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PhD Thesis

The Western Mediterranean Oscillation and Rainfall in the Catalan Countries

Memory presented by

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(*Summary*)

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3RD CHAPTER

WEMOI TRENDS AND CYCLES:

THE EFFECTS ON THE CATALAN COUNTRIES

RAINFALL VARIABILITY

3.1. TRENDS AND PHASES ANALYSIS OF THE WeMO: 1821-2000

In order to detect variability and changes on precipitation, phases and trends on teleconnection indices are searched. WeMOi is the main one, but AOi and NAOi are also studied. Two periods are taken into account, the whole one, 1821-2000, and the most recent one, 1951-2000. The influence of the WeMO phases on the precipitation over the Catalan Countries will permit us to regionalise the study area. T-test is applied to detect significant trends in indices (Önöz and Bayazit, 2003; Power, 2003) in AnClim software (Stepanek, 2005). The analyses are performed monthly, seasonally and annually.

For the 1821-2000 period, WeMOi has a negative and significant trend in the three summer months. The unique other month with a significant trend is October, which is negative too. Seasonally, summer has an obvious negative trend. Winter has a positive and significant trend, however, no winter month has a significant trend. WeMOi has a significant and negative trend during the warm semester and for the entire year (annually) (Table 1).

January	-	**July**	-0.047/ 10 years
February	-	**August**	-0.053/ 10 years
March	-	**September**	-
April	-	**October**	-0.030/ 10 years
May	-	**November**	-
June	-0.041/ 10 years	**December**	-
Winter	+0.021/ 10 years	**Summer**	-0.047/ 10 years
Spring	-	**Autumn**	-
Cold semester	-	**Warm semester**	-0.034/ 10 years
Annual 2[1]	-0.017/ 10 years		

Table 1. WeMOi trends (1821-2000) shown monthly, seasonally and annually. (The cold semester is from October to March; the warm semester is from April to September). Only the significant trends at 0.05 according to t-test are shown.

During the long winter (from December to March), according to section 1.6. of the 1st chapter, the oldest WeMOi period which belongs to Urrutia Brothers is quite negative, but at the end of the 19th century WeMOi shifts to a positive phase until the last quarter of the 20th century, when a new negative phase starts. This is also what characterises the WeMOi evolution in short winter (DJF) (Figure 1). Although the homogeneities which can remain in Urrutia Brothers's period, it was a climatic period with strong atmospheric oscillations which is documented with several catastrophic floods in the Mediterranean basins of Iberian Peninsula (Oliva *et al*., 2006).

[1] In the Catalan version, it is explained how we must work out the annual values in two different procedures. Annual 1 would be the first way, which are the total pluviometric amounts, and Annual 2, the second way, which is the mean of the monthly normalised values according to the 1961-1990 reference period.

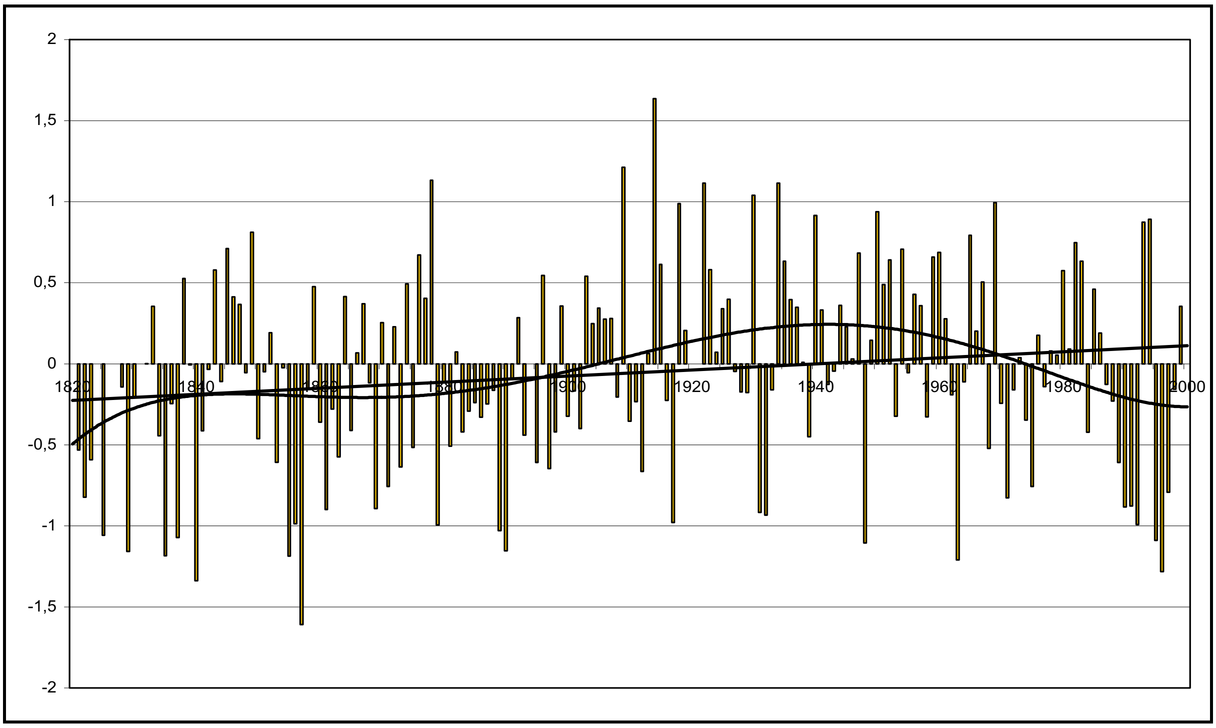


Figure 1. WeMOi winter evolution (December, January and February) during the 1821/22-1999/2000 period (line and 5th degree polynomial regressions are drawn).

In spring (March, April and May), the WeMOi has a slight negative trend, but not significant. At the beginning of the period, some years are very negative. The polynomial regression shows that WeMO had a positive phase from the end of the 19th century to the beginning of the 20th century. Afterwards, there was an alternation of positive and negative phases, which does not allow us to determine a trend in its most recent behaviour (Figure 2).

The summer WeMOi remained in positive values during the 19th century and almost the entire first part of the 20th century too (Figure 3). Its negative and significant trend is favoured because of an alternation of positive and negative phases which has been taking place since the second third of the 20th century. The thermal Iberian low might be reinforced and more frequent.

In autumn, the WeMOi has no well defined oscillations (Figure 4). During the 19th, the WeMOi has mostly positive values, but they were negative during the first third of the 20th century. During the rest of the century, the oscillations are quite irregular, however, some negative trend is deduced due to the appearance of strong negative phases of 4-5 years. The second half of 1980s is the most outstanding cycle, when there were many torrential events in the Valencian Country (Armengot, 2002).

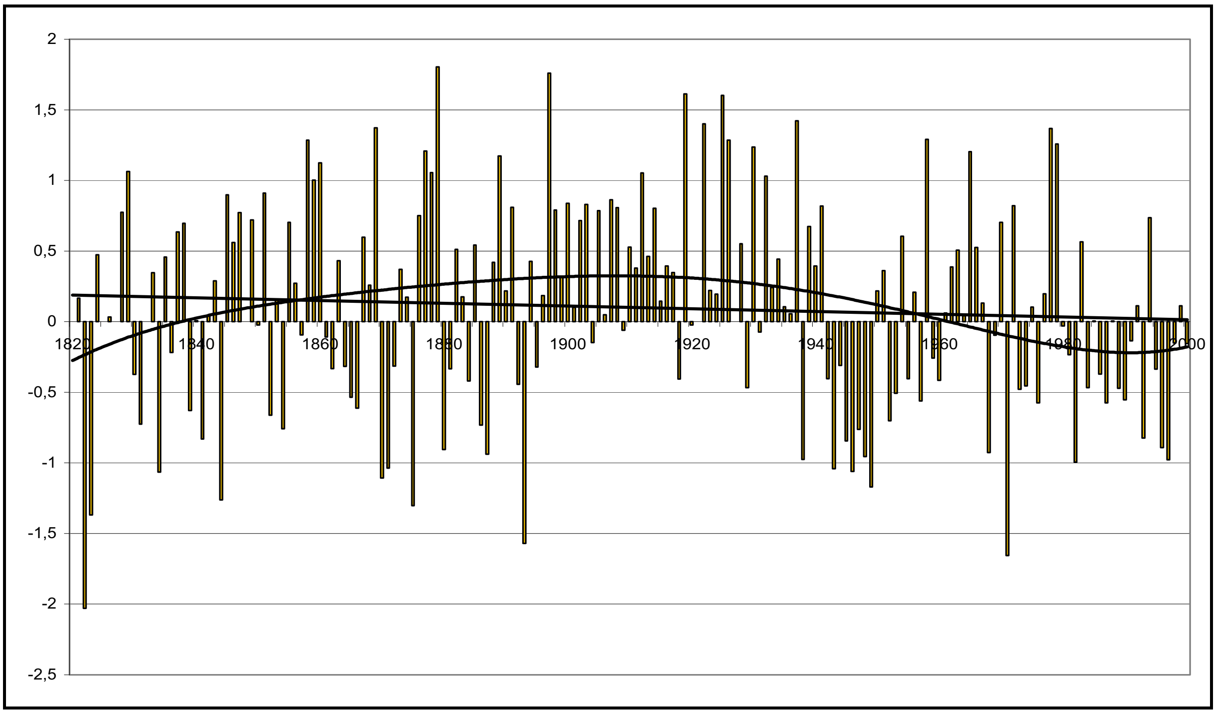


Figure 2. Idem as Fig. 1, but for spring (March, April and May) and for the 1821-2000 period.

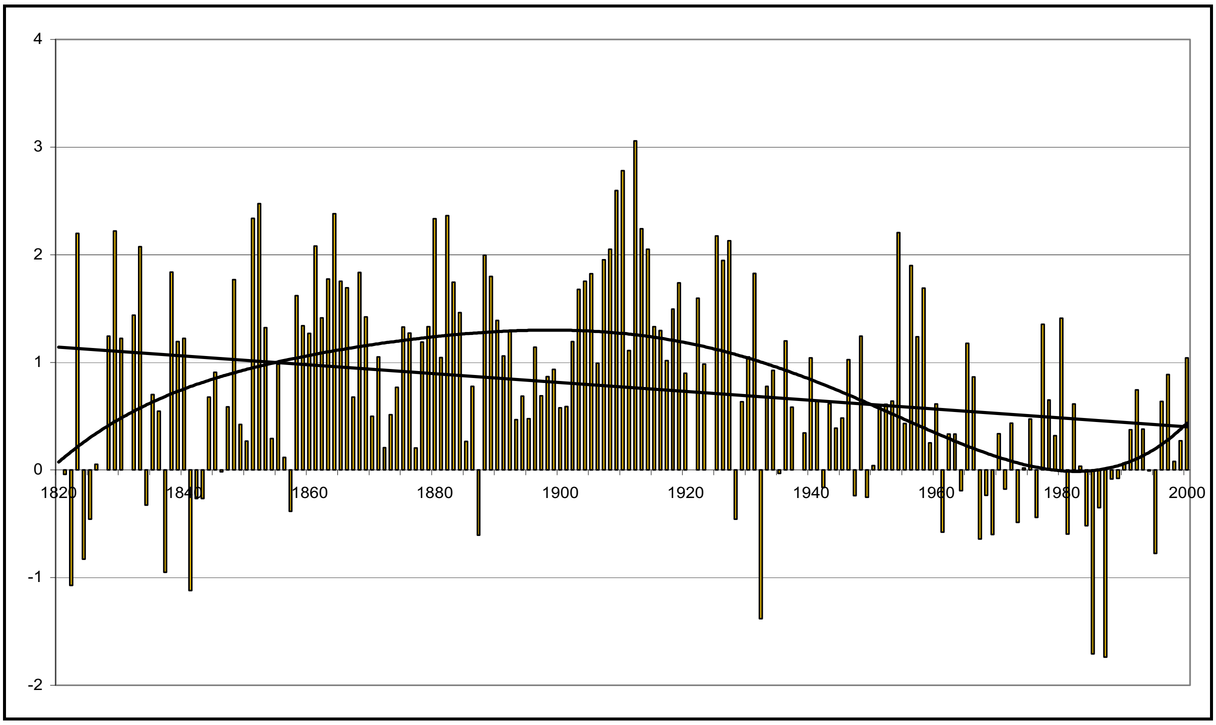


Figure 3. Idem as Fig. 2, but for summer (June, July and August).

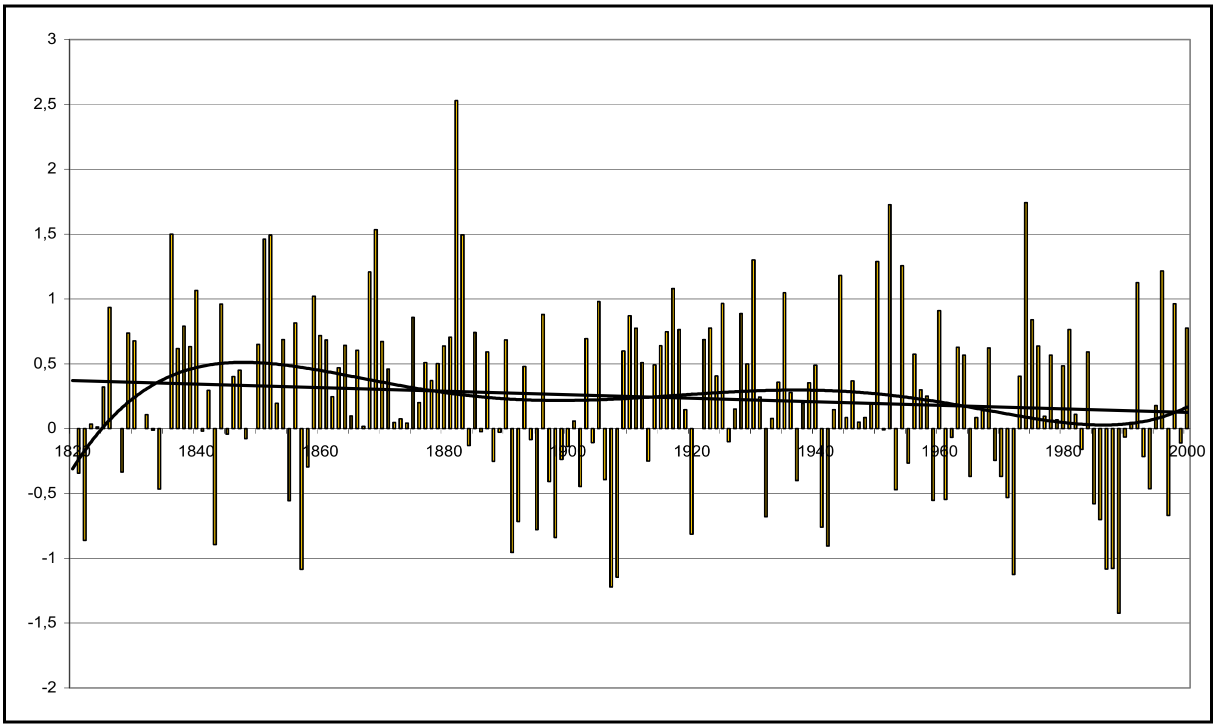


Figure 4. Idem as Fig. 2, but for autumn (September, October and November).

Annually (annual 2), the WeMOi has a negative trend because there is a predominance of negative values since 1960s. Figure 5 represents the overall WeMOi evolution: a first half of the 19th century with certain negative values, some of them being extreme, a positive phase from mid-19th century to mid-20th century and a recent negative phase. The WeMOi has an overall high interannual variability which is coherent with the regional feature of the pattern.

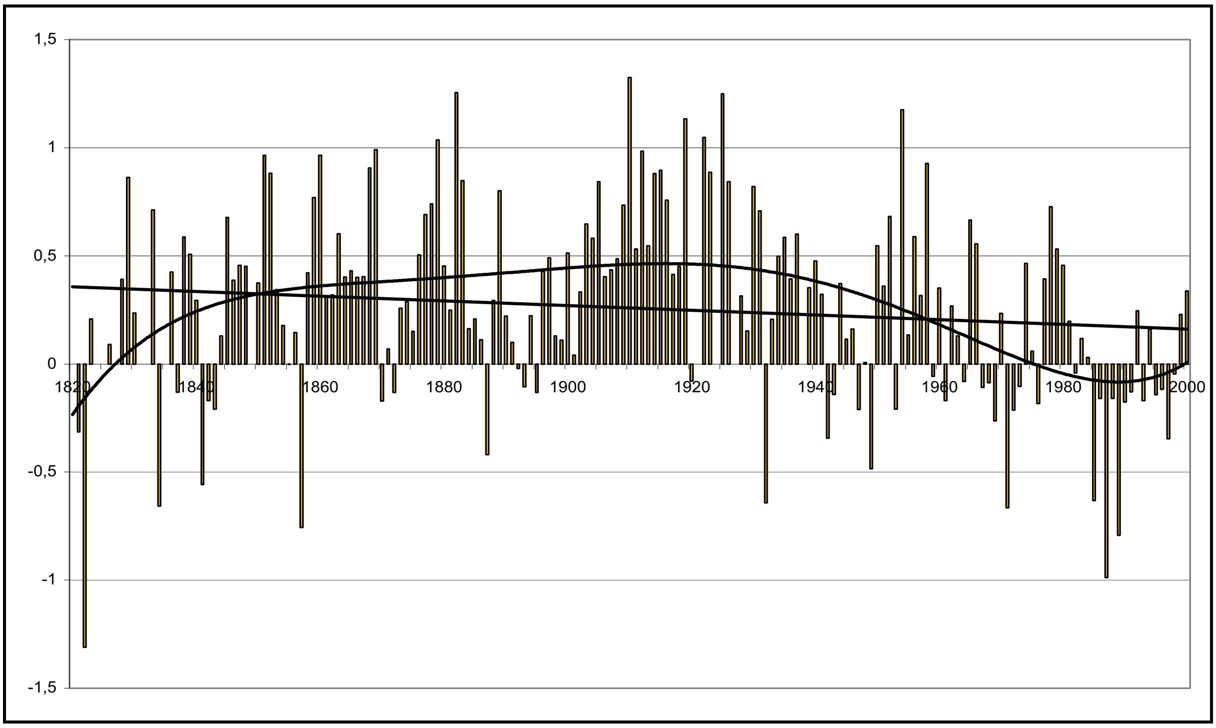


Figure 5. Idem as Fig. 2, but annually.

3.2. TRENDS ANALYSIS AND PHASES OF THE WeMO AND OTHER PATTERNS FOR THE RECENT PERIOD: 1951-2000

It is very important to analyse the 1951-2000 period because it is the period of the Catalan Countries precipitation database. The trend analysis is shown first, followed by the detected phases. The WeMO is the main considered pattern, but other patterns as the NAO or AO are also taken into account. Some relationships between the patterns are studied.

3.2.1. WeMOi TRENDS ANALYSIS

The WeMOi remains with a negative summer trend at 0.05, but somehow weakened as it is not significant in June or in August. NAOi and AOi do not show any trend during this season. In summer, due to the weak atmospheric circulation, the indices of the patterns are not correlated. During the warm semester, the variations are similar to summer. The WeMOi reduces significantly, but the NAOi has a positive and significant trend.

In winter, the WeMOi reduces significantly, being January the only winter month with a significant trend. Recently, the AOi has been increasing significantly during this season. We must remember that both patterns are satisfactorily opposed correlated between them in this second half of the 20th century (section 1.7. in the 1st chapter). AO is more dynamic at the end of the study period due to a reinforced polar vortex, making the WeMO answer with an extreme negative phase (Martin-Vide and Lopez-Bustins, 2006). NAOi also shows a positive trend in winter, but only significant in February. Hurrell and van Loon (1997) also found a positive NAO winter evolution along the last two decades of the 20th century. In spite of the close relationship between the AO and NAO patterns, they are quite different when their indices are correlated with WeMOi; the first one is negative and significantly correlated, and the second one is positive and not significantly correlated. During the cold half of the year, the pattern indices have the same evolution as in winter. The opposed WeMOi and AOi relationship is strengthened.

Both WeMO and AO remain invariable in spring and in autumn. There is a noticeably opposed oscillation between them in autumn, but their trends are not as significant as in winter. Spring is the only period of the year when the WeMOi and NAOi might have a similar behaviour as shown by their trends and the correlation between them. For this reason, the largest influence of NAO, detected in the 2nd chapter, on the Catalan Countries rainfall is in spring.

Annually, WeMOi and AOi have opposed trends and the correlation between both indices is negative and significant at 0.05.

1951-2000	WeMOi trend	NAOi trend	AOi trend	r WeMOi/NAOi	r WeMOi/AOi	r NAOi/AOi
January	**-0.204**	0.139	0.293	**0.36**	0.00	**0.78**
February	-0.096	**0.428**	**0.425**	0.19	-0.11	**0.82**
March	-0.006	**0.337**	0.276	0.18	-0.11	**0.79**
April	0.034	-0.214	0.011	**0.36**	-0.14	0.27
May	**-0.284**	-0.172	0.074	0.17	-0.15	**0.54**
June	-0.089	-0.062	0.052	0.03	-0.21	**0.56**
July	**-0.279**	0.009	-0.018	-0.24	-0.08	**0.48**
August	-0.122	0.095	0.111	-0.06	-0.07	**0.50**
September	-0.125	-0.283	-0.025	0.06	-0.25	**0.52**
October	-0.062	-0.232	-0.062	0.18	-0.22	**0.60**
November	-0.006	0.080	0.146	0.19	-0.12	**0.58**
December	-0.133	-0.024	0.097	**0.46**	-0.10	**0.64**
Winter	**-0.131**	0.210	**0.310**	0.24	**-0.29**	**0.77**
Spring	-0.085	-0.016	0.120	**0.33**	-0.17	**0.45**
Summer	**-0.163**	0.014	0.048	-0.13	-0.17	**0.37**
Autumn	-0.064	-0.145	0.020	0.23	**-0.35**	**0.48**
Cold semester	**-0.083**	0.117	**0.216**	0.20	**-0.35**	**0.70**
Warm semester	**-0.144**	**-0.105**	0.034	0.17	-0.21	**0.34**
Annual 2	**-0.114**	0.008	**0.115**	0.12	**-0.33**	**0.61**

Table 2. WeMOi, NAOi and AOi trends (Z/ 10 years) and Pearson's coefficient correlation between the indices during the period 1901-2000. (Values in bold are those trends and correlations which are significant at 95% confidence level).

3.2.2. WEMO PHASES IN ACCORDANCE WITH THE AO

It is during the cold semester when there is the largest opposed relationship between the WeMO and the AO as the general atmospheric circulation behaves with a more intense dynamism. It is during this period of the year when the WeMO has the largest influence on rainfall in the Catalan Countries (Figure 12 in the 2nd chapter). The opposed phases are studied for the long winter (DJFM) and autumn. Here it is just shown the former season because it is when more solid results are obtained. The autumn analysis can be found in the Catalan version of this manuscript.

Commenting the analysis for the long winter, opposed phases are expected in the temporal evolution of both indices. In the course of the 20th century 7 different phases with different lengths (10-20 years) have been established in the evolution of the winter AOi, as the independent variable modulating the WeMOi behaviour (Figure 6). The WeMOi responds with totally opposed phases of similar periodicities during the second half of the 20th century, while the opposed behaviour is hardly visible in the first half. Therefore, an insignificant negative correlation was expected for the first half of the 20th century (r = −0.1993, p-value = 0.1745). During the last 50 years of the period study, the AO has intensified its dynamism, strengthening its relationship with the WeMO.

The last phase is extremely positive in the AO and negative in the WeMO. This latter phase might explain the current rainfall variability and trend over the Catalan Countries and over other Iberian Peninsula regions. The previous correlation between Gulf of València and Bay of Biscay precipitation (Figure 5, left, in the 2nd chapter) is consistent during their temporary evolution throughout the 1910–2000 period, in such a way that the negative linear trend of the WeMOi in the winter period coincides with an increase of rainfall in València (both are significant), and with a decrease in Bilbao (Table 3).

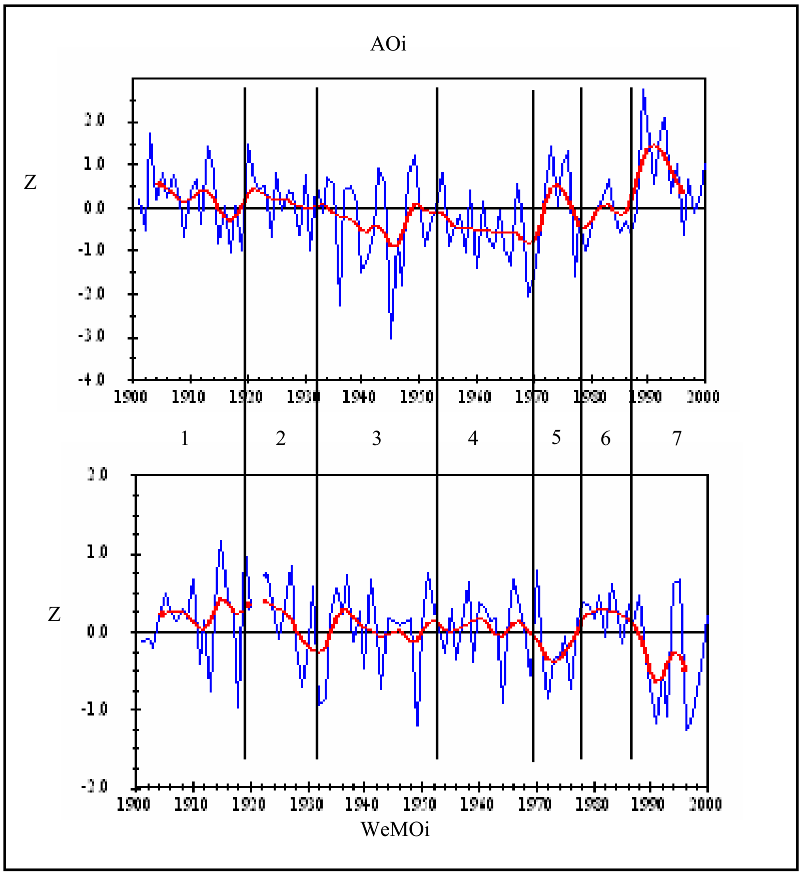


Figure 6. WeMO and AO phases in winter (DJFM) for the 1900/01 to 1999/2000 period (there is a gap in the WeMOi in 1921). Low-pass Gaussian filter, with an input wavelength period of 10 years, of WeMOi and AOi. (From Martin-Vide and Lopez-Bustins, 2006)

Trends 1910-2000	AOi	WeMOi	València pluviometry	Bilbao pluviometry
Z/ 100 years	+0.43	**-0.49**	**+0.42**	-0.24
t-test for coefficient b1 (y = b0+b1x)	t = /1.102/ <1.987 (95%)	t = /-2.111/ >1.988 (95%)	t = /+2.117/ >1.987 (95%)	t = /-1.108/ <1.987 (95%)

Table 3. Temporal trends of AOi, of WeMOi , and of València and Bilbao winter (DJFM) precipitations (1910-2000 period). (Values in bold are those trends which are significant at 95% confidence level). (Adapted from Martin-Vide and Lopez-Bustins, 2006).

In an analysis focused on Catalan Countries precipitation, the 7th phase is chosen to check which rainfall anomalies take place when the atmospheric circulation over Europe is strongly reinforced. The temporal interval of this phase is 1988/89-1999/2000. This phase shows an extreme positive AO phase which enhances an extreme negative phase of the WeMO. The rainfall rises in those areas where the influence of the WeMO is largest: the Valencian Country, except for its inland area, the eastern Pyrenees and the Pitiüses (Figure 7). In contrast, the areas under the AO or the NAO influence are drier: inland Catalonia, Western Strip and western Pyrenees. In Menorca and northern Mallorca, the precipitation is also reduced, but no changes are detected in Pitiüses, and a south-western – north-eastern gradient is subsequently displayed. Northern Alacant mountains is where the biggest rainfall increase takes place as it is where AOi correlates positively, almost significantly, with winter precipitation (Figure 8).

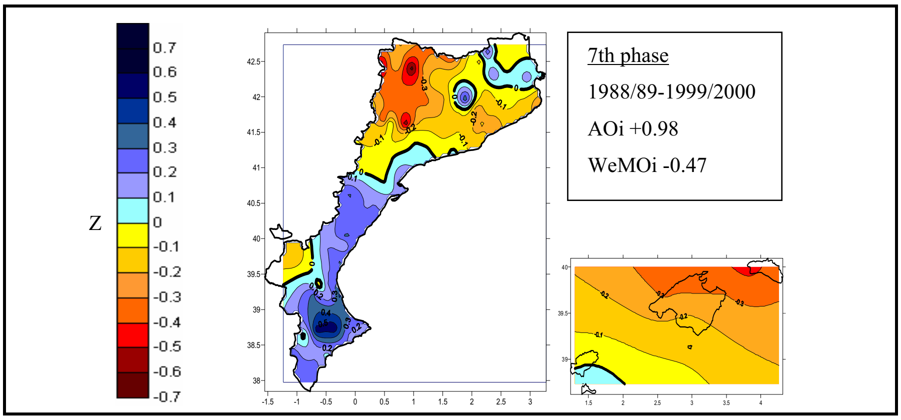


Figure 7. Standardised values means spatial distribution of the Catalan Countries winter precipitation (DJFM), according to the 1961-1990 reference period, in those years of the 7th phase of the WeMO/AO relationship along the 20th century. AOi and WeMOi means for this 7th phase are displayed.

3.3. THE AO AND RAINFALL IN THE CATALAN COUNTRIES

The AO represents the global atmospheric dynamism for the northern hemisphere, above all, in winter, when the polar vortex is stronger. The AO is fully taken into account in this chapter and in the following one, instead of the NAO, because the AO has an opposed behaviour to the WeMO as it has already demonstrated, above all, in winter. It is of high interest the strengthening of the polar vortex since 1989, which has made WeMO go into an extreme negative phase at the end of the last century. Some previous studies have indirectly detected this opposed behaviour between the western Mediterranean basin and the polar vortex (Quereda Sala, 1989). These findings are not very far from what Rossby (1939) found with his study about the zonal cycle index which is currently known as the annular mode.

Figure 8 shows the most interesting correlations between the AOi and rainfall in the Catalan Countries. Although AO and NAO behaviours are similar, we must have a look again at the Figure 12 in the 2nd chapter to see that their influences on rainfall over Catalan Countries are different. The AO's largest influence on Catalan Countries precipitation, in its negative phase, is in January over western Catalonia, the Western Strip and the inland Valencian Country. The most influenced seasons are autumn, by the AO positive phase over the coastland Valencian Country and by the AO negative phase over the Val d'Aran, and winter, by the AO negative phase over inland Catalonia and most inland Valencian region. Lastly, the cold semester enhances the results obtained in winter as the AOi succeeds in correlating with precipitation over the northern Alacant mountains positive and significantly. Even precipitation in the eastern Pyrenees is almost significantly correlated with AOi in plus sign. The AO has the largest influence in western Catalonia in its negative phase. The Balearic Islands rainfall is not significantly correlated with the AOi. The spatial distributions of the correlations of the rest of the periods of the year are displayed in the Catalan version.

The WeMO/AO relationship is also demonstrated when we pay attention to the comparison of these maps with the ones showing the absolute differences of the correlation coefficients between the WeMOi and NAOi with precipitation in the Catalan Countries (Figure 12 in the 2nd chapter). For instance, in the AOi-precipitation map of February (not shown) there is a positive correlation in Northern Catalonia and Castelló province, and these areas are very influenced by WeMO over NAO in this month. Val d'Aran is under WeMO positive phase in autumn, so it is negative and significantly correlated with the AOi. The Balearic Islands, despite not having any significant correlation with AOi, the spatial coefficients distribution can show a south-western – north-eastern gradient as Pitiüses have positive values and Mallorca and Menorca have negative values (Figure 8, cold semester).

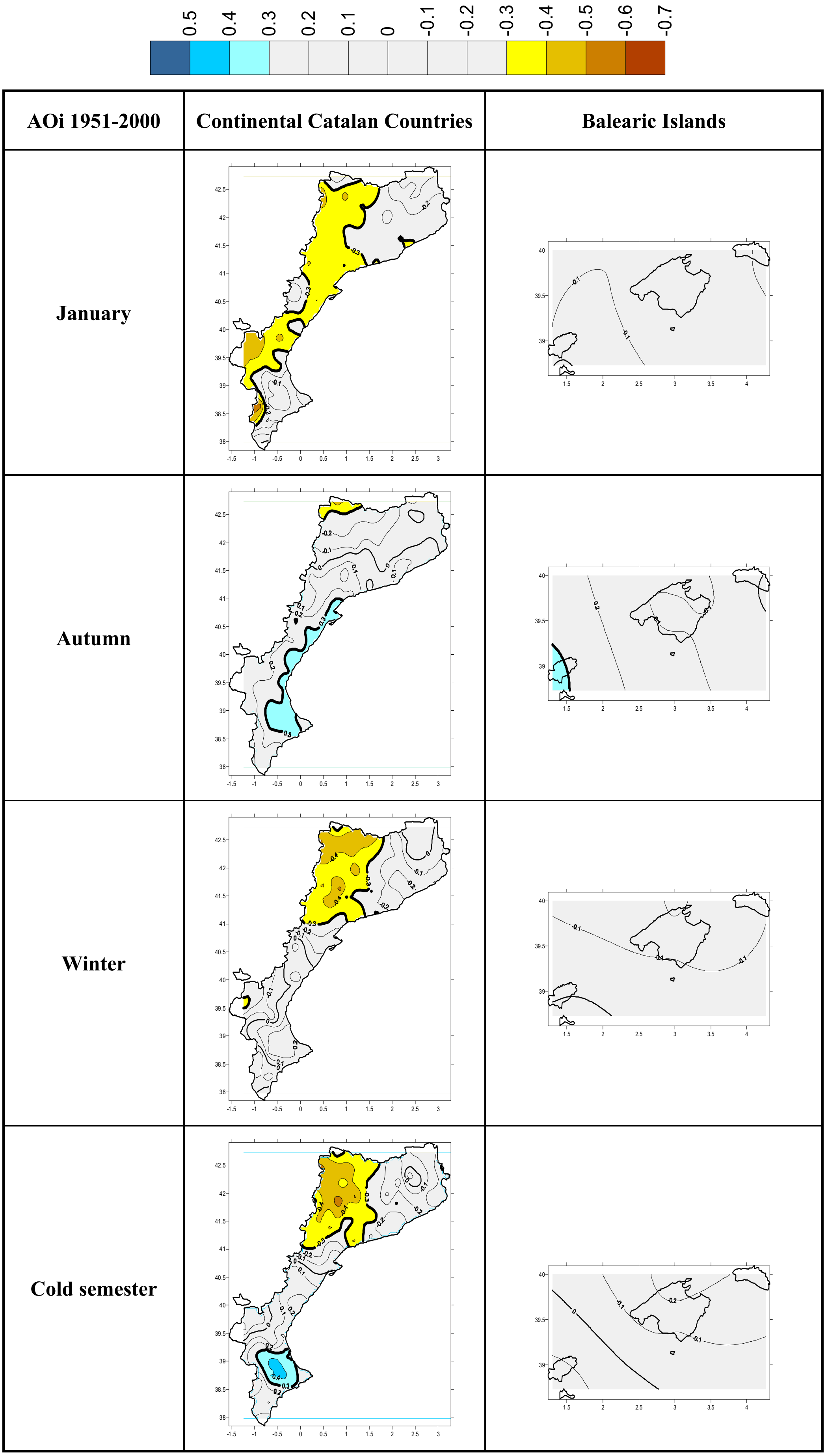


Figure 8. Pearson's coefficients correlation between AOi and Catalan Countries rainfall for January, autumn, winter and cold semester during the 1951-2000 period. (Coloured areas are significant at 95% confidence level).

Summarizing, those Catalan Countries areas where the precipitation increases under a positive AO phase are the areas that are most influenced by the WeMO over the NAO in their respective negative phases. These areas are defined as being strictly Mediterranean due their eastern orientation (section 2.6.3. in the 2nd chapter). The AO and the NAO influence the Catalan Countries rainfall differently: the NAOi has a larger extension of the negative correlations than the AOi; but the AO is the pattern which influences those areas where NAO influence is nil (in its positive -Valencian Country- or in its negative phase -Val d'Aran-).

In extreme AO phases, the winter rainfall anomalies distribution are coherent. In extreme positive phases, precipitation rises remarkably in the Valencian Country, above all, in the northern Alacant mountains. Western Catalonia is where the AO has an influence on its negative phase, so its rainfall decreases. Northern Mallorca rainfall also shows a noticeable reduction (Figure 9). A map showing the opposite is obtained under extreme negative AO phases. However, rainfall reductions are not very strong.

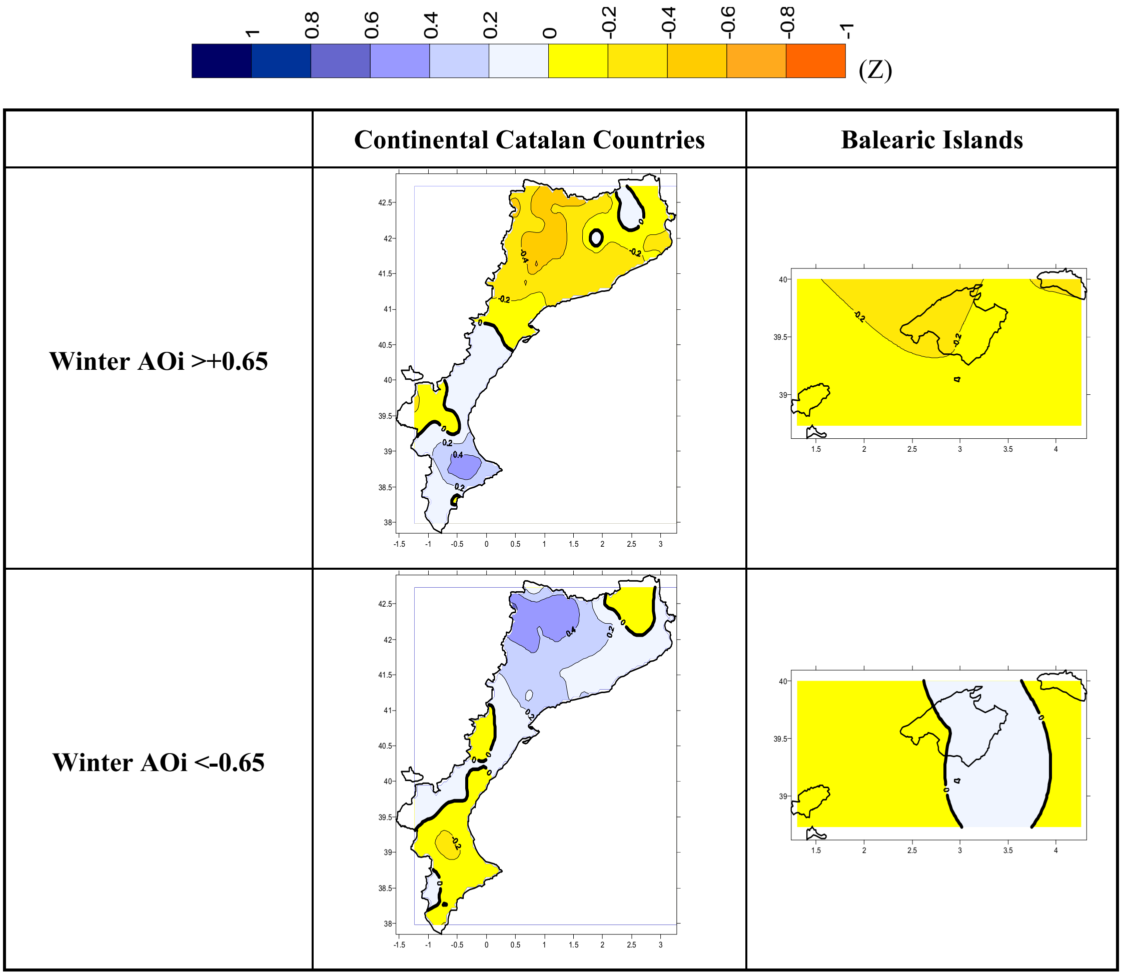


Figure 9. Catalan Countries rainfall in monthly mean standardised values of winter season (DJFM), according to the 1961-1990 reference period, in those years with an extreme positive AO phase during the 1951-2000 period. (0 value corresponds to the rainfall mean of the 1961-1990 reference period). (The threshold used is /0.65/ since long winter is formed by 4 months and AOi might be smoothed).

3.4. TRENDS ANALYSIS IN THE CATALAN COUNTRIES RAINFALL (1951-2000)

The aim is to study how precipitation has evolved in the Catalan Countries during the second half of the 20th century, by means of the trends of the indices of the known teleconnection patterns: WeMO, NAO and AO (Table 2). Analyses are made seasonally and annually. When a reference is made for the correlation between WeMOi or NAOi and Catalan Countries rainfall, we must keep in mind Figures 12 and 13 in the 2nd chapter; and between AOi and Catalan Countries rainfall, last Figure 8. The trends are worked out with the standardised values of the pluviometric series according to the 1961-1990 reference period in order to homogenise the spatial distribution of the series' trends.

The four seasons' and annual trends are shown in Figures 10 and 11. The comments of these trends are as follows:

Spring: Saladié *et al*. (2006) detect a reduction of rainfall during the 20th century in Catalonia. In the current analysis, significant reductions are also detected in the eastern Pyrenees. A decrease is also noticed over the rest of the Catalan Countries, with some significant points such as the southern part of the Gulf of València and eastern Mallorca. In this period of the year, the Catalan Countries are under NAO influence, but the NAOi trend is nil. Therefore, this overall precipitation reduction in Catalan Countries is only because of the AOi increase in this season. It must be mentioned that the March rainfall trend has an important influence on the negative spring trend, since it is the month of the year when there is the most important precipitation reduction. In March, the NAOi has significantly increased and the WeMOi has no trends. Therefore, precipitation in the areas under the WeMO influence in March (Figure 18 in the 2nd chapter in the Catalan version), southern Catalonia and Valencian Country, except for inland areas, does not vary. Both the NAOi and AOi have remarkably increased in March, and the Western Pyrenees and the Western Strip are where these two patterns have the largest influence. Hence the coincidence of the evolution of both patterns leads to a very significant rainfall reduction over this area in March. Rainfall over inland València, *Plana d'Utiel* and *Serrans*, has been reduced due to a negative relationship with the NAOi. In the Balearic Islands, north-eastern Mallorca and western Menorca have significant precipitation decreases because they are under NAO domain. Paredes *et al*. (2006) point out the NAOi increase as the main cause of rainfall reduction in March, but we should also consider the polar strengthening due to stratospheric polar cooling during late winter (López-Bustins, 2006).

Summer: An overall strong precipitation decrease over Catalan Countries, except for the Costa Brava and the Alacant mountains, and a moderate one over the Balearic Islands (maximum in Pitiüses) is detected. Rainfall reduction is significant in different places in the Catalan Countries. The patterns trends can not explain this overall summer precipitation reduction.

Autumn: Neither WeMO nor other patterns have a noticeable trend, so there are no significant rainfall changes throughout Catalan Countries. The most remarkable rainfall reductions, but not significant, are in Menorca and western Mallorca.

Winter: WeMOi has a negative and significant trend, and AOi has a positive and significant rise. Subsequently, there is a precipitation increase along the entire Catalan Countries coastland. The increase is significant inland Northern Catalonia and in Castelló coastland. This area approximately fits with that rainfall area which is negative and significant correlated with WeMOi. Inland Catalonia and certain points in the Valencian Country have some rainfall reduction. The decrease is significant in the Lleida plain due to its significant and negative correlation with AOi. In the Balearic Islands, there is an overall precipitation reduction. The decrease is significant over the north-eastern part where the net NAO influence over WeMO is largest. Pitiüses have almost no precipitation changes due to its negative and significant correlation with WeMOi.

The most pronounced rainfall increase in Catalan Countries takes place in January as it is the period of the year when the WeMOi has the strongest negative trend. The most extensive area with a significant increase are the Castelló mountains, where the WeMOi reaches the highest negative correlation with rainfall in January ($r < -0.50$). Other regions with a significant precipitation increase are the eastern Pyrenees and the inland Valencian province. Norrant and Douguédroit (2006) also detect a significant rainfall rise over the eastern Iberian fringe during the second half of the 20th century. Capdepera (Mallorca) is the only point in Catalan Countries where there is a significant rainfall reduction in January.

Goodess and Jones (2002) and Rodrigo (2006) show an overall Iberian Peninsula rainfall reduction during the second half of the 20th century due to the changes in winter circulation, since the rainy days have increased although with a less intense feature. This is reflected in the inland Catalan Countries. In contrast, in those areas where the Atlantic influence is weak, south-eastern Iberia, these authors detect a rainfall increase because of a rise of the days with intense precipitation. González-Hidalgo *et al*. (2006) also detected positive trends along the Mediterranean coastland of the Iberian Peninsula in winter months, above all, in January. In addition, Rodrigo and Trigo (2007) also detect a maximum winter rainfall increase in València and decrease in Bilbao for the 1951-2002 period like in Table 3. Rodrigo (2006) deduced a winter torrential rainfall reduction in Bilbao which might be related to the lesser frequency of the extreme positive WeMOi in winter. Saladié *et al*. (2002) also detected a winter rainfall rise during the second half of the 20th century, although not significant, over the south-eastern Ebre Valley.

Annual 1: there is an overall rainfall reduction in the Catalan Countries, except for the northern Alacant mountains and some points in Girona, inland Northern Catalonia and in Central Catalonia. Norrant and Douguédroit (2006) also detect a certain decrease in annual rainfall in the eastern Iberian Peninsula during the second half of the 20th century. These changes are hardly explained by patterns trends. Sumner *et al*. (2003) foresee for the end of the 21st century, using a general circulation model (GCM), an annual rainfall increase in south-eastern Iberia which might be related to a torrential rainfall increase. This is only verified in *Banyeres de Mariola* (Alcoià, northern Alacant mountains). The areas with the strongest decrease in annual precipitation are the western Pyrenees. The rainfall reduction in Menorca and north Mallorca is also significant. This overall reduction in rainfall in the Catalan Countries might be caused by an annual pressure increase over the western Mediterranean basin during the 20th century due to the northward shifting of the subtropical high pressure belt (Martín-Vide, 2005).

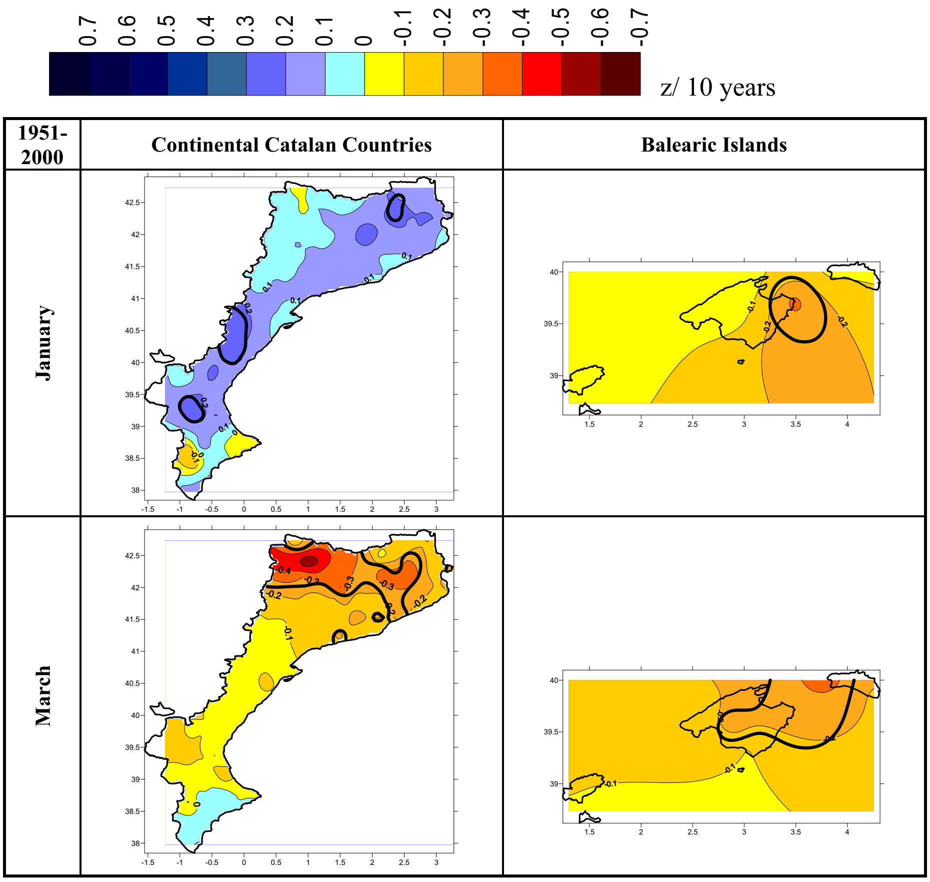


Figure 10. January and March precipitation trends in Catalan Countries for the 1951-2000 period. (AnClim software, Stepanek, 2005. The areas with significant trends at 0.05, according to t-test, have been delimited by a bold outline).

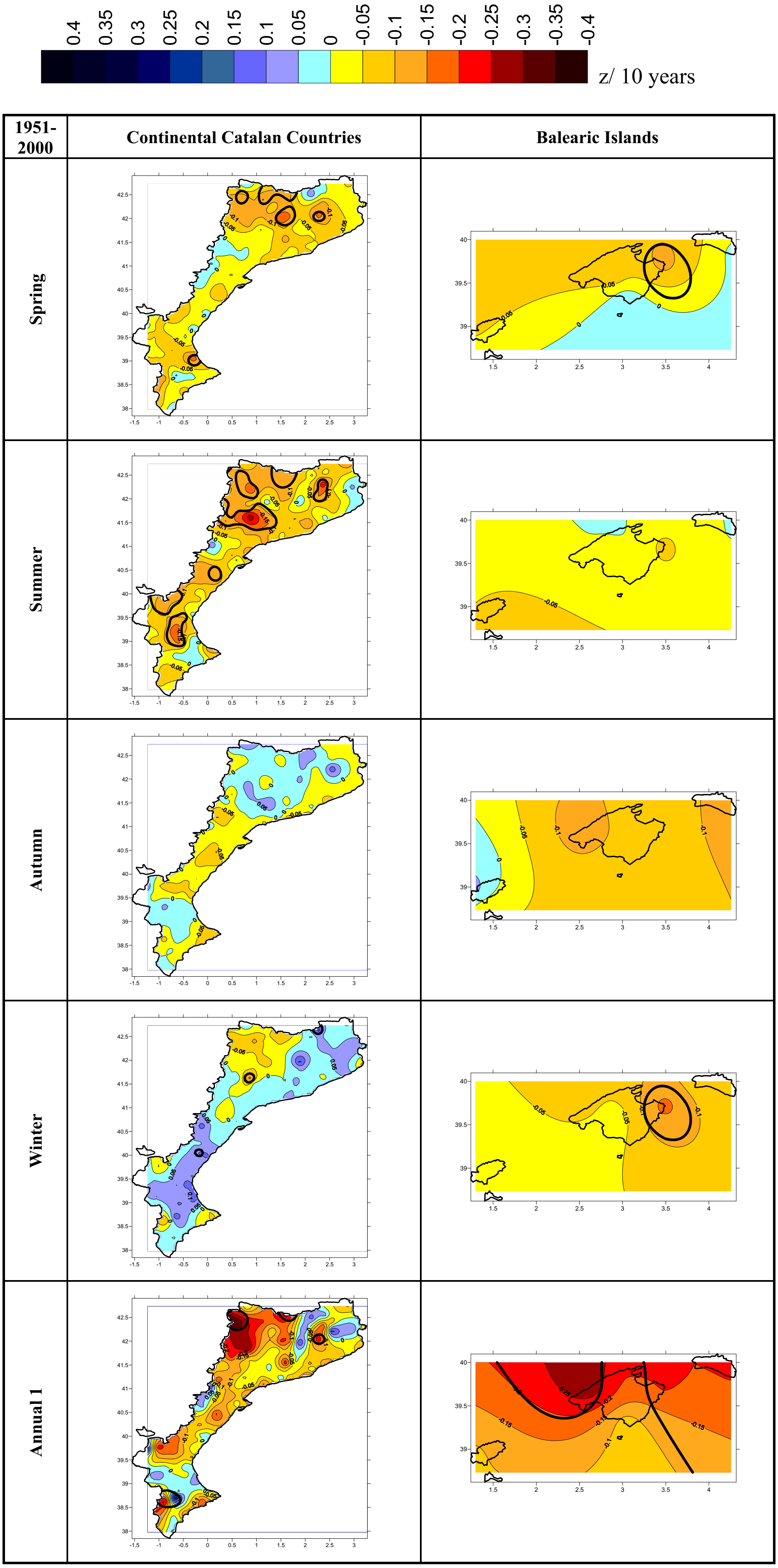


Figure 11. Idem as Fig. 10, but seasonally, half-yearly and annually.

3.5. SPECTRAL ANALYSIS OF THE TELECONNECTION INDICES (1901-2000) AND OF THE CATALAN COUNTRIES RAINFALL (1951-2000)

In order to know the WeMO better and its relationship with the AO, the maximum entropy spectral analysis (MESA) is applied to the WeMOi and AOi values of the long winter during the whole 20th century. Afterwards, it is compared with the MESA applied to the Catalan Countries long winter rainfall during the second half of 20th century. In order to be able to apply the MESA to Catalan Countries rainfall a manual regionalisation is put forward, which is then used in further analyses. An autumn analysis was also carried out, but the results were not so robust, so it is only shown in the Catalan version of this thesis.

3.5.1. WEMOI AND AOI SPECTRAL ANALYSES (1901-2000)

The MESA applied to the WeMOi values of the long winter period establishes periodicities of 5 and 22 years, with a 0.05 significance; these cycles are also found in the AOi (Figures 12a and 12b). Even though they have no statistical significance, other 2- and 8-year peaks appear in the WeMOi. They are also present in the AOi and the NAOi, in which Pozo-Vázquez *et al*. (2000), by means of a cross-spectral analysis since the beginning of the 19th century, found 6-month and 1-, 2- and 8-year peaks. Therefore, as far as cyclicities are concerned, the WeMO has a behaviour remarkably similar to that of the AO, and only slightly similar to that of the NAO. Cyclic variations common to WeMO and AO are approximately those of 2–2.5, 3.5, 5, 8 and 22 years (Figure 12c). The 2-2.5-year peak might be related to QBO influence as it has a periodicity between 24 and 30 months (Marquardt, 1998); and 5-year peak might be a reflection of QBO. On the other hand, the Hale solar cycle has a 22- year periodicity, as it is formed by two Schwabe 11-year solar cycles, so we could consider a hypothetical relationship with the AOi and WeMOi 22-year peak.

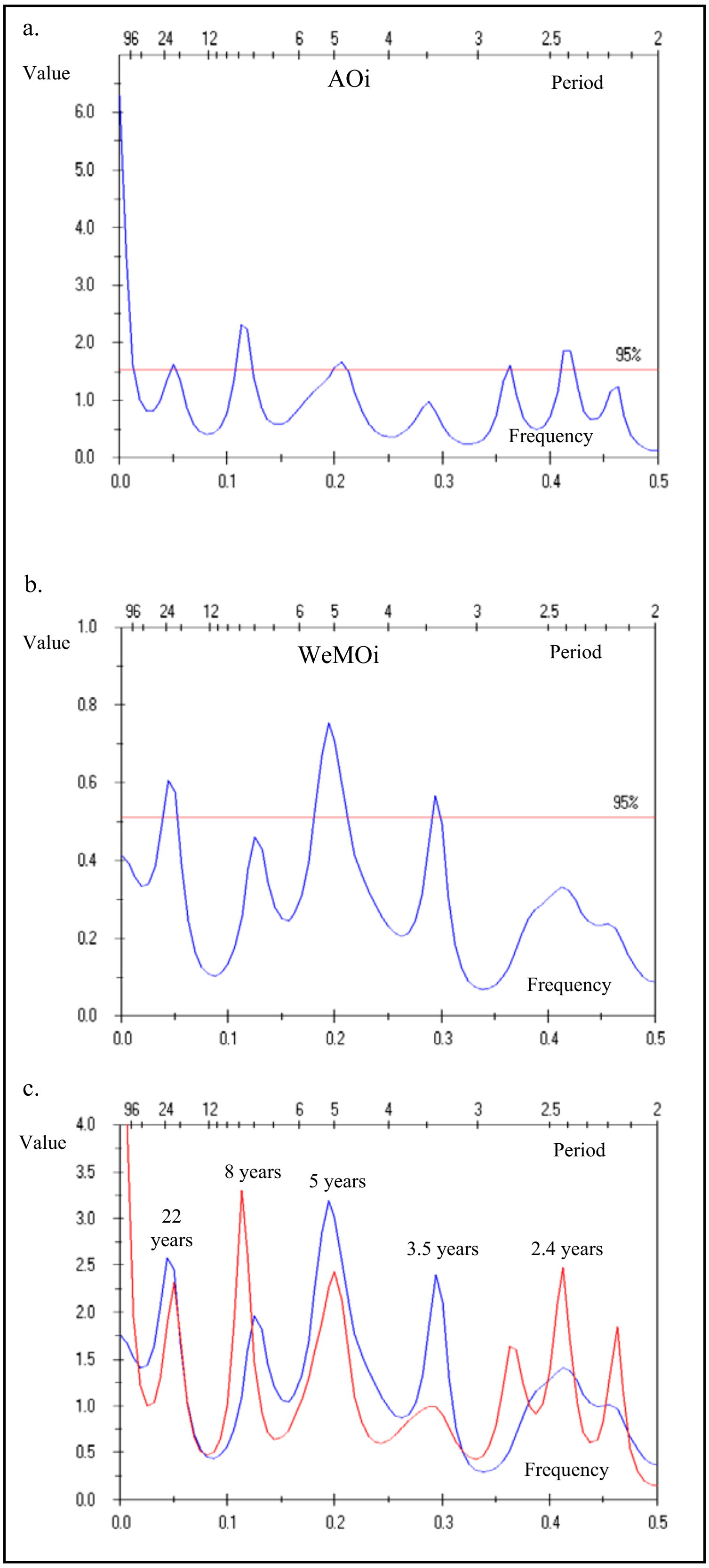


Figure 12. a. Maximum entropy spectral analysis (MESA) output of AOi winter (from December to March) values for the 1900/01–1999/2000 period (200 frequencies were applied and a red line indicates the 95% confidence level). **b.** Idem as (a), but for WeMOi. **c.** Comparison of AOi and WeMOi peaks (AOi –red line– and WeMOi –blue line–). (AnClim software, Stepanek, 2005).

3.5.2. SPECTRAL ANALYSIS OF THE CATALAN COUNTRIES RAINFALL (1951-2000)

For the second half of the 20th century, it must be checked if there are the same peaks previously detected in WeMOi and AOi in winter Catalan Countries precipitation. To establish some periodicities for the all 124 rainfall series, some geographical regions are manually defined to carry out the analysis. Hence, any noise present in individual series is removed and the signal can be amplified.

There are 12 defined regions. The cluster is composed of *comarcas* (administrative divisions) (Figure 9 in the 2nd chapter) according to their climatic and geographical similarities. The identifying name which is given to each region is not totally representative of the all *comarcas* included, since the cluster was created also by following their different correlations with the WeMOi and the NAOi (Figures 12 and 13 in the 2nd chapter), and with the AOi (Figure 8), the shoreline orientation and catchments extensions. The 12 regions manually defined according the above mentioned criteria are (Figure 13):

Region I (València): Alcoià, Camp de Túria, Canal de Navarrés, Comtat, Costera, Foia de Bunyol, Hortes, Marina Alta, Ribera Alta, Ribera Baixa, Safor, València, Vall d'Aiora and Vall d'Albaida.

Region II (Castelló): Alcalatén, Alt Maestrat, Alt Millars, Alt Palància, Baix Maestrat, Camp de Morvedre, Plana Alta, Plana Baixa and Ports.

Region III (Utiel): Alt Vinalopó, Plana d'Utiel, Racó and Serrans.

Region IV (Alacant): Alacantí, Baix Segura, Baix Vinalopó, Marina Baixa and Vinalopó Mitjà.

Region V (Pitiüses and southern Mallorca): Eivissa-Formentera and Migjorn *subcomarca* in Mallorca.

Region VI (northern Balearic Islands): Menorca and northern Mallorca (Ciutat de Mallorca, Llevant, Muntanya, Pla and Raiguer *subcomarcas*).

Region VII (south-eastern Ebre Valley): Baix Camp, Baix Ebre, Matarranya, Montsià, Ribera d'Ebre and Priorat.

Region VIII (western Catalonia and western Pyrenees): Andorra, Alt Urgell, Alta Cerdanya, Alta Ribagorça, Baix Cinca, Baixa Cerdanya/ Cerdanya, Llitera, Noguera, Pallars Jussà, Pallars Sobirà, Pla d'Urgell, Ribagorça, Segrià and Solsonès.

Region IX (Val d'Aran): Val d'Aran (exception: climatic area formed by only one *comarca*).

Region X (*Costa Brava* and Central Catalonia): Bages, Baix Empordà, Baix Llobregat, Barcelonès, Berguedà, Gironès, Maresme, Osona, Selva, Vallès Occidental and Vallès Oriental.

Region XI (Northern Catalonia): Alt Empordà, Capcir, Conflent, Fenolheda, Garrotxa, Pla de l'Estany, Ripollès, Rosselló and Vallespir.

Region XII (northern Daurada Coast and inland): Alt Camp, Alt Penedès, Anoia, Baix Penedès, Conca de Barberà, Garraf, Garrigues, Segarra, Tarragonès and Urgell.

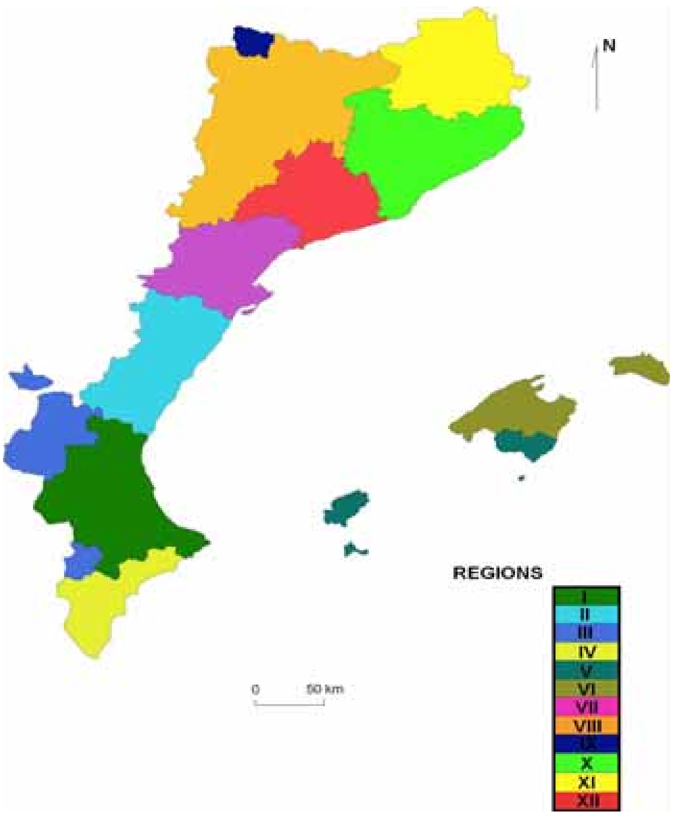
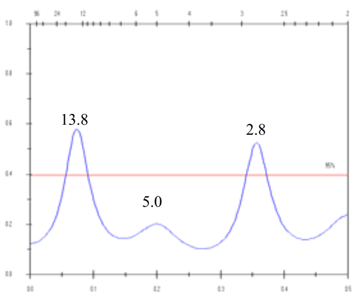
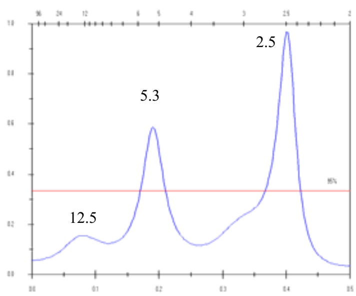
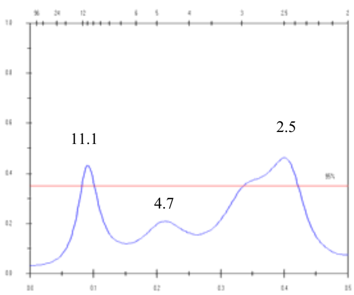
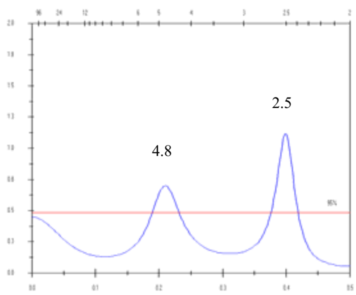


Figure 13. Geographical regions of the Catalan Countries defined following the *comarca* administrative division in 1996, except for Mallorca, where it was done by *subcomarcas*.

Figure 14 shows the MESA applied to the rainfall mean of each region and for the all 124 Catalan Countries series; standardised values are employed taking the 1961-1990 reference period into account. 11-year solar cycle has an hypothetical influence on Catalan Countries winter rainfall, as this peak is significant at 0.05 in regions I, II and IV[2]. In region III, this peak is not significant due to this region being the most inland area in the Valencian Country. In region V it is again significant, and not significant in regions VII and XI; other regions do not detect this peak. This peak is obtained in those regions which are most influenced by the WeMO and are orientated eastwards. The influence might be related to an atmosphere-sea interface as the rainfall series do not show any 22-year peak as indices patterns (Romeu and López-Bustins, 2006); only regions VI and X slightly show this 22-year peak. The 8-year peak in the WeMOi and the AOi has no pluviometric response. In contrast, a 5-year peak is strongly detected in many regions (V, VI, VII, VIII, X, XI and XII), and it is only weakened in the Valencian Country regions. For the precipitation mean of all the 124 meteorological stations, this last peak is the most outstanding one. Lana *et al.* (2005) also found a 5-year peak in the Fabra Observatory (Barcelona). The QBO cycle, a 2.5-year peak, well detected in the WeMOi and the AOi, is also significant in the rainfall in regions I, II, IV, VII, VIII, X and XI. The overall Catalan Countries precipitation show a clear 2.5-year peak. Therefore, a 5-year peak might be the consequent cycle of the 2.5-year peak of QBO. It is important to highlight that the most relevant peak in WeMOi is the 5-year one, the same as in the overall Catalan Countries precipitation. Other peaks in different regions remain without any explanation.

Regions **Corr. with** **WeMOi and AOi**	**MESA**	**Regions** **Corr. with** **WeMOi and AOi**	**MESA**
I VALÈNCIA WeMOi -0.68 (p-value 0.0000) AOi +0.32 (p-value 0.0273)		VII SE EBRE VALLEY WeMOi -0.50 (p-value 0.0002) AOi +0.24 (p-value 0.0914)	
II CASTELLÓ WeMOi -0.62 (p-value 0.0000) AOi +0.13 (p-value 0.3816)		VIII WESTERN CATALONIA WeMOi -0.23 (p-value 0.1122) AOi -0.47 (p-value 0.0007)	

[2] Peaks are an approximation, for instance, regions said to have a 11-year peak might have one of 12-13 years.

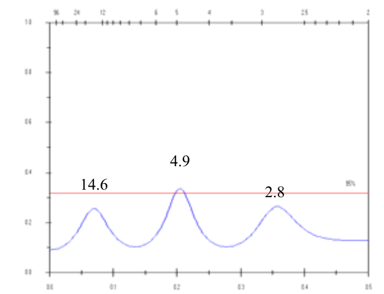
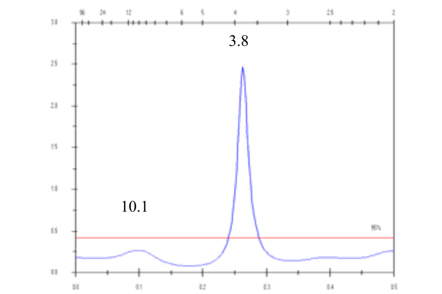
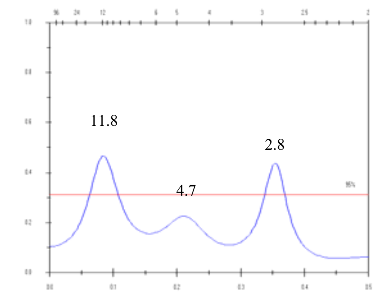
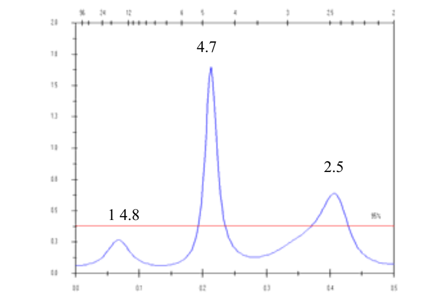
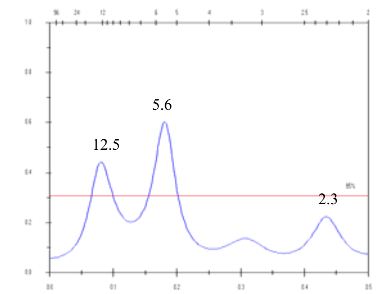
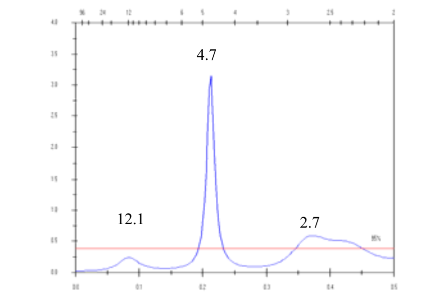
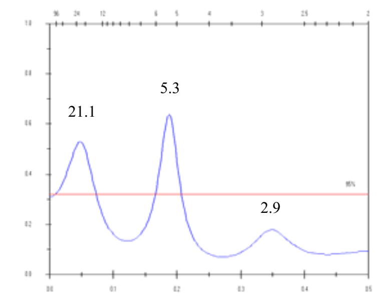
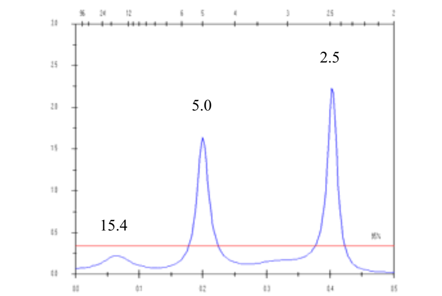
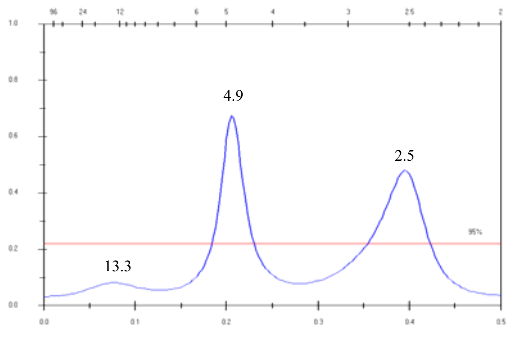
III UTIEL WeMOi -0.53 (p-value 0.0001) AOi -0.17 (p-value 0.2360)		IX VAL D'ARAN WeMOi +0.11 (p-value 0.4955) AOi +0.23 (p-value 0.1484)	
IV ALACANT WeMOi -0.59 (p-value 0.0000) AOi +0.20 (p-value 0.1775)		X BRAVA AND CENTRAL COASTS WeMOi -0.34 (p-value 0.0163) AOi +0.23 (p-value 0.1162)	
V PITIÜSES WeMOi -0.43 (p-value 0.0018) AOi +0.04 (p-value 0.7719)		XI NORTHERN CATALONIA WeMOi -0.45 (p-value 0.0012) AOi +0.05 (p-value 0.7492)	
VI NORTHERN BALEARIC I. WeMOi -0.18 (p-value 0.2186) AOi +0.23 (p-value 0.1150)		XII DAURADA COAST AND INLAND WeMOi -0.38 (p-value 0.0065) AOi -0.35 (p-value 0.0135)	
THE ALL 124 POINTS IN CATALAN COUNTRIES WeMOi -0.53 (p-value 0.0001) AOi -0.18 (p-value 0.2036)			

Figure 14. MESA output of the 12 rainfall regional means in Catalan Countries and for the all 124 meteorological stations in winter (DJFM) for the 1951/52-1999/2000 period. Each correlation (p-value) between WeMOi and AOi and each regional rainfall is displayed to orientate the explanation of the similarity between rainfall and patterns peaks. Abscissas is frequency (down) and period (up), and ordinates are values. Peaks are in years and 200 frequencies were applied. (AnClim software, Stepanek, 2005).

3.6. ANALYSIS OF THE TEMPORAL EVOLUTION OF THE RAINFALL VARIABILITY IN THE CATALAN COUNTRIES: 1951-1975 AND 1976-2000

Rainfall variability might be modulated by the interaction among patterns in influencing Catalan Countries precipitation. The cold half of the year (from October to March) has been taken into account for the analysis, as it is when the WeMO has a considerable role in continental Catalan Countries rainfall. Other periods of the year are available in the Catalan version of this thesis. For the Balearic Islands, I considered the long winter period, since there is no teleconnection patterns influence on insular rainfall in October and November (Figure 22 in the 2nd chapter, Catalan version). The following calculations are worked out for the 1951-2000 study period and for the subperiods, 1951-1975 and 1976-2000: the rainfall mean (X); the correlation spatial distribution between rainfall and the WeMOi, the NAOi and the AOi; the spatial distribution of differences between absolute values of coefficients correlation between precipitation and the WeMOi and the NAOi; the variation coefficient (CV); and a temporal irregularity index (S_1). These two lasts factors will enable us to detect pluviometric irregularities changes, defining the most Mediterranean rainfall areas.

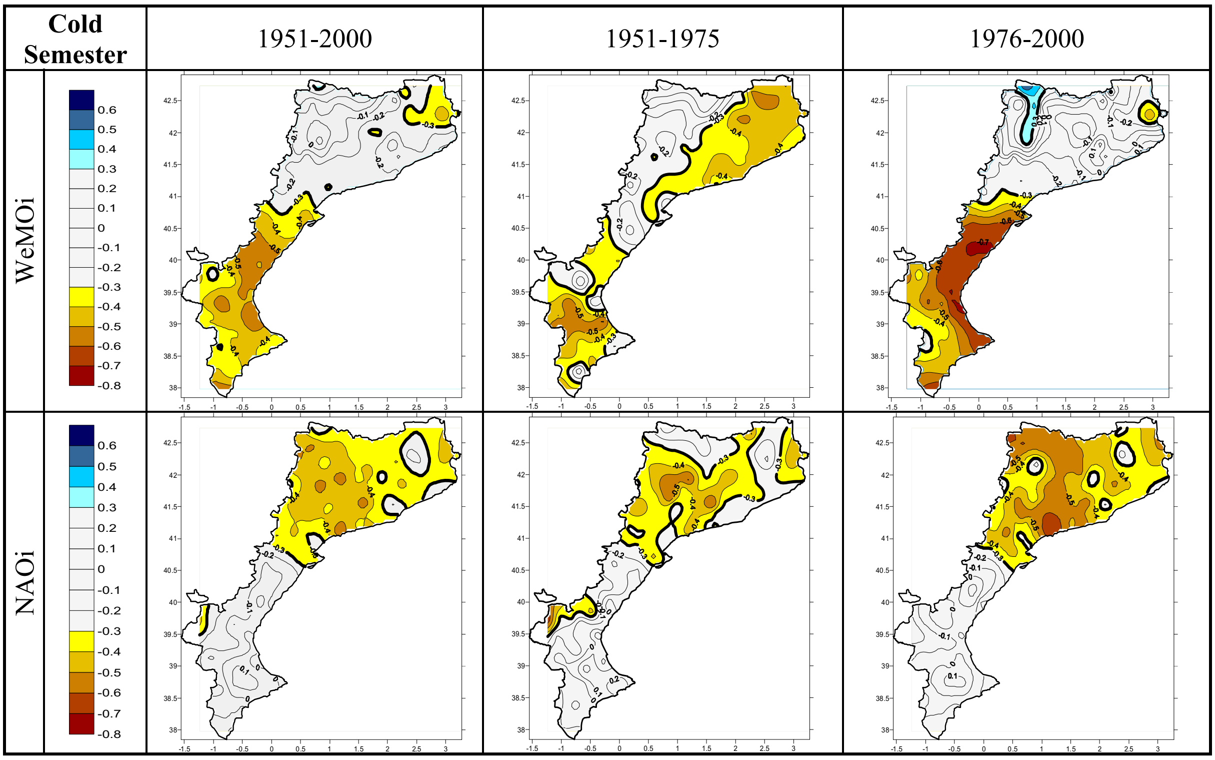
The CV is a measure of relative dispersion to compare rainfall variability between different series and it is defined as the quotient between the standard deviation and the mean, and can be shown as a percentage: CV = (S/X)·100 (%). The S_1 is a temporal irregularity index, originally known as the consecutive disparity index, put forward by Martín-Vide (1987) to assess the pluviometry temporal order. It is defined as the mean of the absolute values of natural logarithms of quotients of each value and the preceding one: $S_1 = (\sum | \ln (P_{i+1} / P_i) |)/(n-1)$. Those years which have 0 mm registration are substituted by a value under 1 mm in order to proceed with the calculation. This index offers a spatial distribution of pluviometric irregularity with certain interesting details within the CV spatial distribution one, outlining the Mediterranean pluviometry (Martín-Vide, 2003).

Although 25 years is less than the required 30 years for climate analyses, it is worth comparing the 1951-1975 and 1976-2000 subperiods, since it is during the second one when there is a global temperature rise. In addition, the two subperiods include 15 years of the 1961-1990 reference period. To work out the correlations, I used the standardised values, whereas for the X, CV and S_1 total pluviometries are used. The threshold for the correlations at 0.05 is 0.39, but the maps are coloured since 0.3 in order to compare with the map of the whole study period, 1951-2000.

3.6.1. CONTINENTAL CATALAN COUNTRIES (Figure 15)

Comparing the two subperiods, it is undeniable that there has been an enhancement of the WeMO in negative phase over the Valencian Country, and a reinforcement of its positive phase over the western Pyrenees. The WeMO role has vanished in Catalonia. In contrast, NAO has strengthened in Catalonia, but weakened in the Valencian Country. The NAO consequently gains terrain over the entire Pyrenees, and only Val d'Aran is better explained by WeMO in its positive phase. The AO maintains its influence on rainfall over western Catalonia. Even the AO appears in new areas of the Valencian Country in its positive phase, above all, in the Castelló province. The NAO completely loses its influence in the Valencian Country, above all, in spring.

Remembering Table 2, the AOi has significantly increased, and the WeMOi has significantly reduced. These trends explain why the AO and WeMO influences have been reinforced over the Valencian Country. Nevertheless, the pluviometric map for the second subperiod 1976-2000 does not show any increase in comparison to the first one over the Valencian Country. This increase is noticeable only for the winter season analysis (see next section 3.7.). The CV has increased around the Valencian Country and Val d'Aran because it is where the WeMO has increased its influence. The WeMO withdrawal from Catalonia is reflected by the CV reduction, above all, over Northern Catalonia and Girona, where the WeMO was more influence than the NAO during the first subperiod. The S_1 also shows a clear reduction over this north-eastern area. In Val d'Aran, both the CV and the S_1 increase because of a larger WeMO influence.



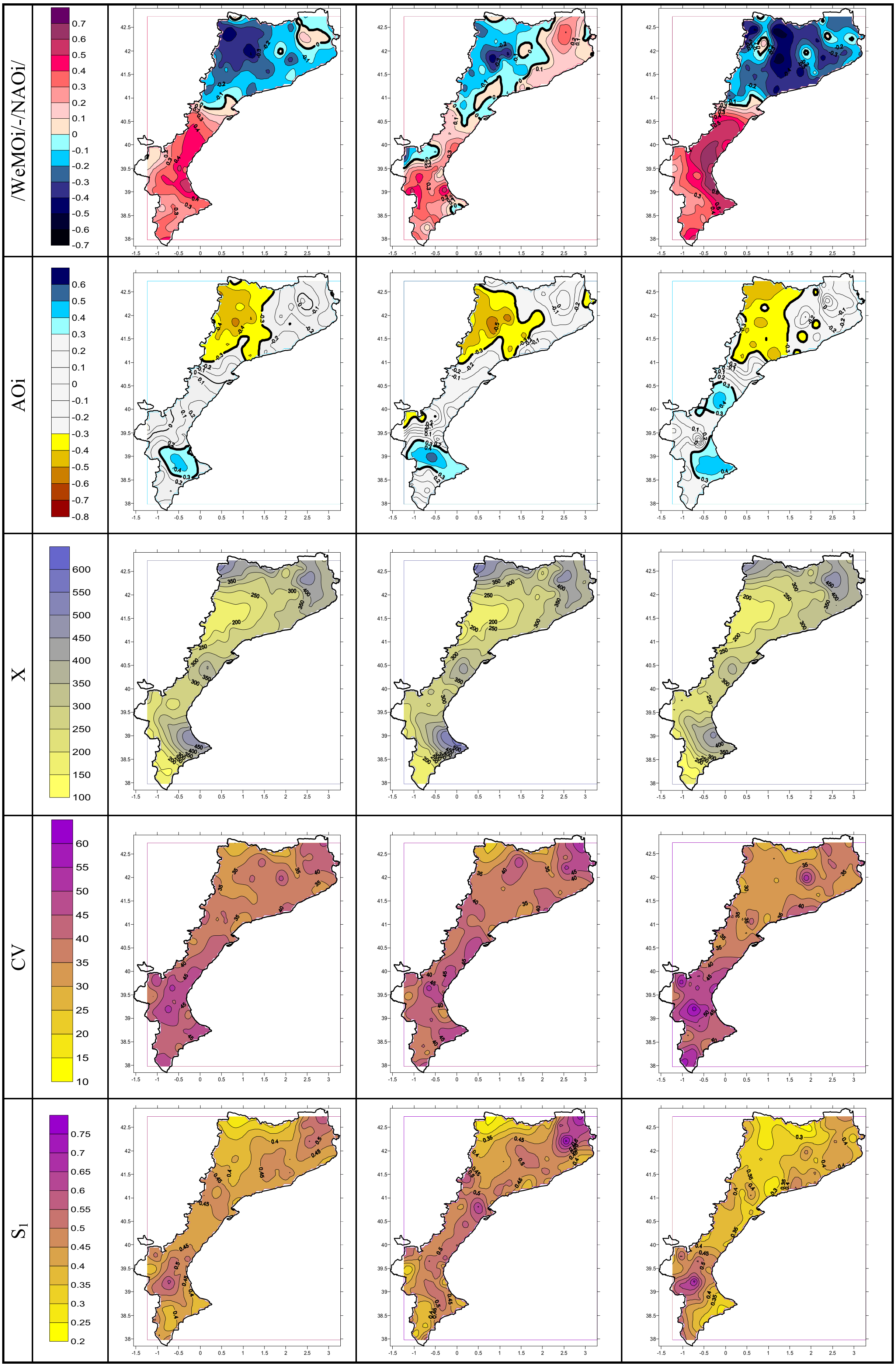


Figure 15. Spatial distribution of the coefficients correlation between the WeMOi, the NAOi and the AOi, and rainfall, difference absolute values of the first two columns, rainfall mean (X) (mm), CV (%) and S_1 in continental Catalan Countries, for the cold semester during the 1951/52-1999/2000, 1951/52-1975/76 and 1976/77-1999/2000 periods.

3.6.2. BALEARIC ISLANDS (Figure 16)

The WeMO has reinforced its influence on the southern half, and the NAO over the northern one. Subsequently, we must divide the Balearic Islands between Eivissa, Formentera and southern Mallorca under a Mediterranean influence, and northern Mallorca and Menorca under an Atlantic one. The AO has no influence during the first subperiod. The AOi negatively correlates with precipitation over the northern half during the second subperiod. No influence is detected in its positive phase during any period.

Despite the WeMOi negative trend during the second half of the 20th century, there is an overall rainfall reduction. The results are quite similar to those detected in continental Catalan Countries. The CV and the S_1 have increased over the western Balearic Islands, above all, in Pitiüses where the WeMOi has enhanced its negative correlation with precipitation.

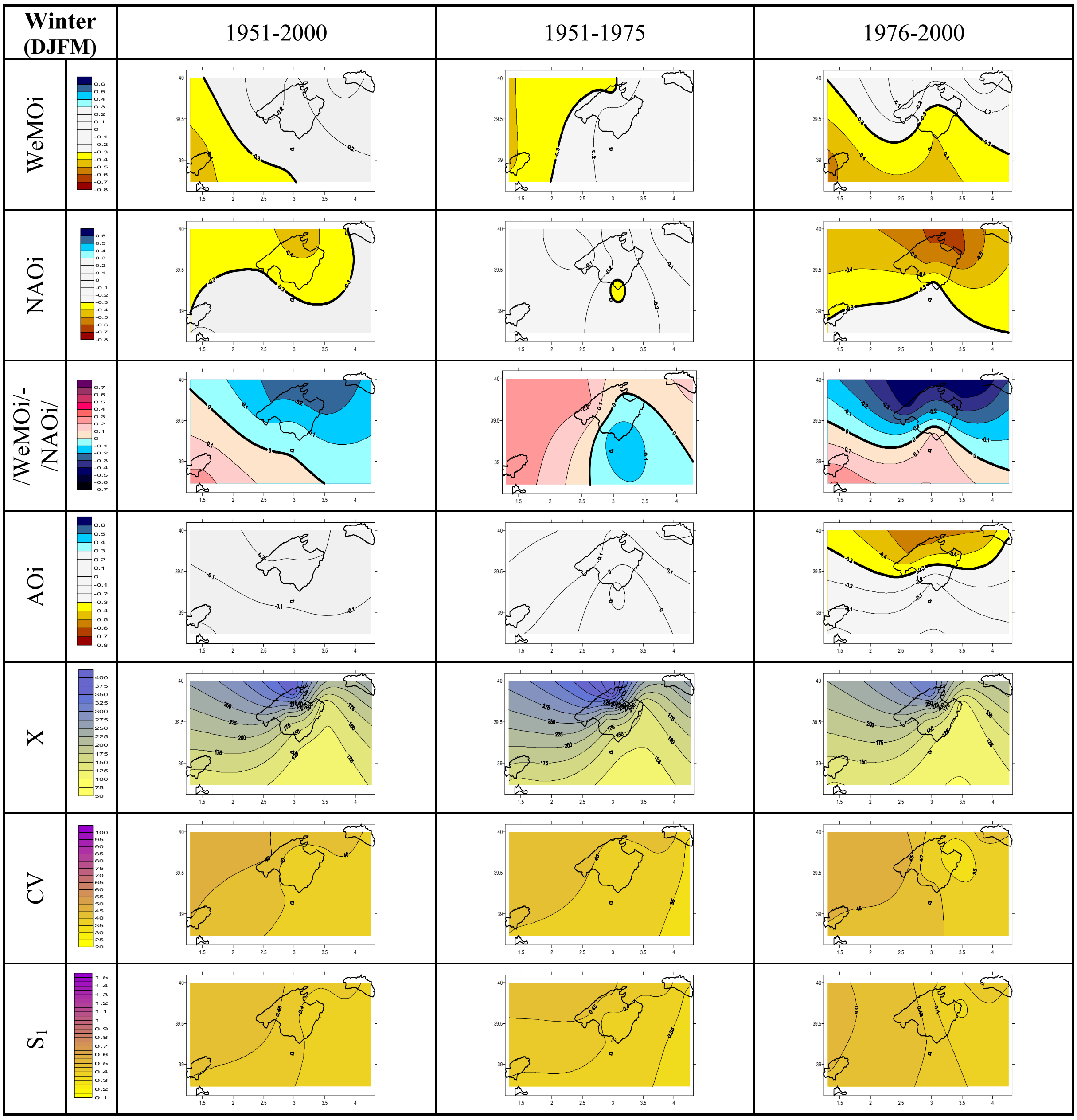


Figure 16. Idem as Fig. 15, but for the Balearic Islands during the long winter (DJFM).

3.7. TEMPORAL EVOLUTION OF RAINFALL OVER THE CATALAN COUNTRIES BY REGIONS ACCORDING TO THE TELECONNECTION PATTERNS

The 12 regions from section 3.5. have been employed to assess the temporal evolution of rainfall over Catalan Countries. The aim is to detect which regions have changed its affinity to one pattern to another. The regions which explain their pluviometry by means of the WeMO pattern in its negative phase over the NAO will be the most Mediterranean ones, and vice versa, those ones under a largest NAO domain over WeMO will be the most Atlantic ones, but always within a Mediterranean climate context (López-Bustins and Azorín-Molina, 2004), except for region IX (Val d'Aran), which has its own oceanic climate. The AO is used to specify the Mediterranean and Atlantic character of those regions which have a well defined WeMO or NAO influence.

I establish 7 categories according to the correlation between the standardised precipitation values of all the series included in each region and the indices of the AO, the NAO and the WeMO (the climatic significance is at 95% confidence level):

A) The overall rainfall region is significant and negatively correlated with the WeMOi, while the correlation with the NAOi is not significant. Furthermore, there is a significant and positive correlation with the AOi.

B) The overall rainfall region is significant and negatively correlated with the WeMOi, while the correlation with the NAOi is not significant.

C) The overall rainfall region is significant and negatively correlated with the WeMOi and the NAOi, although more significantly with the WeMOi (or) The overall rainfall region is negatively correlated, but not significantly, with the WeMOi and the NAOi, but the WeMOi coefficient is higher (or) The overall rainfall region is negatively correlated, but not significantly, with WeMOi but positively with NAOi.

D) The overall rainfall region is significant and negatively correlated with the WeMOi and the NAOi, although more significantly with the NAOi (or) The overall rainfall region is negatively correlated, but not significantly, with both WeMOi and NAOi, but the NAOi coefficient is higher (or) The overall rainfall region is negatively correlated, but not significantly, with the NAOi but positively with the WeMOi, whenever the one obtained with the WeMOi is lower than that one obtained with the NAOi in absolute terms.

E) The overall rainfall region is significant and negatively correlated with the NAOi while the correlation with WeMOi is not significant.

F) The overall rainfall region is significant and negatively correlated with the NAOi while the correlation with the WeMOi is not significant. Furthermore, there is a significant and negative correlation with AOi.

G) The overall rainfall region is positively correlated with the WeMOi with a coefficient that is higher than that one obtained with the NAOi in absolute terms.

From category A to G, there is a gradation from the most Mediterranean domain to the most Atlantic one or less Mediterranean regime. These categories can be grouped in three regimes: the totally Mediterranean one (A, B and C), the Mediterranean one with Atlantic influence (D, E and F) and the totally Atlantic (G).

Then, keeping in mind the WeMOi, the NAOi and the AOi for the second half of 20th century, I assessed the rainfall trend of each region. To carry it out, I worked out the mean of all the standardised values of each series for one region. Afterwards, AnClim software (Stepanek, 2005) is used to apply the t-test to regional series trends. To deduce the % or mm of variation through the standardised value of the trend, according to Jones and Hulme (1996), we must multiply this value by the standard deviation of the mean of the all standard deviations of the series of the region, and to add the mean of all the means of the series of the region to it. The means and standard deviations used to standardise the series come from the 1961-1990 period reference. Once, we obtain a value in mm, it can be converted to % using the mean of the means, and we indicate that the overall region has varied a certain % of its pluviometry along a period according to the 1961-1990 basis period (Saladié, 2003).

In order to follow the coherency with the previous section I analysed the cold half of the year (ONDJFM) period, and the winter (DJF) period since it is the period of the year when the WeMOi has a notorious trend. The results of this section are consistent with the preceding ones in section 3.6.

3.7.1. COLD SEMESTER (ONDJFM) (Figure 17)

It is shown an enhancement of the Mediterranean regime in southern Catalan Countries (Valencian Country and southern Balearic Islands) and an increase of the Atlantic variability in the northern half (Southern and Northern Catalonia and northern Balearic Islands). This divergence of the temporal evolution of pluviometries allows us to divide the study area: north and south. The origin is the same above mentioned: the strengthening of the polar vortex which leads to extreme negative WeMO phases, limiting its influence to the southern half. The reason of this focalization is analysed in the following chapter. Despite the negative and significant trend of the WeMOi, there is no rainfall increase in those regions under its influence. There is an overall precipitation decrease, very remarkable over inland Catalonia and inland Valencian Country, since their rainfall is negatively correlated to the AOi and the NAOi. A noticeable rainfall decrease is also detected in the Castelló region. In Menorca and northern Mallorca is where the rainfall decays most critically and significantly.

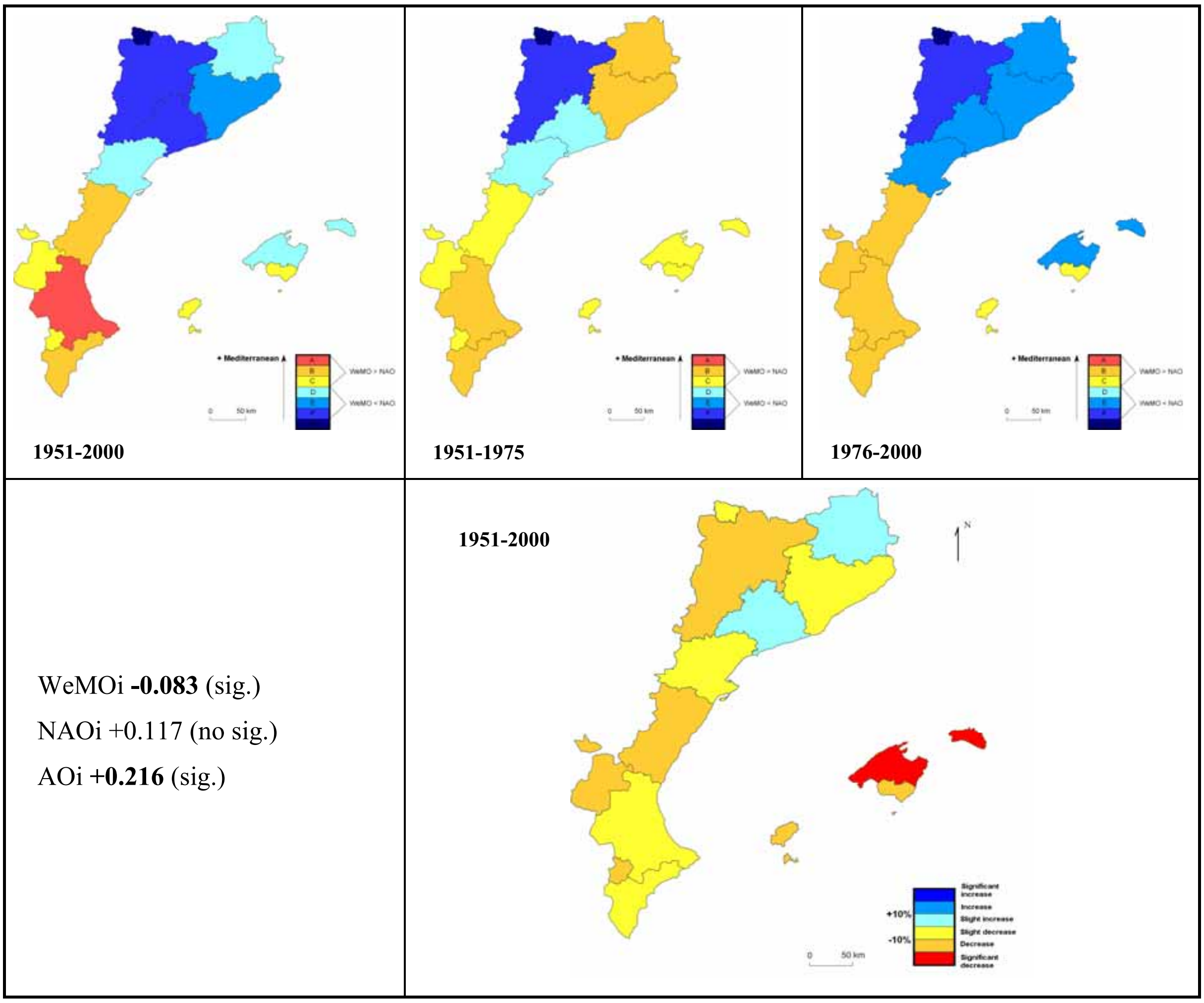


Figure 17. (Above) Temporal evolution of pluviometry for the regions of the Catalan Countries for the 1951-2000, 1951-1975 and 1976-2000 periods in the cold half of the year according to the relationship with the WeMO, the NAO and the AO teleconnection patterns. (Below) The WeMOi, the NAOi and the AOi trends (Z/10 years) and the rainfall variation in each region (in % based on the 1961-1990 reference period) along the 1951-2000 period. Significant trends are detected with the t-test.

3.7.2. WINTER (DJF) (Figure 18)

The polar vortex turns stronger and colder as the AOi positive and significant trend indicates, leading to a significant WeMOi decline. This implies a stronger WeMO influence on the southern half of the Catalan Countries, the Valencian Country and the southern Balearic Islands. The northern half comes under a totally NAO domain. During this season, there is a rainfall increase as a consequence of the indices trends of the teleconnection patterns. The largest increase is in the northern Valencian Country and in Northern Catalonia. Precipitation decays over inland Catalonia and northern Balearic Islands due to a positive NAOi trend.

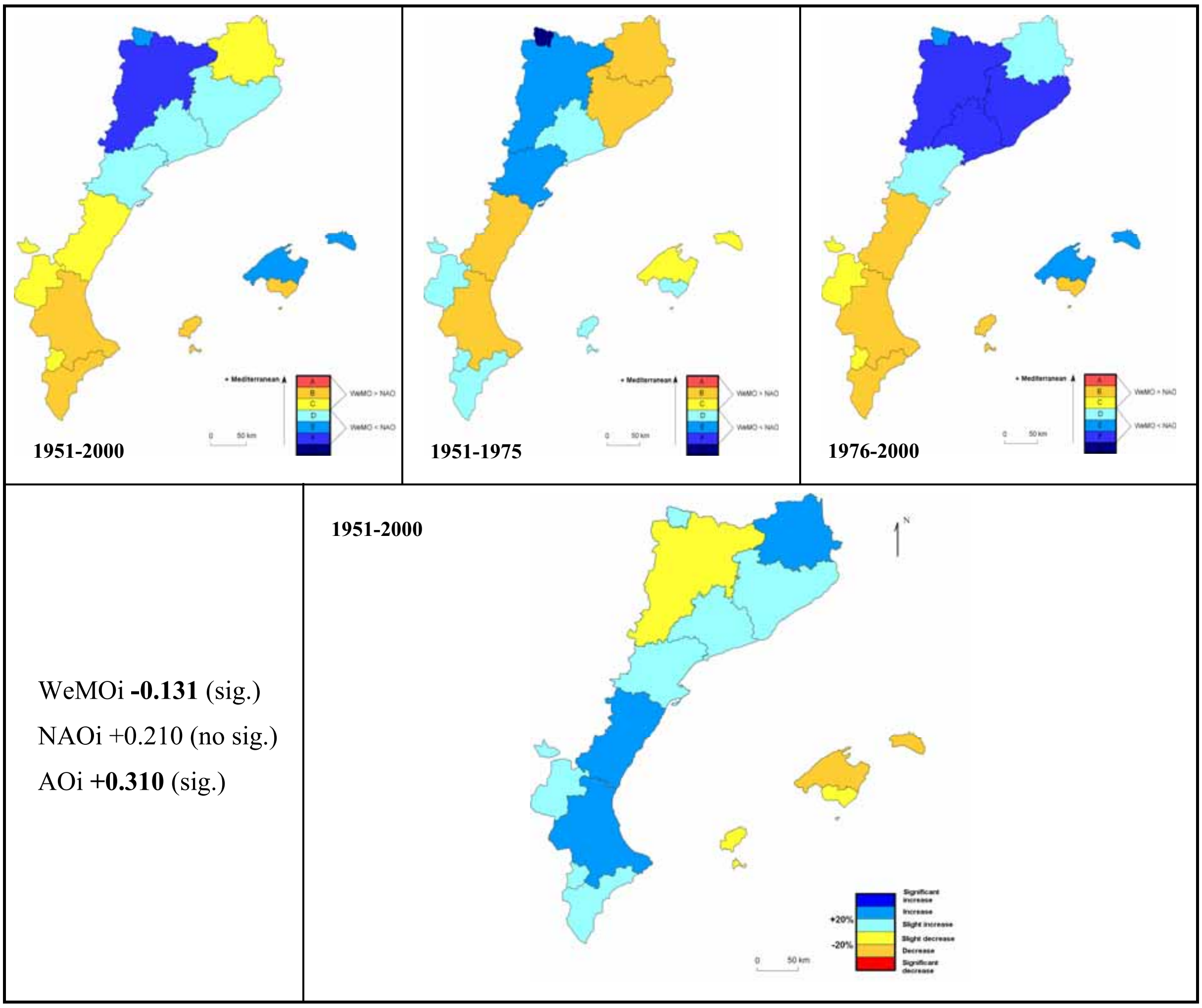


Figure 18. Idem as Fig. 17, but for winter (DJF) during the following periods: 1951/52-1999/2000, 1951/52-1975/76 and 1976/77-1999/2000. The reference period is 1961/62-1990/91.

3.8. TEMPORAL EVOLUTION OF DAILY RAINFALL OVER THE CATALAN COUNTRIES COASTLINE ACCORDING TO THE WeMO

One of the most sensitive indicators of climate change with severe consequences on society is the torrential rainfall (Groisman *et al*., 1999). Its assessment is carried out using the 7 series already employed in the 1st and 2nd chapters. These points are located along the shoreline of the north-western Mediterranean basin. 5 of them are within the Catalan Countries: Perpinyà (region XI), Barcelona (region X), Tortosa (region VII), València (region I) and Torrevella (region IV) (Figure 13); and beyond the study area, northward (Marseille) and southward (Malaga) (Figure 12 in the 1st chapter).

Two subperiods 1951-1975 and 1976-2000 are compared. Indices of irregularity (CI) and rainfall intensity (DI) (section 3.8.1.), rainfall episodes frequency in 24 hours of different thresholds (>100 mm, >50 mm, >10 mm and ≥0.1 mm) (section 3.8.2.), the WeMO calendar (3.8.3.) and daily WeMOi histograms (3.8.4.) are studied.

3.8.1. CONCENTRATION INDEX (CI) AND DAILY INTENSITY (DI)

The torrential precipitation is featured by both a high irregularity and a high intensity at daily resolution. To assess the irregularity it is preferable to use the concentration index (CI) because it assesses the dependence of the total rainfall on the torrential episodes occurrence. Martin-Vide (2004) quantifies the area of the concentration curve or Lorenz curve as the accumulation of the number of rainy days against the rainfall accumulated, and the equidistribution regression. A larger area represents a higher irregularity or daily concentration. To carry it out the author adopted the Gini concentration index: I = 2 S / 10.000 to exponential curves ($y = axe^{bx}$), where S is the area comprised between the regressions' equidistribution, the exponential curve and the ordinates 0 and 100 (Martín-Vide, 2003). This author considers that a value less than 0.56 is a low irregularity, 0.56-0.59 as medium, 0.60-0.69 as high, and ≥0.70 as very high.

The daily intensity (DI) index is used to assess rainfall intensity. It is calculated as the mean intensity of the daily precipitation episodes, dividing the total rainfall amount by the number of the total rainy days ≥0.1 mm (Rodrigo and Trigo, 2007):

ID = Rainfall total amount/ number of rainy days (mm/day)

I consider that a DI value under 2.5 mm/ day is low, 2.5-4.9 mm/day is moderate, 5-9.9 mm/day is high, and ≥10 mm/day is very high. Whereas the CI depends on the torrential episodes, the DI depends on the total number of rainy days, where the weak episodes are also included. The period of the year to analyse is winter (DJF) as it is when WeMOi shows a clear negative trend. Analyses for other periods of the year are displayed in the Catalan version.

In winter, the CI is maximum and very high in Perpinyà. The three points of Atlantic influence (Marseille, Barcelona and Malaga) is where the CI is lowest. The other three locations have a high CI. Malaga has a very high DI since winter is its wettest season; and the DI is high in rest of locations, however, it is near moderation in Tortosa, València and Torrevella.

Comparing subperiods, the CI indicates an increase of the pluviometric irregularity over all the points, but the DI, only in Barcelona and València. The rise of the number of rainy days is noticed everywhere, except for Marseille and Barcelona. In this season, there is a rainfall increase in several points: Perpinyà, Barcelona, València and Torrevella; as it was already shown in Figure 11. Barcelona and València rainfall has clearly increased because of a noticeable rise of torrentiality (Goodess and Jones, 2002; Sumner *et al*., 2003), since the DI and the CI have had a considerable rise. Nevertheless, the CI draws our attention to Torrevella and Malaga, where it has steadily risen, although the last location has remarkably decreased its rainfall intensity (Table 4).

Winter 1951/52-1999/2000	**CI**		**Pluviometry (mm)**	**Number of rainy days**	**DI (mm/day)**	
Marseille	0.644		8,290.8	1,252	6.6	
Perpinyà	0.714		7,966.9	1,256	6.3	
Barcelona	0.630		6,457.9	934	6.9	
Tortosa	0.679		5,694.5	1,022	5.6	
València	0.673		5,497.9	948	5.8	
Torrevella	0.678		3,667.7	618	5.9	
Malaga	0.618		12,297.3	1,036	11.9	
Winter 1951/52-1975/76	**CI**		**Pluviometry (mm)**	**Number of rainy days**	**DI (mm/day)**	
Marseille	0.639		4,565.5	664	6.9	
Perpinyà	0.715		3,877.4	585	6.6	
Barcelona	0.618		2,933.8	479	6.1	
Tortosa	0.677		3,079.2	500	6.2	
València	0.658		2,409.8	468	5.2	
Torrevella	0.634		1,711.5	276	6.2	
Malaga	0.595		6,656.3	493	13.5	
Winter 1976/77-1999/2000	**CI**	**Variation**	**Pluviometry (mm) (variation sign)**	**Number of rainy days (variation)**	**DI (mm/day)**	**Variation**
Marseille	0.653	+0.014	3,725.3 (-)	588 (-76)	6.3	-0.6
Perpinyà	0.717	+0.002	4,089.5 (+)	671 (+86)	6.1	-0.5
Barcelona	0.639	+0.021	3,524.1 (+)	455 (-24)	7.8	+1.7
Tortosa	0.684	+0.007	2,615.3 (-)	522 (+22)	5.0	-1.2
València	0.688	+0.030	3,088.1 (+)	480 (+12)	6.4	+1.2
Torrevella	0.718	+0.084	1,956.2 (+)	342 (+66)	5.7	-0.5
Malaga	0.639	+0.044	5,641.0 (-)	543 (-50)	10.4	-3.1

Table 4. CI and DI values, pluviometry and number of rainy days, for the 1951-2000 period and for the 1951/52-1975/76 and 1976/77-1999/2000 subperiods in winter (DJF) for Marseille, Perpinyà, Barcelona, Tortosa, València, Torrevella and Malaga.

3.8.2. Daily episodes frequency

The following thresholds have been selected to study a frequency change on daily precipitation episodes,: >100 mm (torrential), >50 mm (intense), >10 mm (a little bit intense), ≥0.1 mm (weak) and total pluviometry. Both subperiods are compared and it is easily shown where it has increased, decreased or not varied in a qualitative mode.

3.8.2.1. Annual (Table 5)

Pluviometric reduction is detected in most of the observatories by a decrease in the number of daily episodes over 10 mm. Even torrential rainfall seems to be diminished in several observatories as Perpinyà, València or Malaga due to an increase of the weak episodes. Barcelona and Torrevella are the two meteorological stations where the total pluviometry is higher in the second period; it might be the consequence of the torrential rise. The number of intense and torrential episodes has risen in these locations. The annual WeMOi negative trend is reflected by an increase of the ≥0.1 mm episodes. Burgueño *et al*. (2005) detect a rise of annual rainy days on the Catalonia coastland, above all in the southern region.

Annual	**>100 mm**	**>50 mm**	**>10 mm**	**≥0.1 mm**	**Total pluviometry**
Marseille					
Perpinyà					
Barcelona					
Tortosa					
València					
Torrevella					
Malaga					

Table 5. Qualitative variation of daily episodes of >100 mm, >50 mm, >10 mm and ≥0.1 mm, and total pluviometry between the first subperiod 1951-1975 and the second one 1976-2000, annually. (Blue indicates a rise, red a reduction and grey means no variation).

3.8.2.2. Autumn (SON) (Table 6)

An overall torrential reduction is detected. Some, apart from diminishing its pluviometry, increase the number of weak episodes. Therefore, this reduction is due to the diminishing of torrential events, except for Barcelona where these episodes have risen. Malaga increases its total rainfall due to a higher number of intense events.

Autumn	>100 mm	>50 mm	>10 mm	≥0.1 mm	Total pluviometry
Marseille					
Perpinyà					
Barcelona					
Tortosa					
València					
Torrevella					
Malaga					

Table 6. Idem as Table 5, but for autumn (SON).

3.8.2.3. Winter (DJF) (Table 7)

Winter is the only period of the year with a certain rainfall increase in the Catalan Countries because the episodes of the different thresholds have increased. The reason, above mentioned, is the negative WeMOi trend in this season, with a high influence on the Gulf of València area. In addition, it is also noticed by an increase in the CI and CV throughout the Catalan Countries. This Table 7 enables us to conclude that winter precipitation has become more Mediterranean at the end of the 20th century, above all, in the Valencian Country (Figure 28).

Winter	>100 mm	>50 mm	>10 mm	≥0.1 mm	Total pluviometry
Marsella					
Perpinyà					
Barcelona					
Tortosa					
València					
Torrevella					
Màlaga					

Table 7. Idem as Table 5, but for winter (DJF) for the 1951/52-1999/2000 period.

3.8.2.4. Spring (MAM) (Table 8)

What outstands in this season, already mentioned in section 3.4., is the diminishing of the overall precipitation. It can be attributed to the decrease of the intense episodes between 10 and 50 mm. Negative rainfall trends in spring found by certain studies about the study area and about the Iberian Peninsula (Estrela *et al.*, 2004; López-Bustins, 2006; Norrant and Douguédroit, 2006; Paredes *et al.*, 2006; Saladié *et al.*, 2006) are the consequence of changes in general atmospheric circulation which reduce moderate intense episodes.

Spring	**>100 mm**	**>50 mm**	**>10 mm**	**≥0.1 mm**	**Total pluviometry**
Marseille					
Perpinyà					
Barcelona					
Tortosa					
València					
Torrevella					
Malaga					

Table 8. Idem as Table 5, but for spring (MAM).

3.8.2.5. Summer (JJA) (Table 9)

Torrevella and Malaga almost can not be considered because they have a very low precipitation. Overall, there is a clear reduction of the episodes and total rainfall. The trend is towards drier summers in the Catalan Countries. The irregularity in precipitation does not vary as the episodes reduce according to the total amount of rainfall.

Summer	**>100 mm**	**>50 mm**	**>10 mm**	**≥0.1 mm**	**Total pluviometry**
Marseille					
Perpinyà					
Barcelona					
Tortosa					
València					
Torrevella					
Malaga					

Table 9. Idem as Table 5, but for summer (JJA).

3.8.3. TEMPORAL EVOLUTION OF THE WEMO CALENDAR AND THE SEA TEMPERATURE ROLE

I attempted to represent the WeMO calendars for the 1951-1975 and 1976-2000 subperiods to detect any intraannual variability change (Figure 19). The first detection is a shifting of the WeMOi minimum from the 1st fortnight of October to the 2nd fortnight of October. The WeMOi maximum continues taking place in the 1st fortnight of February as in the 1951-2000 period and the 1951-1975 subperiod, but it is lower than in the other periods (WeMOi <0.40). This is suddenly followed by a WeMOi decline in the 2nd fortnight of February and in the1st fortnight of March because of the probable appearance of north-easterly flows originated by the Central European anticyclone. This is corroborated as the number of episodes >100 mm/ 24 h rises in these fortnights. This last point fits with the AOi and the WeMOi trends in winter. The 2nd fortnight of October now comprises the largest amount of >100 mm/ 24 h episodes, and some torrential events currently tend to occur until the 1st fortnight of November as the WeMOi values become positive later. Therefore, we must conclude that the Mediterranean storms period is being expanded till the beginning of the winter season as Millán *et al*. (2005) have already detected in the Valencian Country.

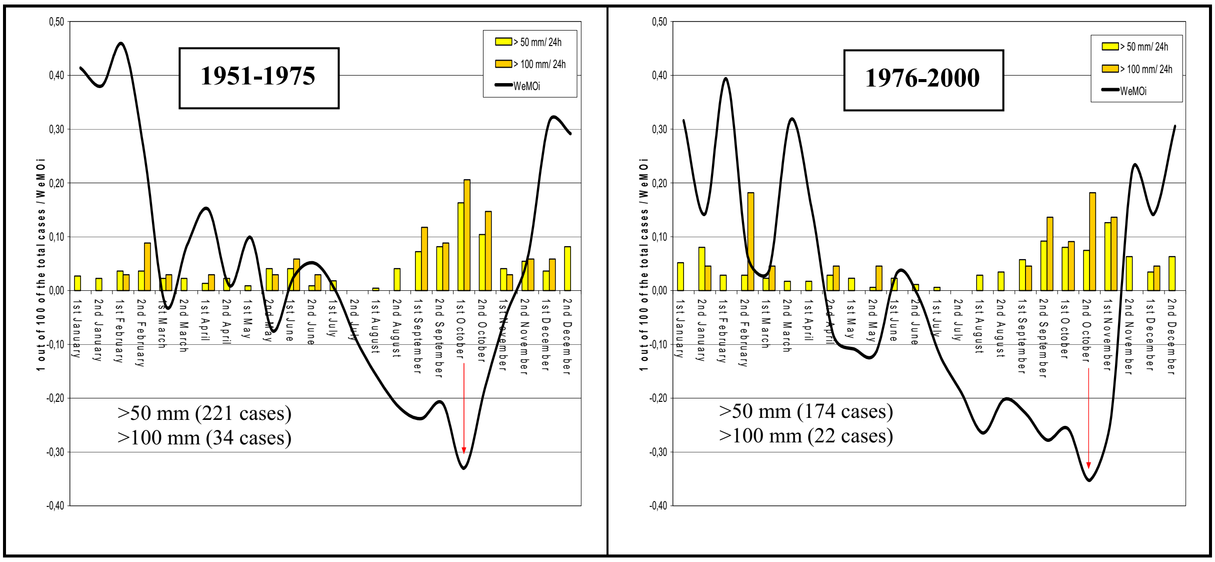


Figure 19. WeMOi intraannual regime by fortnights with the corresponding days with >50 mm and >100 mm in at least one of the 7 observatories for the 1951-1975 (left) and 1976-2000 (right) subperiods.

We might wonder if the changes in the WeMO calendar could be related with a climate change on the medium term as consequence of the Mediterranean Sea warming. Salat and Pascual (2006) do not hesitate to affirm that the sea temperature on the Costa Brava has increased at all depths and year periods in the course of the last 30 years. The data used are from *l'Estartit* (Baix Empordà) meteorological station[3], given by Mr Pascual. The WeMO might be modulated by the sea temperature, since it indicates a higher energy accumulation when it is higher. The WeMOi coincidently reaches the minimum values when the subsurface sea temperature (65-80 m depth) is warmest, end October – beginning November (Table 10). Nowadays, the warmest sea temperature at 80 m depth takes place in November whereas it did in October in the 1970s (Figure 20). Therefore, the period of maximum cyclogenic potentiality is shifting to late autumn. November is the month when the sea temperature has most increased (Figure 21). This noticeable warming in autumn could be the reason why the WeMO has remarkably increased its influence on the Catalan Countries coastland rainfall, above all, on the Valencian Country (Figure 33 in the 3rd chapter in the Catalan version). Some studies point out a rise of the Mediterranean cyclogenesis, as the Algerian low is intensified, because of an increase of the sea temperature (Guijarro, 2002; Millán *et al.*, 1995).

1973-1997	-0,5 m	-5m	-20 m	-35 m	-50 m	-65 m	-80 m	WeMOi
1d July	20,68	20,13	18,43	15,90	14,17	13,42	13,24	-0,12
2d July	21,83	21,38	19,77	16,84	14,80	13,69	13,32	-0,19
3d July	22,11	21,61	20,20	17,79	14,57	13,57	13,40	-0,21
1d August	22,68	22,19	19,90	17,19	14,89	13,84	13,44	-0,26
2d August	22,96	22,50	20,40	16,71	14,79	13,64	13,46	-0,29
3d August	22,68	22,37	21,25	17,81	14,83	13,81	13,51	-0,19
1d September	21,53	21,14	20,18	17,97	15,48	13,88	13,54	-0,25
2d September	21,33	21,10	20,09	17,87	15,58	14,06	13,56	-0,29
3d September	20,24	20,04	19,43	18,62	17,02	15,41	14,35	-0,19
1d October	19,31	19,17	18,87	18,15	17,18	15,71	14,47	-0,25
2d October	18,38	18,24	18,06	17,69	17,13	16,09	15,19	-0,25
3d October	17,64	17,62	17,44	17,30	16,95	16,39	15,48	-0,32
1d November	16,98	16,94	16,88	16,75	16,63	16,19	15,38	-0,39
2d November	16,27	16,14	16,38	16,32	16,27	15,95	15,55	0,16
3d November	15,35	15,42	15,46	15,42	15,38	15,18	14,93	0,23
1d December	14,52	14,63	14,67	14,65	14,62	14,58	14,54	0,01
2d December	13,98	14,04	14,12	14,12	14,10	14,06	13,96	0,26
3d December	13,32	13,47	13,54	13,59	13,65	13,64	13,59	0,31

Table 10. Sea temperatures means (ºC) in *l'Estartit* (Costa Brava) at levels -0.5 m, -5 m, -20 m, -35 m, -50 m, -65 m and -80 m, and daily WeMOi, in groups of 10 days (d) approximately according to each month for the 1973-1997 period. (Orange shows the 3 d of the year with a warmest sea temperature for each depth, and pink the 2 d of the year when daily WeMOi is most negative).

[3] Sea temperature series from *l'Estartit* is the longest and most continuous one in Catalan Countries. The quality of the series is very good, and it starts with continuous registers in 1973.

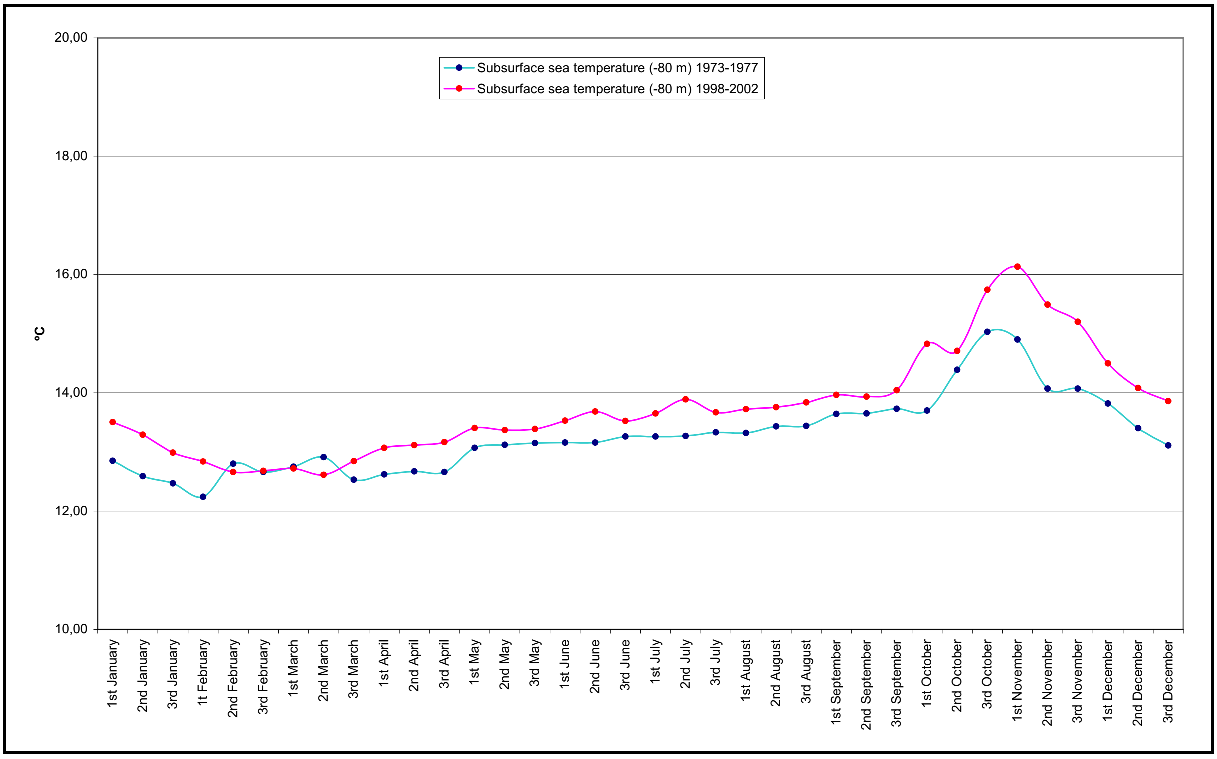


Figure 20. Intraannual temporal evolution by d of sea temperature mean at 80 m depth in *l'Estartit* for the periods of five years 1973-1977 and 1998-2002.

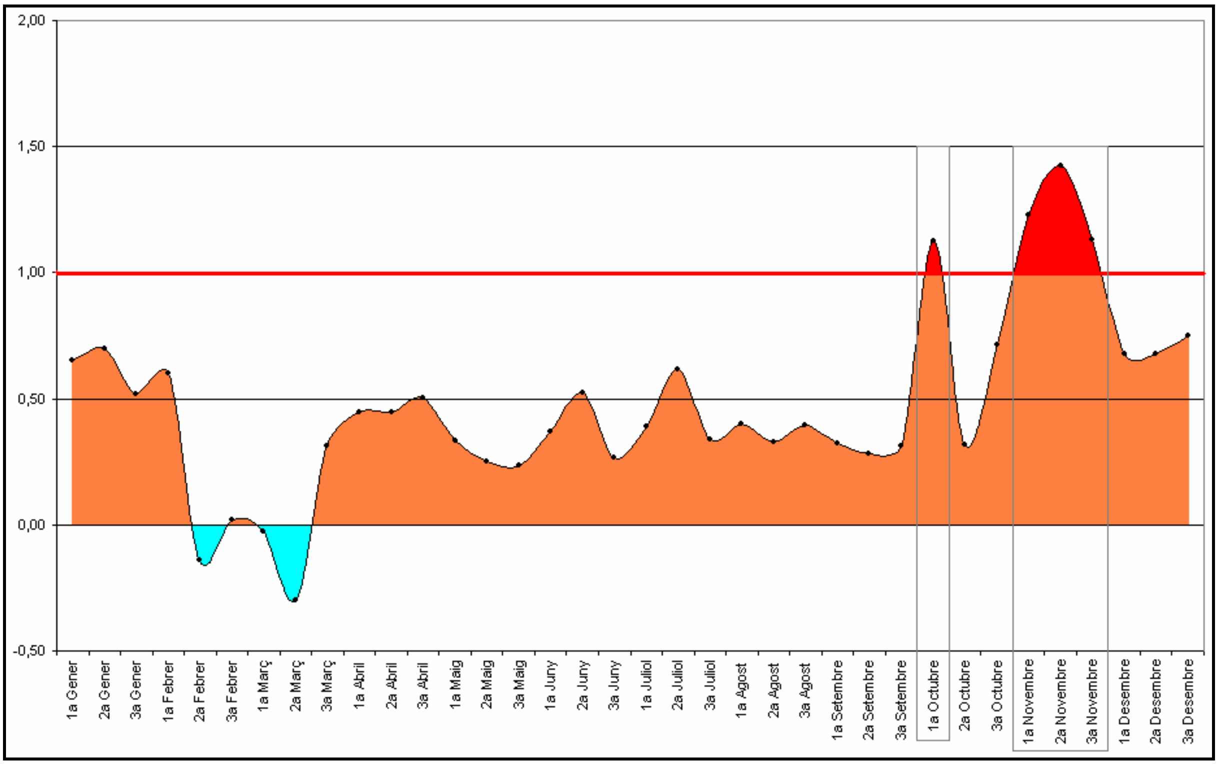


Figure 21. Difference between the sea temperature means (ºC) in 1998-2002 subperiod and 1973-1977 subperiod, at 80 m depth in *l'Estartit*. (Ordinates axis is in Catalan. Have a look at Figure 20 for the translation).

The WeMOi minimum in the 1st fortnight of October has shifted to the 2nd fortnight of October and to the 1st fortnight of November (Figure 19), coinciding with a warming sea temperature in November. Moreover, it must be highlighted that the WeMOi diminishing in midwinter, 2nd fortnight of January and during the transition from winter to spring, 2nd fortnight of February and 1st fortnight of March, is the consequence of certain factors studied in the following chapter. This implies more torrential events in these fortnights; Millán *et al*. (2005) already detected this torrential increase as the back cold fronts have become more frequent during the first half of the year at the end of the 20th century. Sea temperature is slightly colder in these fortnights as the consequence of the arrival of more north-easterly cold air masses (Figure 21).

3.8.4. DAILY WEMOI FREQUENCY DISTRIBUTION

To assess if there has been any variation in WeMOi histogram frequencies during the second half of the 20th century, the 2 subperiods (1951-1975 and 1976-2000) are compared. It is annually and seasonally assessed (Figure 22). Overall, there is a shifting to the negative values, above all, in summer. The daily WeMOi mean during the first period is out of the confidence interval of the daily WeMOi mean during the second subperiod in four seasons and annually. Winter shows an irregular distribution, as it is when the index has the highest variability, and has a rise of negative WeMOi values in intervals between -3 and -1.5. In summer, the distribution is more regular, as it is when the index is more stable, and has a clearer shift towards negative values. These results fit with the overall negative WeMOi trend along the second half of the 20th century (Table 2).

At an annual resolution, the analysis has been amplified to 4 subperiods (1901-1925, 1926-1950, 1951-1975 and 1976-2000) to check if the daily WeMOi has any trend along the entire 20th century (Figure 23). From the initial period, 1901-1925, to the last one, 1976-2000, there is a gradual shifting to negative values. In the first quarter of the century, the most frequent interval was (0, 0.25), and in the most recent one (-0.25, 0). Furthermore, there is a variance reduction along the 20th century as the daily WeMOi values tend to concentrate on central intervals. These changes reflect the overall negative WeMOi trend along the 20th century (Table 1).

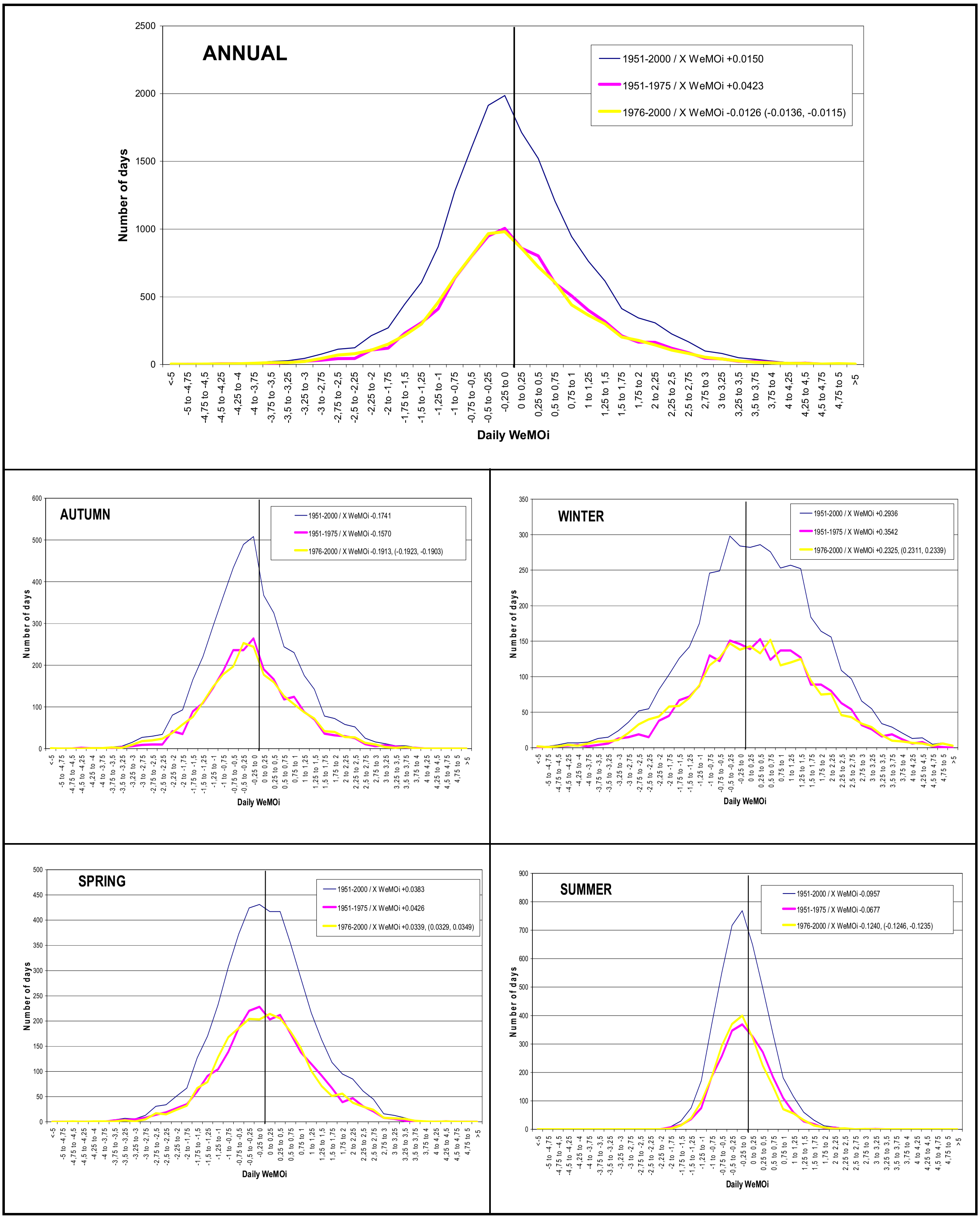


Figure 22. Daily WeMOi frequencies distribution in interval classes of 0.25 for the 1951-2000 period and 1951-1975 and 1976-2000 subperiods. The distributions are made for the whole year, cold and warm semesters, autumn, winter, spring and summer. The mean of the daily WeMOi for each period and confidence interval (95%) for the last period is shown.

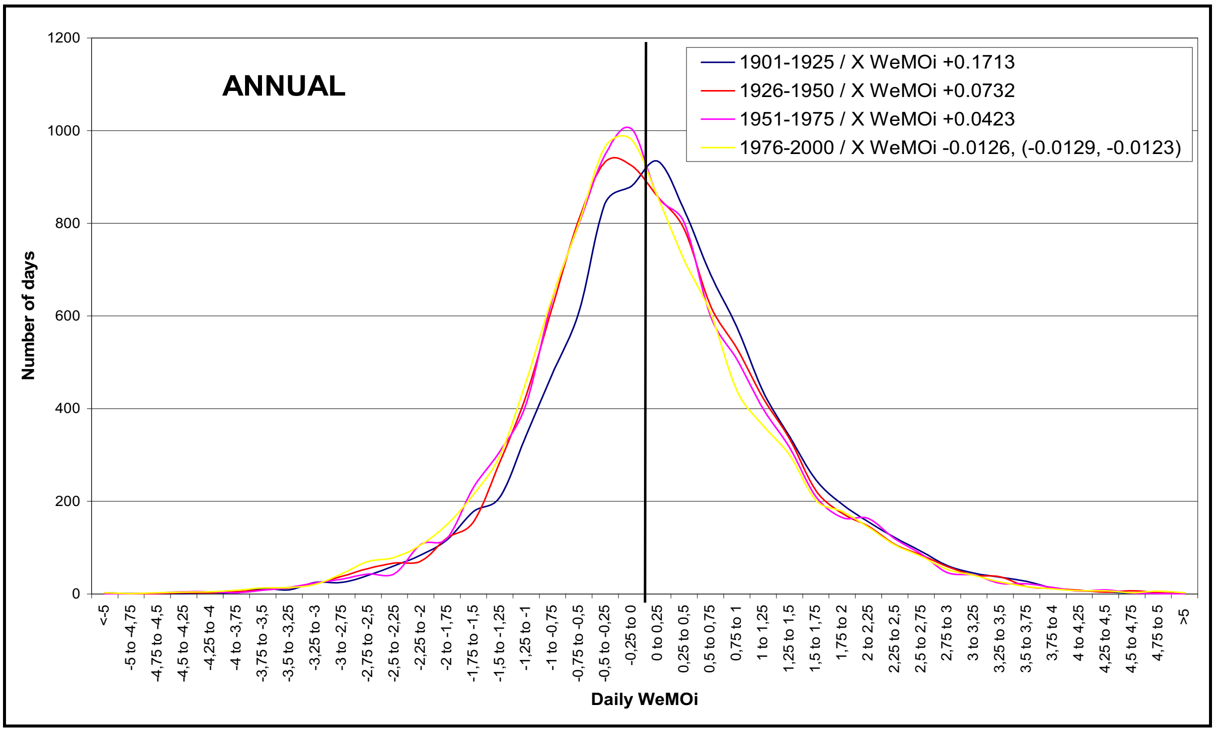


Figure 23. Idem as Fig. 22, but for the 1901-1925, 1926-1950, 1951-1975 and 1976-2000 subperiods considering all the days of the year.

3.8.5. Sum up of the temporal evolution of the daily rainfall irregularity in the Catalan Countries

The negative WeMOi trend shows two directions in its influence on daily rainfall in the Catalan Countries: a higher torrentiality and a higher number of rainy days, which will determine the CI and DI indices. Except for Barcelona, a WeMOi decrease implies an overall rise of the number of rainy days (intensity reduction, DI) because of a shift towards negative values in the daily WeMOi frequencies distribution, a rainfall irregularity increase (CI) due to a higher number of intense and torrential events since daily extreme negative WeMOi values are increased (see section 3.9.6. in Catalan version), a rise of the rainfall means and a higher frequency of rainy sequences over 1 day (see section 3.9.5. in the Catalan version).

In winter, when the WeMOi has a negative and significant trend and consequently it enhances its influence on the southern Catalan Countries rainfall, the torrentiality increases due to more frequent extremely negative WeMOi values. Subsequently, the CI increases, and so does the DI in those cases where intense events proportionally increase over the weak ones. In València, where the WeMO reinforces its influence at the end of the 20th century (Figures 15 and 18), the torrentiality increases showing a higher CI in the second subperiod, and a higher DI too, although the number of rainy days slightly rises (Table 4) leading to a reduction of rainy sequences of 1 day (Table 20 in the Catalan version). Intense and torrential events increase more remarkably than the weak ones in València (Table 7).

3.9. BALEARIC ISLANDS – CATALONIA: AN OPPOSED PLUVIOMETRY?

There was a research during the 2001-2004 period in REN project (2001-2865-C02-01/CLI) of the Education and Science Ministry, which currently continues as a new project named IPIBEX (CGL2005-07664-C02-01). The two research groups which take part in the project are the Group of Climatology at the Physical Geography and RGA Department of University of Barcelona, and the Earth Sciences Department of University of Balearic Islands. One of the aims of the project is to confirm the hypothesis about an opposed relationship between rainfall in the Balearic Islands and Catalonia. In this thesis, taking advantage of having a database available at a monthly resolution with a good spatial covering, a first approach is essayed.

First, we need to revise those circulation patterns which are dominant in these areas and in which periods of the year. The AOi negatively correlates with precipitation in western Catalonia and positively in the south-western Balearic Islands in autumn, winter and cold semester (Figure 8). The NAOi negatively correlates with precipitation in both territories. The WeMO has a similar behaviour to the AO, but obviously, opposed: rainfall in the western Pyrenees is positively correlated with the WeMOi whereas in the south-western Balearic Islands it is negatively correlated in autumn and winter (Figures 12 and 13 in the 2nd chapter). Therefore, I attempt to correlate Catalonia and Balearic Islands rainfall for these two seasons.

Mallorca and Menorca rainfall have a positive and significant correlation with Catalonia rainfall, whereas Pitiüses rainfall is not significant. Pitiüses are well and positively correlated with observatories around Nau cape in the Valencian Country due to its geographical proximity. If we correlate the cold semester rainfall between both areas, there is a negative and significant correlation between *sa Savina* (Formentera) and *Pantà de Sant Llorenç* (Noguera) (-0.31). We might conclude that the pluviometric behaviour between Catalonia and the Balearic Islands is slightly opposed if we compare the rainfall variability in inland Catalonia and Western Fringe, and that one in Pitiüses. Subsequently, I cannot satisfactorily assert the initial hypothesis.

3.10. SOME COMMENTS ABOUT THE FUTURE WINTER RAINFALL IN THE CATALAN COUNTRIES ACCORDING TO THE TELECONNECTION PATTERNS

The most outstanding trends in teleconnection indices is in winter. The WeMOi reduces and the AOi increases, but the NAOi has no significant trend. This last pattern might come into a new negative phase as in the 1960s, and leave the positive phase of the last years of the 20th century. If this happens, Catalonia, inland Valencian Country, Mallorca and Menorca rainfall would rise, but for the moment they still have a diminishing rainfall due to a prolongation of the most recent positive NAO phase. Nevertheless, the NAO pattern certainly depends on the AO one, which presents a strengthening evolution during the second half of the 20th century. This is the consequence of the fact that the winter polar vortex has recently reinforced in midwinter (Shindell *et al*., 1999 and 2001) and in late winter (Labitzke and Kunze, 2005; Labitzke *et al*., 2005; López-Bustins, 2006), which is treated in the following 4th chapter.

The result is an extreme negative WeMO phase which has led to an overall winter rainfall increase (Figure 11) with a major CV in those areas where the WeMO has the largest influence (Figure 28 in the Catalan version and Figure 16): the eastern Pyrenees, the Valencian Country and the Pitiüses. The S_1 indicates the Gulf of València as the area more interannually irregular in winter at the end of the 20th century. Although rainfall does not increase in Pitiüses, it very slightly reduces in comparison to the rest of the Balearic Islands. The WeMOi negative trend is related to an increase of pressure in northern Italy due to a reinforcement of the thermal central European anticyclone (Maugeri *et al*., 2003 and 2004). This anticyclone is the key of the opposed relationship between the WeMO and the AO which is revealed in the next chapter. The winter rainfall increase might be as consequence of torrential nature increase as some authors propose (Goodess and Jones, 2002; Sumner *et al*., 2003; Rodrigo, 2006). What it is assured as consequence of the winter WeMOi negative trend is the rise of the number of rainy days and sequences of more than one day overall in the Catalan Countries in winter.