Vegetatio 98: 1–12, 1992.
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Multivariate analysis of climatic patterns of the Mediterranean basin

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Accepted 2.5.1991

Keywords: Climate, Mediterranean, Cluster analysis, Principal Component Analysis

Abstract

Climatic data from 444 weather-recording stations in the Mediterranean basin are examined by cluster analysis and principal component analysis. The application of numerical clustering distinguished several groups of climatic stations clearly interpretable in geographic and climatic terms. The hierarchical structure of the dendrograms could be used to identify at different scales uniform climatic regions. The complementary application of principal component analysis produced an ordination of climatic types, which clearly showed the main trends of variation in the precipitation and temperature patterns.

Introduction

Most bioclimatic studies until the 1950's were characterized by the search of synthetic expressions of climate. The main aims were to produce maps of homogeneous climatic regions and to assess climate-vegetation relationships (e.g., Lang 1915; de Martonne 1926a, 1926b, 1941). Several studies were done in the Mediterranean region (Emberger 1930; Giacobbe 1949; see Daget 1977a, for a review).

In most cases, climatic variables (in particular precipitation, evaporation and temperature) were combined to allow weather patterns to be correlated with observed vegetation patterns and to provide some quantitative expressions of climatic conditions such as aridity and winter cold.

Tuhkanen (1980) reviewed climatic parameters and indices applied in plant geography. Köppen (1900, 1918, 1936) developed a world climatic classification based on the boundaries between different vegetation regions and the related values of climatic variables. Thornthwaite (1931a, b) did similar work, but later criticized (Thornthwaite 1948) the empirical approach of determining climatic regions by vegetation patterns. He argued that climatic classifications had to be 'developed independently of other geographical factors such as vegetation, soils and land use to provide the key to their geographical distribution'.

At the XVIII International Congress of Geography at Rio de Janeiro in August 1956, some concern was expressed about the state of climatology with indices and formulas being used locally, but with no generally accepted methodology (Capitanelli, in Gaussen 1956). At this same congress, Gaussen (1956) severely criticized the use of climatic formulas because their validity was limited only to the restricted regions where they had been developed. This limitation was clearly recognized by de Martonne (1955) for his own index, but it was also true for the more refined

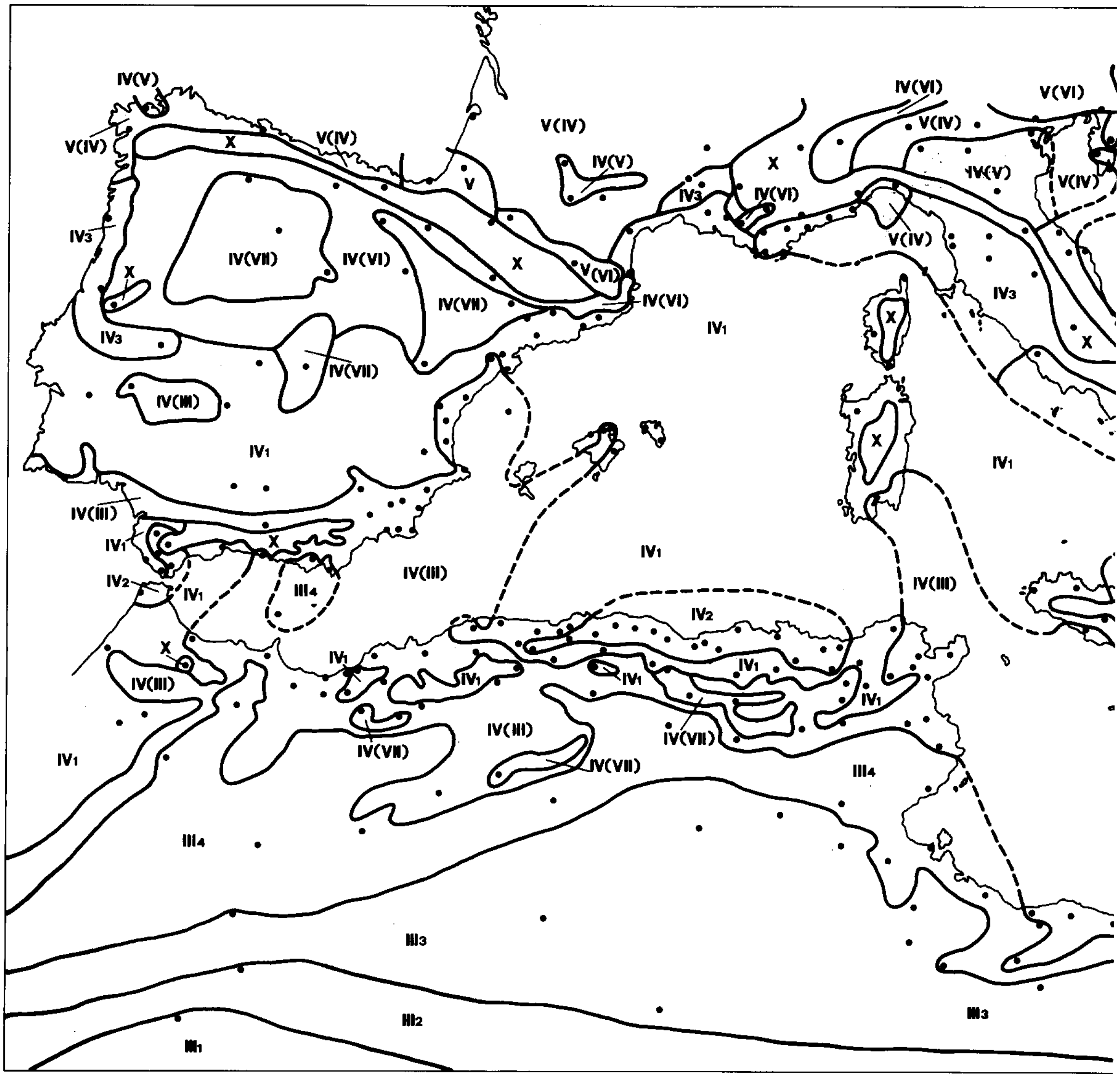
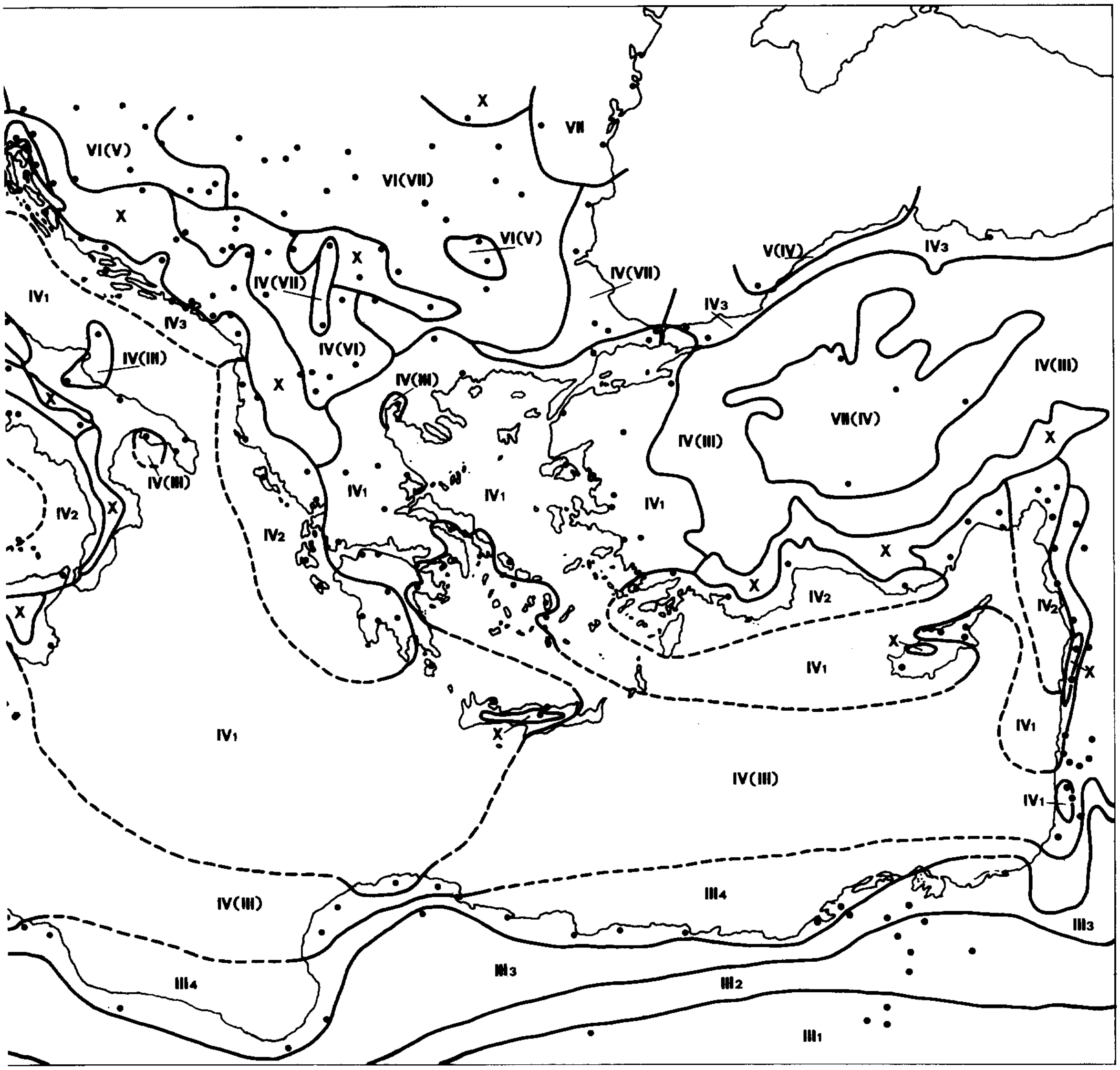


Fig. 1. Location of the climatic stations of the Mediterranean basin and their classification from the *Klimadiagramm-Weltatlas*, section 1_{18} (redrawn from Walter & Lieth 1960).

system of Thornthwaite which was found difficult to apply successfully out of the USA (Gentilli 1953).

Gaussen (1956) pointed out that all the formulas disregarded the variation in temperature, evapotranspiration and precipitation during the year though these were critically important for plant growth. Trends and seasonal cycles logically relate better to phenological and ecological processes than any single index value. A good example is the work by Major (1963) on the relations between the seasonal courses of evapotranspiration and precipitation and the vascular plant activity in a Mediterranean-type climate in California.

Walter (1955), Gaussen (1956) and Bagnouls and Gaussen (1957) proposed the combined representation of temperature and precipitation values through the year to display climatic patterns. Walter (1955) produced the well known standardized format for graphically representing the Bagnouls and Gaussen climatic diagrams. Their use



was successively extended to the complete world and the *Klimadiagramm Weltatlas* by Walter and Lieth (1960) provided what is probably still the clearest ever picture of world climatic types. These diagrams became very popular and have often been applied in vegetation studies to show the associated climatic features.

Although temperature-rainfall diagrams allow markedly different climatic types to be distinguished by eye, they are not an efficient way of detecting climatic gradients. That is why indices continued to be used to define numerical limits between types, especially in the Mediterranean region (e.g. Giacobbe 1949, 1958, 1959, 1964, 1978).

Daget (1977a) described different methods that had been used to define and to set the boundaries of the Mediterranean bioclimate. He criticized the Bagnouls & Gaussen and Walter systems, in particular for their inadequate distinction of climatic divisions, especially in mountain areas, and the unsatisfactory definition of periods of aridity by the simple relation $P < 2T$. Daget concluded that Emberger's (1930) system was better for defining Mediterranean climates. Nahal (1977) reached a similar conclusion. More recently,

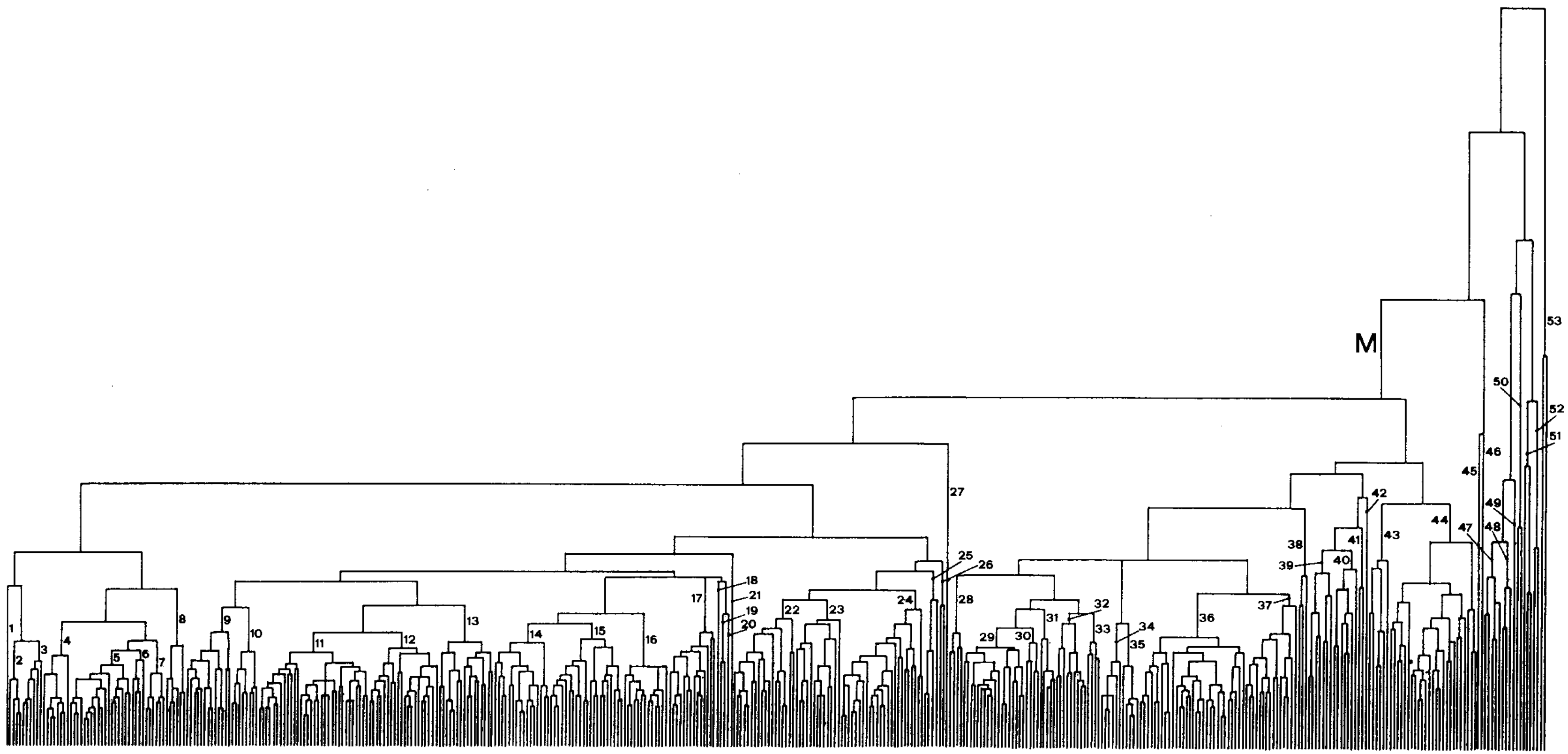


Fig. 2. Dendrogram from cluster analysis of the data from 444 climatic stations in the Mediterranean basin. Numbers refer to interpretable groups of similar stations. M shows the main cluster of proper Mediterranean climates. Station numbers within each cluster are reported in Appendix 1.

Daget and David (1987) concluded that the Emberger method was still the best available, although Daget (1977b) had earlier recognized that it was imperfect in failing to take account of the precipitation regimes.

More recently, Rivas-Martinez (1981, 1983, 1987) outlined a complex climatic classification for Spain, linked to phytosociological categories. Although its last version (Rivas-Martinez 1990) was integrated with the Walter temperature-rainfall diagrams, it did not take into account the criticisms of this empirical approach by Thornthwaite (1948) and Gaussen (1956).

In contrast to the use of synthetic indices, numerical clustering of climatic variables has been found to be an efficient way of detecting homogeneous climatic areas in relatively small regions (Rosini *et al.* 1974; Galliani & Filippini 1985; Hubalek & Horakova 1988; Blasi *et al.* 1990). Principal component analysis was successfully used to study patterns of climate, soil and vegetation in Spain pine forests (Gandullo 1972) and in tundra ecosystems (French 1974, 1981). It was also applied to rainfall values by Pignatti (1984) in a study of Mediterranean climates. This paper reports the use of cluster analysis and principal component analysis of climatic data from the Mediterranean basin. The aims were to test the methodology on a large geographical area and to verify and implement the original Walter and Lieth (1960) climatic classification for this region.

Materials and methods

The 444 climatic stations reported in the *Klimadiagramm-Weltatlas* (Walter & Lieth 1960) under section 1_{18} (Fig. 1 and Appendix 1) were used in this study. The monthly values of precipitation (P) and average temperature (T) were taken for each station by interpolation from the corresponding climatic diagram. A 444 × 24 matrix of stations and climatic variables was produced, where variables 1–12 and 13–24 represented month values from January to December of P and T respectively. The data were normalized and examined by cluster analysis and principal component analysis (PCA) using the SAS statistical package on a VAX mainframe.

A cluster analysis by average linkage agglomeration criterion was done on the complete matrix of Euclidean distances between stations. There is no standardized methodology for identifying clusters (Everitt 1979) and we identified main

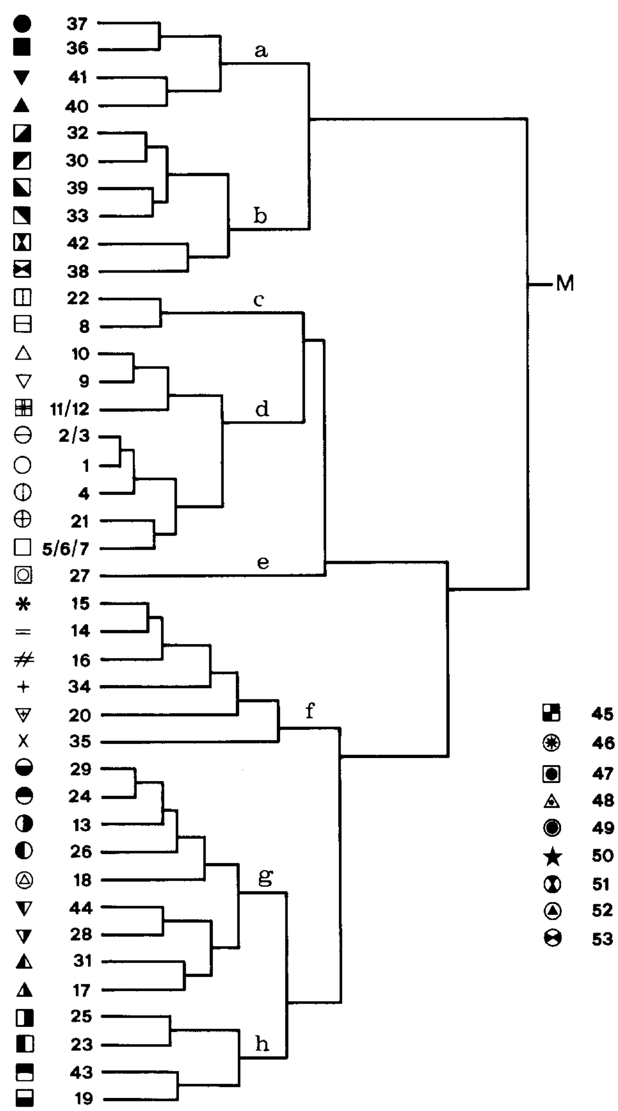


Fig. 3. Dendrogram from cluster analysis applied to the group centroids of climatic stations. Numbers refer to clusters from Figure 2. Letters indicate groups of main climatic types. Only groups of stations of the true Mediterranean region (M) were included in the analysis.

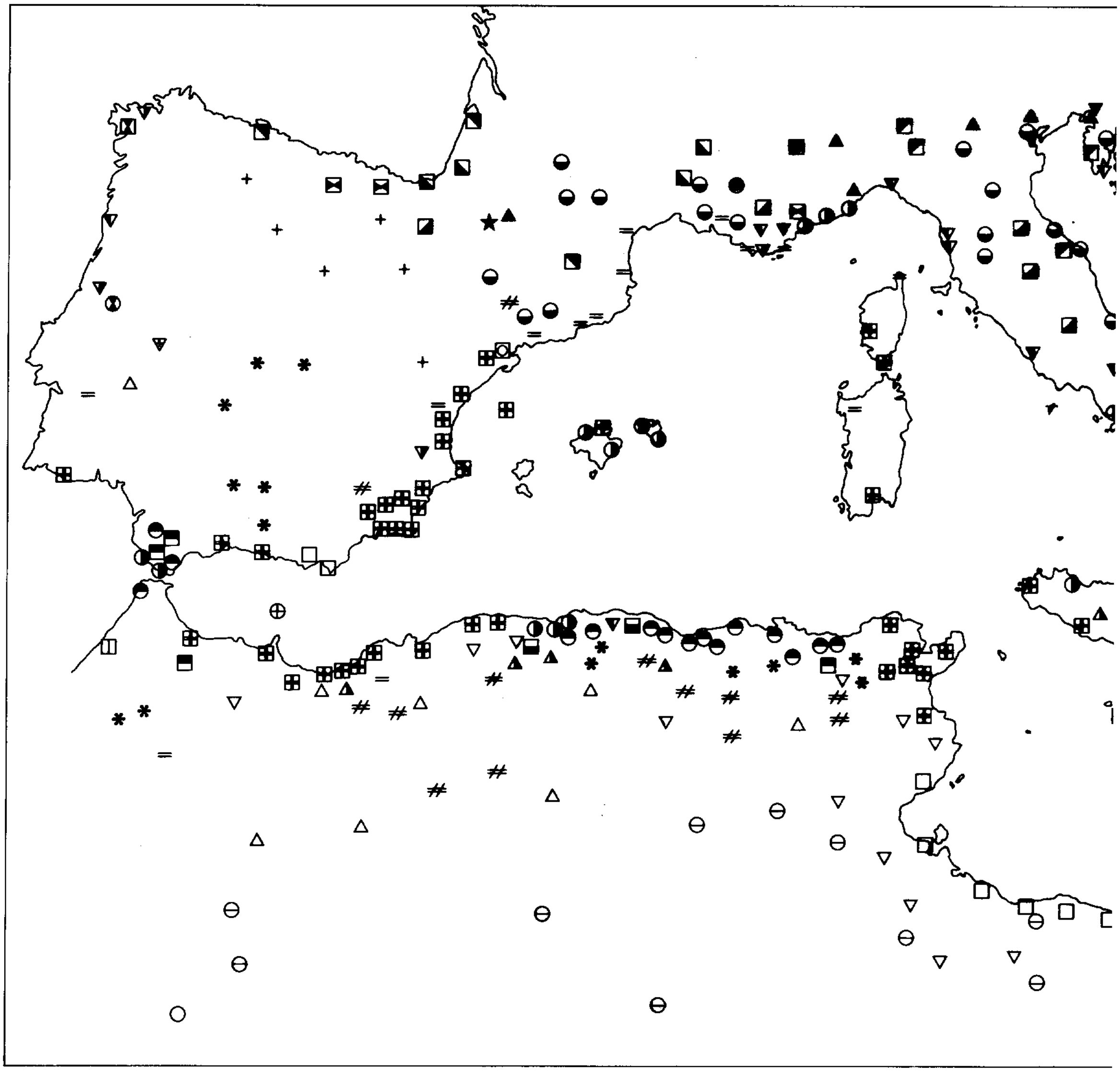
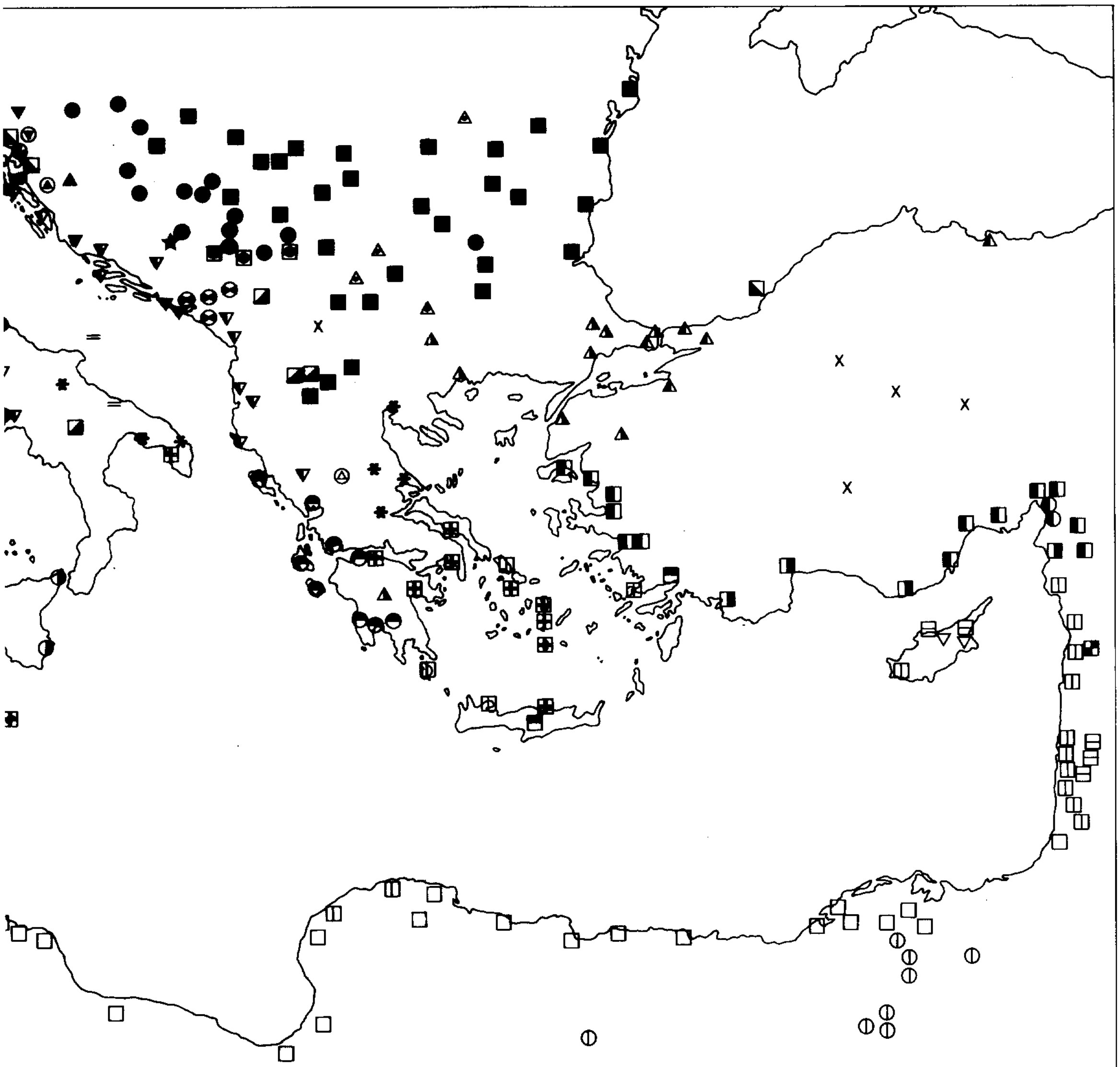


Fig. 4. Geographical distribution of the climatic stations of the Mediterranean basin classified according to the cluster analysis of climatic variables. Symbols as in Figure 3.

clusters by eye. This empirical procedure resulted in all clusters being separated by a minimum of 0.08 units of the dendrogram scale. The centroids of the clusters of stations were calculated by averaging the month values of P and T of the stations in each cluster. This produced a 53×24 matrix of 'climatic types', i.e. averages of similar stations.

To get a clearer clustering of the Mediterranean climatic types, a second cluster analysis was done on the matrix of centroids after removing clusters of clearly non-Mediterranean stations. The correspondance between this second clustering of the climatic stations and their original classification by Walter and Lieth (1960) was evaluated by χ^2 test. The reduced data set was also ordinated by PCA. The results of classification and ordination were compared by indicating the 8 main groups from the second cluster analysis on plots of the principal components from the PCA.



Results

The dendrogram produced by cluster analysis of all the 444 climatic stations is shown in Figure 2. A total of 53 main clusters were distinguished. The stations with non Mediterranean climates remained isolated or formed very distinct groups (clusters 45 to 53). Within the main group of proper Mediterranean stations (Fig. 2-M), clusters 1–44 could be interpreted in either climatic or geographical terms.

Statistical comparison by χ^2 between this classification and that by Walter and Lieth (1960) showed no significant difference ($P > 0.99$) between the two. This result did not change when secondary clusters were used, showing that the hierarchical clustering not only reproduced Walter & Lieth's original classification of climatic types to a remarkable degree, but also provided more detail on the internal variability of the different groups.

The second cluster analysis, relative of the centroids of the 44 'true' Mediterranean groups, produced eight main clusters which could be readily interpreted as different climatic types (Fig. 3).

Figure 4 maps the original 444 climatic stations

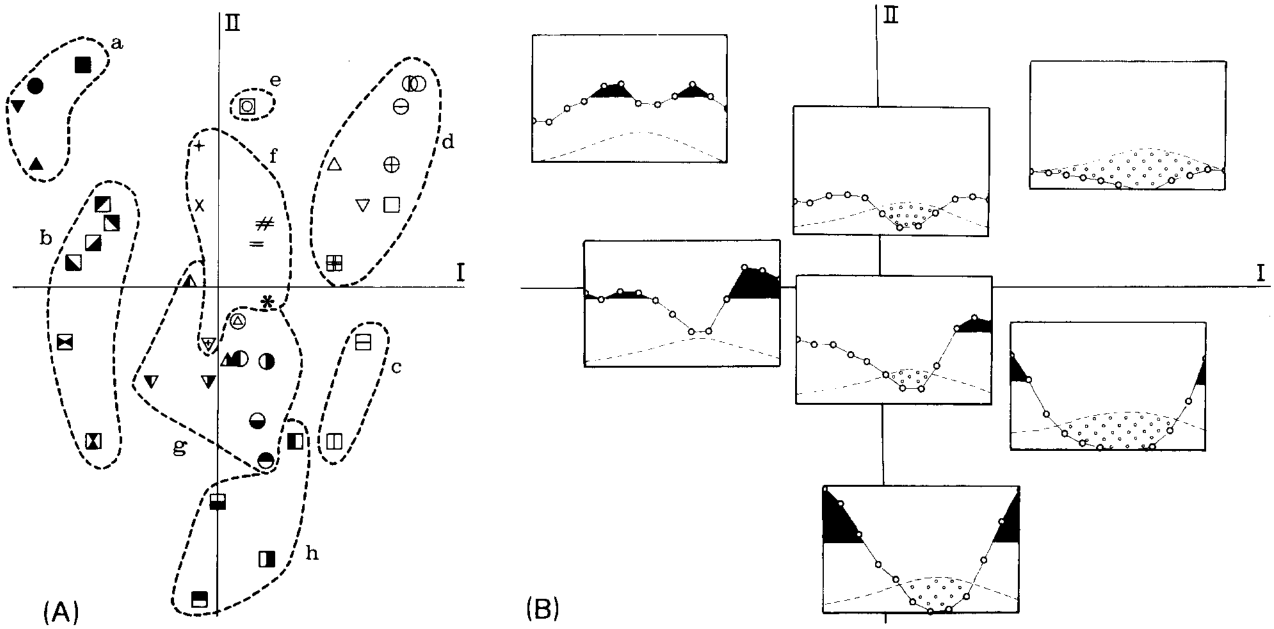


Fig. 5. Ordination of climatic types by the first two principal components. Only groups of stations of the true Mediterranean region (M in Fig. 2 and 3) were included in the analysis. Symbols as in Figure 3. In (A) dashed lines encircle main climatic types as indicated in Figure 3. In (B) average diagrams are shown for each main group; dashed lines show temperature (T) yearly curves, circles refer to precipitation (P) month values, (scales 1 mm = 2 °C), spotted areas indicate P curve below T values, black areas highlight parts of P curves above 100 mm values.

within the Mediterranean basin, showing the stations as classified by the cluster analysis. It can be seen that this classification largely follows the Walter and Lieth's (1960) original map of climatic types for this region (Fig. 1).

The first and second principal components from the PCA accounted for 62.4% and 20.6% of the total variability respectively. Figure 5a shows the ordination of the groups of climatic stations by the first two component axes with the eight main groups derived from the second cluster analysis of centroids also indicated. In contrast, Figure 5b shows the corresponding average diagrams of monthly P and T curves for each group superimposed on the same ordination hyperspace. The climatic pattern is quite clear: the first axis distributed the stations along a precipitation gradient with positive scores for low rainfall desert climatic types, and with negative scores for cold high rainfall regions. The second axis reflects 'Mediterraneity' with negative scores indicating large seasonal difference in climate and positive scores indicating a relatively uniform climate throughout the year.

Discussion

The use of numerical cluster analysis on rainfall and temperature data from 444 climatic stations in the Mediterranean basin showed a pattern of distribution of climatic features that was largely consistent with that in the *Klimadiagram Weltatlas* (Walter & Lieth 1960) map (Fig. 4 vs. Fig. 1).

The very high level of statistical correspondence between the two approaches confirmed the utility and soundness of Walter and Lieth's (1960) classification, which had been largely based on visual comparisons of the climatic diagrams. This can be taken as indirect confirmation of the power of this kind of graphs in displaying climatic patterns.

It should be noted, however, that the dendrograms produced by the cluster analysis improved the definition of climatic types especially at more local scale. The correspondence between the two classifications was high for the relatively more extreme climatic types, but the numerical method was found to be especially advantageous for its capacity to discriminate between transitional zones within the Mediterranean region proper. Moreover, the hierarchical structure of the clusters allowed uniform groups of climatic stations to be defined at various degrees of detail and at different scales, and with a better discrimination of geographical areas. For example, the cluster analysis grouped stations in a way corresponding to the more extreme climatic types III, VI and VII of the original Walter and Lieth (1960) map. On the other hand, clustering subdivided Walter & Lieth broad climatic type IV_1 into several subgroups of stations.

This climatic type was largely represented around the whole Mediterranean basin: islands, Iberian peninsula, south-eastern Italy, Greece, northern Africa, Turkey (Fig. 1). Differently, cluster analysis picked out the eastern Mediterranean region (the western and southern coasts of Turkey) as a separate group because of its relatively greater seasonal variability in rainfall. In particular, the areas surrounding the Sea of Marmora and the Macedonian coasts were clearly separated from type IV_1, becoming closer to type IV_3, i.e. Yugoslavian and Albanian coasts (cf. Figs. 1 and 4 and also Fig. 3). On the other hand, the coastal areas of the islands of Corsica, Sardinia, Sicily and Creete are shown closer to type IV(III) rather than IV_1.

Daget (1977) suggested that the climatic type X in Walter and Lieth's (1960) classification was insufficiently defined. This type was mainly delimited in relation to high altitudes. However, cluster analysis defined this type better in relation to geographical locations and the presence of humid and cold winds (cf. with the wind maps for this region in Anon. 1962; see also Wallen 1977).

Ordination of the climatic data by PCA clearly showed the continuous nature of climatic variation across the Mediterranean region (Fig. 5). The vegetation types corresponding to this distribution of climatic types can be depicted schematically on the PCA space (Fig. 6).

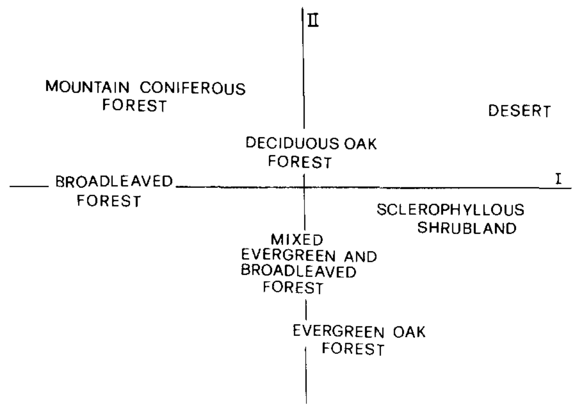


Fig. 6. Schematic distribution of main potential vegetation types according to the first and second principal components of ordination of climatic types (cfr. Fig. 5B).

Climatic indices do not seem to be an appropriate way of defining and displaying climatic variations across countries. They can be usefully applied to local problems, such as determining irrigation schedules in agriculture. However, since Gaussen's (1956) early statements in favour of analyzing continuous trends in climatic variables, the use of climatic formulas and indices should be replaced in phytoclimatic studies by appropriate numerical techniques.

The complementary use of classification and ordination methods has been shown to be very helpful in detecting patterns in data from vegetation and ecological studies (Komarkova 1980; French 1981; Mazzoleni *et al.* in press). Numerical clustering is better at picking out discontinuities and to identifying homogeneous groups, whereas ordination methods are better at display continuous trends and gradients.

The results presented in this paper confirm and amplify the original classification of climatic types proposed by Walter and Lieth (1960) for the Mediterranean basin region. They can however also be used as a flexible basis for further phytoclimatic studies in the Mediterranean area. Different regional scales can be referred to different cutting-off levels in the hierarchical dendrograms produced by cluster analysis of climatic data.

Further details about trends in climatic variations within smaller geographical areas, identified by previous clustering, can be searched by PCA or other ordination methods. Correlations between ordination scores and environmental, vegetation and ecophysiological variables (Woodward & Williams 1987) can be used to generate hypotheses to interpret the observed variability.

Acknowledgements

We are grateful to Mrs. A. de Cindio for transcribing the climatic data. We thank G. Moretti and C. Rossi for drawing the figures, G. Scippa for help with computing and Dr. J. Miles for correcting our English.

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Appendix 1.

Stations of the Mediterranean basin and corresponding climatic types according to the *Klimadiagramm-Weltatlas*, Section 1_{18} (Walter & Lieth, 1960). Numbers in italics in the right columns refer to clusters shown in Figure 3.

N°	Type		N°	Type		N°	Type		N°	Type		N°	Type		N°	Type		N°	Type	
1	III1	1	65	IV(III)	12	129	IV(III)	8	193	IV1	11	257	IV2	24	321	IV(VI)	36	385	VI(V)	37
2	III1	4	66	IV(III)	12	130	IV(III)	8	194	IV1	24	258	IV2	44	322	IV(VI)	36	386	VI(V)	37
3	III1	4	67	IV(III)	12	131	IV(III)	23	195	IV1	24	259	IV2	24	323	IV(VI)	36	387	VI(V)	37
4	III1	4	68	IV(III)	12	132	IV1	13	196	IV1	15	260	IV2	44	324	IV(VI)	38	388	VI(V)	36
5	III1	4	69	IV(III)	14	133	IV1	13	197	IV1	18	261	IV2	44	325	IV(VI)	34	389	VI(VII)	36
6	III2	2	70	IV(III)	12	134	IV1	11	198	IV1	15	262	IV2	44	326	IV(VI)	32	390	VI(VII)	36
7	III2	4	71	IV(III)	12	135	IV1	22	199	IV1	15	263	IV2	22	327	IV(VI)	29	391	VI(VII)	36
8	III2	4	72	IV(III)	12	136	IV1	15	200	IV1	17	264	IV2	43	328	IV(VI)	29	392	VI(VII)	36
9	III2	4	73	IV(III)	12	137	IV1	15	201	IV1	17	265	IV2	25	329	IV(VI)	32	393	VI(VII)	36
10	III2	5	74	IV(III)	11	138	IV1	17	202	IV1	17	266	IV2	25	330	IV(VI)	40	394	VI(VII)	36
11	III2	4	75	IV(III)	11	139	IV1	11	203	IV1	17	267	IV2	25	331	IV(VI)	37	395	VI(VII)	36
12	III3	3	76	IV(III)	11	140	IV1	17	204	IV1	31	268	IV2	23	332	IV(VI)	47	396	VI(VII)	36
13	III3	2	77	IV(III)	10	141	IV1	11	205	IV1	17	269	IV2	23	333	IV(VI)	37	397	VI(VII)	36
14	III3	2	78	IV(III)	11	142	IV1	9	206	IV1	31	270	IV2	26	334	IV(VI)	37	398	VI(VII)	36
15	III3	2	79	IV(III)	11	143	IV1	13	207	IV1	17	271	IV2	26	335	IV(VI)	37	399	VI(VII)	36
16	III3	3	80	IV(III)	11	144	IV1	13	208	IV1	23	272	IV2	25	336	IV(VI)	37	400	VI(VII)	36
17	III3	3	81	IV(III)	14	145	IV1	13	209	IV1	23	273	IV2	22	337	IV(VI)	37	401	VI(VII)	36
18	III3	9	82	IV(III)	10	146	IV1	17	210	IV1	23	274	IV2	22	338	IV(VI)	32	402	VI(VII)	36
19	III3	3	83	IV(III)	16	147	IV1	15	211	IV1	23	275	IV2	22	339	IV(VII)	34	403	VI(VII)	36
20	III3	3	84	IV(III)	11	148	IV1	15	212	IV1	22	276	IV2	22	340	IV(VII)	34	404	VI(VII)	36
21	III3	5	85	IV(III)	9	149	IV1	15	213	IV1	23	277	IV3	20	341	IV(VII)	34	405	VI(VII)	36
22	III3	5	86	IV(III)	11	150	IV1	15	214	IV1	23	278	IV3	28	342	IV(VII)	16	406	VI(VII)	36
23	III3	5	87	IV(III)	16	151	IV1	15	215	IV1	11	279	IV3	44	343	IV(VII)	34	407	VI(VII)	36
24	III3	5	88	IV(III)	10	152	IV1	15	216	IV1	22	280	IV3	39	344	IV(VII)	34	408	VI(VII)	36
25	III4	7	89	IV(III)	16	153	IV1	15	217	IV1	8	281	IV3	29	345	IV(VII)	16	409	VI	36
26	III4	7	90	IV(III)	10	154	IV1	11	218	IV1	23	282	IV3	28	346	IV(VII)	16	410	VI	36
27	III4	21	91	IV(III)	16	155	IV1	14	219	IV1	23	283	IV3	44	347	IV(VII)	16	411	VI	36
28	III4	9	92	IV(III)	16	156	IV1	15	220	IV1	23	284	IV3	44	348	IV(VII)	16	412	VII(IV)	35
29	III4	14	93	IV(III)	11	157	IV1	15	221	IV1	23	285	IV3	13	349	IV(VII)	17	413	VII(IV)	35
30	III4	10	94	IV(III)	11	158	IV1	15	222	IV1	22	286	IV3	13	350	IV(VII)	16	414	VII(IV)	35
31	III4	10	95	IV(III)	11	159	IV1	15	223	IV1	22	287	IV3	13	351	IV(VII)	16	415	VII(IV)	35
32	III4	10	96	IV(III)	11	160	IV1	28	224	IV1	22	288	IV3	44	352	IV(VII)	35	416	X	43
33	III4	9	97	IV(III)	9	161	IV1	27	225	IV1	22	289	IV3	44	353	IV(VII)	36	417	X	43
34	III4	9	98	IV(III)	9	162	IV1	14	226	IV1	22	290	IV3	29	354	IV(VII)	17	418	X	51
35	III4	7	99	IV(III)	12	163	IV1	29	227	IV2	24	291	IV3	29	355	IV(VII)	17	419	X	38
36	III4	9	100	IV(III)	11	164	IV1	29	228	IV2	43	292	IV3	32	356	IV(VII)	36	420	X	50
37	III4	5	101	IV(III)	11	165	IV1	14	229	IV2	24	293	IV3	44	357	IV(VII)	36	421	X	49
38	III4	5	102	IV(III)	12	166	IV1	14	230	IV2	24	294	IV3	32	358	V(IV)	42	422	X	47
39	III4	9	103	IV(III)	14	167	IV1	14	231	IV2	19	295	IV3	29	359	V(IV)	33	423	X	38
40	III4	3	104	IV(III)	15	168	IV1	14	232	IV2	24	296	IV3	29	360	V(IV)	33	424	X	40
41	III4	5	105	IV(III)	15	169	IV1	29	233	IV2	24	297	IV3	46	361	V(IV)	29	425	X	32
42	III4	5	106	IV(III)	11	170	IV1	14	234	IV2	44	298	IV3	44	362	V(IV)	39	426	X	32
43	III4	5	107	IV(III)	11	171	IV1	14	235	IV2	19	299	IV3	44	363	V(IV)	44	427	X	40
44	III4	5	108	IV(III)	5	172	IV1	14	236	IV2	24	300	IV3	44	364	V(IV)	30	428	X	52
45	III4	5	109	IV(III)	9	173	IV1	13	237	IV2	24	301	IV3	44	365	V(IV)	40	429	X	52
46	III4	7	110	IV(III)	6	174	IV1	13	238	IV2	24	302	IV3	44	366	V(IV)	30	430	X	37
47	III4	5	111	IV(III)	5	175	IV1	13	239	IV2	24	303	IV3	44	367	V(IV)	39	431	X	50
48	III4	7	112	IV(III)	6	176	IV1	13	240	IV2	24	304	IV3	44	368	V(IV)	39	432	X	47
49	III4	7	113	IV(III)	22	177	IV1	14	241	IV2	24	305	IV3	44	369	V	30	433	X	53
50	III4	5	114	IV(III)	6	178	IV1	12	242	IV2	24	306	IV3	44	370	V	29	434	X	51
51	III4	5	115	IV(III)	11	179	IV1	12	243	IV2	24	307	IV3	44	371	V	39	435	X	53
52	III4	5	116	IV(III)	11	180	IV1	14	244	IV2	24	308	IV3	44	372	V	39	436	X	51
53	IV(III)	11	117	IV(III)	11	181	IV1	11	245	IV2	43	309	IV3	31	373	V	39	437	X	32
54	IV(III)	10	118	IV(III)	15	182	IV1	13	246	IV2	24	310	IV3	31	374	IV(VI)	40	438	X	47
55	IV(III)	15	119	IV(III)	11	183	IV1	17	247	IV2	13	311	IV3	31	375	IV(VI)	33	439	X	47
56	IV(III)	11	120	IV(III)	11	184	IV1	13	248	IV2	44	312	IV(V)	28	376	IV(VI)	40	440	X	48
57	IV(III)	16	121	IV(III)	11	185	IV1	12	249	IV2	13	313	IV(V)	29	377	IV(VI)	41	441	X	48
58	IV(III)	12	122	IV(III)	9	186	IV1	15	250	IV2	44	314	IV(V)	29	378	VI(V)	41	442	X	48
59	IV(III)	12	123	IV(III)	8	187	IV1	14	251	IV2	24	315	IV(V)	30	379	VI(V)	37	443	X	43
60	IV(III)	12	124	IV(III)	9	188	IV1	29	252	IV2	24	316	IV(V)	29	380	VI(V)	37	444	X	45
61	IV(III)	12	125	IV(III)	6	189	IV1	22	253	IV2	24	317	IV(V)	29	381	VI(V)	37			
62	IV(III)	12	126	IV(III)	22	190	IV1	22	254	IV2	17	318	IV(V)	29	382	VI(V)	40			
63	IV(III)	12	127	IV(III)	8	191	IV1	11	255	IV2	24	319	IV(VI)	32	383	VI(V)	37			
64	IV(III)	12	128	IV(III)	8	192	IV1	22	256	IV2	24	320	IV(VI)	33	384	VI(V)	37			