Department of Physical Geography and Regional Geographical Analysis
Faculty of Geography and History
University of Barcelona

PhD Thesis

The Western Mediterranean Oscillation and Rainfall in the Catalan Countries

Memory presented by
Joan Albert López i Bustins
(*Summary*)

PhD Director

Prof. Dr Javier Martín Vide
University de Barcelona

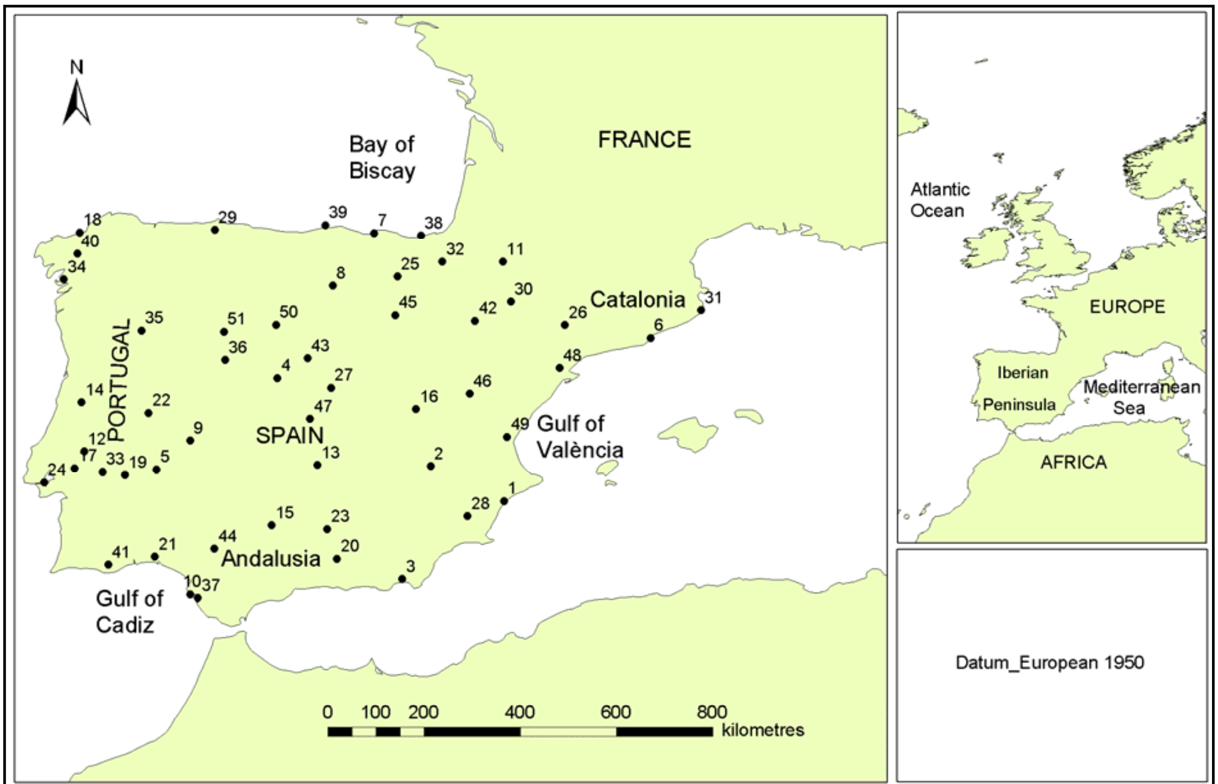
Barcelona, June 2007

2ND CHAPTER

THE STUDY AREA DEFINITION AND WEMO APPLICATION TO ITS PRECIPITATION

2.1. STUDY AREA JUSTIFICATION

The Catalan Countries are the study area of this thesis due to their particular climate behaviour within the western Mediterranean basin. A first approach to select this study area is carrying out an approach with the whole Iberian Peninsula (Martin-Vide and Lopez-Bustins, 2006). In the Iberia study, 51 meteorological stations are used, previously homogenised by Dr Vicente-Serrano (University of Saragossa), for such a long period (1910-2000) (Figure 1). Martín-Vide (2001) demonstrated that low pressures do not imply precipitation over the eastern Iberian Peninsula, but some relative high pressures do. Therefore, it was advisable to correlate this rainfall area with the WeMOi to check some improvements in the study of its variability. The NAOi is also correlated with the Iberian rainfall to make a comparison of the influence areas.



1. Alacant
2. Albacete
3. Almería
4. Ávila
5. Badajoz
6. Barcelona
7. Bilbao
8. Burgos
9. Cáceres
10. Cadiz
11. Canfranc
12. Chouto
13. Ciudad Real
14. Coimbra
15. Córdoba
16. Cuenca
17. Coruche
18. Corunna
19. Extremos
20. Granada
21. Huelva
22. Idanha
23. Jaén
24. Lisbon
25. Logroño
26. Lleida
27. Madrid
28. Murcia
29. Oviedo
30. Huesca
31. Palafrugell
32. Pamplona
33. Pavia
34. Pontevedra
35. Rio Torto
36. Salamanca
37. San Fernando
38. San Sebastián
39. Santander
40. Santiago de Compostela
41. São Brás
42. Saragossa
43. Segovia
44. Sevilla
45. Soria
46. Teruel
47. Toledo
48. Tortosa
49. València
50. Valladolid
51. Zamora

Figure 1. Map of locations of the 51 Iberian meteorological stations.

During the cold half of the year, as many other patterns, the WeMO has its largest influence. In summer, there is no correlation due to the convective precipitation predominance associated to sea-breeze (Sb) fronts (Azorín-Molina and López-Bustins, 2004). The NAO has a greatest domain over the Iberian Peninsula, except for the eastern and north fringes, as the left column in Figure 2 shows. The NAO influence is largest in extension in January and in intensity in December over the southern Plateau, whereas the WeMO is confined to the eastern Iberian fringe and to the Gulf of Cadiz in its negative phase, and to the north fringe in its positive phase (central column). This WeMO positive phase is largest both in extension and in intensity over the Basque Country (Bay of Biscay) in January. In a third column, the difference between the absolute values of the correlation coefficients obtained with both patterns is worked out. The WeMO influence is largest over the NAO influence on the Gulf of València in October and February, but it is largest in December over the Bay of Biscay. This strong influence of the positive WeMO phase was unexpected because the WeMO was initially put forward for the eastern Iberian fringe, suggesting a certain Mediterranean variability on the Bay of Biscay climate. Although the Gulf of Cadiz rainfall is well correlated with WeMOi, it is under NAO domain because it is better correlated with NAOi than with WeMOi (Figures 2 and 3).

Figure 3 shows a regionalization according to the prevailing pattern over the rainfall and its phase. Most of the Iberian Peninsula (southern and western halves) is under NAO domain in the negative phase, but the eastern fringe (Catalan Countries) under the negative WeMO phase (eastern and south-eastern advections) and the north fringe is under the positive WeMO phase (north-western advections). At this stage, I must point out the role of the peninsula orography which permits us to regionalise these different pluviometric areas (Figure 4). The Ebre Valley allows a prolongation of the WeMO influence to the inland areas (Figures 2 and 3). The daily concentration index of precipitation (CI) defined by Martin-Vide (2004) is highest, within the Iberian Peninsula, over the eastern fringe (over 0.61 CI value) with the maximum over the Gulf of València. The CI spatial distribution also shows an inland incision through the Ebre Valley. Therefore, there might be some relationship between the WeMO influence and the rainfall irregularity according to the CI. In the Catalan version of this thesis and in Martin-Vide and Lopez-Bustins (2006), you can find monthly distribution maps of the rainfall anomalies in extreme WeMO phases where the results are coherent.

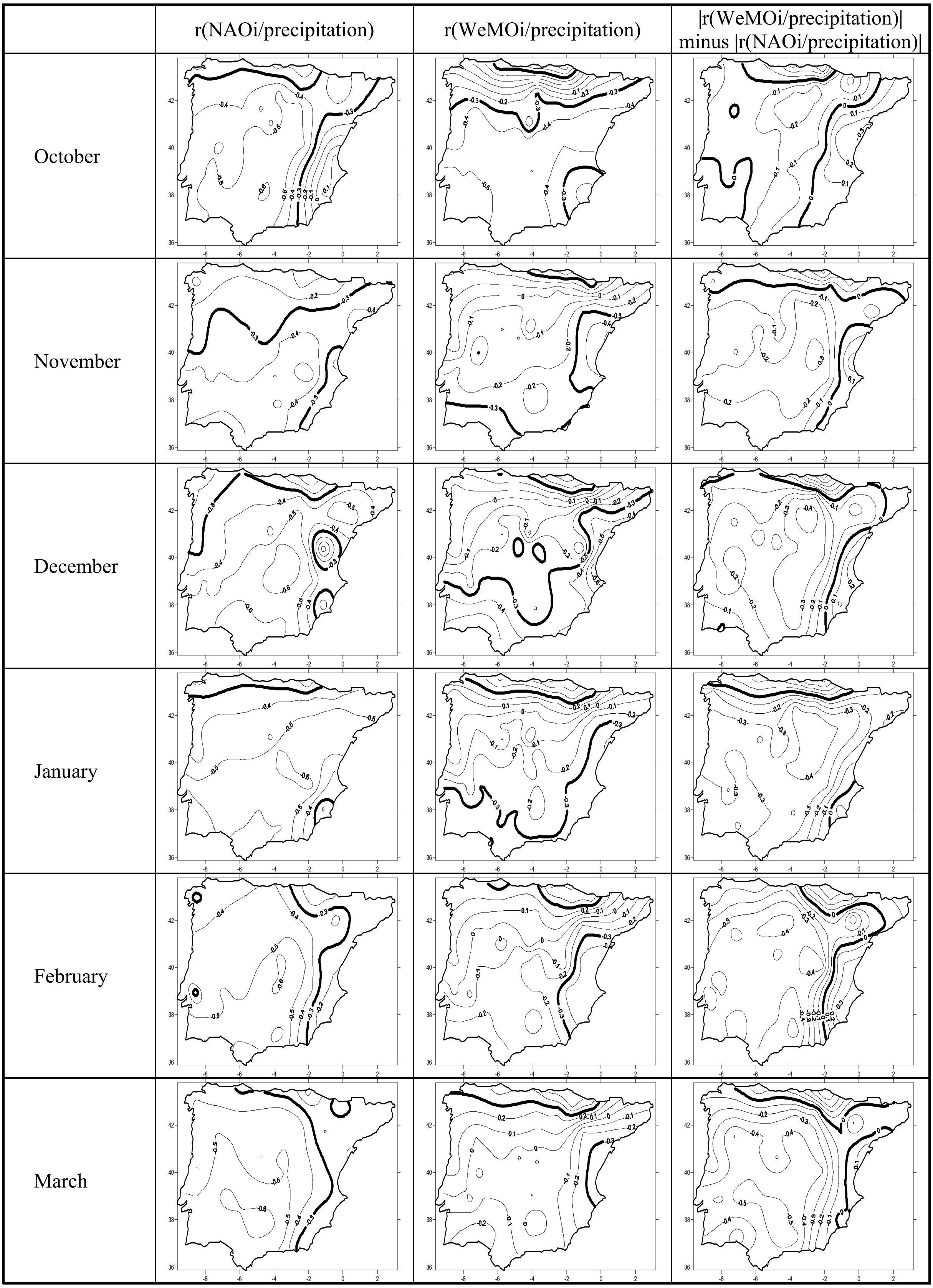


Figure 2. Spatial distribution of the Pearson's correlation coefficients between the Iberian Peninsula rainfall and the NAOi (left column), and the WeMOi (central column), for each one of the months of the cold half of the year or semester (ONDJFM) during the 1910-2000 period. The third map is the result of subtracting to the absolute value of the coefficient obtained with the WeMOi the one obtained with the NAOi. (The line /0.3/ is in bold in the maps of the first and second columns to identify the significant areas at 0.01. The line 0 is in bold in the maps of the third column to identify the most influenced area by the WeMO over the NAO. The interpolation method used is Kriging[1], which is the same used in all the maps of this thesis).

[1] This is the most appropriate method for climatological applications for monthly or longer periods (Armengot, 2002).

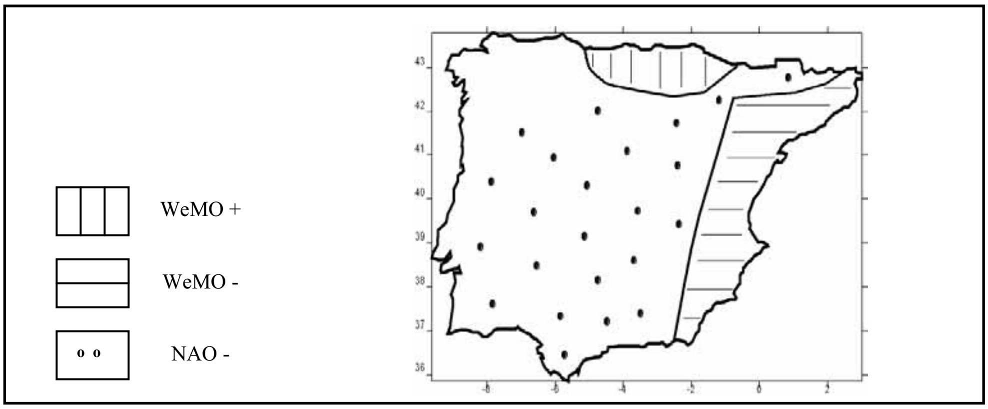


Figure 3. Regionalisation of the Iberian Peninsula following a pluviometric rise according to WeMO and NAO phases from October to March.

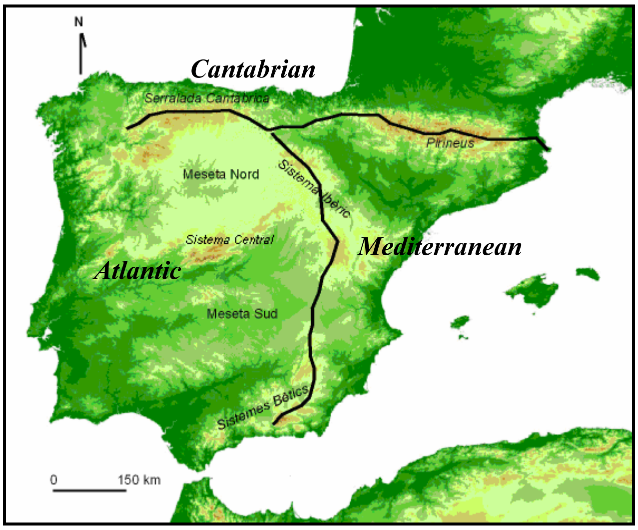


Figure 4. Orographical scheme in Iberian Peninsula which divide the Atlantic, Cantabric and Mediterranean rainfall domains.

Bilbao and València are the two meteorological stations whose winter precipitation is best correlated in each one of the WeMO phases, and are not significantly correlated with NAOi (Figure 5). Hence, the rainfall correlation between València and Bilbao in winter (DJFM) is -0.31 (p-value 0.0030). This is an opposed relationship that is quite larger than the one found for the opposed influenced areas by NAO (Huelva and San Sebastián) (Martín-Vide, 2003). Figure 6 shows the running means of Bilbao and València winter rainfall, and the WeMO and NAO indices for the 1910-2000 period. There is a clearly opposed oscillation between the '80s and the '90s. During the mid-'80s, the WeMO was positive, and the Bilbao rainfall values were positive, but negative in València. The values were inversed at the beginning of the '90s when the WeMO set up a strong negative phase. The NAO role was weak along the whole period. The WeMO has allowed to find out two pluviometric regions, Gulf of València and Bay of Biscay, which are quite near and have an opposed behaviour.

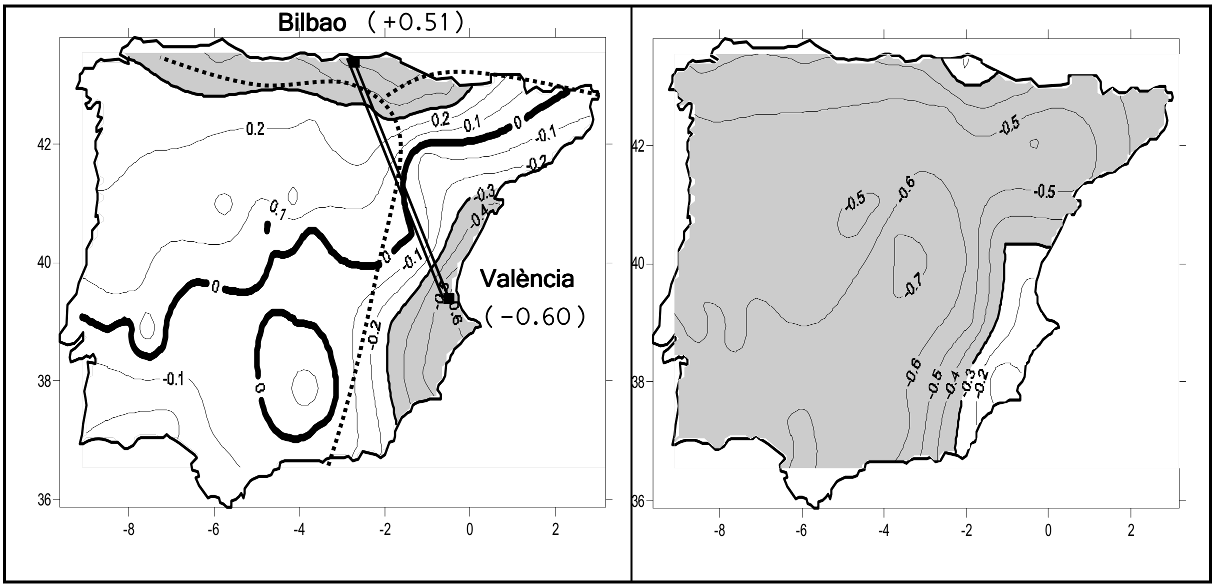


Figure 5. Spatial distribution of the correlation coefficients between the winter Iberia rainfall (DJFM) and the WeMOi (left), and the NAOi (right) for the 1910-2000 period. (The shaded areas are significant at 0.01). (The WeMOi map shows the Bilbao-València transect and the coefficients corresponding to both study points. The main mountain ranges are indicated by a dashed line).

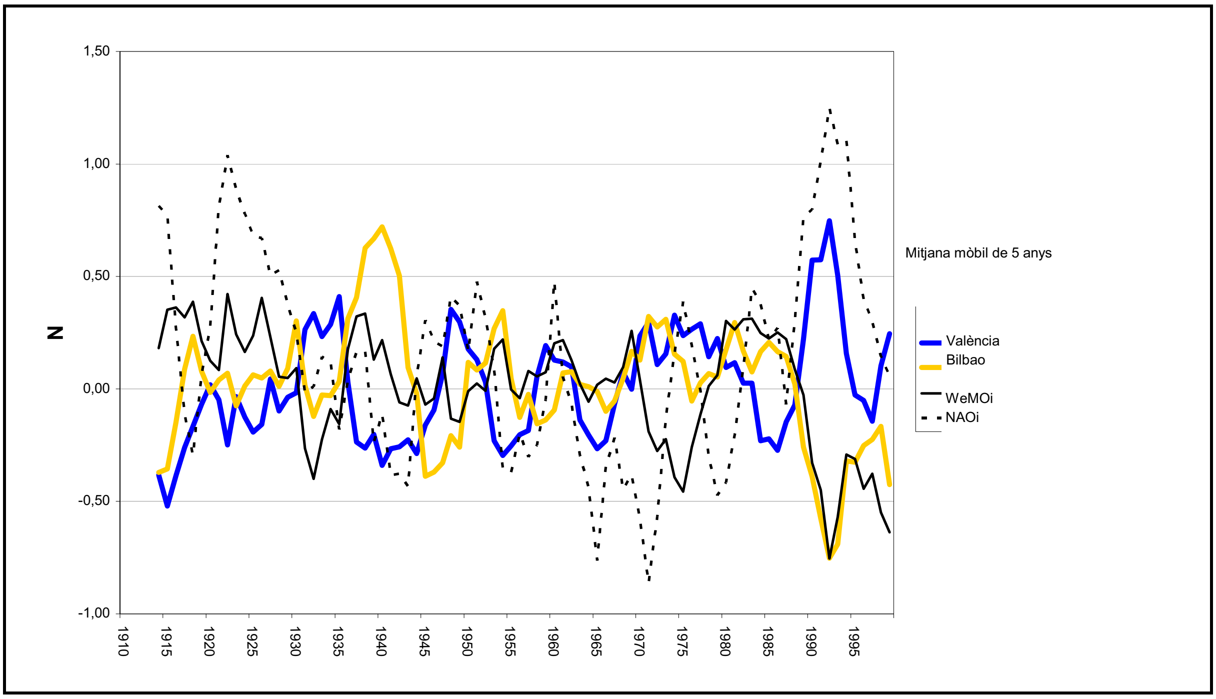


Figure 6. Standardised winter rainfall values (DJFM) in València and Bilbao, the WeMOi and the NAOi during the 1910-2000 period. (The graphic shows 5-year running means).

The main reasons to select the Catalan Countries as the study area are the following:

Climatological feature

- This area is weakly correlated with the pattern used in the Iberian rainfall analyses, NAO. Hence, it is featured by being leeward to the Atlantic winds. Thus, it is endogenous to the Mediterranean Sea with its own pluviometric variability.
- The Catalan Countries area includes the entire maximum WeMO region influence in its negative phase.
- This area is very close to the one delimited by the 0.61 value of the CI of the daily Iberian rainfall in Martin-Vide (2004), showing the Catalan Countries as the area with the most irregular rainfall behaviour.
- Establishment of an own circulation pattern for the particular climate of the Catalan Countries, shared with the Basque Country on the opposed phase.

Geographical feature

- The Catalan Countries are the coastland area which is centred and oriented towards east within the north-western Mediterranean basin.
- Balearic Islands inclusion in the area study is due to their singular location in the middle of the Western Mediterranean basin.

2.2. CATALAN COUNTRIES CLIMATE

The Catalan Countries climate is mostly Mediterranean, except for the oceanic climate in Val d'Aran, but with a wide variety of subclimates. Figure 7 shows a simple Köppen classification over the Catalan Countries (from the *Atles dels Països Catalans* –Catalan Encyclopaedia, 2000–). The Balearic Islands, most of the Valencian Country and the coastland of Catalonia have a mild temperate and humid climate with a warm and dry summer with some steppe areas. Inland Catalonia and the Valencian Mountains have a colder and more humid climate. Generally speaking, the Catalan Countries climate depends on the local orography. It is a climatic featured by the extreme anomalies, from long spells to torrential rainfall, which lead to a remarkable hazard over the study area.

An isohyets map for the Catalan Countries (1951-1990) is used later to validate the database (*Geografia General dels Països Catalans*, 1992 –Figure 8–). This map shows the Pyrenees as the most humid region, together with the Transversal mountain range, which extends the rainy area to the Central Coast and south Costa Brava. The 700 mm isohyet distinguishes the humid region from the less humid region. The areas described above, Montsant sierra, Maestrat mountains, Tortosa-Beseit mountains, Tramuntana sierra and eastern Mallorca orographies, and the southern Gulf of València are the most humid. The driest are the Catalan central plain, inland Valencian province, mostly the Alacant area, southern Mallorca and the Pitiüses (Eivissa and Formentera).

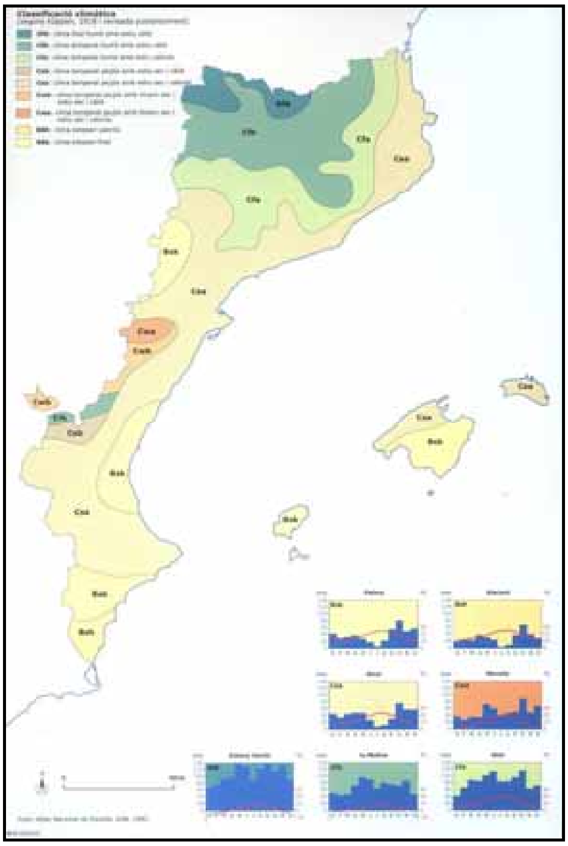


Figure 7. Köppen climate classification (*Atles dels Països Catalans*, Catalan Encyclopaedia, 2000).

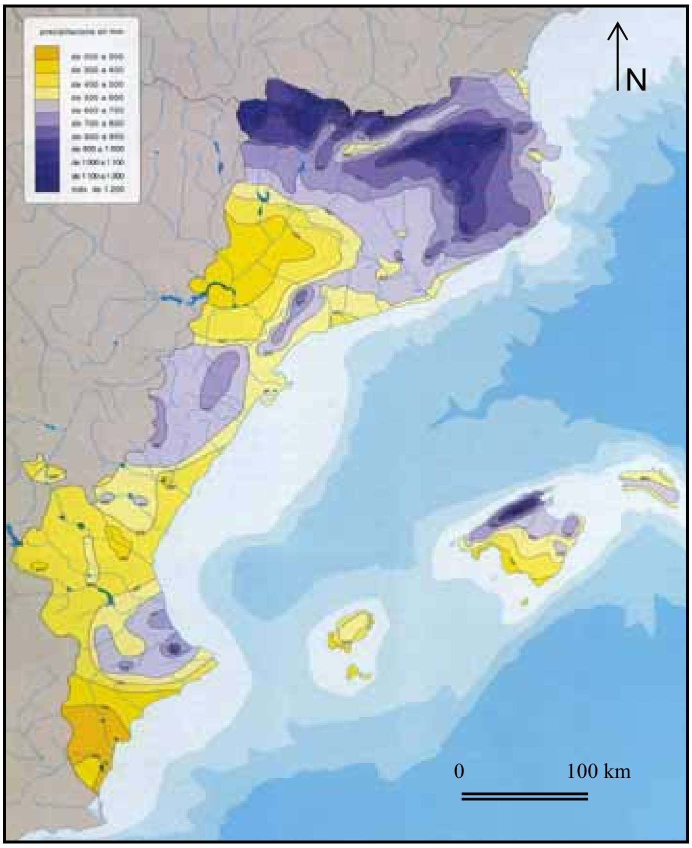


Figure 8. Annual isohyets map of the Catalan Countries for the 1951-1990 period (*Geografia General dels Països Catalans,* Catalan Encyclopaedia, 1992).

2.3. DATABASE ELABORATION

A very dense network of meteorological stations is necessary to be able to analyse the eastern Iberian façade rainfall. The 1951-2000 period has been selected to establish a homogeneous network since it is a recent period where there are enough series available. The temporal resolution is monthly. The spatial homogeneity has been constructed using the *comarca*[2] division. This administrative division constantly varies a little bit. For this thesis, I use the *comarca* division in 1996 (Figure 9), when 89 *comarcas* constituted the Catalan Countries. To obtain an equilibrated and equidistance network distribution, I select the best series of each *comarca*. A superficial extension mean of the all *comarcas* is worked out (787.9 km²) to be used as reference. There is a large difference between the biggest one, Mallorca (3,633.6 km²), and the smallest one, València (134.6 km²). The smallest ones are in *Horta de València*, and the biggest ones in the Western Strip and in the Balearic Islands.

The criteria used to select the number of observatories per *comarca* are the following:

- If the mean *comarca* extension 787.9 km² > *comarca* extension = 1 station
- If the mean *comarca* extension < *comarca* extension = 2 stations
- If the mean *comarca* extension × 2 < *comarca* extension = 3 stations
- If the mean *comarca* extension × 3 < *comarca* extension = 4 stations
- If the mean *comarca* extension × 4 < *comarca* extension = 5 stations

The sum of the number of observatories proposed to select is 133 (Table 1). The Pitiüses and Menorca should be corresponded with just one, but for their insularity condition they obtain two each one. In the case of the Pitiüses, one is for Eivissa, and the other for Formentera.

Once the conditions are defined to select the monthly series in each observatory, the following criteria are established to obtain the series most reliable:

1) Unique series, i.e., the register must have always been taken in the same station.
2) The series must be completed in 85% (510 months).
3) If the *comarca* has not any series available with the two former conditions, it can be composed of two series, 3 maximum, following these rules:
   - The distance between the observatories can not surpass the 15 km.
   - The altitude difference between the observatories can not surpass 500 metres.
4) If there is no observatory that complies with the above criteria in a *comarca*, it must be left empty .

[2] A *comarca* is a traditional region or local administrative subdivision found in Catalan Countries, in parts of Spain, parts of southern France, the Central American republic of Panama, Portugal, and Brazil.

Some *comarcas* might have several unique or composed series available. The most valuable ones have been selected according to:

1) Among the unique series:
- The most completed series.
- The most representative series of the *comarca*, and they should be located far from other selected series in the same *comarca* or in the adjacent *comarcas*.

2) Among the composed series:
- The series which belongs to the observer or a relative.
- Subjectivity and intuition, using some metadata, play an important role when selecting the most convenient series.

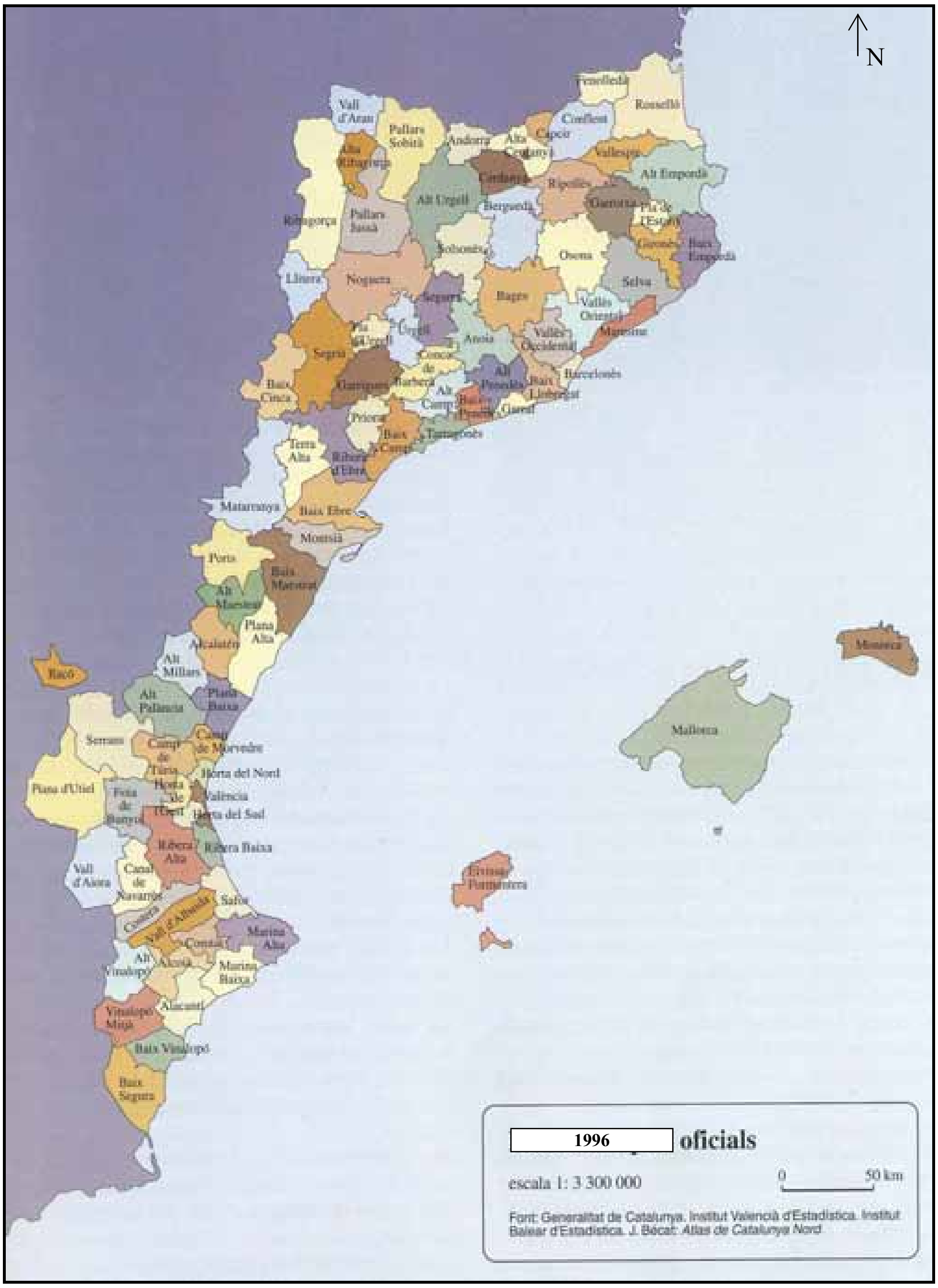


Figure 9. Administrative division of the Catalan Countries in *comarcas* (*Geografia General dels Països Catalans*, volum 7, Concepte i Evolució, Catalan Encyclopaedia, 1996).

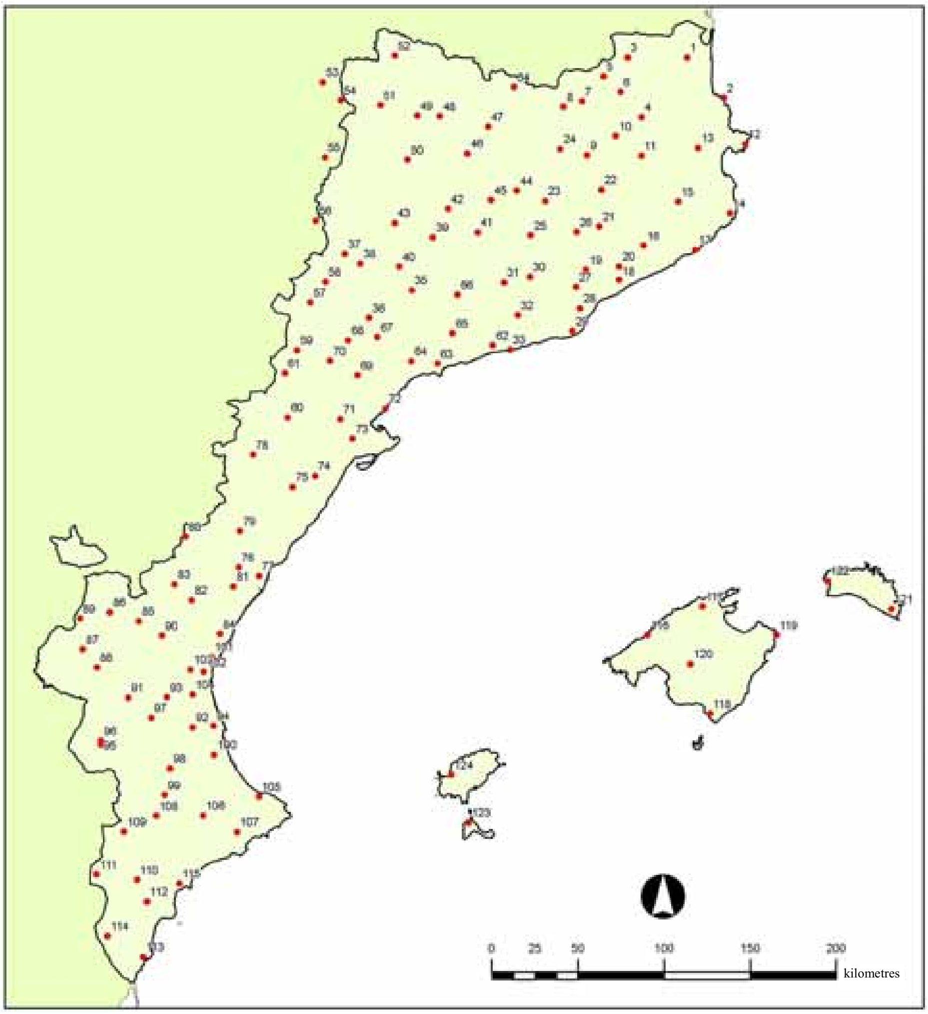
	Comarca Name	km²	q	ns		*Comarca* Name	km²	q	ns
	CATALONIA				**47**	Alt Palància	964.9	1.22	2
1	Alt Camp	538.0	0.68	1	**48**	Alt Vinalopó	645.0	0.82	1
2	Alt Empordà	1,357.5	1.72	2	**49**	Baix Maestrat	1,221.4	1.55	2
3	Alt Penedès	592.8	0.75	1	**50**	Baix Segura	957.3	1.21	2
4	Alt Urgell	1,447.5	1.84	2	**51**	Baix Vinalopó	489.2	0.62	1
5	Alta Ribagorça	426.9	0.54	1	**52**	Camp de Morvedre	271.1	0.34	1
6	Anoia	866.3	1.10	2	**53**	Camp de Túria	814.9	1.03	2
7	Bages	1,299.1	1.65	2	**54**	Canal de Navarrés	709.3	0.90	1
8	Baix Camp	697.1	0.88	1	**55**	Comtat	376.4	0.48	1
9	Baix Ebre	1,002.7	1.27	2	**56**	Costera	528.1	0.67	1
10	Baix Empordà	701.7	0.89	1	**57**	Foia de Bunyol	817.3	1.04	2
11	Baix Llobregat	485.7	0.62	1	**58**	Horta del Nord	140.4	0.18	1
12	Baix Penedès	296.2	0.38	1	**59**	Horta de l'Oest	187.3	0.24	1
13	Barcelonès	144.7	0.18	1	**60**	Horta del Sud	165.7	0.21	1
14	Berguedà	1,184.9	1.50	2	**61**	Marina Alta	759.3	0.96	1
15	Cerdanya	546.6	0.69	1	**62**	Marina Baixa	578.8	0.73	1
16	Conca de Barberà	650.2	0.83	1	**63**	Ports	903.9	1.15	2
17	Garraf	185.3	0.24	1	**64**	Plana Alta	957.3	1.21	2
18	Garrigues	797.6	1.01	2	**65**	Plana Baixa	605.2	0.77	1
19	Garrotxa	735.4	0.93	1	**66**	Plana d'Utiel	1,725.9	2.19	3
20	Gironès	575.4	0.73	1	**67**	Serrans	1,400.1	1.78	2
21	Maresme	398.9	0.51	1	**68**	Racó	370.1	0.47	1
22	Montsià	735.4	0.93	1	**69**	Ribera Alta	970.1	1.23	2
23	Noguera	1,784.1	2.26	3	**70**	Ribera Baixa	276.8	0.35	1
24	Osona	1,260.1	1.60	2	**71**	Safor	429.6	0.55	1
25	Pallars Jussà	1,343.1	1.70	2	**72**	València	134.6	0.17	1
26	Pallars Sobirà	1,377.9	1.75	2	**73**	Vall d'Albaida	721.6	0.92	1
27	Pla de l'Estany	262.8	0.33	1	**74**	Vall de Cofrents	1,141.2	1.45	2
28	Pla d'Urgell	305.1	0.39	1	**75**	Vinalopó Mitjà	798.6	1.01	2
29	Priorat	498.6	0.63	1		**WESTERN STRIP (ARAGON)**			
30	Ribera d'Ebre	827.3	1.05	2	**76**	Baix Cinca	960.9	1.22	2
31	Ripollès	956.2	1.21	2	**77**	Llitera	624.8	0.79	1
32	Segarra	722.8	0.92	1	**78**	Matarranya	1,646.0	2.09	3
33	Segrià	1,396.7	1.77	2	**79**	Ribagorça	1,847.0	2.34	3
34	Selva	995.1	1.26	2		**NORTHERN CATALONIA**			
35	Solsonès	1,001.2	1.27	2	**80**	Alta Cerdanya	539.4	0.68	1
36	Tarragonès	318.9	0.40	1	**81**	Capcir	177.0	0.22	1
37	Terra Alta	743.4	0.94	1	**82**	Conflent	882.3	1.12	2
38	Urgell	579.7	0.74	1	**83**	Fenolheda	599.1	0.76	1
39	Val d'Aran	633.6	0.80	1	**84**	Rosselló	1,489.2	1.89	2
40	Vallès Occidental	583.2	0.74	1	**85**	Vallespir	551.9	0.70	1
41	Vallès Oriental	851.0	1.08	2		**BALEARIC ISLANDS**			
	VALENCIAN COUNTRY				**86**	Eivissa-Formentera	653.5	0.83	2
42	Alacantí	673.2	0.85	1	**87**	Mallorca	3,633.6	4.61	5
43	Alcoià	539.7	0.68	1	**88**	Menorca	694.4	0.88	2
44	Alcalatén	648.7	0.82	1					
45	Alt Maestrat	662.9	0.84	1	**89**	**PRINCIPALITY OF ANDORRA**	468.0	0.59	1
46	Alt Millars	667.4	0.85	1		**Mean**	**787.9**	**km²**	**133**

Source: Valencian Statistics Institute, Catalan Statistics Institute, Spanish Statistics Institute, Balearic Statistics Institute, *Atles de Catalunya Nord* de J. Becat, *Gran Geografia Comarcal* de 1981-85, Principality of Andorra website, Aragon Government website, among others.

Table 1. Number of series (ns) of each *comarca*, dividing the *comarca* extension by the mean of the *comarcas* extensions (q).

Out of the 133 required series, 124 are obtained (93.2%), a high percentage that enables us to constitute a very dense observational network with a monthly resolution for the Catalan Countries (1 series per about 560 km²) which will validate the study area analyses. The following *comarcas* have no series: *el Capcir*, *el Pla de l'Estany*, *l'Alt Maestrat* and *Racó*, all of them are small. Furthermore, there are some *comarcas* that required 2 observatories, but they only have 1 (*Ports*, *Camp de Túria*, *Foia de Bunyol* and *Pallars Sobirà*). Finally, a huge *comarca*, *Noguera*, has only 2 out of 3 which correspond to it. 80 (89.9%) out of the 89 *comarcas* obtain the necessary series. There are 4 observatories, 3 in *Ribagorça* and 1 in *Llitera*, which are not located in the *comarca* itself. They are very close to its borders, permitting an analysis of the *comarca*'s rainfall by means of interpolation analyses (Figure 10).

1. Perpinyà	16. Breda	31. Sta. Margarida de M.	46. Organyà
2. Cap de Biarra	17. Tossa de Mar	32. Vilafranca del P.	47. La Seu d'Urgell
3. Sornià	18. Argentona	33. Cubelles	48. Sort
4. El Tec	19. Caldes de Montbui	34. Ransol	49. Molinos
5. Noedes	20. Llinars del Vallès	35. Els Omellons	50. Talarn
6. Fillols	21. Torrellebreta	36. La Granadella	51. Vilaller
7. Montlluís	22. Torelló	37. Raïmat	52. Vielha
8. Llívia	23. Puig-reig	38. Lleida	53. Plan
9. Campdevànol	24. La Pobla de Lillet	39. Agramunt	54. Seira
10. Camprodon	25. Callús	40. Mollerussa	55. Graus
11. Castellfollit de la R.	26. Moià	41. Torà	56. Binèfar
12. Cadaqués	27. Sabadell	42. Ponts	57. Mequinensa
13. Figueres	28. Barcelona (O. Fabra)	43. Pantà de St. Llorenç	58. Fraga
14. Palafrugell	29. El Prat de Llobregat	44. Tentellatge	59. Favara de Matarranya
15. Girona	30. El Bruc	45. Solsona	60. Pantà de Pena



61. Massalió	77. Castelló de la Plana	93. Montroi	109. Villena
62. El Vendrell	78. Morella	94. Sueca	110. Novelda
63. Vila-seca	79. Atzeneta del M.	95. Aiora	111. Pinós
64. Riudecanyes	80. Cortes d'Arenós	96. Teresa de Cofrents	112. Elx
65. Valls	81. Betxí	97. Millars	113. Torrevella
66. Rocafort de Queralt	82. Sogorb	98. Canals	114. Oriola
67. Cabacés	83. Viver	99. Ontinyent	115. Alacant
68. Flix	84. Sagunt	100. Benifairó de la V.	116. Valldemossa
69. Miravet	85. El Villar	101. Massalfassar	117. Pollença
70. Vilalba dels Arcs	86. Tuéjar	102. València	118. Ses Salines de Santanyí
71. Roquetes (O. Ebre)	87. Utiel	103. Manises	119. Capdepera (Far)
72. L'Ametlla de Mar	88. Requena	104. Picassent	120. Algaida
73. Amposta	89. Sinarques	105. El Verger	121. Sant Lluís
74. Sant Jordi del M.	90. Llíria	106. Gorga	122. Ciutadella
75. Sant Mateu del M.	91. Emb. de Forata	107. Callosa d'en Sarrià	123. Sa Savina
76. Pant. de Benadressa	92. Algemesí	108. Banyeres de M.	124. Sant Antoni de Port.

Figure 10. Monthly precipitation of the Catalan Countries for the 1951-2000 period.

2.4. DATABASE SOURCE AND VALIDATION

To obtain a feasible database, I searched previous databases which contained reliable and homogeneous series (Table 2). Out of the 124 series, 57 come from the NESAP database (CCRG) (Saladié *et al*., 2005), mostly throughout Catalonia and the Western Strip; 9 for the Balearic Islands come from the Earth Sciences Department of the University of Balearic Islands, 4 in Northern Catalonia come from Meteo France, other 4 from the ECA&D project and 2 from reliable sources. The less reliable are the 48 coming from the Spanish Meteorological Office (INM), which are mostly spread throughout the Valencian Country, however, I have chosen the ones used by the Mediterranean Environment Study Centre (CEAM) of València.

2 out of the 124 series selected were withdrawn, Énguera and Barraques, because they have either lots of gaps at annual resolution (Énguera) or lots of false 0 (Barraques). They were substituted by the Millars and Viver observatories, respectively. In Table 2, the name of the selected series or observatory points with their source are displayed for each *comarca*.

I counted the number of months with data of each series. The most complete period is at the beginning of 70s, and the least is during the first and last years. Saladié (2003) pointed out a significant decline at the end of the 20th century due to the lockout of several hydroelectricity stations.

Once the database is created, its rainfall spatial distribution coherency needs to be checked. Figure 11 shows the annual precipitation mean for the 1951-2000 period which is compared with the isohyets maps from the *Geografia General dels Països Catalans (1992)* based on the 1951-1990 period (Figure 8).

Comarca	Name O 1	Name O 2	Name O 3	Name O 4	Name O 5
Alacantí	Alacant				
Alcalatén	Atzeneta de M.				
Alcoià	Banyeres de M.				
Alt Camp	Valls				
Alt Empordà	Cadaqués	Figueres			
Alt Maestrat					
Alt Millars	Cortes de A.				
Alt Palància	Sogorb	Viver			
Alt Penedès	Vilafranca del P.				
Alt Urgell	Organyà	la Seu d'Urgell			
Alt Vinalopó	Villena				
Alta Cerdanya	Montlluís				
Alta Ribagorça	Vilaller				
Andorra	Ransol				
Anoia	el Bruc	Santa Margarida			
Bages	Callús	Moià			
Baix Camp	Riudecanyes				
Baix Cinca	Fraga	Mequinensa			
Baix Ebre	l'Ametlla de Mar	Roquetes (Ebre)			
Baix Empordà	Palafrugell				
Baix Llobregat	el Prat de Ll. (Ap.)				
Baix Maestrat	Sant Jordi del M.	Sant Mateu del M.			
Baix Penedès	el Vendrell				
Baix Segura	Oriola	Torrevella			
Baix Vinalopó	Elx				
Barcelonès	Barcelona 'O. Fabra'				
Berguedà	la Pobla de Lillet	Puig-reig			
Capcir					
Camp de Morvedre	Sagunt				
Camp de Túria	Llíria				
Canal de Navarrés	Millars				
Cerdanya	Llívia				
Comtat	Gorga				
Conca de Barberà	Rocafort de Queralt				
Conflent	Fillols	Noedes			
Costera	Canals				
Eivissa-Formentera	Sant Antoni 'Far'	sa Savina			
Fenolheda	Sornià				
Foia de Bunyol	Emb. de Forata				
Garraf	Cubelles				
Garrigues	la Granadella	els Omellons			
Garrotxa	Castellfollit de la R.				
Gironès	Girona				
Horta del Nord	Massalfassar				
Horta de l'Oest	Manises				
Horta del Sud	Picassent				
Llitera	Binèfar				
Mallorca	Algaida	Capdepera 'Far'	Pollença	ses Salines de S.	Valldemossa
Maresme	Argentona				
Marina Alta	el Verger				
Marina Baixa	Callosa d'en Sarrià				
Matarranya	Favara de Mat.	Massalió	Pantà de Pena		
Menorca	Ciutadella	Sant Lluís			
Montsià	Amposta				
Noguera	Ponts	P. de Sant Llorenç			
Osona	Torelló	Torrellebreta			
Pallars Sobirà	Sort				
Pallars Jussà	Molinos	Talarn			
Pde Estany					
Pd'Urgell	Mollerussa				
Plana Alta	P. de Benadressa	Castelló de la Plana			
Plana Baixa	Betxí				
Plana d'Utiel	Requena	Sinarques	Utiel		
Ports	Morella				
Priorat	Cabacés				
Racó					
Ribagorça	Graus	Plan	Seira		
Ribera Alta	Algemesí	Montroi			
Ribera Baixa	Sueca				
Ribera d'Ebre	Flix	Miravet			
Ripollès	Campdevànol	Camprodon			
Rosselló	Cap de Biarra	Perpinyà			
Safor	Benifairó de la V.				
Segarra	Torà				
Segrià	Lleida	Raïmat			
Selva	Breda	Tossa de Mar			
Serrans	Tuéjar	el Villar			
Solsonès	Solsona	Tentellatge			
Tarragonès	Vila-seca				
Terra Alta	Vilalba dels Arcs				
Urgell	Agramunt				
Val d'Aran	Vielha				
València	València				
Vall d'Aiora	Aiora	Teresa de C.			
Vall d'Albaida	Ontinyent				
Vallès Oriental	Caldes de Mont.	Llinars del V.			
Vallès Occidental	Sabadell				
Vallespir	el Tec				
Vinalopó Mitjà	Novelda	Pinós			

Source	Number (% of the total)	Reliability
NESAP (CCRG, Rovira i Virgili University)	57 (46.0%)	Reliable
Dept of Earth Sciences (University of Balearic Islands)	9 (7.3%)	Reliable
European Climate Assessment & Dataset	4 (3.2%)	Reliable
Meteo France	4 (3.2%)	Reliable
Andorran observer	1 (0.8%)	Reliable
Official Bulletin	1 (0.8%)	Reliable
	76 (61.3%)	
Spanish Meteorological Office (INM)	48 (38.7%)	Doubtful

Table 2. Database sources to constitute the observatories (O) network in the Catalan Countries (1951-2000).

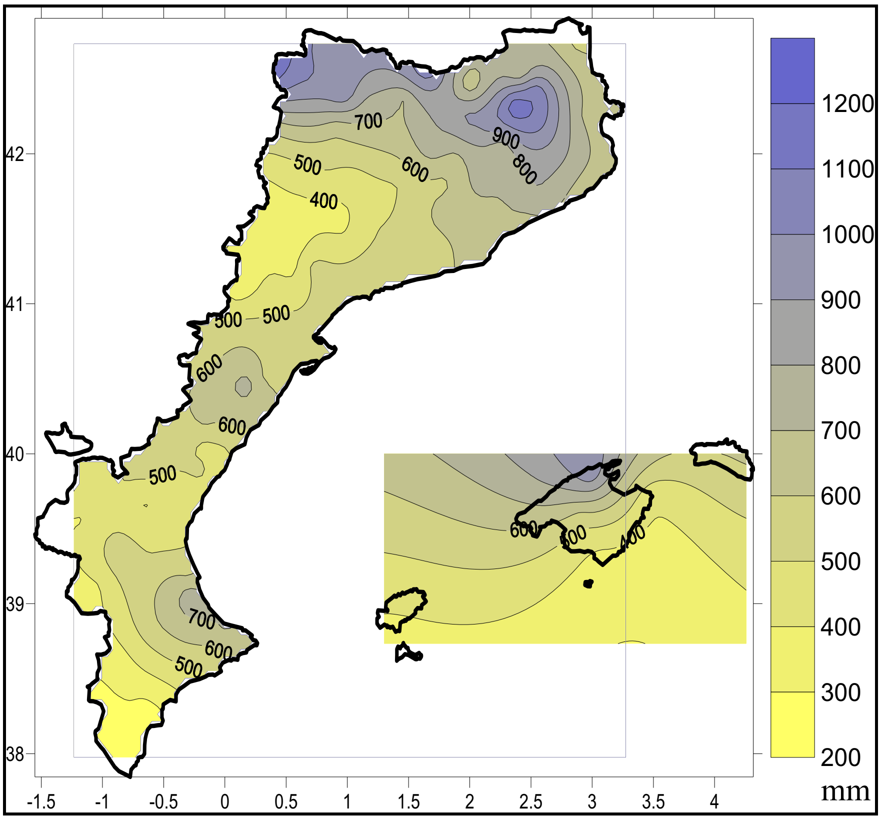


Figure 11. Annual isohyets map of the Catalan Countries using the new database (1951-2000).

The spatial rainfall distribution is coherent overall the study area:

- The wettest Catalan regions are included within the 700 mm isohyet.
- Rainfall maxima over the western Pyrenees and the eastern Pyrenees which are divided by the dry corridor in the Cerdanya region.
- Dry region over the Catalan central plain, being even drier in the Western Strip.
- Humid area in the Castelló mountains.
- North Alacant – south Valencian mountains are an orographical division, making the southern Gulf of València humid, and south and inland Alacant the driest area of the Catalan Countries.
- Balearic Islands: the north-south pluviometric gradient, being northern Mallorca and Menorca the wettest area and the Pitiüses the driest one.

The reliability of the database is not directly due to the homogeneous series, but to the very dense network achieved for the study area with some minimum quality control. This very dense network is preferable to a grid where some local phenomena might not be detected. The correct spatial distribution of rainfall is demonstrated, so the few remaining inhomogeneous series will slightly alter the main results. In addition, 2/3 of the observatories are unique series.

2.5. WeMO INFLUENCE ON THE CATALAN COUNTRIES RAINFALL

The monthly precipitation is correlated with WeMOi for the 1951-2000 study period. It is also correlated with NAOi in order to compare with the WeMOi, and the difference between the correlation coefficients is also calculated to check which of both patterns has the largest influence, (the monthly maps are not displayed in this version; please consult the Catalan version). The WeMO negative influence is greater than the NAO negative influence in February and October. In December, the precipitation is very satisfactorily correlated with the WeMOi, and also with the NAOi. February is the month when the WeMO has the largest influence both in extension and in intensity on the Catalan Countries, reaching the maximum value in southern inland Castelló. But the largest absolute difference in this month between the WeMOi and the NAOi is on the Castelló coastland. The loss of the NAO signal on the Catalan Countries rainfall in February in comparison with the neighbouring months, January and March must be emphasized.

The Balearic Islands rainfall is not well correlated with patterns due to the different flows which contribute precipitation to them. Nevertheless, the best correlation with the WeMOi is reached in December, but it is also when the NAOi is very well correlated, like in the continental Catalan Countries. Therefore, it is also in February when the WeMO has a largest influence over NAO, specifically, in the Pitiüses, however, it must be recognised that there is no almost WeMO influence on Mallorca and Menorca precipitation.

On the other hand, the WeMOi is positively correlated in December in the Val d'Aran (north-western Catalan Countries) because it is located on the northern face of the Pyrenees and its climate is subsequently oceanic, where it rains with north-westerly flows (positive WeMO phase).

Overall, the Valencian Country is more influenced by the WeMO than Catalonia. It might be explained due to the shoreline orientation (Martin-Vide and Lopez-Bustins, 2004). The Valencian Country faces east, permitting the easterlies flows to affect the area more directly than when the shoreline is orientated towards the south as in Catalonia. Southerly flows usually take place in NAO negative phases because of a low being situated west of the Iberian Peninsula. The eastern Pyrenees is also directly affected by the WeMO because the Costa Vermella, and Rosselló and Empordà plains face east too.

A seasonal analysis has been also carried out using the mean rainfall standardised values of the months of each season according to the 1961-1990 reference period (Figure 12). The NAO negative phase is absolutely predominant in spring over the Catalan Countries, whereas in autumn it is the WeMO. Val d'Aran is the only area which shows feasible positive correlation between its precipitation and WeMOi (autumn). In summer, both patterns have no influence on the rainfall in the Catalan Countries as expected like in the Iberian Peninsula analysis because most of the patterns have their maximum dynamics during the cold semester. On the other hand, in winter there is a clear division between Catalonia and the Valencian Country: Catalonia is under the NAO domain and the Valencian Country under the WeMO domain.

Northern Catalonia and northern Girona are under the WeMO domain due to the aforementioned east orientation of the coast. The highest values of the correlation coefficients between the Catalan Countries precipitation and NAOi take place over the inland Valencian Country (spring) and over inland Catalonia (winter), and with the WeMOi in the areas around the Alacant mountains – southern Gulf of València (autumn-winter). In autumn and winter, when the WeMO has the largest influence, three areas must be pointed out: 1) The eastern Pyrenees and the Rosselló and Empordà plains, 2) the Castelló province and 3) the southern Gulf of València and the north Alacant mountains.

Referring to the analysis of the Balearic Islands, the significant correlation between its rainfall and NAOi in spring must be highlighted above all, in Mallorca. In winter, there is also a significant correlation between rainfall and NAOi in northern Mallorca. In contrast, the WeMOi is only significantly correlated to the Balearic precipitation in Eivissa both in autumn and in winter. The maps of absolute difference between both patterns show that the Balearic Islands are totally under NAO influence in spring, and under WeMO in autumn. In winter, there is a clear division between the north-eastern part (Menorca and northern Mallorca) which is under NAO domain, and the south-western part (southern Mallorca and Pitiüses) which is under WeMO domain (Figure 13). This division reflects the division taking place between Catalonia and the Valencian Country. This south-west – north-east gradient on Balearic Islands might be caused by the orographical effect of the Pyrenees because the Pitiüses and southern Mallorca are leeward to the north winds and are only influenced by eastern and southern Mediterranean flows (Grimalt, personal communication). The Pitiüses have a similar behaviour to that of the north-eastern Alacant *comarcas* due to the relative geographical closeness between both areas (a little less than 100 km). Neither is there a relationship between rainfall and teleconnection patterns in the Balearic Islands in summer due to both scarce precipitation and the predominance of convective storms over inland Mallorca (Alomar and Grimalt, 2006).

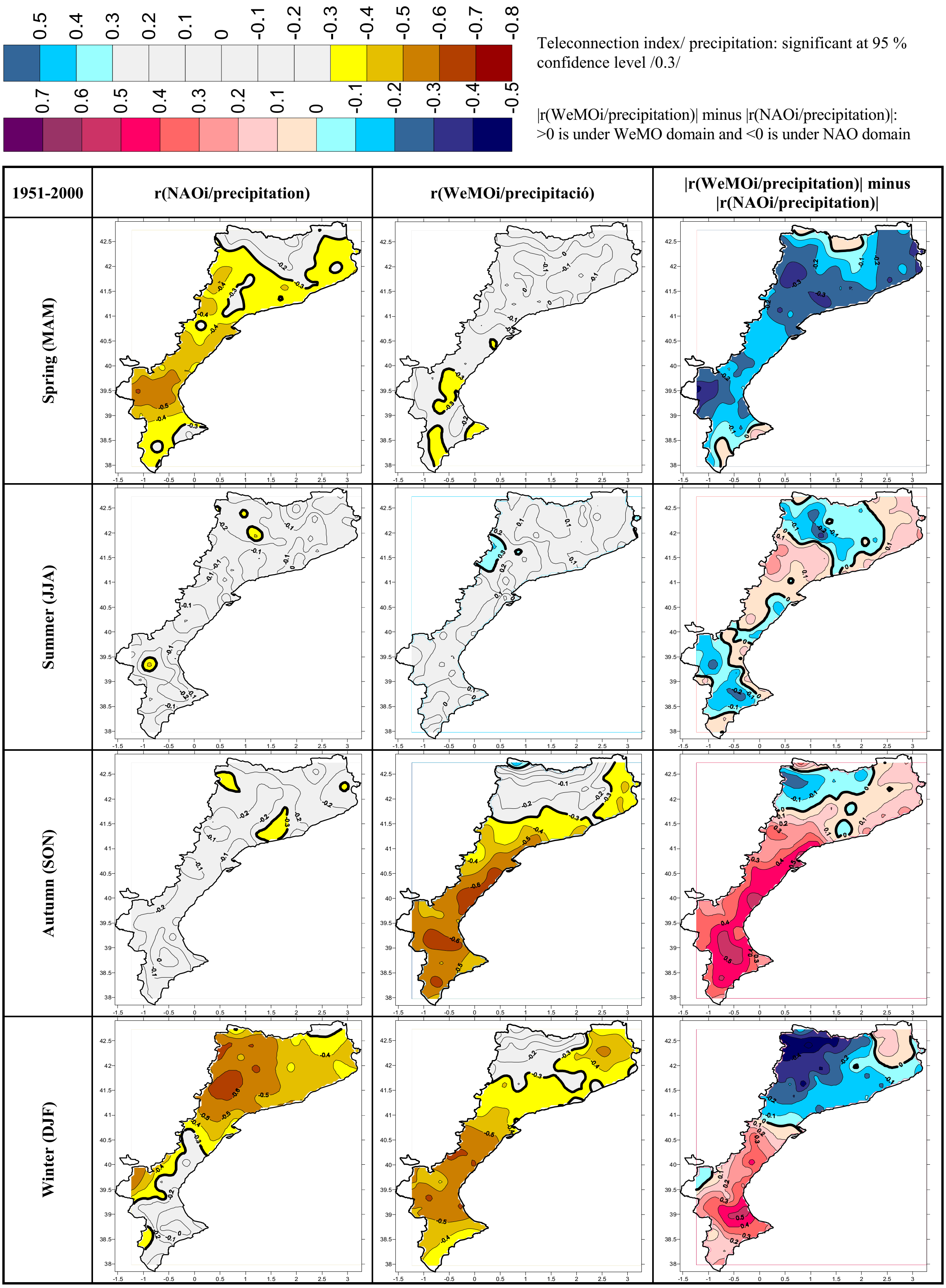


Figure 12. Spatial distribution of the Pearson's correlation coefficients between the continental Catalan Countries precipitation and NAOi (left column), and WeMOi (central column), for each one of the seasons for the 1951-2000 study period. The right column shows the differences between the absolute values obtained with the WeMOi minus the values obtained with the NAOi. (The coloured areas of the two first columns are significant at 0.05. The coloured areas in the right column distinguish the NAO influence –negative values– from the WeMO influence –positive values–).

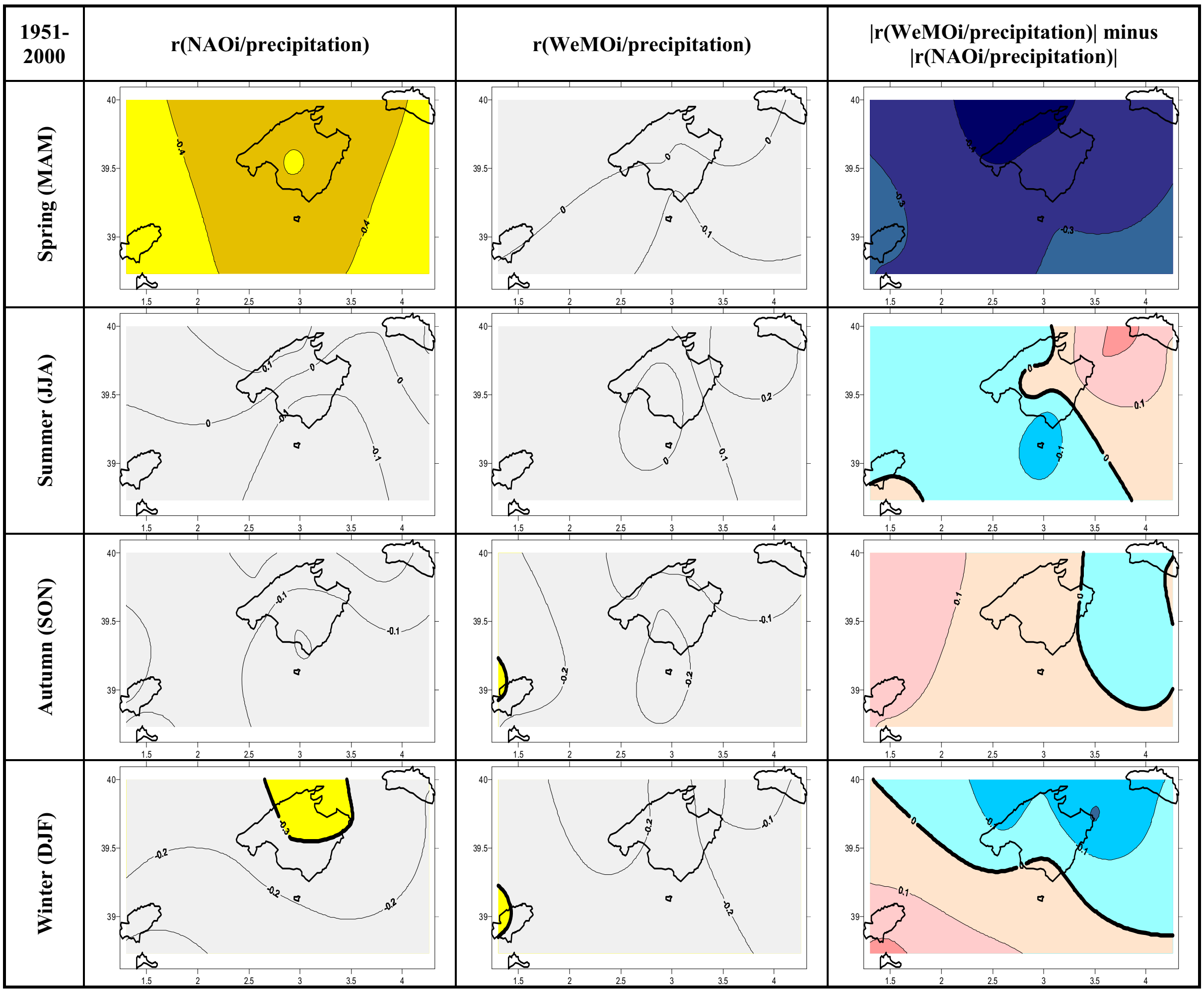


Figure 13. Idem as Fig. 12, but for Balearic Islands.

2.6. RAINFALL ANOMALIES IN THE CATALAN COUNTRIES IN EXTREME WeMO PHASES

Using the 1961-1990 reference period, the rainfall anomalies are calculated in % for the years when the WeMO is extremely positive or negative. A seasonal analysis is performed, except for summer, a period when the WeMO is irrelevant. The thresholds established are WeMOi >+0.75 and WeMOi <-0.75. Hurrell (1995) established the threshold /1/ for the NAO monthly extreme phases analyses. Consequently, for the seasonal analyses it would be convenient to reduce this threshold to /0.75/ since there is less variability. The standardised values mean of the months of each season of those selected years are displayed in the following figures. The value 0 is the rainfall mean of the 1961-1990 reference period. The anomalies analysis is also performed for the NAO extreme phases in order to make a comparison with the WeMO.

2.6.1. EXTREME POSITIVE WEMO PHASE (WEMOI >+1)

Winters in an extreme positive WeMO phase is when there is a very pronounced rainfall reduction throughout the study area, the maximum being the Gulf of València. Autumn is the second season when the decrease is most perceptible, above all, in the Valencian Country. Winter is when there is the largest rainfall reduction in the Valencian Country but autumn is when the WeMOi is best correlated. Therefore, this point demonstrates that these maps can show a different WeMO influence on Catalan Countries rainfall (Figure 14). The decreases are slighter in spring. In addition they are more noticeable in extreme positive NAO phases. This last result is feasible since the NAO has a greater influence than the WeMO over the study area in spring. In winter and autumn, the extreme positive NAO phase does not succeed in reducing the precipitation like the WeMO does over the continental Catalan Countries, except for western Catalonia. This last point justifies once again the proposition of the definition of this new pattern. On the other hand, the Val d'Aran has a remarkable rainfall increase in extreme positive WeMO phases in winter and in autumn. It is also noticed around the nearby areas facing the south Pyrenees because the north-westerly winds from the Atlantic can flow beyond the Pyrenees orographical division when they are strongly reinforced.

The Balearic Islands are only analysed for autumn and winter, when the WeMO influence is noticeable (Figure 15). In winter, the extreme positive WeMO phases produce a rainfall increase quite larger than the increase produced by the extreme positive NAO phases. The highest reduction in extreme positive WeMO phases obviously takes place in the Pitiüses. Even Formentera has no precipitation decrease in extreme positive NAO phases. This anomalies analysis according to the extreme positive phases shows a WeMO influence on the rainfall in the Balearic Islands that is remarkably superior to the NAO influence. In autumn, the WeMO influence on rainfall reduction is superior to the NAO influence, above all, in western Eivissa and eastern Menorca.

2.6.2. Extreme negative WeMO phase (WeMOi <-1)

In winter, it is when there is the most extended rainfall rise over the continental Catalan Countries in an extreme negative WeMO phase, above all, in the valleys in southern València (Albaida valley), in Ports (north inland Castelló) and most of Catalonia (Figure 14). Precipitation in western Catalonia is greatly increased in extreme negative NAO phases. The Valencian Country has the largest rainfall rise in autumn under WeMO influence, whereas NAO has no influence over all the continental Catalan Countries during this season. Spring has the highest variations according to the negative NAO phases in inland areas, and these variations are not so noticeable as with the WeMO phases. A slight precipitation decrease is detected in the north-western Pyrenees with extreme negative WeMO phases in autumn.

The Balearic Islands are divided by the NAO and WeMO influences in winter (Figure 15). The Pitiüses responds to a higher increase with the extreme negative WeMO than with the NAO one. Mallorca has rainfall rises with both patterns, and Menorca a slight rise with a negative NAO phase and none with the WeMO. Overall, the very negative WeMO leads to rainfall increases in Balearic Islands, higher than those expected due to the previous weak correlations with the WeMOi (Figure 13). In addition, over the south-western half of the Balearic Islands, the WeMO shows to have a larger influence than NAO with remarkable rainfall anomalies in the Pitiüses. On the other hand, in autumn, the NAO gives more noticeable rainfall rises than the WeMO, above all, in western Eivissa.

2.6.3. Summary

The WeMO shows the Mediterranean cyclogenesis in its most dynamical period in autumn and winter, since the Catalan Countries rainfall anomalies are well detected according to the WeMO extreme phases, with a predominant influence over any other pattern. The regions which present a major response are the ones that are orientated towards the east: 1) the Valencian Country, 2) the east half of the Pyrenees with the Rosselló and Empordà plains and 3) the Pitiüses. The WeMO influence on the Balearic Islands is more outstanding in the pluviometric anomalies analysis during the extreme WeMO phases than in the correlations analysis, being more noticeable in that extreme positive WeMO phase.

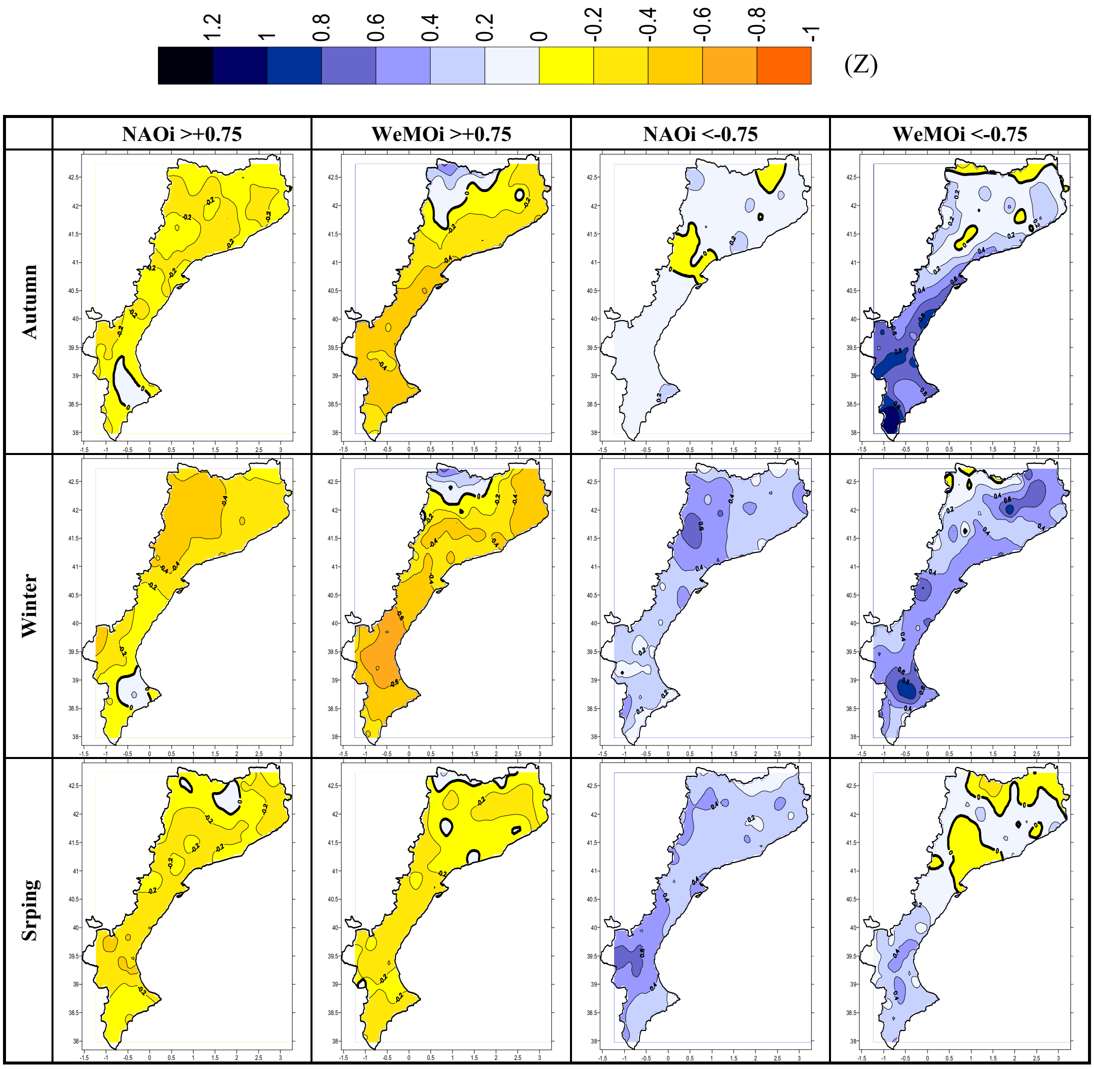


Figure 14. Rainfall anomalies in the continental Catalan Countries in Z values, according to the mean standardised values of the months of each season for the 1961-1990 reference period, in years with an extreme positive phase (>+0.75) and negative (<-0.75) of the WeMO, for winter, spring and autumn, of the 1951-2000 period. (The value 0 corresponds to the rainfall mean).

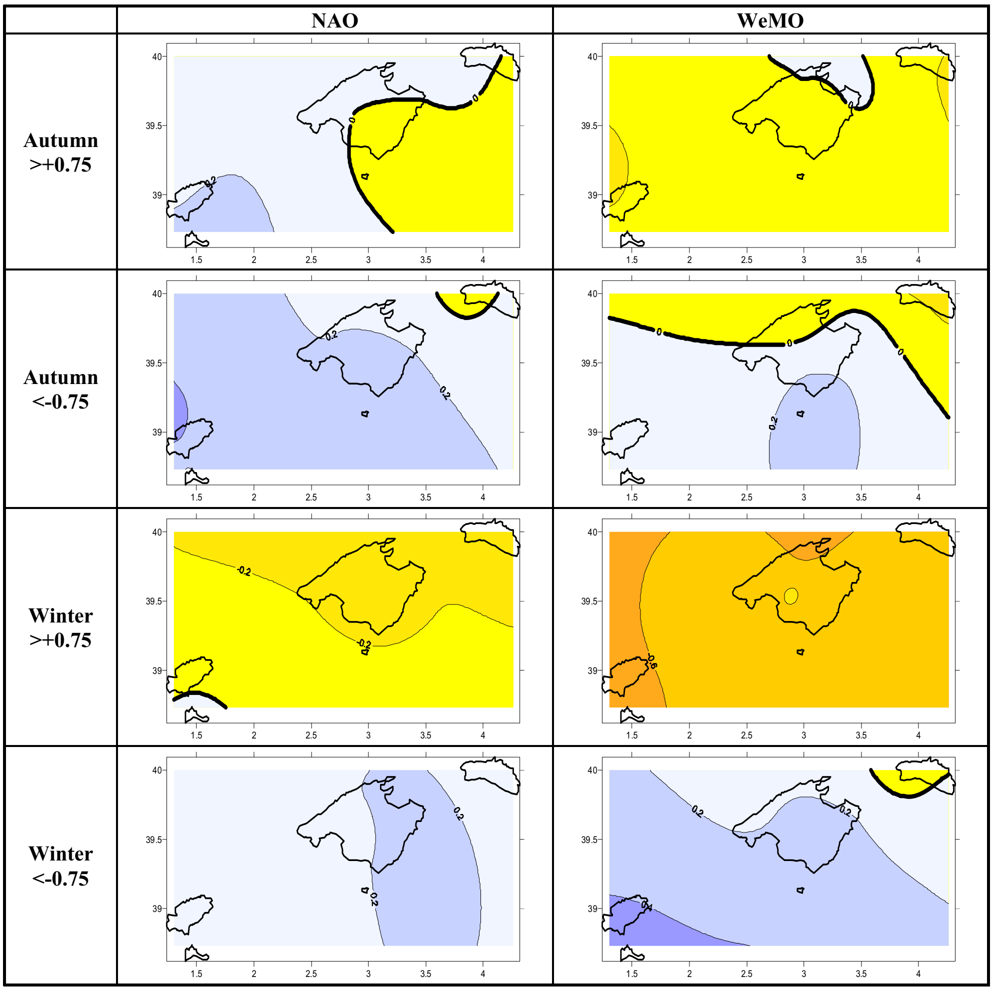


Figure 15. Idem as Fig. 14, but for the Balearic Islands in autumn (SON) and in winter (DJF).

2.7. DAILY WeMOi APPLICATION

The 7 reference meteorological stations of the Figure 12 in the 1st chapter are defined as the first order series, out of which 5 are the from Catalan Countries coast, and two are from beyond the north and south limits. Thus a daily WeMOi application for the whole north-western Mediterranean shoreline can be performed.

2.7.1. CORRELATIONS BETWEEN THE RAINFALL IN 7 METEOROLOGICAL STATIONS AND WEMOI, NAOI AND ATMOSPHERIC PRESSURE IN SAN FERNANDO AT DAILY RESOLUTION

Martin-Vide and Lopez-Bustins (2004) detected that WeMO is more influent than NAO at a major temporal resolution (from annually to monthly, and monthly to daily). Table 3 shows that the WeMOi is generally better correlated than NAOi and San Fernando pressure with the precipitation series at daily resolution. Tortosa, which is located in the middle of the study area, is where the WeMOi obtains the highest coefficient correlation. But València is the location where the WeMO has the largest influence over the NAO. Perpinyà and Torrevella precipitation also has a better correlation with the WeMOi than with the NAOi. In contrast, the distances between both patterns influence are shortened in Barcelona and Malaga; they are even inversed in Marseille. Overall, the areas under WeMO domain fit with those areas detected in the previous monthly and seasonal analysis.

Taking San Fernando pressure into account, the series that best correlate with it, even over the WeMOi and the NAOi, are the ones obtained at the observatories located on the coasts facing south: Marseille (French Riviera), Barcelona (Central Catalan Coast) and Malaga (*Costa del Sol*). On the other hand, the rest are better correlated with the WeMOi than with the NAOi and San Fernando pressure due to the aforementioned eastward orientation of the coast where they are located: Perpinyà (*Costa Vermella* – Rosselló plain), Tortosa (*Costa Daurada* – Ebre delta), València (*Costa dels Tarongers*) and Torrevella (*Costa Blanca*).

1951-2000	Marseille	Perpinyà	Barcelona	Tortosa	València	Torrevella	Malaga
WeMO D	-11.6	**-24.3**	-23.2	**-29.4**	**-28.1**	**-18.1**	-36.8
NAO D	-15.2	-15.5	-18.6	-17.9	-13.2	-7.3	-30.2
SF D	**-21.3**	-22.0	**-25.1**	-26.0	-20.9	-12.2	**-42.0**

Table 3. Pearson's correlation coefficient significances between the 7 reference meteorological stations rainfall and WeMOi, NAOi and San Fernando (SF) pressure at daily resolution for the 1951-2000 period. The correlation is significant at 0.05 if the value is ≥/1.96/ and at 0.01 if the value is ≥/2.58/. (The bold values correspond to the highest significance obtained among the variables of the first column for each observatory).

The local geographical features of the coast and the relief orientation are very important. Even minor differences on local orographies can determine the dependence on a Mediterranean or Atlantic variability. Table 4 and Figure 16 show real examples. There are about two precipitation episodes in daily extreme negative WeMO and NAO phases in February. The rainfall responses in the 7 reference meteorological stations are different according to the intensity reached by each pattern. If the WeMOi is more negative than the NAOi, it will rain over those observatories with an eastern orientation, but will only slightly rain over the rest. The synoptic situation is a low located on the Gulf of Cadiz in transition to the Mediterranean Sea (situation defined as Mediterranean –Azorín-Molina and López-Bustins, 2004–), the flows are easterly (Figure 16, left). If the NAOi is more negative than the WeMOi, it will rain over the ones facing south, but there will be almost no precipitation over the ones facing east due to the continental southerly wind track over the Iberian Peninsula. The synoptic situation is a low pressure system west to the Iberian Peninsula with south/ south-westerly advections which are humid just for the coasts facing south (situation defined as Atlantic type) (Figure 16, right). Lastly, it is worthy to mention that the NAOi does not succeed in explaining the daily precipitation better than the San Fernando pressure in any observatory (Table 3).

Date	WeMOi	NAOi	Marseille	Perpinyà	Barcelona	Tortosa	València	Torrevella	Malaga
03/02/1959	-2.91	-2.09	10.5 mm	**108.9 mm**	10.7 mm	8.6 mm	**20.6 mm**	6.5 mm	15.8 mm
21/02/1969	-0.93	-2.65	**15.4 mm**	0.9 mm	**15.8 mm**	1.1 mm	1.2 mm	0 mm	**11.3 mm**

Table 4. Rainfall in the 7 meteorological stations in two different episodes in February (Figure 16) according to WeMOi and NAOi. (In bold, the most outstanding amounts).

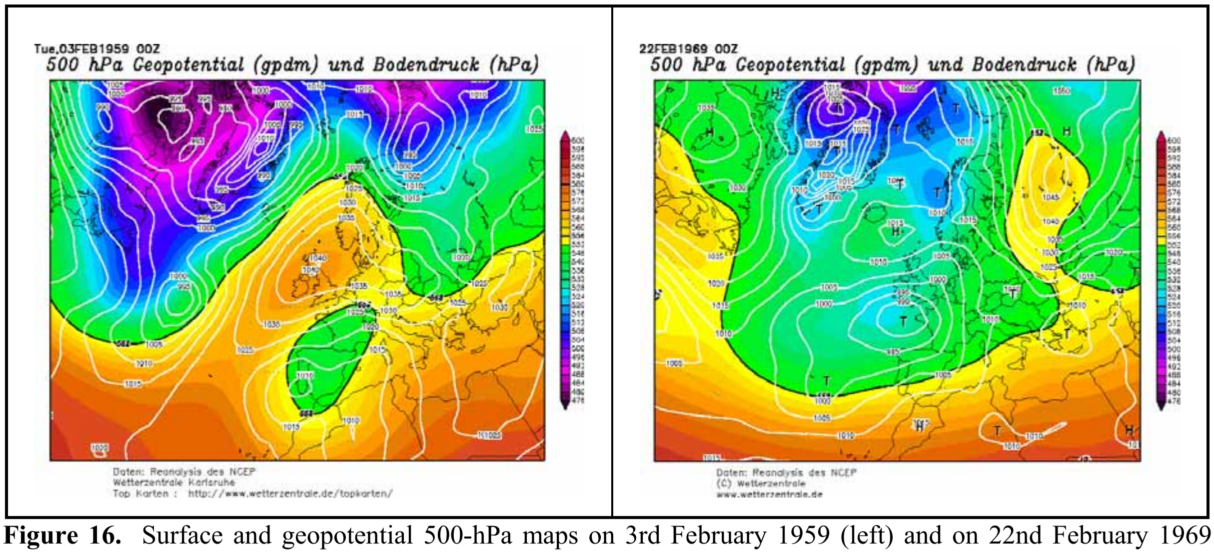


Figure 16. Surface and geopotential 500-hPa maps on 3rd February 1959 (left) and on 22nd February 1969 (right) (00 h UTC).

2.7.2. DAILY WEMOI AS A TOOL FOR FORECASTING INTENSE AND TORRENTIAL RAINFALL

This analysis is bidirectional. Firstly, we have to calculate the daily WeMOi intervals distribution of rainfall episodes, to be able to detect the more frequent index values. Secondly, we must establish different WeMOi thresholds to calculate the occurrence frequency of daily precipitation of the different thresholds. Some studies have analysed torrential events probabilities and frequencies according to the NAO behaviour, but without using the daily index values (Haylock and Goodess, 2004; Rodrigo, 2006).

2.7.2.1. Daily WeMOi distribution in torrential events

The threshold selected is >100 mm/ 24 h and the period is 1951-2000. The episodes are selected from the 7 reference series, and 57 cases are detected, although València and Torrevella have a common case. Each date when one of this events takes place is related to a daily WeMOi and NAOi value (Table 7). It is worth observing that no episode has been corresponded with a positive WeMOi value, whereas the NAOi is positive in 32% of the cases. The highest daily episodes >100 mm concentration is in the (-2, -1) interval (Figure 17). It does not imply that extreme negative WeMOi values do not favour the occurrence of episodes, but the empirical frequency of extreme negative WeMOi values is less. The NAOi includes episodes with very positive values, there being more than one episode in the (1, 2) interval, and the most frequent values are in the central intervals (-1, 0) and (0, 1) (Figure 17). The WeMOi neutral interval is (-1, 1) (Lopez-Bustins and Azorin-Molina, 2005), but often a more strict interval is used (-0.5, 0.5) (López-Bustins and Azorín-Molina, 2004), above all with monthly WeMOi values which have less variability.

The WeMOi is negative (-1.14) on 13th September 1963, but the NAOi is simultaneously positive (+1.00) (Figure 18). The NAO action centres –low Iceland and Azores high– are well located to favour a positive phase, but at the same time there is an anticyclonic ridge from the Eastern Atlantic to Central Europe, together with the Argel low, favouring easterly flows (a negative WeMO phase). This synoptic map shows that the regional WeMO pattern is totally independent from the NAO one at a daily resolution. The precipitation was torrential over the Rosselló plain and intense[3] in Catalonia and the Valencian Country. On the contrary, Marseille and Malaga registered little precipitation. It is demonstrated that the points beyond the Catalan Countries area are more dependant on the NAO.

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[3] In this thesis, torrential rainfall (>100 mm/ 24 h) is distinguished from intense rainfall (>50 mm and <100 mm in 24h). Other thresholds might be used in other studies.

DATE	LOCATION	PRECIP (mm)	Daily WeMOi	Daily NAOi	DATE	LOCATION	PRECIP (mm)	Daily WeMOi	Daily NAOi
1951-09-12	Tortosa	112.8	-0.83	1.09	1971-11-07	Tortosa	124.5	-2.18	-1.87
1951-10-30	Marseille	106.8	-1.44	-0.10	1971-12-05	Barcelona	196.0	-2.65	0.09
1953-12-06	Perpinyà	113.5	-2.44	0.71	1972-10-17	Torrevieja	119.8	-1.70	-2.45
1956-11-16	Malaga	104.4	-0.55	-0.16	1973-06-04	València	101.4	-0.37	-0.34
1956-11-17	València	262.6	-1.12	0.66	1973-10-02	Marseille	140.0	-1.48	-0.85
1957-05-29	Tortosa	116.6	-0.62	-1.38	1977-05-18	Perpinyà	127.2	-1.78	-1.38
1957-09-27	Malaga	313.0	-0.50	-0.73	1977-10-18	Perpinyà	111.2	-2.21	-0.80
1957-10-14	València	125.1	-1.70	0.07	1979-01-18	Malaga	121.5	-4.10	-4.77
1958-06-18	València	123.0	-1.55	-1.71	1980-02-26	València	101.5	-0.20	0.10
1959-02-03	Perpinyà	108.9	-2.89	-2.07	1982-02-16	Perpinyà	177.8	-2.41	-1.27
1959-09-02	Perpinyà	186.1	-0.84	0.04	1982-04-18	València	105.6	-0.58	-1.30
1959-09-20	Tortosa	114.4	-1.49	0.45	1982-10-21	Tortosa	119.7	-2.68	-0.13
1959-09-29	Perpinyà	127.1	-1.68	-1.13	1982-11-06	Malaga	147.1	-4.05	-2.37
1959-10-25	Torrevieja	114.8	-0.48	1.58	1984-02-27	Malaga	126.6	-1.68	-2.48
1960-06-05	Tortosa	104.2	-0.82	-1.1	1985-02-21	Torrevieja	220.0	-1.84	0.35
1962-02-24	Tortosa	104.5	-2.03	-3.42	1985-10-26	Perpinyà	136.6	-1.89	-1.51
1963-09-13	Perpinyà	105.6	-1.14	1.00	1986-03-01	Perpinyà	117.8	-4.21	-4.79
1963-09-15	València	111.1	-1.10	0.04	1987-10-04	Barcelona	144.1	-2.79	-0.28
1965-10-10	Perpinyà	165.2	-0.88	-2.19	1989-09-04	València	134.4	-0.69	-0.74
1965-10-19	Tortosa	176.5	-1.35	0.66	1989-09-04	Torrevieja	240.0	-0.69	-0.74
1965-10-29	València	147.5	-1.81	0.26	1989-11-14	Malaga	140.2	-3.04	-2.63
1966-10-10	València	148.4	-1.51	-1.06	1989-12-01	Torrevieja	112.2	-1.82	0.50
1969-02-18	Malaga	112.3	-4.16	-4.61	1992-09-26	Perpinyà	124.6	-2.20	-0.89
1969-02-22	Malaga	151.0	-1.81	-2.89	1994-09-29	Barcelona	114.6	-1.78	-1.89
1969-03-04	Perpinyà	116.8	-1.19	-1.17	1994-10-10	Tortosa	110.3	-2.32	-0.17
1969-04-04	Perpinyà	112.5	-2.21	-0.06	1999-11-12	Perpinyà	222.0	-2.96	-2.31
1969-10-05	València	108.2	-1.56	0.79	2000-09-19	Marseille	200.0	-0.23	-2.02
1970-10-11	Perpinyà	121.6	-1.61	0.12	2000-10-23	València	165.0	-2.27	-0.05
1971-10-06	València	140.3	-2.73	0.87					

Table 7. Episodes >100 mm in 24 h on the 7 reference observatories during the 1951-2000 period with the corresponding to daily WeMOi and NAOi values.

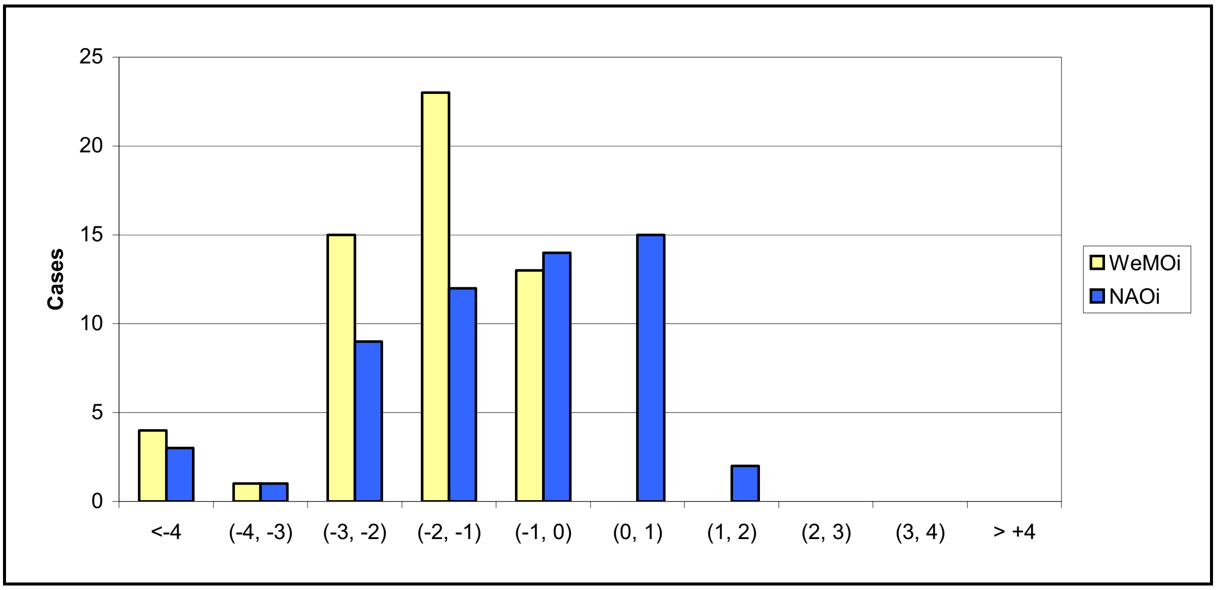
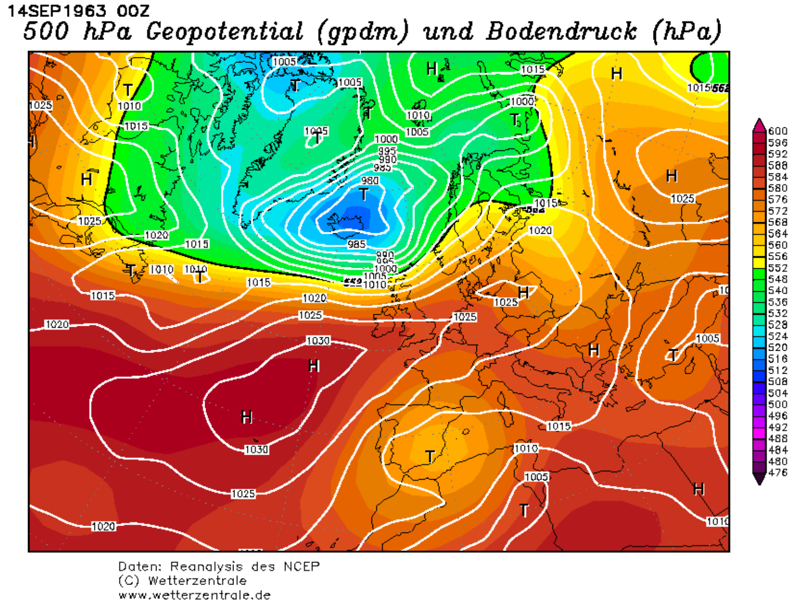


Figure 17. WeMOi and NAOi values distribution of the days when at least 1 out of the 7 observatories has registered >100 mm/ 24 h during the 1951-2000 period.



Precipitation (mm)

Marseille (9.4 mm)
Perpinyà (105.6 mm)
Barcelona (76.5 mm)
Tortosa (72.9 mm)
València (43.0 mm)
Torrevella (0 mm)
Malaga (0 mm)

WeMOi -1.14
NAOi +1.00

Figure 18. Surface and geopotential 500-hPa map on 14th September 1963 (00 h UTC). Precipitation amount of the 7 meteorological stations and daily WeMOi and NAOi values are displayed in the right column.

2.7.2.2. Frequency analysis of episodes with different thresholds according to the WeMOi value

To assess the frequency of the episodes of each observatory, first, the normal frequency occurrence of each point of the episodes with different thresholds is calculated (Table 8). The observatory point with the highest rainfall mean is Barcelona, but the one with the highest frequency in daily precipitation ≥0.1 mm is Perpinyà. The >10 mm threshold is maximum in Barcelona, but the most torrential is in Perpinyà.

1951-2000	Marseille	Perpinyà	Barcelona	Tortosa	València	Torrevella	Malaga
≥0.1 mm	22.7 %	25.1 %	22.3 %	22.4 %	19.3 %	10.9 %	15.0 %
>10 mm	5.0 %	4.2 %	5.2 %	4.2 %	3.3 %	1.8 %	4.6 %
>100 mm	0.02 %	0.09 %	0.02 %	0.05 %	0.07 %	0.03 %	0.04 %
X 1951-2000	589.7 mm	579.1 mm	630.5 mm	549.6 mm	452.3 mm	249.4 mm	560.3 mm

Table 8. Daily frequency occurrence in precipitation ≥0.1 mm, >10 mm and >100 mm and rainfall mean in each location for the 1951-2000 study period.

If we establish the WeMOi threshold <-2, the highest occurrence probabilities of a rainy day in València is almost 72% (Table 9). Tortosa and Malaga will probably register precipitations slightly over 70%. Although Torrevella obtains the lowest frequency, its probability increases fourfold since its normal frequency is 10.9%. With >10 mm, Malaga and Perpinyà obtain the highest percentages, narrowly followed by Tortosa. The daily frequency with a threshold >100 m is noticeably higher (1.2%) than the initial 0.09% (Table 8) in Perpinyà.

The most interesting frequencies are those obtained with an extreme WeMOi value. If the WeMOi is lesser than -4, the frequency of a rainy day is over 90% in Tortosa, and over 80% in Perpinyà, Barcelona, València and Malaga. The frequency of a > 10 mm rainy day is over 60 % in Perpinyà and Malaga. The frequency of 100 mm in 24 h is over 10% in Malaga.

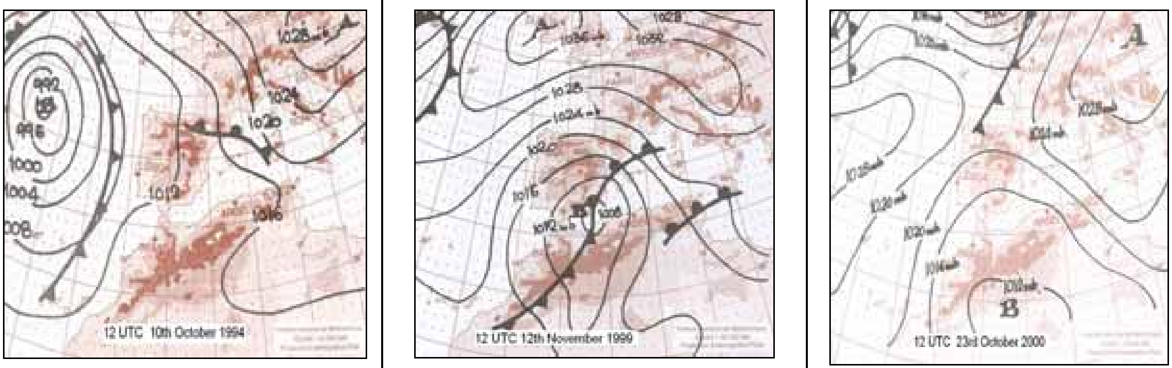
Daily WeMOi (days)	Episode threshold	Marseille	Perpinyà	Barcelona	Tortosa	València	Torrevella	Malaga
<-4 (29)	≥0.1 mm	51.7 %	82.8 %	86.2 %	93.1 %	82.8 %	44.8 %	89.7 %
	>10 mm	3.4 %	62.1 %	41.4 %	34.5 %	20.7 %	0 %	65.5 %
	>100 mm	0%	3.4%	0%	0%	0%	0%	10.3%
<-2 (659)	≥0.1 mm	39.7%	59.5%	61.8%	71.3%	71.8%	44.9%	70.6%
	>10 mm	10.3%	27.2%	22.9%	25.2%	22.2%	8.3%	39.9%
	>100 mm	0%	1.2%	0.3%	0.6%	0.3%	0%	0.6%
>+4 (44)	≥0.1 mm	40.9 %	84.1 %	4.5 %	29.5 %	2.3 %	2.3 %	0 %
	>10 mm	2.3 %	13.6 %	0 %	2.3 %	0 %	0 %	0 %
	>100 mm	0%	0%	0%	0%	0%	0%	0%
>+2 (1.035)	≥0.1 mm	28.5%	44.1%	8.3%	12.9%	3.1%	2.2%	2.9%
	>10 mm	1.4%	2.2%	0.6%	0.3%	0%	0.1%	0.1%
	>100 mm	0%	0%	0%	0%	0%	0%	0%

Table 9. Frequency of ≥0.1mm, >10 mm and >100 mm episodes according to the following WeMOi thresholds <-4, <-2, >+4 and >+2 at daily resolution in 7 observatories during the 1951-2000 period.

In an extreme positive phase, low rainy day frequencies are expected. Nevertheless, some observatories show contradictory behaviours. The threshold >+2 reduces the frequency of a rainy day to under 10% in Barcelona, València, Torrevella and Malaga, but above normal frequencies are obtained in Marseille and Perpinyà. The >10 mm episodes are below normal frequencies (Table 8) everywhere and torrential events do not take place. With a >+4 WeMOi threshold, Perpinyà even strongly increases its rainy day frequency over 80%; Marseille, over 40%, and Tortosa, almost 30%. Perpinyà reaches a higher % with a >+4 WeMOi threshold than with a <-4 one. This is due to the passage of Atlantic fronts over western France and the humid Atlantic flows succeed in reaching the Rosselló plain through the Aquitaine plain. The >10 mm episodes have a 13.6% frequency in Perpinyà with >+4, much lesser than with <-4, and 2.3% in Tortosa and Marseille. The rest obviously remain with a 0%. The precipitation episodes are weak when the flows come from the Atlantic; they never have a torrential feature.

2.7.2.3. Assessment of the WeMOi use for calculating the pluviometric frequencies at daily resolution in the Catalan Countries

Daily WeMOi is another tool to be considered in reanalyses and forecasts of intense and torrential rainfall episodes. It is also suitable to calculate a rainy day probability. In this sense, a rainy day (≥0.1 mm) is 4 times more probable than the normal frequency in some locations in the Catalan Countries when the WeMOi is extremely negative, or positive on the Rosselló plain. Higher rainy episodes (>10 mm) are as much as 8 times more probable, above all in Perpinyà where they are as much as 10 times, in an extreme negative phase. Nevertheless, the extreme positive WeMO phase does not succeed in increasing these >10 mm episodes in Northern Catalonia, since Atlantic flows coming from the Aquitaine plain are relatively humid but weakened. Anyway, in extreme WeMO phases, both negative and positive, the highest probability of >10 mm occurrence is in Rosselló plain. Torrential events do not take place in those days extremely negative (WeMOi <-5) necessarily, but with moderate negative values which are more frequent. Synoptic situations with negative WeMOi of (-3, -2) interval lead to precipitations over 100 mm in 24 h in different points in Catalan Countries (Figure 19).



110.3 mm - Tortosa - WeMOi –2.32 | 222.0 mm - Perpinyà - WeMOi –2.96 | 165.0 mm – València - WeMOi –2.27

Figure 19. Synoptic situations of torrential episodes in Catalan Countries with negative WeMOi values (-3, -2). (From Martin-Vide and Lopez-Bustins, 2006. Maps are from the daily meteorological bulletin of the Spanish Meteorological Office).

Daily WeMOi functional nature in foreseeing rainy intense episodes in Catalan Countries is demonstrated in a central location of the study area, Tortosa. It is very close to the Valencian Country, where WeMO most influences on precipitation. Moreover, Tortosa is where is most probable a rainy day occurs with <-4 WeMOi (93.1%) and a largest amount of >50 mm/ 24h episodes is accumulated (77 cases). 69.8% of the 4.071 rainy days in Tortosa for the 1951-2000 period took place with a negative WeMOi, clearly surpassing the 53.0% of negative WeMOi days for the entire 1951-2000 study period. 96.1% of the 77 (>50 mm/ 24 h) episodes are corresponded with negative WeMOi values and the 9 (>100 mm/ 24 h) episodes too, without any exception (Figure 20). Hence, the probability of a torrential event on a day with positive WeMOi in Tortosa is practically nil.

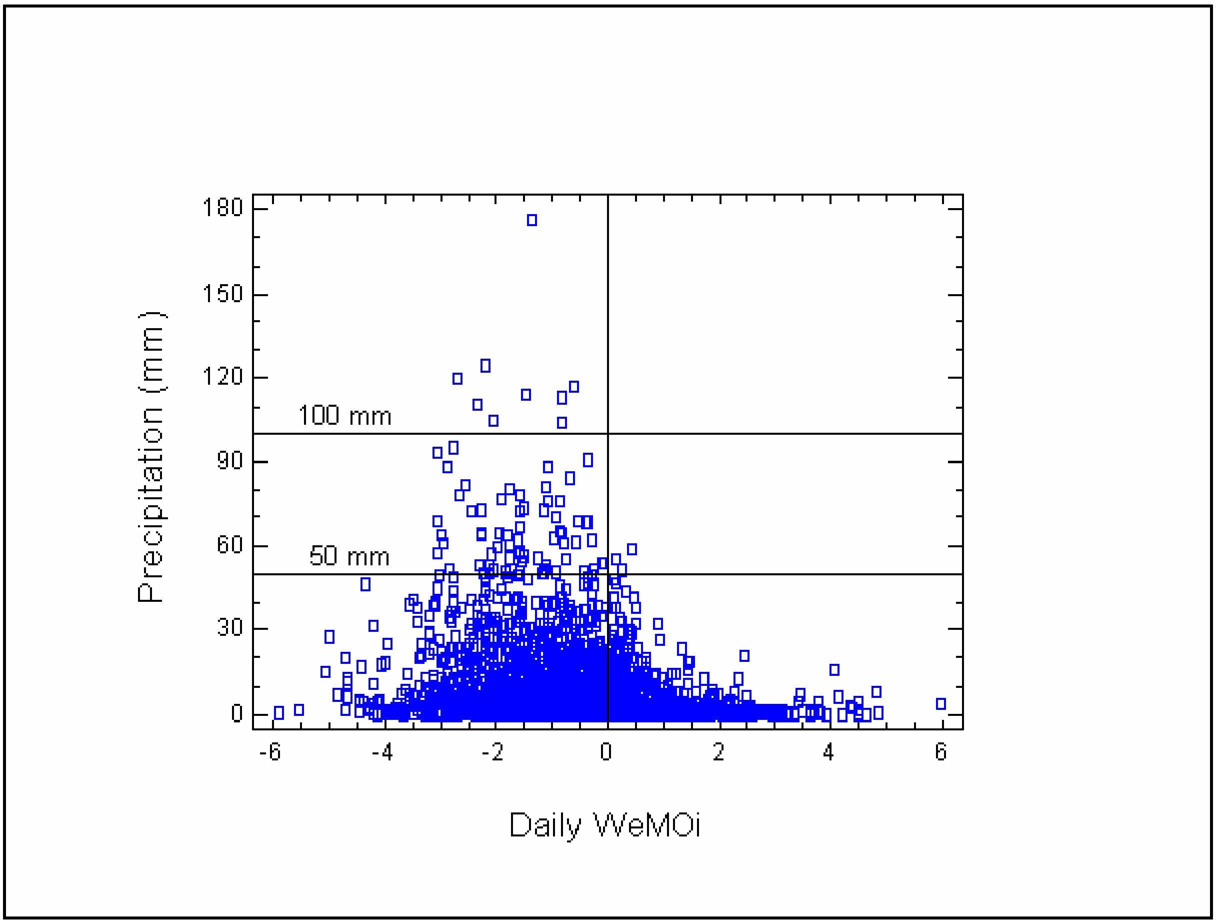


Figure 20. Statistical distribution of the daily WeMOi values for the rainy days of the 1951-2000 period in Tortosa. (Extracted from Martin-Vide and Lopez-Bustins, 2006).

2.8. WeMO CALENDAR CONSTRUCTION

The goal is to study the WeMO annual variability. The mean of the daily WeMOi values by fortnights is worked out. Subsequently, 24 values are obtained to detect WeMO seasonality. The WeMO is in its extreme negative phase in autumn, specifically in the 1st fortnight of October (Figure 21). In the months of autumn, Mediterranean storms are more frequent, favoured by warmer sea water, leading to a deeper Argel low and a low pressure system over the Gulf of Cadiz (Figure 19).

In winter, the WeMO is in a positive phase which reflects the passage of cold fronts north of the Iberian Peninsula. In spring, the WeMO has a more irregular variability, showing an oscillation around 0. The neutral phase is frequent in this season, so convective precipitation is abundant (López-Bustins and Azorín-Molina, 2004). The Sb fronts are also very common in summer since the WeMOi is quite near to 0, but negative and the end of the season. Overall, the positive winter phase is steadily reduced until autumn, to rise again in a new positive phase in late autumn. This sudden shift might be related to the cooling of the sea surface temperatures leading to the Mediterranean cyclogenesis cessation. The sub-superficial layers are warmest on the Catalan coast in autumn (Salat and Pascual, 2006), favouring a major cyclogenesis which is reflected with a WeMOi negative minimum. All this explains why the rainiest season with torrential events is in autumn along the Catalan Countries coastland.

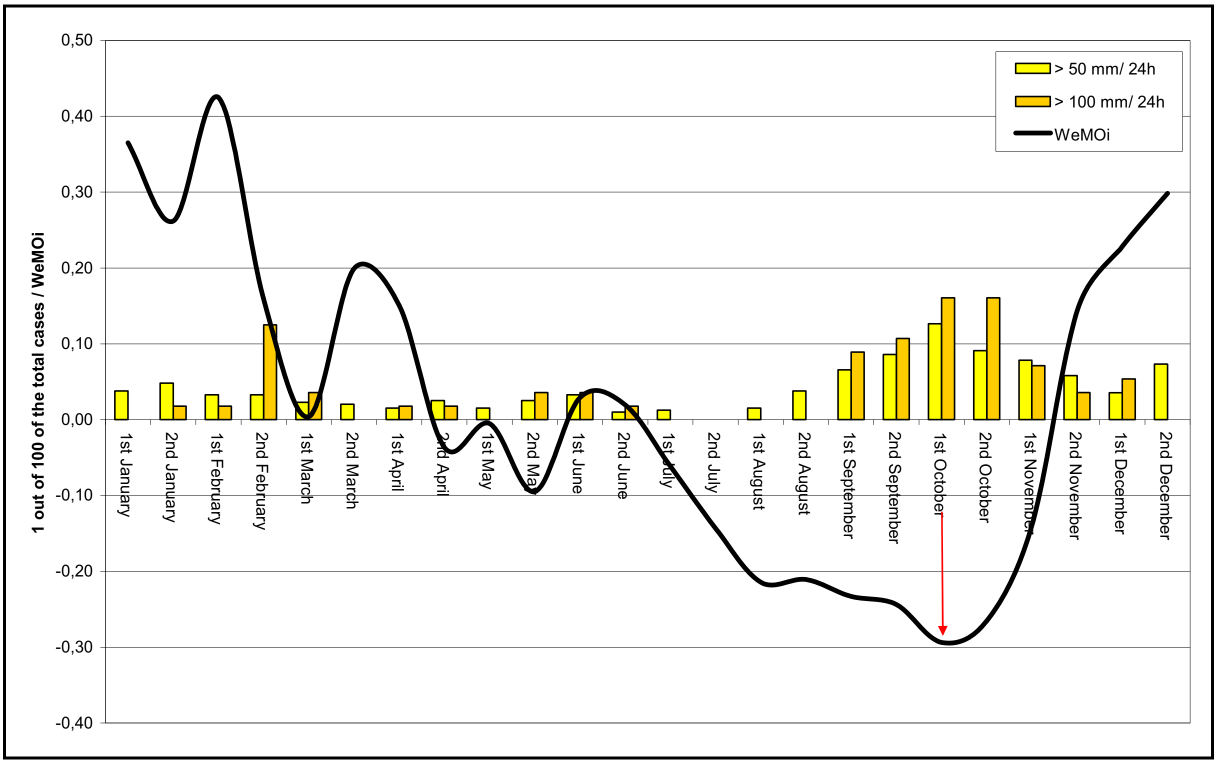


Figure 21. WeMOi evolution along the year by fortnights for the 1951-2000 period, and >50 mm (395 cases) and >100 mm (56 cases) in 24 h episodes which have taken place at least in one of the 7 observatories.

The episodes over 50 mm and 100 mm in 24 h which have taken place at least in one of the 7 observatories are distributed along the WeMO calendar. The major concentration of the episodes is in autumn. There is a steady rise of torrential events since the 1st fortnight of August. These episodes are most frequent in October, when WeMOi is most negative. Later they are reduced until the end of November, when WeMO returns to its positive winter phase. Even, >50 mm in 24 h episodes are most frequent during the 1st fortnight of October when the WeMOi minimum in autumn takes place. Grimalt *et al.* (2006) also detected the maximum annual concentration of torrential events (>100 mm/ 24 h) in Mallorca in October for the 1935-2005 period. It must be mentioned that there is a second maximum in the frequency of torrential episodes during the 2nd fortnight of February, which fits with a WeMO decrease in late winter due to the Central European anticyclone strengthening. Hence, easterly (Figure 22, left) and north-easterly (Figure 22, right) humid flows over the Catalan Countries are favoured. These synoptic situations correspond to a negative and a neutral-negative WeMO phase, respectively.

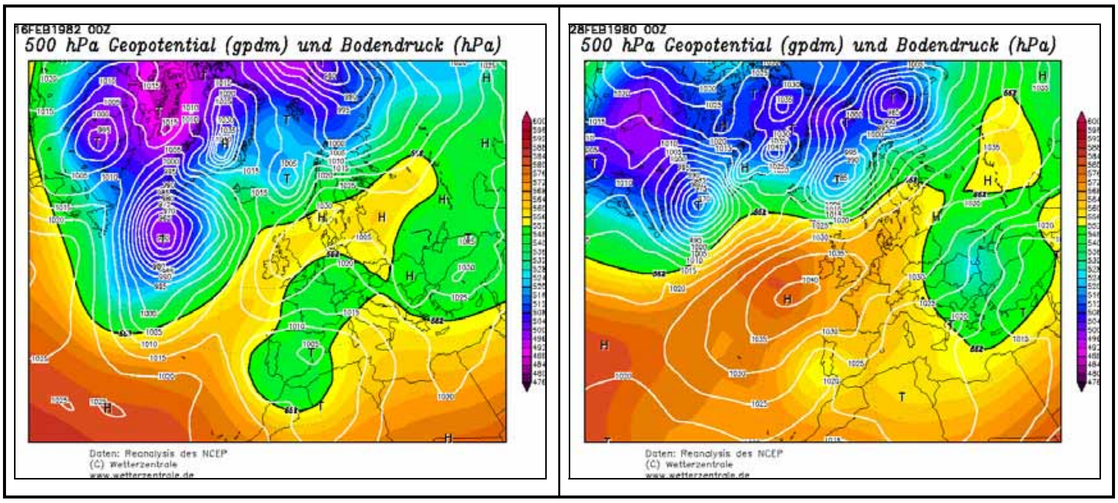


Figure 22. . Surface and geopotential 500-hPa maps on 16th February 1982 (left) and on 28th February 1980 (right).