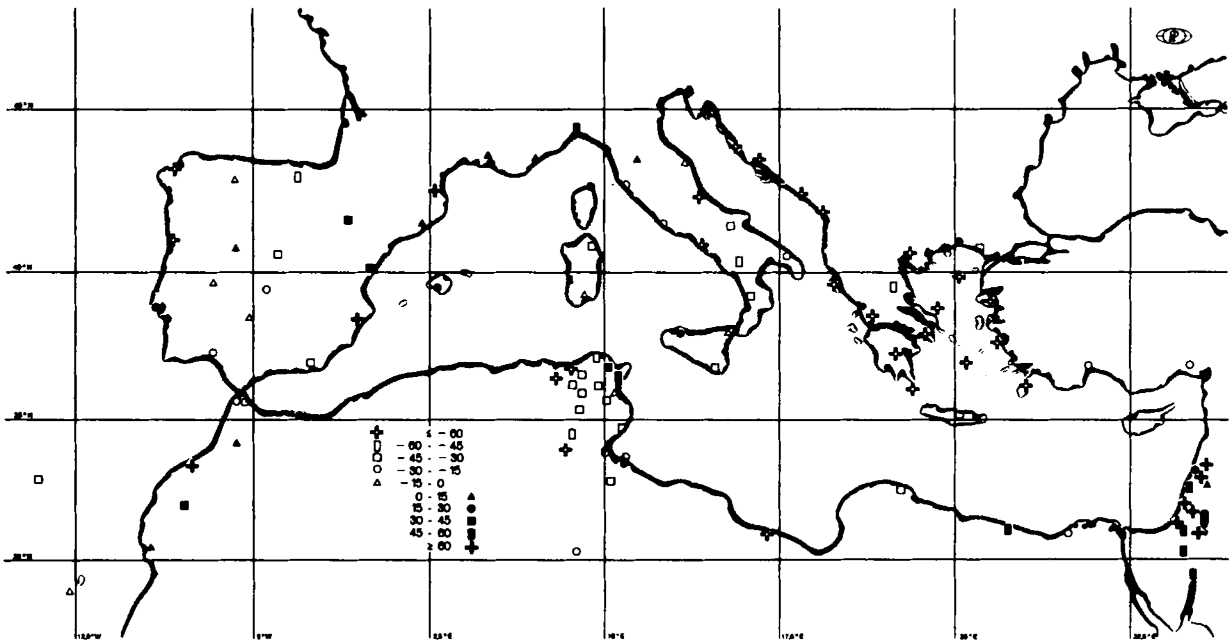

Figure 4(h)

(systematically higher percentages at arid stations compared with continuously lower variations at humid stations). To achieve a homogeneous and equivalent representation the following method was applied: divisions of both sets of data (mm-values, percentages) each into five positive and negative classes of deviation (with intervals of about $\sigma/4$, i.e. the span between the second classes (positive to negative) amounts to the standard deviation roughly) provide equivalent class intervals of 15 mm or 3 per eent; i.e. at a station where 3 per cent of MAP equal 15 mm (equivalent to MAP = 500 mm) both deviations (mm and percentages) always fall into corresponding classes. The total number of stations is divided into two approximately equal quantities by this 'standard value' of MAP = 500 mm. The stations which are more arid show an increasingly shorter span in the mm-value spectrum compared to the span in the percentage-value spectrum, the stations which are

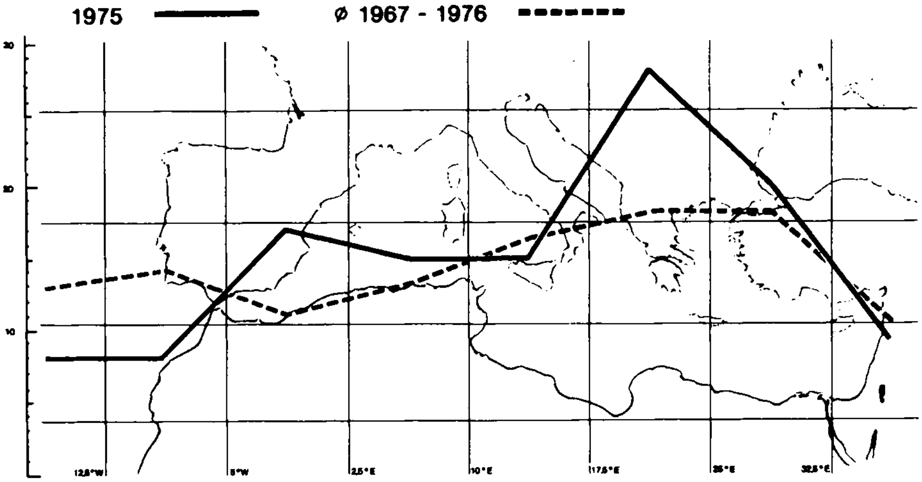

Figure 3(i)

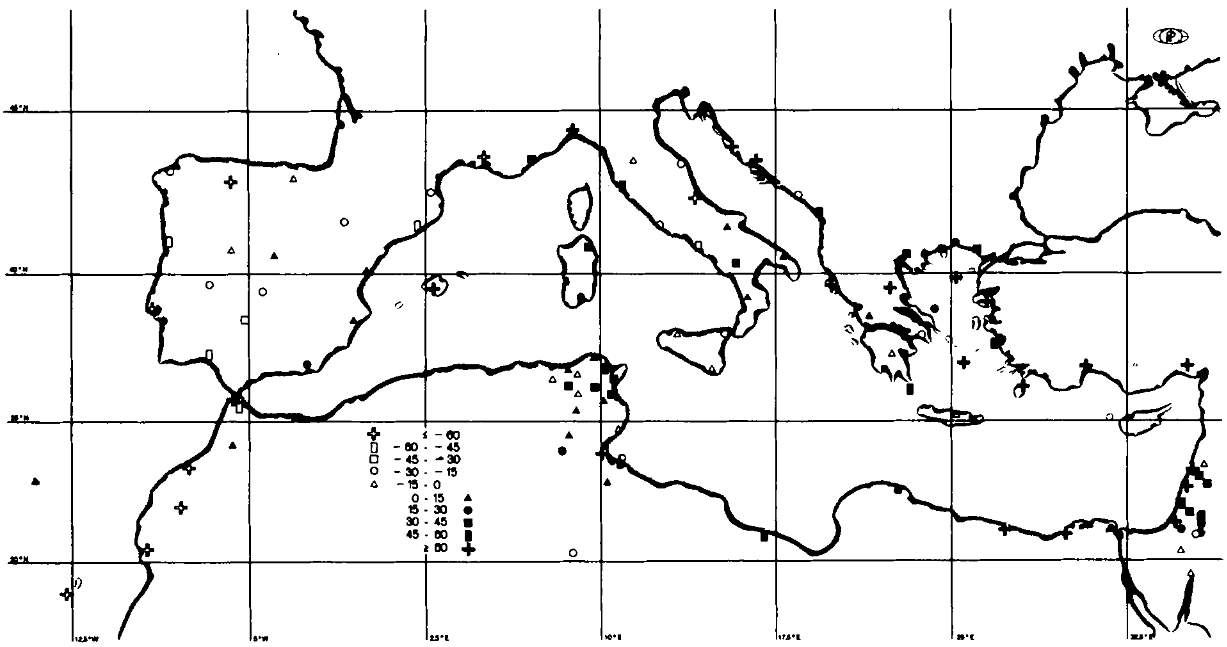

Figure 4(i)

more humid show an increasingly longer one. To compensate for this asymmetry the mm-deviations have been multiplied by an adjusting factor F, which, because of its dependance on the station-specific mean annual precipitation (MAP), acts as an equalizing quantity between the diverging value ranges:

$$F = (500/\mathrm{MAP} - 1)/2 + 1.$$

Multiplication by the fraction 500/MAP would result in an analogous transformation of the mm-value range into the spectral factorization of the percentages (i.e. the transformed values would group into classes in the same way the percentages do). By halving the difference between 500/MAP and the 'standard value' 1 of factor F an equalizing middle course between the diverging spectral factorizations can be achieved. Thus the

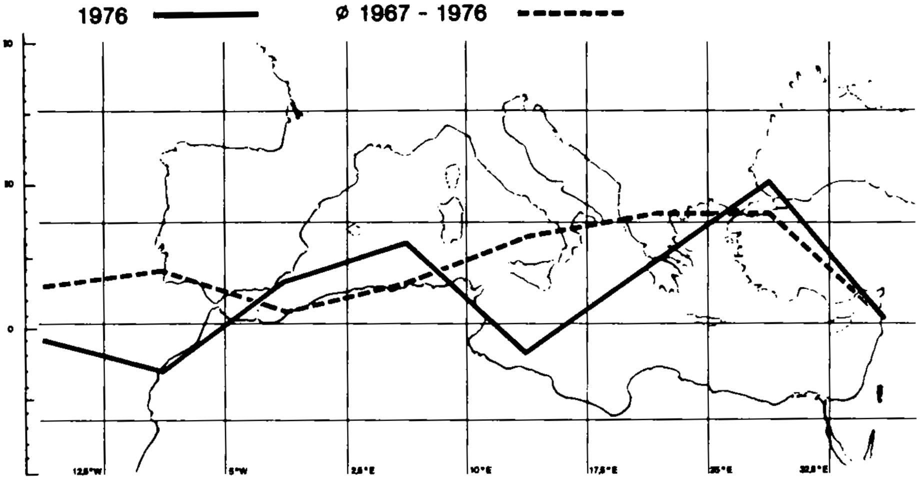

Figure 3(j)

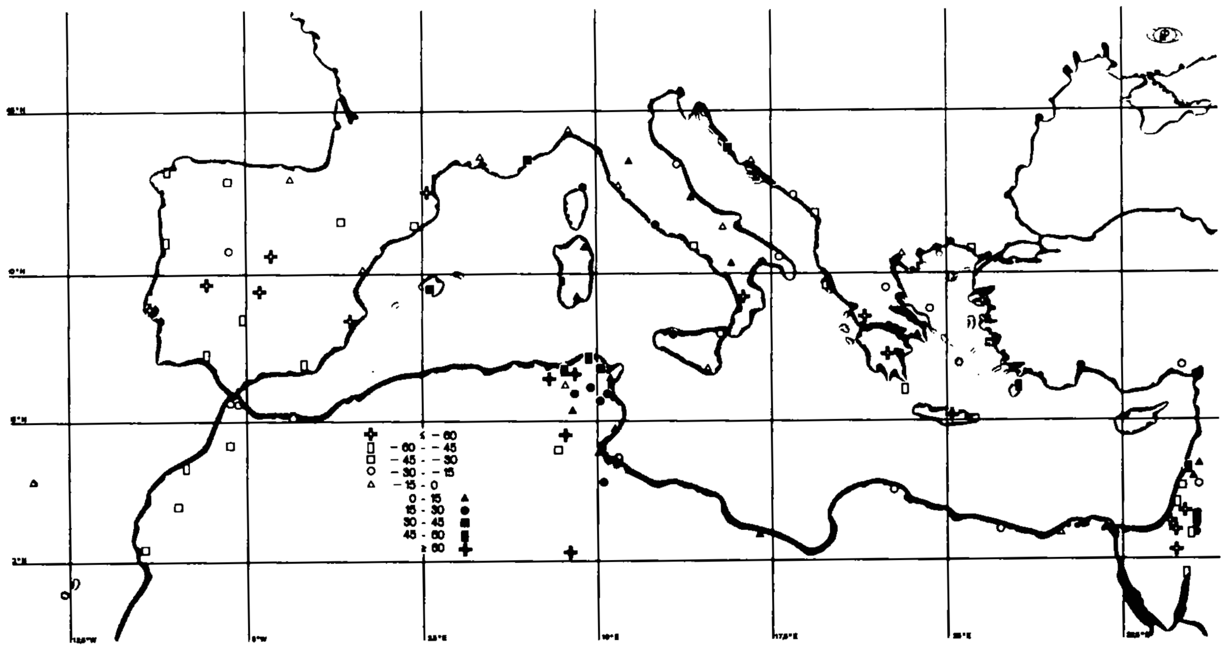

Figure 4(j)

values mapped in Figure 4 are the product of mm-deviations and factor F. They represent a quantity which is assigned to classes located between those of the mere mm- and the mere percentage-values. Obviously this transformation is identical with the introduction of station-specific class boundaries for mm-deviations with the class intervals resulting from multiplication of the 'standard value' 15 mm (which stands for a station with MAP = 500 mm) by the inverted factor $1/F$.

Figure 4 presents the transformed deviations of trough precipitation for the separate years as defined above. Individual peculiarities at some stations contrasting with the general pattern of the station's environment (e.g. Messina 1968, Dubrovnik 1969, Agrinion 1971) manifest some special properties of rainfall such as discontinuity, dependance on specific local factors (topography, transformation of radiation and energy at the earth's surface, small-scale convectional extremes) and intervention of many intermediate mechanisms down from the upper circulation. Nevertheless a number of coherent tendencies can be recognized. In accordance with Rudloff (1967, p. 70), who, for data series of longer periods, distinguishes between significant climatic variations and subordinate climatic oscillations by means of the $\sigma/2$-boundary, deviations in the upper three classes (considering the absolute values)—i.e. almost outside the $\sigma/2$-boundary of the data set at hand—can be termed to be significant, whereas the two lowest classes do not reflect more than subordinate oscillations.

The two years (1967 and 1974) with well-balanced patterns of trough distribution show quite different deviations of precipitation according to the contrasting absolute trough frequencies: there are widespread positive anomalies in 1967 (Figure 4a) which occur most clearly and coherently on the Iberian peninsula, above Italy and Yugoslavia and at the eastern border of the study area (eastern Aegean Sea, southern part of Turkey, Israel), related, at least for the first two regions, to the above-average trough frequencies slightly offset to the west. In contrast to that, negative anomalies are predominant in 1974 (Figure 4h). They can be recognized distinctly above Tunisia, Italy, Yugoslavia and Greece. However, apart from Israel being the single region with trough frequencies above the average, there are still some regions showing positive anomalies (central Morocco, and the western border of the Mediterranean Sea), which, considering the below-average trough frequencies, indicate that different qualities of trough structure and intensity, too, are responsible for the resulting precipitation pattern. This becomes even more significant when looking at 1971 (Figure 4e) which is characterized by a particularly accentuated trough distribution: the highest positive coherent precipitation deviations occur in Morocco. Besides the extraordinary accumulation of troughs in the 2nd longitudinal band, this is explicable by the high frequency of trough amplitudes above the average in this region and an increased occurrence of quasi-stationary troughs, which can be recognized by the steep decline of trough frequency from the second to the third longitudinal bands. It is above the Iberian peninsula, however, that the positive deviations are not as significant as would be expected from the extremely high trough frequency. They are even lower than in 1967 with its significantly lower trough frequency in the western longitudinal bands. This probably results from the fact that it is the quasi-stationary upper troughs of high amplitude occurring above the average in the western trough maximum of 1971 that achieve their strongest meteorological effects in latitudes further south and nearer to the maximum ordinate, whereas the regions to the north often show nothing else but increased degrees of cloudiness and changeable weather conditions with precipitation anomalies which are no longer maximal. Further east, in 1971, there are predominantly negative deviations which occur both in the central area of below-average trough frequencies and in the eastern longitudinal bands of the secondary trough maximum. Lower intensities in the latter region seem to have overcompensated for the increased frequencies as a whole.

In contrast to that, in 1972 (Figure 4f) there are very high positive anomalies of precipitation in the central part stretching from the eastern Iberian peninsula to the western part of Greece though the trough frequency in this area is not located as significantly above the average as it is in some other cases. This can be explained partly by the fact that in the area of the mean trough minimum which is composed mostly of dissipating or collapsing examples which originated further west, an anomaly such as the one in 1972 with young troughs very often initially stretching from the Bay of Biscay shows particularly striking effects. Such troughs are frequently combined with positive inclinations of the horizontal axis, higher velocities of drifting and lower amplitudes. This also fits quite well to the latitudinally limited extent of highest precipitation deviations (higher positive deviations in the southern part of Tunisia only might be the result of induced secondary disturbances).

1976 (Figure 4j) first shows negative deviations all over the Iberian peninsula and Morocco in accordance with the below-average trough frequency in the western longitudinal bands. These deviations mostly belong to significant quantity orders (18 out of 23 stations within the upper three classes). Further east, where there is a trough frequency slightly above the average, positive deviations begin to prevail; however, it is only above the northern part of Tunisia where a subregional accumulation of significant quantity orders can be observed. Still further east, negative deviations clearly predominate again, not only around the trough minimum above southeast Italy and Greece, but also (except for single stations in the southern Aegean Sea and the northern part of Israel) in the eastern marginal area with a trough frequency roughly corresponding to the average.

Both similarities and differences are shown in the year before, 1975 (Figure 4i), which, regarding the trough pattern, differs from 1976 mainly because of a distinct maximum in band 6 (17·5–25° E) instead of the central minimum. Thus significantly positive deviations of trough precipitation can be observed above Greece, Turkey and Egypt, though again some (Greek) stations do not correspond with this general pattern. Worth mentioning is the occurrence of significantly positive deviations both further east above Israel and further west above Yugoslavia. This might indicate enlarged longitudinal extensions of these troughs. Less distinct than in 1976 are both the positive deviations above Tunisia and the negative deviations above the Iberian peninsula according to the secondary trough maximum located further west.

The most striking point in 1973 (Figure 4g) is the accumulation of significantly positive deviations above central Tunisia although the trough frequencies in the primarily important upstream regions are only grouped at or even below the average. This might be due to the combined effect of intensified troughs in this upstream region and of stronger effects to the rear of the trough maximum in the fifth and sixth longitudinal bands, though the widespread negative deviations all over the western part of the Mediterranean area and the almost total absence of higher positive deviations above Italy do not point to peculiarities of such a kind. The positive deviations above Greece are not highly prominent either, with only about half of the stations within the range of significance. But the significantly negative deviations on the eastern margin of the study area exactly coincide again with the steeply declining trough frequency there.

Finally the years from 1968 to 1970, which show the previously mentioned increasing accentuation of trough distribution and the westward shifting of the trough maximum, will be compared. 1968 (Figure 4b) with trough frequencies above the average at the western and eastern peripheries shows an accumulation of positive deviations above Morocco, the western and central part of the Iberian peninsula, and Israel; in between only smaller areas of positive deviations appear above southern Tunisia and the southern part of the Aegean Sea (with possible effects at the rear of the eastern trough maximum there). The following year 1969 (Figure 4c) with its broad trough maximum between 10 and 32·5° E shows some reductions of trough precipitation above Israel, whereas in the regions to the west hardly any remarkable increase in precipitation can be observed (exceptions: Antalya, Marsa Matruh, Dubrovnik); instead the general negative anomaly is maintained all over the western Mediterranean Sea (to a lesser extent above Yugoslavia and Italy, to a greater extent above Greece). It is in 1970 (Figure 4d) that drastic changes take place: Israel becomes totally an area of highly negative anomalies whereas the the whole region stretching from the Tyrrhenian Sea to the coast of Asia Minor shows positive deviations (some two-thirds of all stations there belong to the upper three classes, some two-thirds of these to the highest class). Whereas the density of stations with significantly positive anomalies decreases to the east (from over 75 per cent in Italy/Yugoslavia to under 50 per cent in Greece), four such stations still can be recognized in the northern part of Tunisia being a possible hint of increased longitudinal dimensions or of rear trough processes in the maximum ordinate range. Anyhow the shifting of the mean trough axis by two longitudinal bands (= 15° of longitude) to the west between 1968 and 1970 has brought mean losses in trough precipitation of about 159 mm or 36·7 per cent of MAP to the Israeli stations at the eastern periphery, and at the same time mean increases of about 156 mm or 18·3 per cent of MAP to Italian and Yugoslavian stations in the central part of the study area (see Table II). These rates are clearly higher than those estimated from the average trough axis positions in section 2.

4. CONDITIONS OF CIRCULATION

Patterns of trough frequency and precipitation deviations

In order to integrate the various patterns of trough frequency and their corresponding precipitation deviations into the general conditions of circulation, various parameters of the 500 hPa circulation—zonal index, mean geopotential anomaly and a measure of relative vorticity (Figures 5–7)—have been calculated as average values for each year (September to August) related to four different sections (between 30 and 45° N or 45 and 60° N and between 57·5 and 12·5° W or 12·5° W and 32·5° E). In view of the essential importance of the conditions of air flow upstream these sections also cover the Atlantic region in the latitudinal range mentioned above. As a measure of the vertical component of the relative vorticity which is given (using cartesian coordinates, see Holton, 1979, p. 83) by $\zeta = \partial v/\partial x - \partial u/\partial y$ (u, v: horizontal wind components), an approxim-

Table II. Trough precipitation differences between the individual years of 1970 and 1968 in Italy/Yugoslavia and Israel, in absolute mm and per cent of the mean annual precipitation (MAP)

Italy/Yugosl.	mm	per cent	Israel	mm	per cent
Firenze	173·4	24·3	Nahariya	− 190·7	− 27·7
Grosseto	157·0	25·0	En-Ha-Horesh	− 176·1	− 28·3
Roma	96·7	14·6	Lord	− 188·0	− 30·3
Napoli	186·0	19·8	Saad	− 302·8	− 76·5
Potenza	129·4	17·4	Nazareth	− 241·7	− 37·2
Cosenza	273·1	29·6	Jerusalem	− 306·4	− 51·3
Messina	102·4	12·9	Beer Sheva	− 124·4	− 58·3
Ragusa	104·8	17·4	Mizpé Ramon	− 22·9	− 26·6
Palermo	32·4	7·6	Dafna	− 261·1	− 38·6
Ancona	146·8	20·4	Tirat Zevi	− 74·9	− 26·9
Pescara	100·8	12·6	Sedom	− 17·5	− 31·4
Foggia	32·2	7·0	Elat	− 2·9	− 7·5
Brindisi	51·0	8·1			
Zadar	216·6	22·9			
Split	143·3	16·9			
Dubrovnik	325·5	26·4			
Ulcinj	381·4	27·5			
Average	156·0	18·3		− 159·1	− 36·7

ation of the change of the meridional wind component in the zonal direction and of the zonal wind component in the meridional direction was applied by means of geopotential gradients depending on latitude (already described in detail by Jacobeit, 1985, p. 46). In addition to these quantities Table III presents the average annual values of the mean geographical latitude, of the inclination (0 = zonal, 1 = diagonal direction) and of the intensity (average maximal geopotential gradient over 5° of latitude) of the main branch of the westerlies at the 500 hPa level above the Atlantic just as they result from the mean geopotential fields of the individual years.

Most striking is the almost continuously inverse course of the zonal index (Figure 5) between the northern and southern sections of the Atlantic (only in 1974 is there no correspondingly steep drop in the northern zonal index). This can be attributed partly to the latitudinal shifting of the main branch of the upper westerlies (see Table III), and partly to differently structured expansions or shiftings of the Atlantic centres of action. At normal positions (Azores high in the southern, Icelandic low in the northern section) the zonal index to the south will decrease due to dominating anticyclonic effects of low gradient; to the north at the high-gradient southern flank of the subpolar area of low pressure it will increase. In contrast to that, an anticyclonic (cyclonic) influence extending further north (south) may reduce the northern zonal index and raise the southern one; this, however, will always happen depending on the degree of shifting of the dominating centres (anticyclonic: low-gradient) and the marginal air flows (cyclonic: high-gradient) and of the general form of circulation (diagonal at continued high westerly current intensity; meridional when blocking covers extended

Table III. Mean geographical latitude, inclination (0 = zonal, 1 = diagonal direction) and intensity (average maximal geographical gradient over 5° of latitude) of the main branch of the westerlies (500 hPa level) above the Atlantic

	67	68	69	70	71	72	73	74	75	76
Latitude	48·5	45·5	44·5	51·5	47·5	48·5	48·5	44·5	46·5	48·5
Inclination	0·50	0·24	0·23	0·54	0·49	0·50	0·76	0·23	0·48	0·50
Intensity	109·8	99·0	99·8	100·9	98·6	120·7	107·7	125·9	106·4	114·2

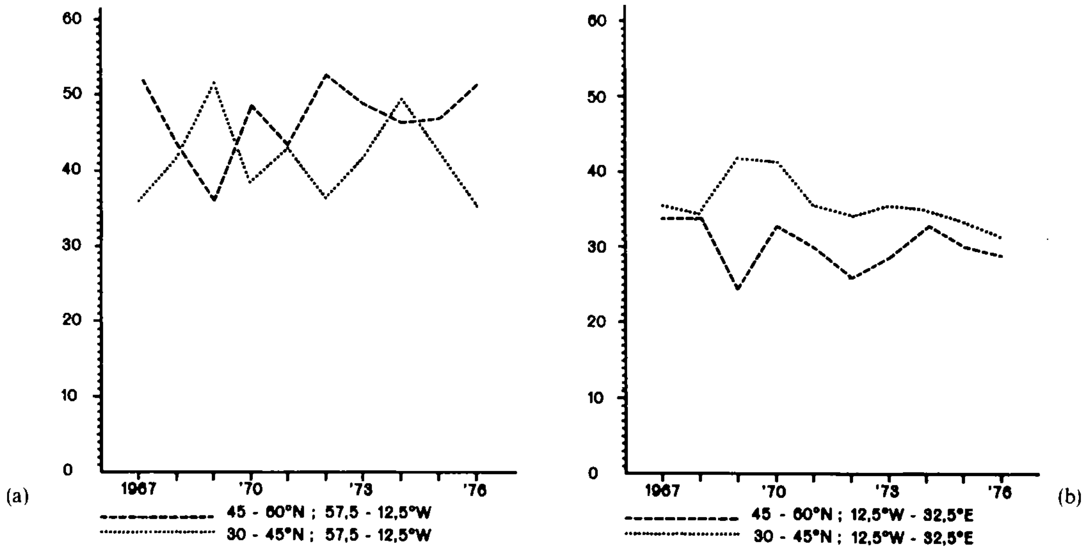

Figure 5. Mean annual zonal index (km/h) at the 500 hPa level

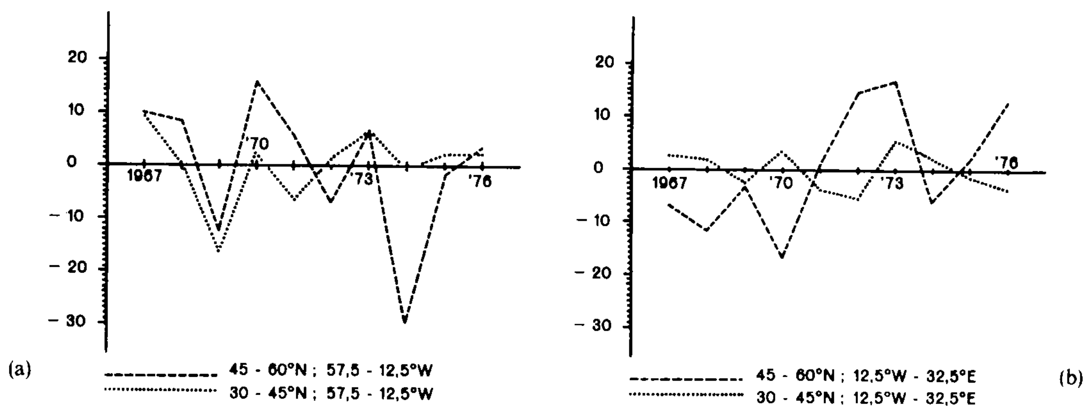

Figure 6. Mean annual geopotential anomaly (gpm) at the 500 hPa level

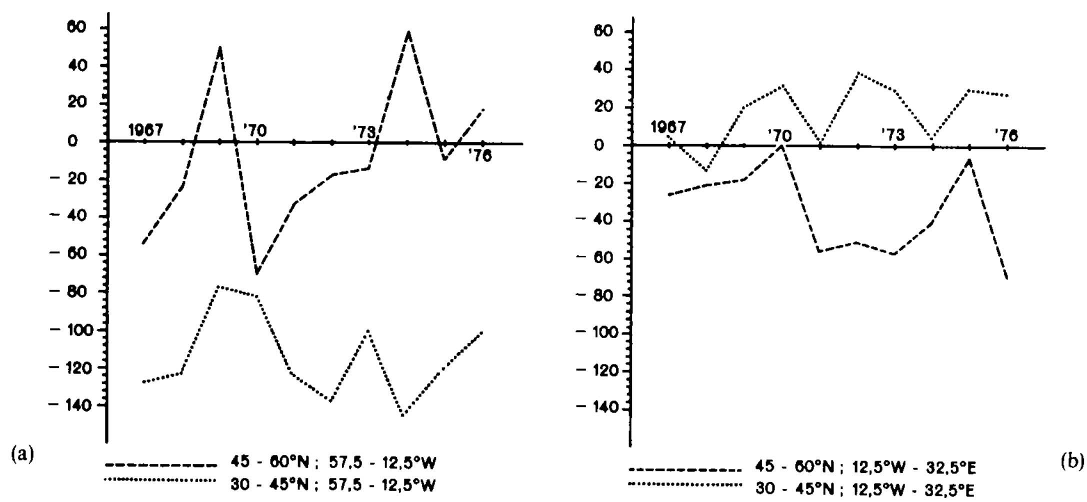

Figure 7. Mean annual measure of relative vorticity (see text) at the 500 hPa level

latitudinal areas; cellular when cut off from the area of origin). A relative accumulation of such anomalies will affect even the annual average which then becomes interpretable in terms of circulation variations.

Looking at the mean vorticities (Figure 7) the generally different absolute-level in the various regions stands out (highly anticyclonic in the southern North Atlantic influenced by the Azores high, generally tending to the cyclonic side above the Mediterranean with its location including the long-wave trough position, generally tending to the anticyclonic side in the continental region north with its more frequent blocking situations and a more poleward position when cut-off processes have taken place). More interesting in the present context, however, is the temporal variation in each section which not only indicates stronger or weaker curvatures of the respective sign as a measure of intensity of the corresponding pressure regime, but also reflects stronger or weaker wind shears which operate most efficaciously at high-gradient zones (e.g. anticyclonic (cyclonic) shearing equatorward (poleward)of the jet maximum on the margin of an upper trough (ridge)) that alter in time both their mutual intensity as well as their spatial configuration.

Considering the yearly varying conditions of circulation (Figures 5–7, Table III) two years (1969 and 1974) stand out. In both years the most southern mean latitude (44·5° N) of the main branch of the upper westerlies above the Atlantic, the highest zonal index above the southern North Atlantic and the highest positive values of relative vorticity at negative geopotential anomaly above the northern North Atlantic are assumed. Nevertheless these corresponding elements of a shifting of the extratropical upper westerlies towards the equator take different circulation forms. 1974 shows the highest intensity of the Atlantic main branch of the westerlies, a zonal index only slightly dropping above the northern North Atlantic (in spite of the southward shifting of the westerlies), a distinct anticyclonic vorticity above the southern North Atlantic at a merely average geopotential (negative shearing on the southern margin of the main branch which has shifted far to the south!) and a comparably high zonal index above the northern continental area. All this points to a more zonal circulation which in the Mediterranean area is reflected in the minimal trough frequency at comparably low vorticity, in its well-balanced distribution at dominating drifting troughs and in the largely negative anomalies of trough precipitation. In total contrast, 1969 shows one of the lowest intensities of the Atlantic main branch of the westerlies, the lowest zonal index in both northern sections, and the highest relative vorticity at the highest negative geopotential anomaly above the southern North Atlantic. All this hints at a significant cyclonic anomaly above the Atlantic, as well as the maximal trough frequency outside the Mediterranean longitudinal bands of Figure 3 and slightly retrograde arranged minima in the mean annual geopotential field above the eastern North Atlantic (not shown here). The downstream sequence in this kind of meridional configuration consequently initiates a below-average trough frequency above the western Mediterranean area and an above-average one above the eastern part (see Figure 3c). The high zonal index above the Mediterranean area does not oppose the outlined circulation pattern because at such positions and dimensions of the reference region the high meridional gradients just enter the area of calculation in connection with high-amplitude troughs.

1970 is characterized by a completely different circulation anomaly. The Atlantic main branch of the westerlies reaches its most northern position (51·5° N) at a relatively low intensity, the zonal indices above the Atlantic show a precisely inverted distribution compared to 1969 (relatively high in the north, relatively low in the south), and the relative vorticity above the northern North Atlantic, at the highest positive geopotential anomaly, becomes significantly anticyclonic. Above the southern North Atlantic, however, at an average geopotential, the relative vorticity is still relatively high (less anticyclonic than the average). This is due to an anticyclonic centre which, above the eastern Atlantic, is significantly shifted from its normal position to the north, and which is accompanied closely downstream by a pronounced cyclonic turn (relatively high vorticity above the regions to the east, a significant trough axis maximum between 10 and 17·5° E).

The situation in 1967 is very similar concerning the Atlantic zonal index distribution and the anticyclonic anomaly of vorticity above the northern North Atlantic. It maintains, however, a pronounced anticyclonic vorticity with a positive geopotential anomaly above the southern North Atlantic. This indicates decisive differences in the kind of circulation: 1967 is characterized by a wedge-shaped widening of the Azores high to the north with a diagonal direction of air flow, 1970 shows a shifting of the anticyclonic centre of action to the north with meridional kinds of circulation. This is confirmed both when looking at the mean annual geopotential fields which, in 1967, indicate double the inclination of the Atlantic anticyclonic axis of 1970, and when considering the daily classification of air flow types (Jacobeit, 1985) which shows above-average occurrence of Mediterranean troughs with diagonal wedges of high pressure above the Atlantic in 1967, but with meridional ridges of high pressure above the Atlantic in 1970. The consequences for the Mediterranean area are that in 1967 at high trough frequencies a relatively balanced distribution of predominantly mobile troughs to the various longitudinal areas and the broadly scattered positive anomalies of trough precipitation were found. In contrast, in 1970 an accumulation of quasi-stationary troughs in longitudinal positions strikingly shifted westward from the mean long-wave trough area and positive anomalies of trough precipitation that concentrate above the northern part of Tunisia, Italy, Yugoslavia and Greece.

Basic connections of circulation are less distinct in the remaining years. For example, 1972 shows some affinities to 1967 (position of the Atlantic main branch of the westerlies, diagonalized anticyclonic structure above the Atlantic, distinct (normal) distribution of the zonal indices there, pronounced anticyclonic vorticity above the southern North Atlantic); however, there is no further distinct anticyclonic regime above the northern North Atlantic (only almost average values of geopotential anomaly and relative vorticity). On the other hand the geopotential anomaly above the northern continental area becomes positive (Figure 6b) and the zonal index there becomes low (Figure 5b). Thus it seems as if a reduction of Mediterranean troughs in the long-wave range and an accumulation of Atlantic-induced troughs in the western part of the mean trough minimum are generated (see Figure 3f). The corresponding precipitation anomaly (Figure 4f) accordingly shows positive deviations in the middle section and negative ones on both margins.

1976 resembles 1972 in several aspects. The most striking difference to be recognized is the relatively increased (reduced anticyclonic) vorticity above the southern North Atlantic which, at the distinct anticyclonic regime above the central longitudinal areas (frequent quasi-stationary upper ridges), might be caused by cyclonic cut-off upstream. Thus the deviations of trough precipitation in the Mediterranean area only show limited or isolated positive anomalies (Figure 4j).

Similarily arranged as in 1967, 1970, 1972 and 1976, but less contrasting from each other are the Atlantic zonal indices in 1975 and 1973, both years showing above-average trough maxima in eastern longitudinal bands. In 1973 it is the more northerly and particularly inclined main branch of the Atlantic westerlies, the slightly higher anticyclonic tendency above the northern North Atlantic, the higher vorticity above the southern North Atlantic, and the further westward position of the trough maximum that show certain affinities to the meridional year of 1970. These tendencies, however, are less distinct, are overlapped by an anticyclonic regime similar to 1976 above central longitudinal areas (pronounced negative vorticity in the continental north), and thus, over all, are connected to only modest positive anomalies of trough precipitation (Figure 4g). In contrast, 1975 shows an above-average accumulation of troughs with diagonal anticyclonic circulation above the Atlantic (Jacobeit, 1985), a trough maximum slightly more distinct and located further east, and positive precipitation anomalies in the eastern Mediterranean area of more striking character (Figure 4i).

1968 and 1971 are (in addition to 1967) the essential years showing widespread above-average trough precipitation in the western part of the study area. Both years are characterized by zonal indices above the two Atlantic sections approaching each other in the middle of the value range, by moderate anticyclonic deviations in geopotential and vorticity above the northern North Atlantic, pronounced negative vorticity above the southern North Atlantic, and by two distinct trough maxima (the first one in the west, a second one between 25 and 32·5° E). In 1971, however, the distribution pattern is much more accentuated and linked to a shorter wave-length. The infinitely small (1968) or even negative (1971) geopotential anomaly (in spite of a pronounced anticyclonic vorticity) above the southern North Atlantic has to be attributed to the trough maximum nearby which, in its rear, still draws down the constant pressure surface while anticyclonic shearing and a gradual transition to anticyclonic curvatures have already set in.

Varying qualities of trough structure and intensity

Section 3 has already indicated that trough precipitation anomalies do not only depend on variable trough frequency but on different qualities of trough structure and intensity, too. These varying qualities may be seen as 'within-type changes' according to Barry and Perry (1973, pp. 374) who have used that expression for weather- or circulation-type-internal changes of the characterizing parameters. Table IV shows, for some

Table IV. Maxima of geopotential anomaly (G_m) and of the measure of relative vorticity (V_m) of Mediterranean upper troughs (mean annual values for selected years, separated according to the trough axis position into eight longitudinal bands)

Longitudinal band		1	2	3	4	5	6	7	8
1968	G_m	−75·7	−100·3	−112·8	−85·4	−134·2	−143·9	−155·2	−129·9
	V_m	274·1	326·1	277·9	299·2	295·5	309·7	330·2	306·7
1969	G_m	−97·8	−78·8	−114·6	−132·2	−112·1	−108·3	−87·8	−131·4
	V_m	292·7	272·6	270·9	267·3	268·6	302·3	271·7	282·5
1970	G_m	−106·1	−123·1	−117·6	−158·2	−129·1	−105·7	−102·0	−87·5
	V_m	301·0	307·5	315·1	392·8	305·8	320·9	257·4	200·2

selected years and separated according to the trough axis position into eight longitudinal bands, the mean values of two different type-internal intensity parameters of Mediterranean upper troughs: the maxima of geopotential anomaly (G_m) and of the measure of relative vorticity (V_m) within the range of trough action south of 45° N which have been calculated for the field of overlapping nine-grid-point-areas of 10 or 15° of latitudinal or longitudinal extension. Four major aspects are to be recognized:

(i) The year of 1969 is characterized by a generally lower intensity of the Mediterranean troughs. This may be one of the decisive reasons that trough precipitation anomalies do not fit quite well to the observed trough frequency distribution of this year (see section 3).

(ii) Sometimes trough frequency and trough intensity maxima coincide (as in 1968) or vary in a similar way (westward drifting of the trough vorticity maximum from 1968 to 1970 parallel to the retrograde shifting of the trough axis maximum). This means that trough frequency and intensity modify the precipitation pattern at the same time in the same direction.

(iii) Sometimes this coincidence does not exist: e.g. 1970 with the striking maxima of trough intensity being located one longitudinal band further west than the prominent trough axis maximum (Figure 3d). This means that part of the positive trough precipitation anomalies in 1970 (Figure 4d) may not be caused by the highly increased trough frequency of band 5, but by the marked intensification of the few troughs of band 4, at least at some stations nearby. In particular the positive anomalies of trough precipitation in the northern part of Tunisia may be the result of these special conditions.

(iv) Geopotential anomaly and relative vorticity maxima are not always in full accord: 1968 shows another maximum of V_m in band 2 which is not accompanied by an analogous value of G_m, and the maxima of G_m in 1969 are located outside the area of maximal vorticity and trough frequency. This implies that trough intensity arises from several peculiarities that may develop independently and may result in different effects. Other investigations have indicated (Jacobeit, 1985, p. 219) that rainfall frequency might be more sensitive to variations in geopotential anomaly whereas rainfall intensity might be more sensitive to variations in relative vorticity. This would induce some further unsteadiness into the patterns outlined above.

Variation of other autonomous cyclonic elements

In conclusion it has to be emphasized that in the present paper only the anomalies of precipitation caused by upper troughs have been examined. These anomalies do not conform necessarily to the anomalies of the total amount of precipitation since autonomous variations of frequency and intensity of the other cyclonic elements of air flow may well develop, perhaps even in phase opposition, too. The station of Alexandria, for example, shows a number of different anomaly combinations between the yearly deviations of total and of trough precipitation (see Table V): parallel positive ones in 1975, 1969, 1967, parallel negative ones in 1968, 1970, 1974, 1973 (in both groups the percentages of trough precipitation related to the total amount of precipitation

Table V. Annual total precipitation R and annual trough precipitation R_{tr} (percentages of the decade average) together with the annual percentage Pc of trough precipitation in relation to the total precipitation for the rainfall station of Alexandria

	67	68	69	70	71	72	73	74	75	76	ϕ
R	140·7	53·8	124·2	49·5	134·3	115·0	78·6	95·3	143·1	65·7	100
R_{tr}	108·4	83·7	120·0	61·1	43·2	62·4	51·0	75·1	297·0	98·5	100
Pc	20·8	42·0	26·1	33·3	8·7	14·7	17·5	21·3	56·1	40·5	28

may well be both above and below the average), and also years (e.g. 1971 and 1972) that have higher amounts of total precipitation, but lower amounts of trough precipitation and therefore particularly low relative percentages. Finally the year of 1976 shows high percentages of trough precipitation which, however, were caused by a general deficit in precipitation, whereas trough precipitation has scarcely changed. It is likewise of great importance for the general conditions of precipitation that further elements of airflow generating rainfall such as Mediterranean cyclonic waves, cyclonic cells and zonalised currents are considered. They are the main subject of a further paper still in preparation.

5. CONCLUSIONS

Recent variations of circulation and climate can be studied by investigating even rather short periods of time as far as they display different modes or anomalies which may also act on larger time-scales as more persistent ones. Thus the data-covered decade from September 1966 to August 1976 has been divided into separate years to reveal variable upper trough distribution patterns and corresponding anomalies of trough precipitation. Inducing large-scale circulation anomalies consist of accumulating individual configurations of a similar nature which still appear as tendencies in larger-scale frameworks such as annual averages.

Summing up the most important and most striking deviations based on separate years can be characterized as follows: zonal currents above the Atlantic in relatively low latitudes result in a reduced trough frequency above the Mediterranean area with higher percentages of mobile troughs, in a relatively balanced trough distribution pattern and, except in the extreme east of the study area, in distinctly negative deviations of trough precipitation. Cyclonic anomalies above the eastern North Atlantic result in trough frequencies below the average above the western part of the study area, above the average over its eastern part with corresponding precipitation anomalies shifted somewhat to the east. Broadly similar though slightly shifted patterns are to be expected at the positions of the cyclonic anomaly further east above the marginal bands farthest west. Meridional forms of circulation with anticyclonic control above the eastern North Atlantic and reduced wave length result in increased trough maxima shifted to the west (compared to the long-wave trough position) with prevailing quasi-stationary troughs and positive precipitation anomalies concentrating on the central and the transitional longitudinal areas to the east. With the Atlantic anticyclonic control being not blocking-meridional but wedge-shaped diagonal, a rather balanced trough distribution at a high level with prevailing mobile troughs and broadly scattered positive deviations of trough precipitation can be observed. Anticyclonic anomalies above the continental north which reduce trough frequency in the eastern long-wave trough area and raise it in the western area of the mean trough minimum, favour positive anomalies of trough precipitation in the central section and negative ones on both margins.

These anomalies (composed of frequency and within-type changes) would gain substantial significance if they occurred with systematic frequency on a larger time scale (not restricted to isolated years) and not being counterbalanced by phase-opposite anomalies of further cyclonic elements of the airflow. Such a continuous transition of circulation anomalies over different time scales (see Flohn, 1973, p. 85) can be presumed at least as long as the same basic boundary conditions are given. Thus losses in precipitation of about 10 to 15 per cent would have to be expected in the central longitudinal areas with a comparable increase in the western and eastern marginal areas if persistent cyclonic anomalies were formed above the eastern North Atlantic. Conversely a meridional anticyclonic anomaly above this area would bring about precipitation increases of comparable degree in the central longitudinal areas and corresponding deficits at least in the eastern marginal areas. The conditions of such persistent anomalies, however, can only be discussed in the context of the hemispherical circulation and of further causal mechanisms such as nondeterministic triggering or external enforcement (see Mitchell, 1976; Lorenz, 1976).

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REFERENCES

Barry, R. G. and Perry, A. H. 1973. *Synoptic Climatology. Methods and Applications*. London, 1973.
Butzer, K. W. 1960. 'Dynamic Climatology of Large-scale European Circulation Patterns in the Mediterranean Area', *Meteorologische Rundschau*, **13**, 97–105.
Flohn, H. 1950. 'Neue Anschauungen über die Allgemeine Zirkulation der Atmosphäre und ihre klimatische Bedeutung', *Erdkunde*, **4**, 141–162.
Flohn, H. 1952. 'Allgemeine atmosphärische Zirkulation und Paläoklimatologie', *Geologische Rundschau*, **40**, 153–178.
Flohn, H. 1973. 'Globale Energiebilanz und Klimaschwankungen', *Bonner Meteorologische Abhandlungen*, **19**, 1–113.
Hess, P. and Brezowsky, H. 1977. 'Katalog der Großwetterlagen Europas', *Berichte des Deutschen Wetterdienstes*, **15**, 113.
Holton, J. R. 1979. *An Introduction to Dynamic Meteorology*. International Geophysics Series, 23.
Jacobeit, J. 1985. 'Die Analyse großräumiger Strömungsverhältnisse als Grundlage von Niederschlagsdifferenzierungen im Mittelmeerraum', *Würzburger Geographische Arbeiten*, **63**, 1–284.
Lorenz, E. N. 1976. 'Nondeterministic theories of climatic change', *Quaternary Research*, **6**, 495–506.
Meteorological Office 1962. *Weather in the Mediterranean*. Vol. 1: *General Meteorology*. London, 1962.
Mitchell, J. M. 1976. 'An overview of climatic variability and its causal mechanisms', *Quaternary Research*, **6**, 481–493.
Rudloff, H. V. 1967. Die Schwankungen und Pendelungen des Klimas in Europa seit dem Beginn der regelmässigen Instrumentenbeobachtungen (1670), Braunschweig, 1967.
Urbani, M. and D'Angiolino, G. 1974. Tipi di circulazione nella media troposfera sull' Europa e sul Mediterraneo. Servizio Meteorologico Roma, Nota Tecnica, 21.