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

4TH CHAPTER

THE STRATOSPHERE AND THE WEMO

4.1. THE NEW ROLE OF THE STRATOSPHERE IN THE WEATHER FORECAST

Very early studies already showed that extreme anomalies in the stratosphere can occasionally be propagated downward to the surface level (Julian and Labitzke, 1965; Quiroz, 1977). Some studies are currently confirming those previous studies in which stratosphere is considered as a good predictor of tropospheric weather (Christiansen, 2006; Matthes *et al*., 2006, Thompson *et al*., 2006). Camara *et al*. (2007) suggested stratospheric variations in the development of tropospheric seasonal forecasting models. Some studies even attempt to establish certain levels in the stratosphere in order to predict weather in the troposphere, as Siegmund (2006) did at level 50-hPa over the North Pole. Researchers therefore question the hypothesis that states that the stratosphere is a better predictor of the troposphere than the troposphere itself. The mechanism involved in the way extreme circulation in lower stratosphere circulation affects the troposphere is not yet fully understood, but it is likely that synoptic-scale baroclinic waves are taking part (Wittman *et al*., 2004). Nevertheless, research into dynamic couplings between the troposphere and the stratosphere, during the evolution of extreme anomalies in the stratospheric northern annular mode (NAM), has been currently improved with the use of some GCMs (Omrani *et al*., 2006). Despite these improvements, some deficiencies are remaining in the last Intergovernmental Panel on Climate Change (IPCC) (2007) when most of the GCMs do not totally consider the role of the stratosphere (Baldwin *et al*., 2007).

The object of analysis is the stratosphere due to the main role played by the polar vortex in winter. From November to April, a deep low is established in the stratosphere of the northern hemisphere, which reaches the tropospheric levels. Furthermore, there is a considerable thickness reduction of these atmospheric layers in winter which leads to a stratosphere-troposphere coupling (Baldwin and Dunkerton, 1999). This stratosphere-troposphere coupling has now been appropriately studied, but there are still some uncertainties with regard to its temporal and spatial irregularity (Baldwin and Dunkerton, 2005).

The present study attempts to follow the work done by Baldwin and Dunkerton (2001) as they detected different circulation patterns in the northern extratropical troposphere following the occurrence of stratospheric anomalies, major midwinter warmings (MMWs) or coolings / cold events (CE), through this stratosphere-troposphere coupling which takes place in winter. An earlier forecast of the stratospheric state would be very useful for determining the winter season on the Iberian Peninsula and throughout Europe. Baldwin *et al*. (2003)

detected the strongest modulation at surface level of the NAM at 150-hPa in February, which partly explains why I present an initial approach taking only February into account in this English version (in Catalan version January and March are considered). I focus on the study of morphological and structural changes in circulation patterns and their effects on those teleconnection patterns (AO, NAO and WeMO) and on precipitation over the Catalan Countries in February following the occurrence of a stratospheric anomaly. Subsequently, a significant part of WeMO variability depends on the middle to low stratosphere behaviour.

There are several factors influencing the occurrence of the different stratospheric anomalies in the North Pole. We must highlight the solar activity, QBO, ENSO, volcanoes and greenhouse gases. The second and third ones are dependant on solar activity, and volcanoes and greenhouse gases are totally independent.

In section 4.2., I define the stratospheric anomalies and select those February months with a potential influence of a stratospheric anomaly at surface level by means of the AOi. In the next section, 4.3., I study the current and future relationship between the AO and the WeMO according to greenhouse gases role in stratosphere, relating it to a torrential rainfall increase over coastland Valencian Conutry in midwinter (Millán *et al*., 2005; Millán *et al*., 2006), and also, the role of the polar stratospheric ozone (O_3) depletion during late winter in the spring rainfall decrease over inland Catalan Countries (Saladié, 2003; López-Bustins, 2006).

4.2. THE MMWs-COOLINGS AND THE CATALAN COUNTRIES RAINFALL

4.2.1. INTRODUCTION TO THE MMWS AND COOLINGS

For this analysis the 1958-2000 period was considered, as daily NCEP/NCAR reanalysis grid data (Kalnay *et al*., 1996) are only available since 1958 on the Climatic Research Unit (CRU) website. Consequently, 43 winters were considered. In 16 of these, there is an MMW (Labitzke and collaborators, 2002) (Table 1). MMWs are selected due to their influence on wind, temperature and pressure anomalies in the stratosphere. Thus, MMWs are circulation anomalies in the middle to low stratosphere which disturbs the polar vortex and replaces it with an anticyclonic circulation over the North Pole (Figure 1), and they are usually preceded by significantly important fluxes from the troposphere (Quiroz *et al*., 1975). The break-down in the polar vortex takes place when the latter is entered by planetary-scale Rossby waves (Quiroz, 1977; Baldwin *et al*., 2001). These waves are usually created in the troposphere, transporting westward angular momentum upwards to interact with the lower stratosphere circulation. Hence, our main criteria for detecting an MMW are both at 10-hPa, an easterly flow over 60ºN and a positive temperature difference between 90ºN and 60ºN. In Table 1, those temperatures ($T_{30h\text{-}Pa\ N\ Pole}$) which in January, are much higher than -72ºC or those that in February are much higher than -67ºC, are related to a weak and warm polar vortex. Other warmings in the stratosphere, minor warmings or Canadian warmings, do not succeed in strongly increasing pressure in the middle to low stratosphere or in establishing easterlies, i.e., to split up or shift the polar vortex. Major warmings usually take place in January or February, which is why they are named MMWs.

On the other hand, the coolings are those episodes when the polar vortex is stable and strong, leading to low temperatures at its core. Our criteria for detecting a strong and cold polar vortex in midwinter are $T_{30h\text{-}Pa\ N\ Pole}$ January ≤-75ºC or $T_{30\text{-}hPa\ N\ Pole}$ February ≤-70ºC and the strengthening of westerlies at 10-hPa over the high latitudes.

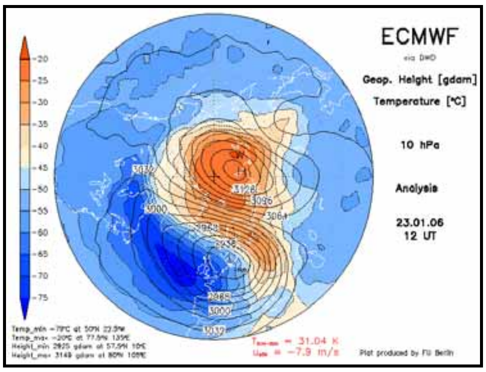


Figure 1. Geopotential height and temperature at 10-hPa in northern hemisphere on 23rd January 2006 at 12 UTC (Source: Stratospheric Research Group, *Freie Universität Berlin*, Germany).

T (ºC)	G	F	AOi	<-0.50	>0.50	T (ºC)	G	F	AOi	<-0.50	>0.50
X (58-00)	-72	-67	G	F	M	X (58-00)	-72	-67	G	F	M
	≤-75	≤-70					≤-75	≤-70			
1958	-71	-49	-0.95	-1.73	-2.55	1980	-80	-70	-1.72	-0.07	-1.22
1959	-74	-73	-1.89	3.15	1.9	1981	-81	-56	0.78	0.24	-1.32
1960	-60	-70	-2.22	-1.85	-1.53	1982	-71	-69	-0.59	1.35	1.24
1961	-65	-73	-0.92	1.2	0.53	1983	-79	-62	2.04	-0.85	0.02
1962	-79	-67	1.96	0.1	-2.88	1984	-80	-65	1.16	0.25	-1.93
1963	-74	-52	-2.86	-1.07	0.78	1985	-53	-66	-2.22	-1.49	0.73
1964	-78	-77	1.12	-0.34	-0.33	1986	-76	-74	0.01	-2.05	2.59
1965	-76	-73	-0.7	-1.87	-0.73	1987	-60	-49	-0.31	-1.02	-1.43
1966	-76	-60	-2.9	-1.36	-0.9	1988	-77	-80	0.85	-0.67	-0.07
1967	-80	-78	-0.02	1.73	2.04	1989	-82	-57	3.62	3.6	1.74
1968	-58	-68	-0.32	-1.57	2.24	1990	-80	-63	1.35	3.41	3.55
1969	-72	-74	-3.08	-2.91	-1.4	1991	-70	-57	1.17	-0.09	-0.36
1970	-49	-62	-2.10	-0.87	-2.01	1992	-66	-59	1.64	1.76	1.38
1971	-54	-66	0.01	-0.77	-0.88	1993	-80	-68	4.06	1.12	1.33
1972	-79	-70	0.54	0.25	0.13	1994	-66	-77	-0.14	-0.48	2.03
1973	-73	-44	2.03	1.2	0.98	1995	-70	-57	0.54	1.79	0.53
1974	-78	-79	0.54	-0.34	-0.13	1996	-81	-75	-0.61	0.78	-1.11
1975	-65	-68	1.93	0.85	0.42	1997	-79	-83	0.35	2.53	1.3
1976	-80	-78	0.51	2.22	0.86	1998	-67	-64	-1.56	0.72	0.17
1977	-60	-69	-3.38	-1.47	0.45	1999	-67	-69	0.41	0.95	-1.47*
1978	-74	-66	0.44	-2.37	0.84	2000	-84	-74	1.38	1.82	0.04
1979	-75	-60	-1.85	-0.48	-0.62	* March 1999 (-52) >			X March (-57)		

MMW
Cooling
MMW Transmission
MMW NO Transmission

Table 1. North Pole temperature (ºC) at 30-hPa in January and February (temperatures corresponding to MMWs are marked in pink; in blue, the ones related to coolings). AOi values (properly negative values (<-0.50) after an MMW are pink coloured; in blue, those properly positive ones (>0.50) after a cooling). The years with the occurrence of an MMW are coloured, in orange the ones where MMW transmission was successful, and in yellow, the ones where the MMW was not propagated to the troposphere. (Data source: Labitzke and collaborators (2002), Stratospheric Research Group, *Freie Universität Berlin*, Germany). (In 1999, the MMW took place on 26th February according to ERA-40 dataset. Subsequently, the positive temperature anomaly took place in March; Charlton and Polvani, 2007). (This table is adapted from Lopez-Bustins *et al*., 2006a).

4.2.2. Factors conditioning the polar vortex variability

4.2.2.1. Solar cycle – QBO

It is widely known that a signal of the 11-year sunspot cycle exists in the stratosphere in late winter over the North Pole, mainly in February[1], according to the QBO phase (Labitzke, 1987, 2005; Labitzke and van Loon, 1988; van Loon and Labitzke, 1994, 2000). These studies show that the rules of the Holton-Tan effect (Holton and Tan, 1980, 1982), which implies that major warmings are more common in an east phase of the QBO, are abruptly broken down when the solar influence is manifest in midwinter.

We identify a solar cycle – QBO modulation influencing Catalan Countries rainfall as the MMWs tend to occur when the QBO phase is west in solar maxima, and when the QBO phase is east in solar minima. Those years in solar maxima with an east QBO phase or in solar minima

[1] It reinforces the idea about selecting the February month as a first approach of the analysis in this English version.

with a west QBO phase would not favour an MMW occurrence; consequently, low stratospheric temperatures in the North Pole would be more probable. In Figure 2, the 11-year solar cycles (Schwabe cycles) concerning the study period are reconstructed. It should be noted that 14 (88%) of the 16 MMWs fit well with the solar cycle – QBO relationship; only two cases are incorrectly suited. Both of these are in the east phase of the QBO, one in a solar maximum (1971) and the other in medium solar activity (1999). The west phase of the QBO fits better than the east phase as there is no MMW in solar minima with the west phase (Labitzke *et al*., 2006).

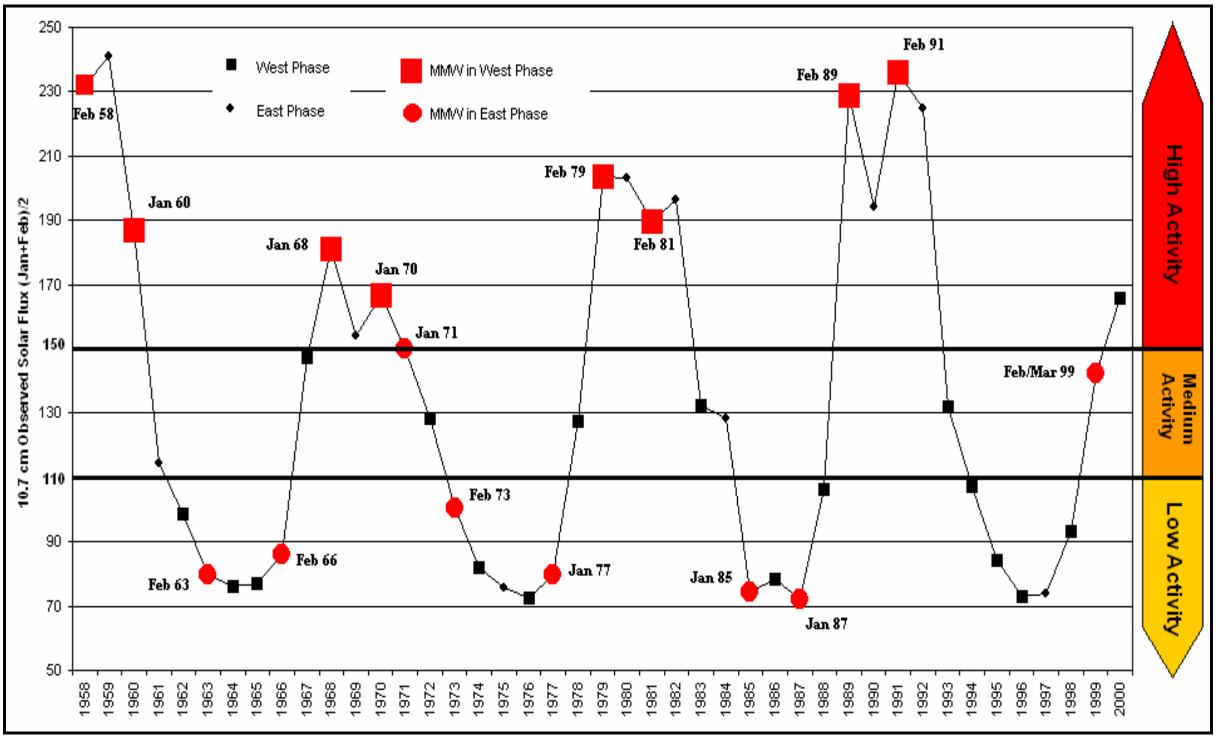


Figure 2. Occurrence of MMWs (1958-2000) according to the solar activity (JF) (10.7 cm observed solar flux, Penticton, Canada, 2800 MHz, National Geophysical Data Center) – QBO (40–50-hPa) (JF) relationship (Marquardt and Naujokat, 1997). Dots are years in the east phase of the QBO (n = 18); squares are years in the west phase of the QBO (n = 25). Big and red dots and squares are years with an MMW occurrence. 150 and 110 units of the 10.7 cm observed solar flux have been fixed as the thresholds to distinguish among high, medium and low solar activity in the 11-year sunspot cycles. (From Lopez-Bustins *et al*., 2007).

4.2.2.2. ENSO

When sea surface temperature (SST) is very cold in western South America under a stable atmosphere, due to a strong anticyclone over eastern Pacific Ocean, the cold events of ENSO takes place, La Niña. Subsequently, the dynamism in low atmospheric layers leads to a cooling in tropical troposphere, and simultaneously, a warming in the middle to low stratosphere in tropics (van Loon and Labitzke, 1987). Thus, the temperature gradient is increased between the tropics and the Polar latitudes, leading to a strengthening of the zonal circulation. In winter, it is when this temperature gradient is higher because the North Pole has the lowest temperature due to a lack of sunshine. Therefore, MMWs hardly take place during La Niña.

On the other hand, when El Niño takes place the temperature is warmer in the tropical troposphere leading to a greater convection within the equatorial belt which cools the tropical tropopause. Consequently, the temperature decreases in the low tropical stratosphere, which contrasts with the tropical troposphere which remains very warm. The tropospheric Aleutians low deepens, thus making the stratospheric Aulentian high stronger. Hence, the heat and O_3 transport is amplified (which is done by the planetary waves and Brewer-Dobson (B-D) circulation), leading to a warming in the Arctic stratosphere due to a break-down of the polar vortex and an early O_3 stratospheric increase over high latitudes.

In several years, the ENSO phase is neutral and it does not take part in the dynamism. In solar minima, it is when we must consider at most the ENSO phase because a high solar activity alters the mechanism. Generally speaking, the stratosphere does not behave in accordance with the theory in solar maxima.

Labitzke and van Loon (1999) detected 6 years in the 1956-1998 period where El Niño took place in solar minima: 1964, 1966, 1973, 1977, 1987 and 1988 (Figure 3). Only in 1964 and 1998, no MMW occurred. The QBO phase was west in both years, therefore, not favourable for an MMW occurrence. Moreover, Mt Agung erupted in 1963, warming the tropical stratosphere which concealed the ENSO signal (Labitzke and van Loon, 1989). A cooling took place in 1964 and no variations were detected in 1998. Only 4 years with La Niña phenomenon in solar minima occurred: 1965, 1974, 1976 and 1997. 1965 was the only year without a cooling occurrence although the QBO phase was west, but no MMW took place either. On the other hand, La Niña took over from QBO in 1997 as it avoided an MMW occurrence. This is a clear example about no rules in the order of the factors to determine stratosphere variability. Today, it is still under study. In those years in solar maxima, ENSO phenomena do not regionalise as well as in solar minima (Figure 3).

4.2.2.3. Explosive tropical eruptions

The violent eruptions inject a huge amount of ashes and solid particles into the Equatorial stratosphere, from where they are spread throughout the globe. These particles fall out of the stratosphere very early. On the other hand, large amounts of gases with sulphur and water vapor content are at the same time injected into the stratosphere during the explosive eruption, and they form the nuclei for minute drops, the so- called sulphate aerosol which consists of 75% sulphuric acid and which can remain for several years in the stratosphere. They have an important incidence on the radiation budget. The short-waves are reflected and the long-waves are absorbed. Subsequently, the troposphere cools and the stratosphere warms. The effect on the polar vortex is similar to La Niña events (in solar minima), maintaining low temperatures with low O_3 concentration in the core of the vortex. Furthermore, these aerosols affect the O_3 chemistry, reducing its concentration in the stratosphere at the North Pole. This depletion may lead to a colder and stronger polar vortex (Langematz, 2000). This mechanism takes place in late winter when the first rays of sunlight appear.

It is well proved that polar vortex remains cold and stable even in the second winter after these big tropical eruptions due to the durability of these aerosols in the stratosphere (Labitzke and van Loon, 1999). Therefore, the years to analyse (in the Catalan version) are 1964, 1983 and 1992, and then: 1965, 1984 and 1993. If we look at Table 1, we will see that the January months after Agung and El Chichón eruptions are anomaly cold, not in case of Pinatubo eruption due to QBO circulation in the following months. Actually, January is the month most influenced as Prohom *et al*. (2003) found. It is associated to strong westerlies at surface level. The volcanoes forcing is the largest one over the other ones (Labitzke and van Loon, 1989). Its occurrence is random, and when it takes place usually favours a cooling despite the other factors role.

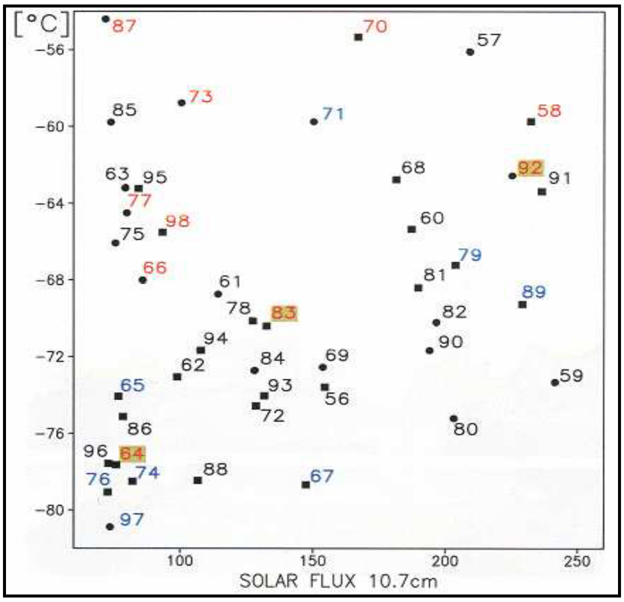


Figure 3. Ordinate: Monthly mean 30-hPa temperatures (ºC) in the North Pole (JF), 1956-1998; abscissa: solar activity (10.7 cm solar flux). Squares denote westerly and dots easterly winds in the lower equatorial stratosphere (QBO); red denotes El Niño and blue La Niña in the ENSO phenomenon. The numbers are the years, and green shading denotes the explosive eruptions of three tropical volcanoes. From Labitzke and van Loon (1999).

4.2.2.4. Greenhouse gases

The emissions of anthropogenic greenhouse gases have steadily increased over the last decades. They have lead to alterations in the radiation budget. Consequently, the troposphere warms and the stratosphere cools (Shindell *et al*., 2001).

These gases favour a strengthening of the polar vortex as the upper troposphere warms in low latitudes and cools in high latitudes significantly in response to increases in greenhouse gases. Hence, the tropopause rises in the tropics and sinks in the North Pole. It leads to a major temperature gradient between the Equator and the Pole to be compensated. This physical mechanism is strictly detected in winter (DJF) when the high latitude remains without sunshine, but these gases also contribute to an O_3 depletion in the North Pole during late winter (end-February) and early spring (March and April). This chemical mechanism also favours a stronger polar vortex (Labitzke and van Loon, 1999; Langematz, 2000; Rex *et al*., 2004).

Looking at the Table 1, we will see that coolings were more frequent than MMWs in the last decade of the 20th century.

4.2.2.5. Summary table

The influences of the whole last factors in polar vortex variability have been briefly catalogued in Table 2. Subsequently, planetary waves may break down the polar vortex depending on its initial state as a consequence of interaction of the all factors.

Weak vortex **Strong and cold vortex** **Vortex is indifferent to this factor**	**QBO**		**ENSO**		**VOLCANOES**	**GREENHOUSE GASES**
	West	**East**	**El Niño**	**La Niña**		
High SOLAR activity (>150 10.7 cm solar flux)						
Low SOLAR activity (<110 10.7 cm solar flux)						

Table 2. Summary box of the interaction of the all forcings in polar vortex variability.

4.2.3. AOi: An index for assessing the stratosphere-troposphere coupling

Baldwin and Dunkerton (2001, 2005) analysed the polar vortex forecast at surface level. The daily AOi was used to analyse the behaviour of the NAM at surface level as the NAM lowest level is the AO. It was detected that the NAM at higher levels (150-hPa) predicts the AO much better than the AO itself in winter, mainly in January and February (Figure 2). Furthermore, using separate averages for weak-warm and strong-cold polar vortex anomalies in the middle to low stratosphere in winter over the North Pole, they detected a transmission of the anomaly from upper levels to the surface, with negative AOi values in the occurrence of MMWs and positive AOi values in the occurrence of coolings. Nevertheless, a lag was found between approximately 1 week and 2 months when composites were performed of time-height development of the NAM. Charlton *et al*. (2003) have already used the AO to show that the state of the troposphere may be predicted by the state of the stratosphere.

Not all the stratospheric anomalies are efficiently transmitted from the stratosphere to the troposphere because the variability of the AO itself can conceal it (Baldwin and Dunkerton, 1999). Therefore, an analysis of each identified MMW and cooling was made in order to establish whether a transmission to the troposphere occurs. Table 1 also shows monthly AOi values in January, February and March (Thompson and Wallace, 2000). For the MMWs, the threshold –0.50 was established in the AOi to separate the slightly negative values from the very negative ones. Hurrell (1995) used the threshold /1.0/ to establish extreme phases in the monthly NAOi, and I therefore considered that >/0.50/ can clearly show the sign of the phase, but not extremely. Considering the lags involved in the transmission, some anomalies occurring in one month are reflected at surface level in the following month. For instance, in 1979 and 1981, the warm anomaly appears at the end of February in the stratosphere, but is not well reflected in the troposphere until March due to a certain lag; in 1970 and 1985, the anomaly appears at the beginning of January, and is consequently well propagated in the same month because the lag is shorter than 3 weeks. During the 1958-2000 period, 13 (81%) out of 16 MMWs were well-transmitted from the stratosphere to the troposphere. In 1989 the AOi was clearly positive in January, due to a cooling influence, +3.62, which remained during the following months, and did not enable a stratospheric warming anomaly, which took place that February, to succeed in reaching surface level; something similar occurred in 1973.

The cooling propagation is similar to the MMWs and 20 (77%) out of 26 coolings were well-transmitted as the AOi was >0.50 (Table 1). In 1960, the MMW anomaly remained at surface level with negative AOi values until March, preventing a satisfactory transmission of the cooling which took place in the stratosphere that February.

This analysis considers those February months in which stratospheric anomalies were detected in the troposphere. The month most influenced by the MMWs is February, with 10 years; January appears to be influenced in just 4 years and March in 9 years. On the other hand, the cooling anomalies are most frequent in January, with 13 years. For February, in 10 years a cooling influence was found, the same frequency as in March.

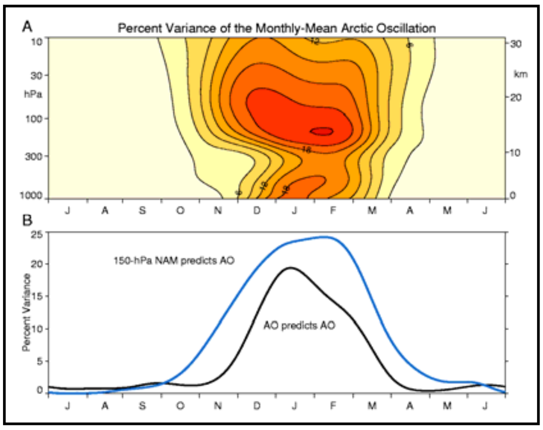


Figure 4. (A) Predictability of the monthly-mean AOi (1000-hPa NAM) after a 10-day lead. Values are obtained by linear regression between the daily NAM time series and the monthly-mean AOi beginning after 10 days, and are displayed as percent variance of the monthly-mean AOi. (B) Cross sections through (A) at 1000 and 150-hPa. Blue curve: 150-hPa NAM predicts the monthly-mean AOi; black curve: AOi predicts the monthly-mean AOi. From Baldwin *et al*., (2003).

4.2.4. RAINFALL ANOMALIES IN THE CATALAN COUNTRIES DURING THE OCCURRENCE OF MMWS AND COOLINGS

The main aim of this analysis is to detect an MMW or a cooling influence upon the troposphere, seeking changes in the structure and morphologies of circulation patterns, and to relate the latter to rainfall anomalies on the Catalan Countries. To this end I performed a daily objective classification of circulation patterns at SLP for February in two different ways: I first classified the 1961-1990 period, which is taken as a reference period in order to define the most frequent daily circulation patterns for February; secondly, I made the same synoptic classification of all the days in February with an MMW or CE influence previously detected by means of the AOi (Table 1).

The method I used to identify the main atmospheric patterns was the principal components analysis (PCA), a widely used technique for this purpose and for a variety of spatial and temporal climatological scales (Barnston and Livezey, 1987; Barry and Carleton, 2001; Esteban *et al*., 2005, 2006). I used a 2.5º SLP data resolution from the NCEP/NCAR reanalysis project (Kalnay *et al*., 1996), covering the window 70ºN:30ºN; 30ºW:20ºE (357 grid points). The T-mode data matrix was also used, in which the days are the variables and the grid points are the cases (Huth, 1996; Maheras *et al*., 1999b; Romero *et al*., 1999); other options in the PCA process involve the use of the correlation matrix or rotation with the Varimax criterion (Richman, 1986). The results enabled us to derive two possible spatial patterns for each principal component (PC) retained and rotated, one in its positive phase and the other in its negative phase (Huth, 1996, 2000). The correlations between each real day (variable) and each of these spatial patterns was also obtained, finally permitting the similar days to be grouped and averaged, an SLP pattern to be obtained and an AOi value for every principal spatial pattern to be considered. In this step I obtained the main monthly patterns for February over the 1961-1990 period and the main circulation patterns related to the February month under a stratospheric anomaly influence. In section 3, only the three most frequent circulation patterns are shown, but they constitute approximately 70-90% of the cases.

The February rainfall means for the Catalan Countries were calculated for the 1961-1990 period. Subsequently, I calculated the February rainfall anomalies according to the 1961-1990 reference period for those years under an MMW or cooling influence in order to associate them with the circulation patterns obtained.

4.2.4.1. Reference period: 1961-1990

The 1961-1990 matrix comprises 357 cases (grid points) and 847 variables (1961-1990: 23 years × 28 February days + 7 years × 29 February days). The three most frequent circulation patterns with regards to the 1961-1990 reference period in February are shown in Figure 5a. The most frequent is a zonal circulation over Western Europe associated with a positive AO and WeMO phase (PC1+). The second, PC2+, is a pattern showing a positive AO phase and a negative WeMO phase at the same time, where a blocking high, between the Scandinavian Peninsula and Central Europe, shifts westerlies north-eastward. The following one, PC3+, is a low shifted southward involving a south-westerly maritime flow over the western Iberian Peninsula. The driest areas in February are inland Catalan Countries where humid flows hardly arrive. The wettest ones are the western Pyrenees and northern Mallorca, where Atlantic flows have the largest influence on the study area. North-eastern area and south Gulf of València are also humid due to some winter Mediterranean flows displayed in PC2+.

4.2.4.2. Under an MMW influence

The second classification, with only February months under an MMW influence according to the AOi (Table 1), indicates an alteration of this order (Figure 5b). 282 days (February months in 1958, 1960, 1963, 1966, 1968, 1970, 1971, 1977, 1985 and 1987, 28 days × 8 years + 29 days × 2 years) are classified. The most frequent circulation pattern in the reference period and the one under an MMW influence look similar, but the AOi is positive in the former case and negative in the latter one. The WeMO remains in a positive phase. Under an MMW influence, this most frequent pattern is weakened and shifted southward, and the storms therefore travel to lower latitudes. The second most frequent circulation pattern under an MMW is the third one of the reference period, but in a more negative AO phase (WeMO remains in a slightly positive phase). It shows an increase in the frequency of humid south-westerly advection over the western Iberian Peninsula. The change in the frequency order of these patterns is the most reliable result of the MMW influence on troposphere circulation. This Atlantic flow leads to dry conditions in the Catalan Countries, being driest in the eastern fringe. Actually, the winds lose their humidity after crossing over the Iberian continental mass. Inland Catalan Countries and most Balearic Island have no considerable variations in rainfall.

The blocking situation over Central Europe (PC2+ in Figure 5a) is now weakened and lies in the least frequent position. This second most frequent pattern in the reference period implies wetter conditions on the eastern fringe because of the east and north-east advections with Mediterranean humidity over eastern Iberia (Azorín-Molina and López-Bustins, 2004), named backdoor cold fronts by Millán *et al*. (2005). Thus, a weakening in this second pattern of the reference period during those February months, influenced by MMWs, also implies reduced precipitation in most of the Catalan Countries.

4.2.4.3. Under a cooling influence

An analysis was conducted once again for those days under a cooling influence according to the AOi (Table 1) in February. 283 days (February months in 1959, 1961, 1967, 1976, 1989, 1990, 1993, 1996, 1997 and 2000, 28 days × 7 years + 29 days × 3 years) are classified. The three most frequent circulation patterns under a cooling influence are more stable than those under the effect of MMWs because they agglutinate more cases. The most frequent pattern is a strengthening of the western circulation as the main action centres are reinforced (Figure 5c); it is shown by PC2+ with a high AOi and a negative WeMO phase.

The Atlantic anticyclone moves northward and eastward, with a new position over Central Europe and consequently, the strengthened westerlies are shifted to Scandinavian latitudes. This new circulation pattern shifts the PC1+ and PC2+ of the reference period (Figure 5a), which match the PC1+ and PC3+ in Figure 5c with an increased AOi, to their respective new positions, second and third. The PC3+ of the reference period (Figure 5a) does not appear among the three most frequent patterns under the influence of a cooling. The rainfall anomalies map in February shows a big difference between Catalonia, and the Valencian Country and Northern Catalonia. Catalonia has dry conditions mainly due to the disappearance of the PC3+ of the reference period. There is a notable rainfall increase over the two other regions due to the more frequent backdoor cold fronts (north-easterly winds) (PC2+ in Figure 5c). These fronts bring heavy rainfalls over the Mediterranean fringe; consequently, the strengthening of the westerlies by a cooling influence might lead to an increase in torrential events over the eastern Iberian fringe. Balearic Islands clearly show the south-western – north-eastern gradient of the interacted influence of the Mediterranean and Atlantic flows.

4.2.4.4. The key of the opposed relationship between the AO and the WeMO

Thanks to the objective synoptic classification, I attributed the key of the negative relationship between AO and WeMO to the winter thermal anticyclone over Central Europe. In those episodes when the polar vortex is cold and strong (coolings), that relationship enhances itself. This is why the opposed correlation between both patterns is greater in the second half of the 20th century as AOi comes more positive. A colder polar vortex leads to a major vorticity at surface level which is reflected with more intense westerlies at high latitudes due to a contraction of the vortex core. As the polar low deepens, the Atlantic anticyclone ridge strengthens (40-50ºN), moving north-eastwards to reactive the thermal anticyclone over Central Europe. Therefore, AOi turns very positive[2] and WeMOi negative as Padua is at 45ºN. This negative WeMO phase is defined by north-easterlies flows which are driven by this high pressure ridge at mid-latitudes.

In a cold polar stratosphere, we may deduce backdoor cold fronts (Estrela *et al.*, 2002; Azorín-Molina and López-Bustins, 2004) over Catalan Countries. The origin of these fronts is a very cold and continental air mass, which strongly contrast with the warm sea water mass in Mediterranean basin. They lead to torrential rainfall in the Alacant mountains, where the valleys

[2] The pressure belt at 45ºN approximately is the southern end of the AO dipole.

face north-east in southern Gulf of València, in Pitiüses, and in Northern Catalonia and in the eastern Pyrenees for the humidity collected by the flows travelling over Gulf of Lion.

This Central Europe anticyclone is stronger in February after being cooled along the whole winter, and this explains why the pluviometry of the Valencian Country, eastern Pyrenees and Pitiüses is totally dependant on WeMO in this month (Figures 18 and 22 in the 2nd chapter). On the other hand, mostly Catalonia is not directly related to WeMO when it depends on this winter thermal high, because the shoreline of Catalonia is approximately parallel to these north-easterly flows.

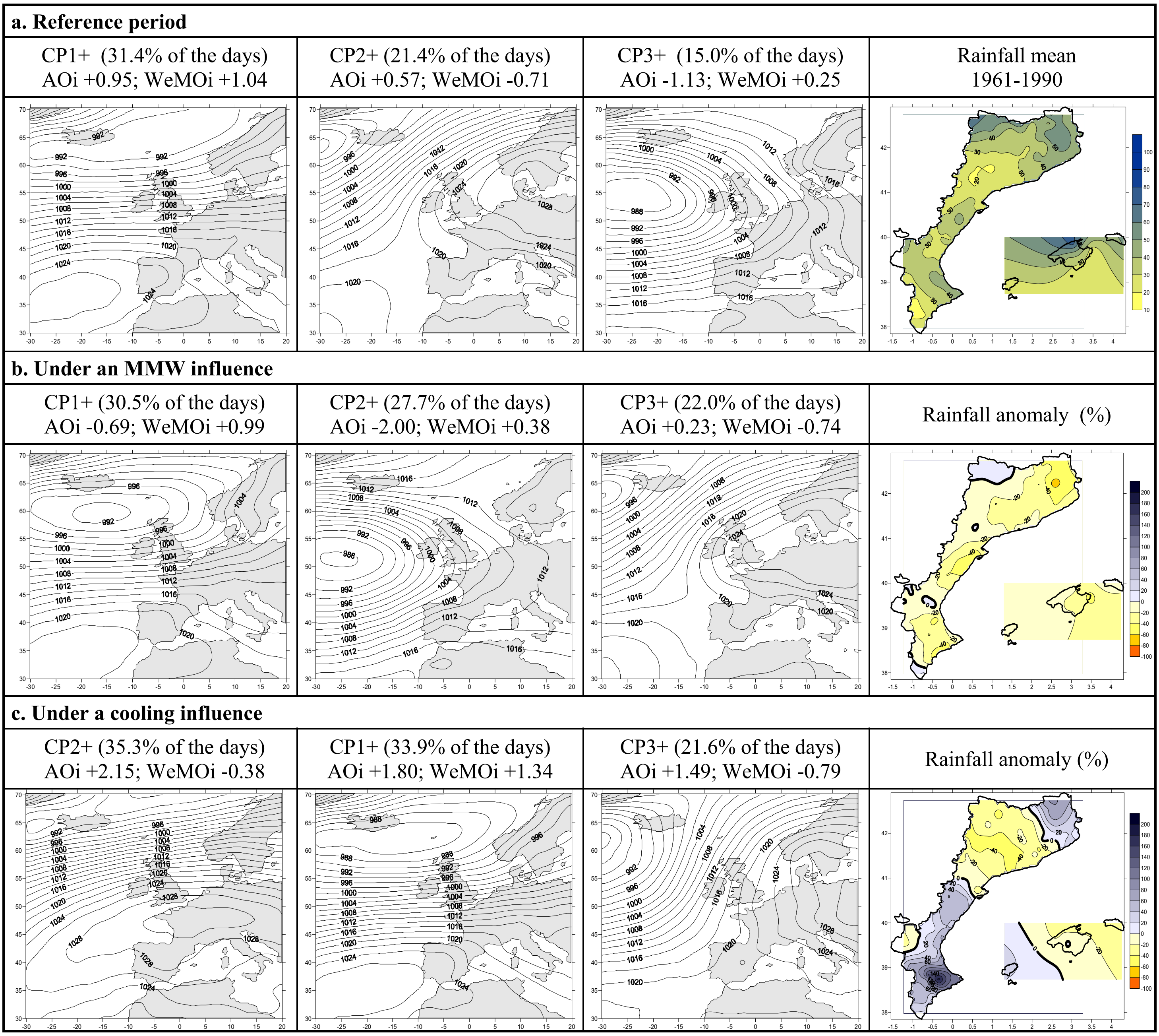


Figure 5. a. The three most frequent circulation patterns in February for the 1961-1990 reference period with their corresponding AOi and WeMOi values and the rainfall mean map of the period. **b.** Idem as (a), but for those February days which are under an MMW influence and the corresponding rainfall anomalies map according to the 1961-1990 reference period. **c.** Idem as (b), but for those February days which are under a cooling influence.

4.2.4.5. Winter stratospheric temperatures in the North Pole (30-hPa) and the Catalan Countries rainfall

To conclude, in general terms, the results obtained show a significant reduction of the frequency of the westerlies over Europe's mid-latitudes in those February months under an MMW influence. Blocking situations over Eastern Europe are favoured, enabling the lows to be shifted southward. Therefore, after an MMW occurrence we should expect a slight increase in precipitation in western Pyrenees and no variation inland Catalonia and in Balearic Islands some weeks later, and a decrease on the eastern fringe in February. On the contrary, in those February months under a cooling influence, the westerlies are strengthened and shifted northward over Scandinavia, and the north-easterly winds over the Iberian Peninsula are favoured, as an anticyclone is well established over Central Europe. Consequently, after a cooling occurrence we should expect a decrease in precipitation in Catalonia, inland Valencian Country, northern Mallorca and Menorca some weeks later, and an increase on most Valencian Country, Northern Catalonia, Girona province and Pitiüses.

In February, the most frequent pattern under a cooling influence, PC2+ (Figure 5c) is an anticyclone over Central Europe, which is a representative pattern of the negative phase of the WeMO. This oscillation is negatively correlated to rainfall of a torrential nature over the eastern Catalan Countries fringe; it might therefore account for a precipitation increase and its irregularity in this area when this circulation pattern is more frequent after the occurrence of a cooling.

Baldwin and Dunkerton (2001) also detected an overall southward shift of the Atlantic storm tracks during weak vortex regimes associated with an AO negative phase and vice versa during strong vortex regimes. In the same sense, Haigh *et al*. (2005) showed an equatorward shift of the position of the subtropical jets with a high-latitude stratospheric heating using a GCM. Camara *et al*. (2007) studied winter rainfall variability over Europe by means of the stratosphere-troposphere coupling, pointing out that a weak polar vortex is related to undefined westerlies around 60ºN a few weeks later. This allows storms to reach lower latitudes and to lead to a rainfall increase in Southern Europe. My results therefore confirm these previous studies.

The novelty of my study involves describing in detail those changes in synoptic surface circulation patterns over Western Europe between an MMW and a cooling occurrence, these being consistent with the above-mentioned studies. Another new contribution of this study is to have carried out a downscaling to Catalan Countries rainfall of these stratospheric anomalies, where I succeeded in distinguishing precipitation differences between inland and coastland Catalan Countries.

Currently, much remains to be established with regard to the relationship between tropospheric climatic variables and stratospheric anomalies; thus, Baldwin (2000) once put forward several questions regarding troposphere-stratosphere coupling, to be answered during the research development within the project titles Stratospheric Processes And their Role in Climate (SPARC – World Climate Research Programme). We ought to consider that the different factors at play in the mechanism have their own variability. In the same sense, it is not well-understood why the solar cycle – QBO relationship influences the occurrence or non-occurrence of an MMW, but recent studies deal with this phenomenon (Gray *et al*., 2006). Baldwin and Dunkerton (2005) once said '*Solar effects may be more likely to occur, for example, in the late winter when solar modulation of the polar vortex appears to be largest*'. Although verification of solar effects in the troposphere may be difficult and requires further research (Baldwin and Dunkerton, 2005), this is the first study which attempts to assess solar forcing on Catalan Countries weather types by means of stratosphere-troposphere coupling, as I downscaled the spatial distribution of rainfall anomalies to the study area according to the circulation patterns obtained under the different solar cycle – QBO conditions. Haigh and Roscoe (2006) have recently confirmed this solar cycle – QBO modulation influencing the wind circulation of the northern hemisphere, and have already calculated a new index relating to the solar and QBO indices, which shows a stronger signal in the whole winter NAM atmosphere than the two variables separately. Haynes (2005) currently leads a project on atmospheric science research at the University of Cambridge within the SOCLI Programme funded by NERC, which investigates stratosphere-troposphere dynamical coupling and the features of the downward propagation of the solar cycle influence.

Throughout this study, it can be seen that noteworthy rainfall anomalies can take place over the Catalan Countries, depending on stratospheric behaviour in late winter. Similar effects were found in other preliminary essays which were conducted for January and March for Iberian Peninsula, but the results were not as robust as in February (Lopez-Bustins *et al*., 2006a). Although the results show obvious circulation patterns according to the AO phase selected, both in MMWs and coolings, my study focuses on describing the path followed by the stratospheric anomalies from the stratosphere to the troposphere and how surface circulation clearly falls under their influence. It was therefore inappropriate to join the years in which no transmission was previously detected. Furthermore, there is a lag in the propagation of stratospheric anomalies which has not yet been suitably established (Baldwin and Dunkerton, 2005), leading me to select the influenced month individually.

4.2.5. THE NET INFLUENCE OF THE SOLAR CYCLE – QBO MODULATION

A new analysis was performed without taking the AOi into account. I knew it was not entirely rigorous to select only the months in which the AOi indicates a correct transmission of the anomaly, so it was reasonable to add this section. The same objective classification method was applied. The years were selected according to the solar cycle – QBO relationship (Figure 2). There are 17 years under the solar cycle – QBO conditions (QBO west phase in solar maxima and QBO east phase in solar minima) which might favour an MMW during the 1958-2000 period; 479 days (February months in 1958, 1960, 1963, 1966, 1968, 1970, 1973, 1975, 1977, 1979, 1981, 1985, 1987, 1989, 1991, 1997 and 2000, 28 days × 14 years + 29 days × 3 years). The circulation patterns in Figure 6a follow the same frequency order as the one in the February analysis under an MMW influence, taking AOi into account (Figure 5b). However, the most frequent pattern in Figure 6a does not shift southwards as in Figure 5b, and the second one is slightly weakened. This is due to the inclusion of years in which there is either an MMW non-occurrence or a missing stratosphere-troposphere transmission. Consequently, the rainfall anomalies are quite similar but are also weakened (Figure 6a). An 11-year solar cycle – QBO signal might be found in rainfall over the Catalan Countries, but it is occasionally concealed. What I highlighted was the maintenance of the PC3+ of the reference period (Figure 5a) in the second position as in Figure 5b. It means a more frequent cut-off of lows over the western Iberian Peninsula increasing precipitation over the most inland Catalan Countries. On the other hand, the rest of the study area continues being under dry conditions.

There are 18 years under solar cycle – QBO conditions (QBO west phase in solar minima and QBO east phase in solar maxima) which might favour a cooling over the study period; 510 days (February months in 1959, 1962, 1964, 1965, 1969, 1971, 1974, 1976, 1980, 1982, 1986, 1988, 1990, 1992, 1994, 1995, 1996 and 1998, 28 days × 12 years + 29 days × 6 years). Generally speaking, a predominantly anticyclone synoptic situation over the Iberian Peninsula is shown by PC1+ and PC3+ in Figure 6b, leading to dry conditions in inland Catalan Countries. The increase in precipitation, however, takes place over the coastland areas due to the maintenance of the frequency in the humid north-easterly winds over the western Mediterranean basin. Furthermore, the second most frequent pattern (PC2+) is the third under a cooling influence (PC3+ in Figure 5c), associated with easterly winds over the Iberian Peninsula, which also contributes some precipitation to the eastern fringe (Catalan Countries). I pointed out that the PC3+ from the 1961-1990 reference period in Figure 5a does not appear among the three most frequent patterns under these solar cycle – QBO conditions favouring a cooling. Therefore, South-North wind circulation would not be favoured over Western Europe, and this would lead to a rainfall reduction over inland Catalonia and the northern Balearic Islands. But, an important rainfall increase would be detected along the all Catalan Countries coastland. This PC3+ from the 1961-1990 reference period did not appear either among the 3 most frequent circulation patterns under a cooling influence taking AOi into account (Figure 5c).

In order to provide some guarantee of the results of the whole analysis, the February months were reanalysed according to the solar cycle – QBO relationship regardless of the AOi, and the results have shown a similar, but weakened, effect on the Catalan Countries as the circulation patterns hardly change their structure and morphology. The results of this were recently corroborated as the MMW which took place at the end of January 2006 was strongly anomalous; although the AOi (NOAA) was slightly negative the following February, it was strongly negative in March and, consequently, rainfall anomalously increased in March 2006 over the western Iberian Peninsula and the Mediterranean fringe remained drier than normal (López-Bustins, 2006). In January 2006, the QBO phase was east in a solar minimum, tallying with the theory of the solar cycle – QBO modulation influencing the stratospheric temperature in the North Pole during midwinter. Notwithstanding, other factors, such as eruptions of tropical volcanoes or ENSO can occasionally alter this modulation, influencing the middle to low stratosphere in the North Pole (van Loon and Labitzke, 1987; Labitzke and van Loon, 1989).

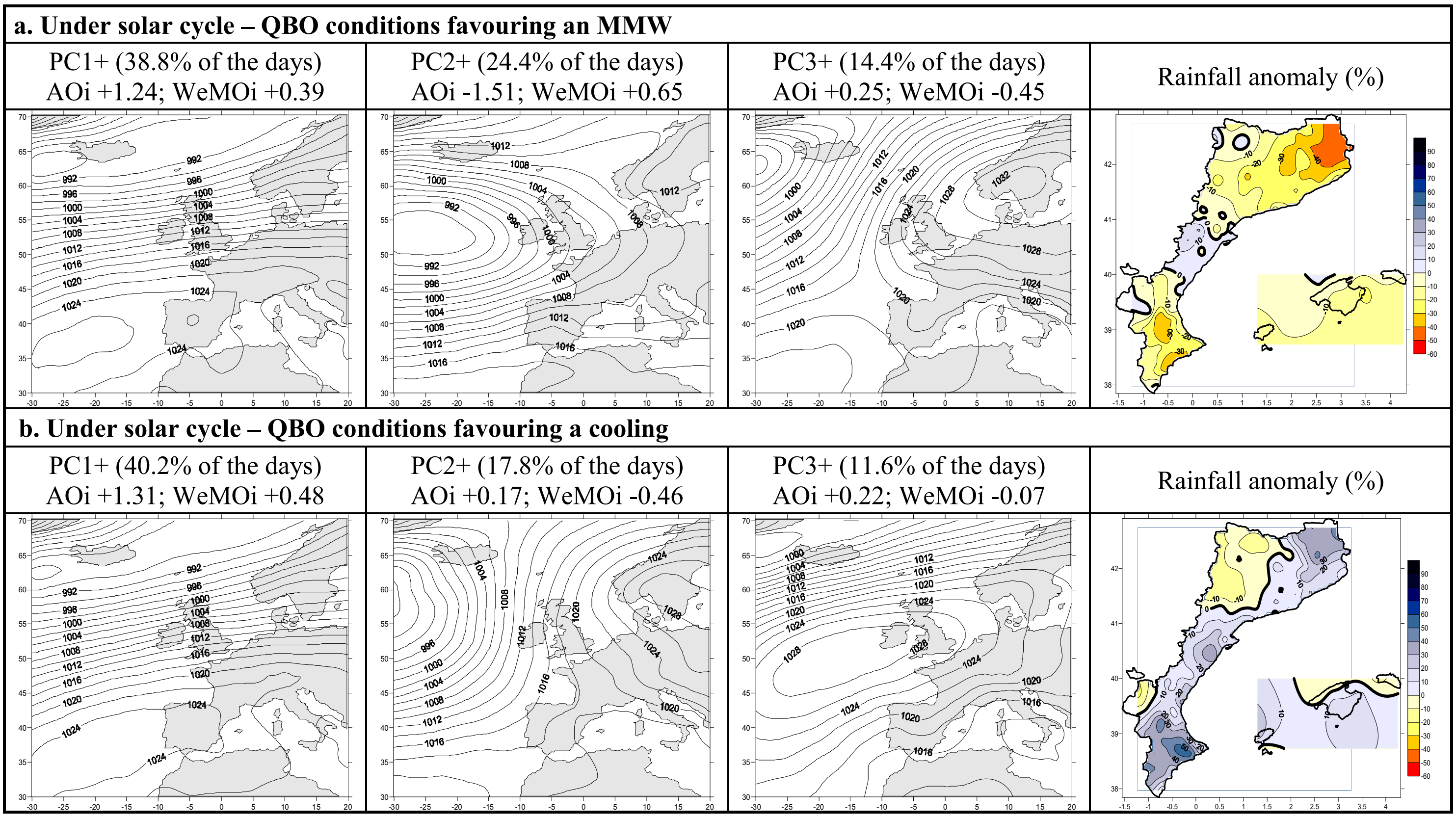


Figure 6. a. The three most frequent circulation patterns in February with their corresponding AOi and WeMOi values in those days which are potentially under an MMW influence according to the initial conditions of the solar cycle – QBO relationship of the 1958-2000 period, and the map of rainfall anomalies in the Catalan Countries according to the 1961-1990 reference period. **b.** Idem as (a), but for those which are potentially under the influence of a cooling. (Adapted from Lopez-Bustins *et al*., 2007).

4.3. THE GREENHOUSE GASES AND THE TORRENTIAL RAINFALL INCREASE IN THE CATALAN COUNTRIES

4.3.1. THE DUALITY OF THE GREENHOUSE GASES FORCING

The greenhouse gases, as above mentioned, have a double forcing on polar vortex. According to Shindell *et al*. (1999, 2001), greenhouse gases are the factor which has a largest effect on the general circulation of the atmosphere when they ran the GISS model. They reached the conclusion that these gases play a crucial role in the recent trends of AOi, over the solar and volcanic factors. The given off halogens contribute to O_3 depletion in the North Pole favouring a cold polar vortex until the early spring. The dynamical forcing of the greenhouse gases is the unique capable of leading to a steadily increase of the winter AOi, which has been detected along the last decades (Shindell *et al*., 2001). This dynamical forcing consists of the elevation of the tropical tropopause with a consequent deepening of it in the North Pole, favouring a cooling, due to a seesaw effect (Stocker, 1998) (Figure 7). Hypothetically, this fact suggests that the positive AOi trend and the strengthening of the polar vortex may have an anthropogenic origin.

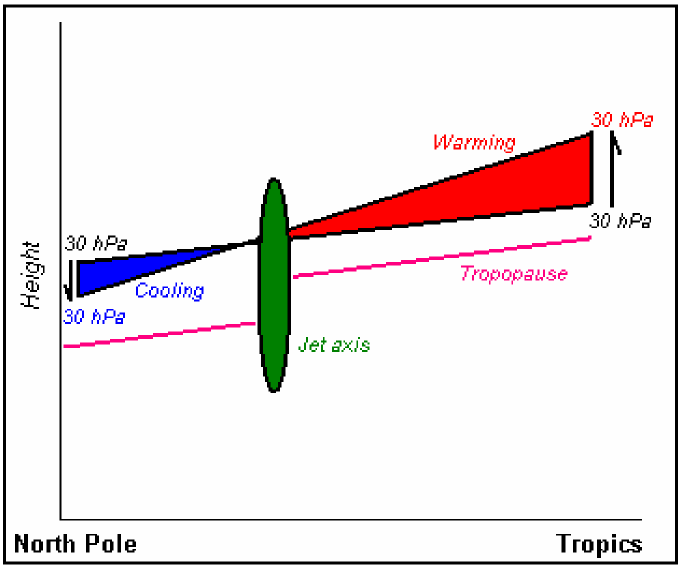


Figure 7. Draft of the geopotential height change at 30-hPa when the tropical stratosphere warms and temperature gradient is increased between the Equator and the North Pole, leading to a largest meridional gradient of the altitude. (Adapted from Robock (2000) in the study of the explosive eruptions on climate).

The period study is confined from December to February[3], where the role of the greenhouse gases is important for the polar vortex state. Later, March is analysed separately, period of year when the described influence and the O_3 depletion forcing meet.

[3] The dynamical forcing of the greenhouse gases takes place during the winter months because there is no sunshine on the North Pole and it favours a largest gradient of temperature between the Equator and the Pole.

4.3.2. THE WINTER INFLUENCE OF THE GREENHOUSE GASES

The winter temperature of the low polar stratosphere has a certain negative trend, although not significant (Table 3). The same happens with the geopotential height at 30-hPa level (not shown) due to a major frequency of occurrence of coolings during the last decade of the 20th century, and a less frequency of MMWs (Table 1). The winter trends of the AOi and WeMOi during the second half of the 20th century are justified. This recent negative WeMO phase in winter might lead to an intensity rise of the polar vortex.

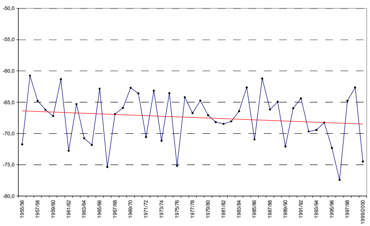
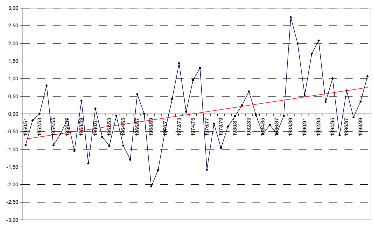
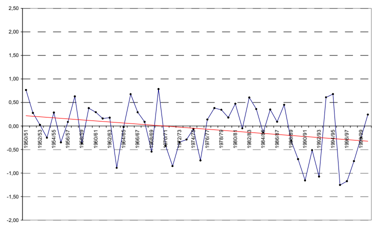
t-test for the coefficient b_1	T North Pole 30-hPa	AOi	WeMOi
Trend (value/ 10 years)	-0.48 ºC t = /-1.0034/ < 2.0161 (95%)	**+0.30** t = /-2.1373/ > 2.0101 (95%)	**-0.11** t = /3.3484/ > 2.0101 (95%)
Graphic			

Table 3. Trends and temporal evolution of the temperature (ºC) at 30-hPa in the North Pole for the 1955/56-1999/2000 period (Labitzke and collaborators, 2002) and of the AOi and the WeMOi for the 1950/51-1999/2000 period. (The significant trends at 0.05 are in bold).

In Figure 4 of the 3rd chapter, the opposed winter phases between the WeMO and the AO are better defined during the second half of the 20th century, as the three last ones have a strong oscillation. The 7th phase starts at the end of 1980s, where the AOi increases due to polar vortex strengthening, coinciding with an extreme negative WeMO phase. In order to check the importance of this last phase, we can notice that the winter precipitation (DJF) in the Catalan Countries has a positive trend in the Gulf of València and in north-eastern Catalonia (Figure 9 in the 3rd chapter), being significant in several meteorological stations in January (Figure 8 in the 3rd chapter).

In order to check how these gases may influence surface circulation over Europe the temporal evolution of the most frequent circulation patterns along the 1958/59-1999/2000 period is shown. Following the analysis of Lopez-Bustins *et al.* (in press), I used 3,791 days which are the whole days comprised in December, January and February for the 1958/59-1999/2000 period. The steps followed in the PCA and the grid size are the same as in the other analyses. The first 4 factors are retained because they contain more than 80% of the variance and the LEV-diagram shows a break in the slope at the 4th component (not shown).

The three most frequent circulation patterns are shown, and they agglutinate almost the 80% of the 3,791 days classified. The most frequent, PC1+, is a westerly circulation defined by a positive WeMO phase. This circulation pattern does not bring any humidity to the Catalan Countries, only to Val d'Aran, and slightly to Northern Catalonia and Menorca as these regions are not under the orographic effect of Pyrenees. The second most frequent pattern, PC3+, has the key, since it is a positive AO phase and a negative WeMO phase simultaneously, featured by the Central European anticyclone which shifts westerlies to the circumpolar latitudes. The last circulation pattern, PC2+, is a negative AO phase defined by the cut off polar lows towards north-western Iberia due to a high blocking in Eastern Europe. This pattern favours precipitation over inland Catalan Countries, whereas PC3+ in those coastland areas (Figure 8a).

Using the Mann-Kendall test[4] (Sneyers, 1992), we can notice that PC3+ significantly increases its absolute frequency at 0.05, and PC2+ decreases at 0.10. The PC1+ rises although without any signification (Figure 8b). It is coherent with an increase in the SLP over Central Europe (Shindell *et al*., 1999; Maugeri *et al*., 2004) and in the frequency of an anticyclone weather type in the Alps (Stefanicki *et al*., 1998) in winter. Simultaneously, a reduction of the number of cyclones at mid-latitudes in Europe (45º-50ºN) (Trigo, 2006), a decrease of the cloudiness associated to Atlantic fronts in Poland (Wibig, in press), and a major frequency of north-easterly and easterly winds over the Catalan Countries has been also detected in winter. Martín-Vide *et al*. (2004) detect a circulation pattern of identical morphology that PC3+ as the most frequent in the January-February period during 1978-1999, which is different to the one of the previous 1956-1997 period showing a more meridional circulation over Western Europe. The AOi has the largest increase in this two-month period (Table 2 in the 3rd chapter). Less polar lows over north-western Iberian Peninsula implies less frequency of the pass of Atlantic fronts over the Catalan Countries in winter. The absolute frequency trends of these circulation patterns are consistent with the AOi and WeMOi trends (Table 2 in the 3rd chapter) and with the spatial trends of the Catalan Countries precipitation in winter during the second half of the 20th century (Figure 9 in the 3rd chapter).

The winter month when this pattern has most increased is January (not shown). This is coherent with monthly precipitation trends in Figure 8 in the 3rd chapter, where January is when the rainfall increase is most extended over the Catalan Countries. Monthly WeMOi trends show January to be the only one with a significant negative trend (Table 2 in the 3rd chapter). To conclude, it must be pointed out that the greenhouse gases, by means of a physical mechanism, might have a direct incidence on the Catalan Countries rainfall, making

[4] It is only in this analysis that I have used the Mann-Kendall test, instead of the t-test, in order to calculate the % of the confidence levels of the trends.

wetter weather in winter featured by certain torrentiality, above all, in January. This is consistent with the conclusions of Prohom (2003), who pointed out the January month to be the period of the year when the tropical vulcanism has a largest effect on atmospheric circulation over Europe as the polar vortex comes stronger.

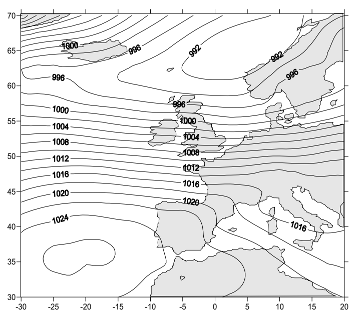
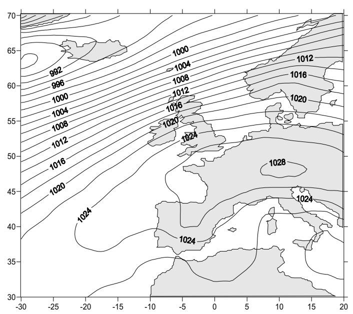
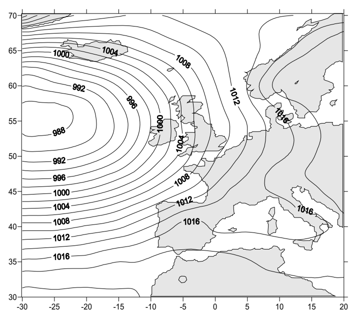
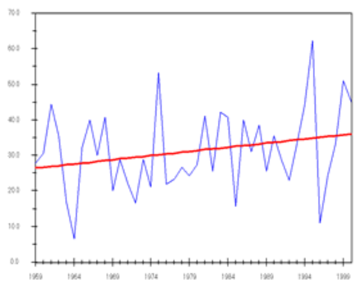
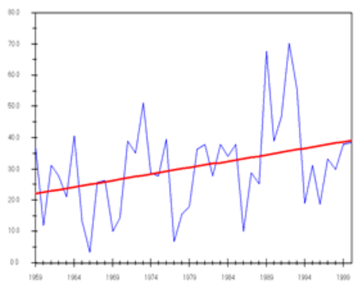
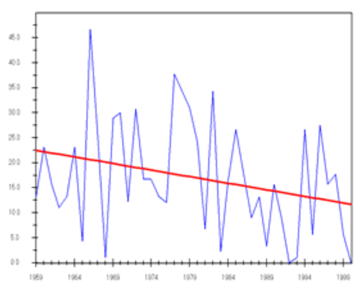
PC1+ (31.2% of the days) AOi +0.38 WeMOi +1.30	PC3+ (30.7% of the days) AOi +1.18 WeMOi -0.34	PC2+ (17.1% of the days) AOi -0.89 WeMOi +0.01
		
+2.4% per decade; no significant trend	+4.1% per decade; significant trend (95% confidence level)	-2.6% per decade; significant trend (90% confidence level)
		

Figure 8. a. The three most frequent circulation patterns over Western Europe in winter (DJF) during the 1958/59-1999/2000 period (AOi and WeMOi values are shown). **b.** Trends according to Mann-Kendall test and temporal evolution of annual absolute frequencies in winter of the three circulation patterns (linear regression is drawn).

4.3.3. THE GREENHOUSE GASES AND ITS INFLUENCE ON THE WINTER-SPRING TRANSITION PERIOD (MARCH)

The delay of the spring arrival in polar stratosphere is one of the clearest signals of the climate change (Rex *et al*., 2004). In the northern hemisphere, the change is not so evident, but in 1990s the polar vortex used to dissolve very late, already in midspring. These events were called *late final warmings*. The most outstanding example was in 1997, and a contrary event, the one in 1984. Both years recorded the most extreme positive and negative temperatures, respectively, at 30-hPa in the Arctic polar stratosphere in March along the last three decades in the 20th century (Figure 9).

Chlorofluorocarbons (CFCs) emission has been significantly reduced, due to its high capacity of O_3 depletion, after Montreal Protocol in 1987, but their highest concentration in stratosphere has been estimated about 2000. Because of their long life expectancy, a critical concentration in atmosphere might remain until 2050.

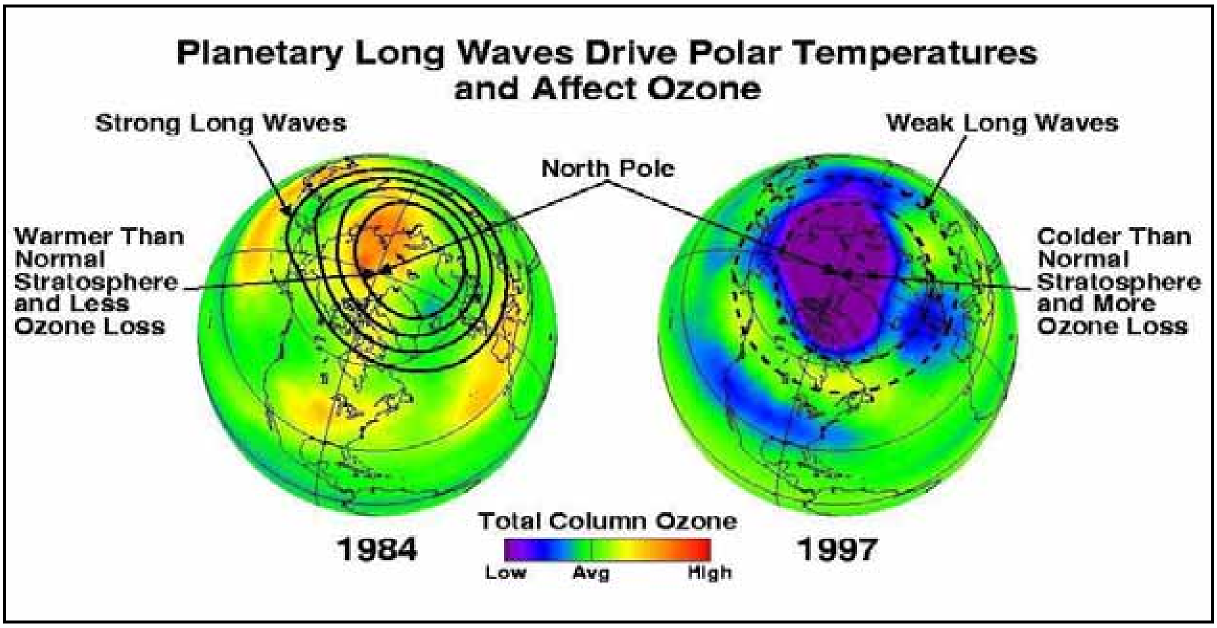
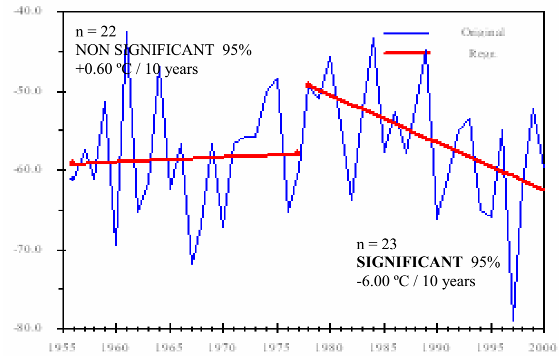


Figure 9. Relationship between planetary waves propagation and temperature in polar stratosphere in its effect on O_3 concentration. The extreme and opposed anomalous cases in 1984 and 1997. (From Barry and Phillips, 2001).

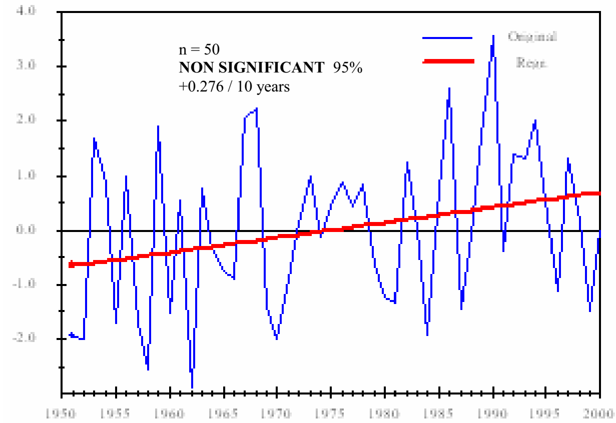
According to Table 2 in the 3rd chapter, in the 1951-2000 period, the AOi shows a certain positive trend in March, but it is not significant as in the entire winter (DJFM) (Table 3), and the WeMOi does not show any trend. The stratospheric temperature in March does not show any trend (-0.023 ºC/ 10 years) along the 1956-2000 period. Labitzke and Kunze (2005) detected the most significant and negative trend in the middle to low stratosphere in the North Pole in March, when they divide the period in two subperiods. At the end of the 1970s, it is when the massive O_3 depletions start due to the anthropogenic greenhouse gases (CFCs) emissions. The temporal evolution of temperature shows that the polar vortex is turning colder year-to-year along the last decades of the 20th century. This drop of the stratospheric temperature in March is also detected in later studies (Labitzke *et al*., 2005; Kim and Choi, 2006; Langematz and Kunze, 2006).

Although the weak reliability of temporal trends shorter than 30 years, two subperiods are established in the WeMOi and in the stratospheric temperature in the North Pole (30-hPa): 1956-1977 and 1978-2000. These two periods are not defined in the AOi, since it has steadily increased along the whole 1951-2000 period. The stratospheric polar temperature significantly decreases along the second subperiod (Figure 10a), which implies that the polar vortex strengthens with a major vorticity consequently. When the vortex becomes more dynamical in the second subperiod, the anomalies are better transmitted to the surface. The extreme positive AOi values in the 1951-2000 period are very often in the last 20 years, and the negative ones are not so low as in the first 15 years (Figure 10b). The WeMO behaviour is very coherent as its index significantly decreases since the end of the 1970s. In the 1990 decade, the WeMOi remains mostly in negative values, which are very extreme in some years (Figure 10c).

a. North Pole temperature (30-hPa) (1956-2000)



b. AOi (1951-2000)



c. WeMOi (1951-2000)

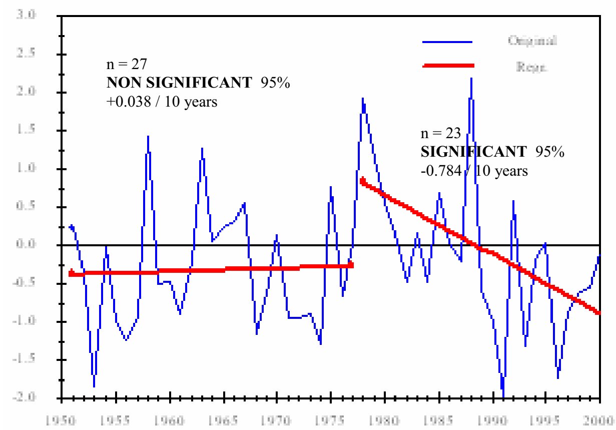


Figure 10. a. Trend and temporal evolution of temperature at 30-hPa in the North Pole in March for two subperiods: 1956-1977 and 1978-2000. **b.** Trend and temporal evolution of AOi in March for the 1951-2000 period. **c.** Trend and temporal evolution of WeMOi in March for two periods: 1951-1977 and 1978-2000. (T-test application using AnClim software –Stepanek 2005–).

Precipitation in March throughout the Catalan Countries is featured by the strongest decrease of the year in the 1951-2000 period (Figure 8 in the 3rd chapter). In this month, the AOi has a positive trend and the WeMOi has no changes; the NAOi has a positive and significantly increase (Table 2 in the 3rd chapter). The significant reductions in precipitation are in those areas where there is a significant and negative correlation with NAOi and AOi, Pyrenees (above all in the western Pyrenees) and northern Balearic Islands. The Valencian Country has little changes. These results coincide with those one found for the entire Iberian Peninsula (Aguilar *et al*., 2006; López-Bustins, 2006; Norrant and Douguédorit, 2006; Paredes *et al*., 2006), and the internal Catalan basins (Saladié *et al*., 2006).

In order to check which are the most frequent circulation patterns in early spring in those years when the polar stratosphere has the largest O_3 depletion and in those years when O_3 is abundant I selected those years when the temperature in March was above the normalised value /0.75/ of the 1970-2000 period. The end of the '60s and beginning of the '70s was the moment when the incidence of CFCs on O_3 depletion and the strong decrease in stratospheric temperature in the North Pole started. The temperature mean in the North Pole at 30-hPa for the 1958-2000 period is -57.4 ºC[5]. The open interval of standardised values (0.75, +0.75) is established to constitute both groups: March days with an anomalous warm polar stratosphere (temperature >+0.75) and March days with an anomalous cold stratosphere (temperature <-0.75). These normalised values correspond to -51.4 ºC and -63.4 ºC. The selection allows us to form two groups of 7 March months: warm ones (1974, 1975, 1978, 1980, 1984 and 1989) and cold ones (1970, 1976, 1982, 1990, 1994, 1995 and 1997). Notice that extreme cold months are mostly later than the warm ones, reaffirming the idea about the polar stratosphere cooling in March (Figure 11).

Using the same method of PCA I pretend to define the morphology and structure of those circulation patterns under anomalous conditions in polar stratosphere. The transmission of the extreme behaviour of vortex to the surface level is understood by the above mentioned stratosphere-troposphere coupling (see section 4.2.3., Baldwin and Dunkerton, 1999, 2001, 2005).

The matrix and steps of the multivariate analysis are the same as the ones applied in earlier sections, but only selecting the days of March which are of interest. The analysis is done for both groups of the same size, 217 days (31 days × 7 years). I must remark that the extraction was of the first 6 components, in both groups, which contain about the 90% of the variance in both analyses.

---

[5] This period is selected again as consequence of the lack of NCEP/NCAR reanalysis data before 1958 in the CRU website.

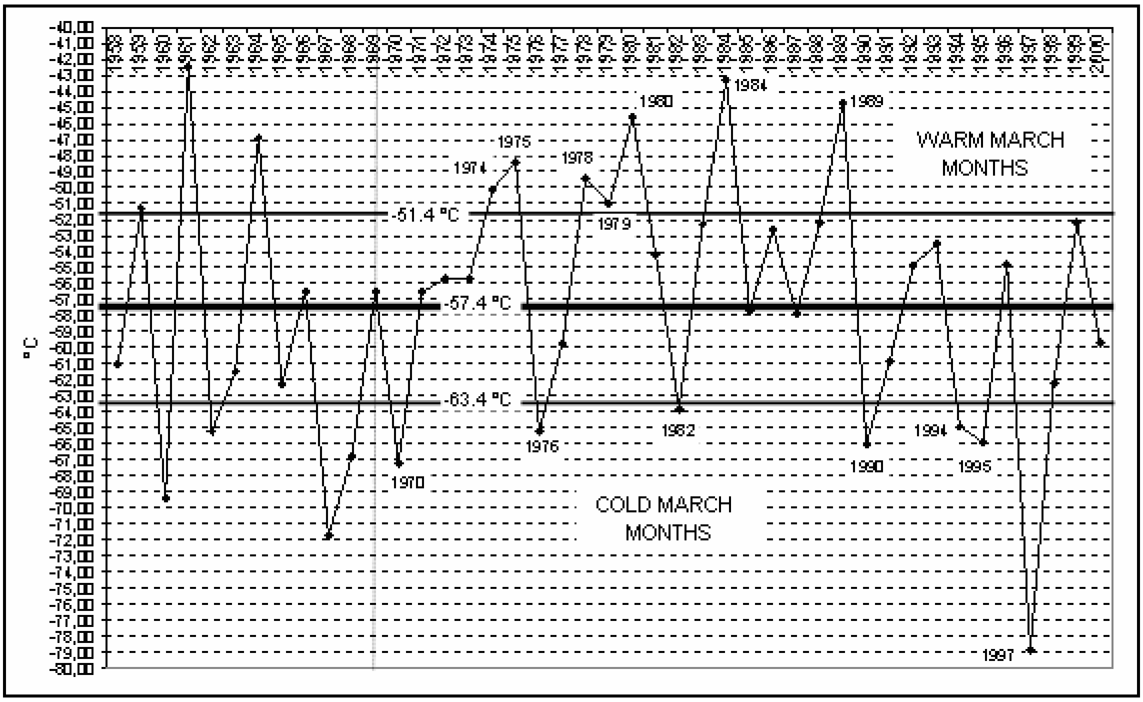


Figure 11. Temporal evolution of the stratospheric temperature at 30-hPa in the North Pole with their corresponding thresholds to select those extreme March months. (From López-Bustins, 2006).

The most frequent circulation pattern during the warm March months is a westerly circulation shifted southwards, which is a positive AO phase, but weakened (Figure 12a). On the other hand, in the cold March months, the positive AO phase is reinforced, with a certain strengthening of the pressure centres, and a displacement towards Central Europe of the Atlantic anticyclone; simultaneously, westerlies strengthen and move polewards (Figure 12b). Thus, western Catalonia has very dry March months, whereas in the southern Valencian Country they are slightly dry with slight precipitation increases in the Alacant mountains. This is why PC1+ in cold March months is a negative WeMO phase featured by the typical north-east and east advections, induced by a backdoor cold front over the Catalan Countries. In the western Pyrenees, above all in the north face (Val d'Aran), the cold March months also cause a rainfall reduction, although somewhat weaker because the PC2+ shows north-westerly flows which lead to precipitation over the area.

Hinssen *et al*. (2007) have also detected a strengthening of the westerlies due to O_3 loss as consequence of the anthropogenic greenhouse gases in late winter. These authors mention the role of the ice cover in the Arctic as an additional factor that contributes to the reinforcement of the vorticity in the North Pole. A thinner ice cover implies warmer temperatures at surface level which do not favour the robust formation of a thermal anticyclone, enabling the penetration into troposphere of an anomalous cyclone circulation from the stratosphere.

Referring to the warm March months again, the overall Catalan Countries obtain noticeable rainfall increases due to the second most frequent circulation pattern which favours the formation of a low in the middle of the western Mediterranean basin with a backdoor cold front (Estrela *et al*., 2002) when a potent blocking high lies in Scandinavia. To sum up, the cold months are associated to positive extreme AO phases, and the warm ones to rather negative ones as the PC2+ shows in Figure 12a. The precipitation drop in most of the Catalan Countries in March might be related to the non-occurrence of warm months, whereas 4 cold months occurred, during the last decade of the 20th century.

The role of the north-easterly flows associated to coolings loses some effect on the Catalan Countries rainfall. Actually, the most representative PC of them, PC1+, has hardly more cases than PC2+. Consequently, the positive precipitation anomalies are located in the Alacant mountains. The negative anomalies are spread throughout the study area because neither PC1+ nor PC2+ of the cold March months are meteorological situations favouring precipitation over the Iberian Peninsula. In Figure 29 in the 3rd chapter (in the Catalan version), the AO, in its positive phase, enhances its influence on the Alacant region rainfall during the last decades of the 20th century. It might be related to a major absolute frequency of PC1+ in Figure 12b.

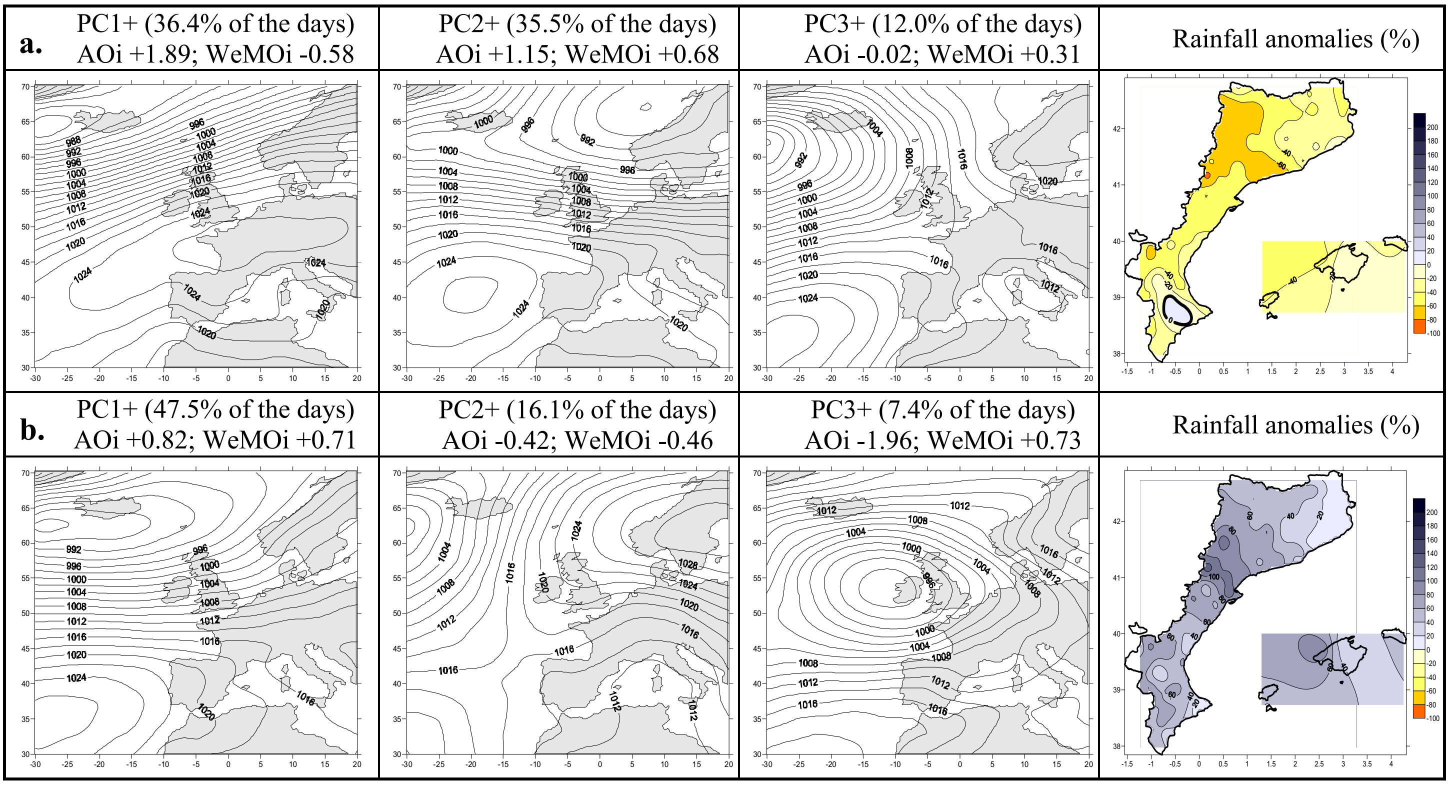


Figure 12. a. The three most frequent circulation patterns with their AOi and WeMOi values for those days of the 7 March months with an anomalous cold stratosphere for the 1970-2000 period, and the corresponding map of rainfall anomalies according to the 1961-1990 reference period. **b.** Idem as (a), but for those days of the 7 March months with an anomalous warm stratosphere.

It is undoubtedly demonstrated that the rainfall decline in most part of the Catalan Countries in March during the 1951-2000 period (very strong in western Pyrenees and northern Balearic Islands; Figure 8 in the 3rd chapter) is due to a major frequency of the circulation patterns linked to coolings in late winter during the 1990s.

Rainfall consequences in March 1997 (the coldest one in the North Pole stratosphere in the 1970-2000 period) in the Catalan Countries are very noticeable as ¾ parts of the study area have a negative anomaly. The most affected regions were the Pyrenees, inland Castelló and the Western Strip, and the eastern Balearic Islands, where the registered precipitation was 0 mm (Figure 13a). On the other hand, in March 1984 (the warmest one), precipitation was anomalously abundant in Catalonia, and moderately positive in the inland Valencian Country and most of the Balearic Islands (Figure 13b).

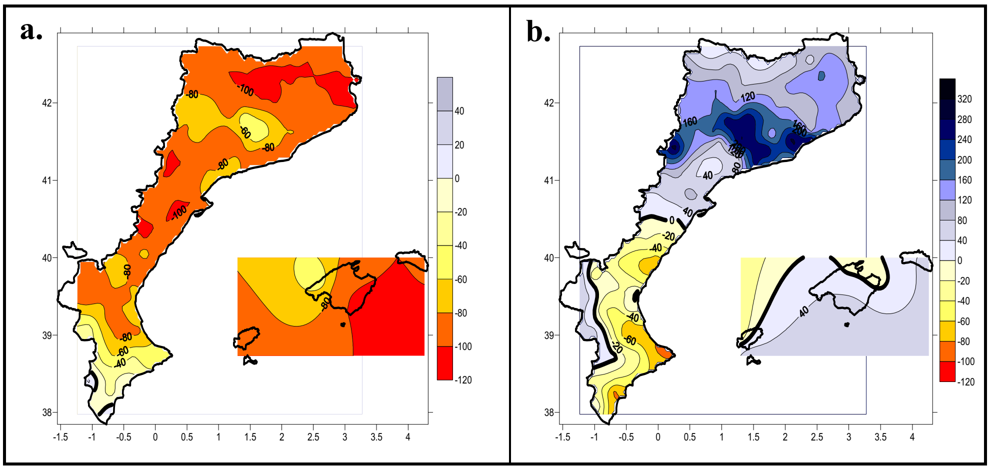


Figure 13. a. Rainfall anomalies (%) in March 1997 according to the 1961-1990 reference period. **b.**. Idem as (a), but for March 1984.

4.4. DIAGRAM TO CONCLUDE