The Role of the Stratosphere in Iberian Peninsula Rainfall: a Preliminary Approach in February

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Abstract

This paper attempts to establish a connection between stratospheric anomalies in the North Pole and rainfall on the Iberian Peninsula through the occurrence of major midwinter warmings (MMWs) and cold events (CEs), taking February as a preliminary approach. We define the MMWs as the warmings which break down the polar vortex, whereas the CEs are the episodes in which the polar vortex remains cold and undisturbed. Both anomalies lead to a wind anomaly around the north polar stratosphere which is connected with a shortly lagged tropospheric anomaly through a stratosphere-troposphere coupling in winter. A T-mode principal component analysis (PCA) was used as an objective pattern classification method for identifying the main daily surface level pressure (SLP) patterns for February for the 1961-1990 reference period. Subsequently, those February months with an MMW or a CE influence in the troposphere are identified in the whole study period (1958-2000) by means of the Arctic oscillation index (AOI). Thus, performing the same analysis for the selected February months, new principal patterns for detecting changes in surface circulation structure and morphology are obtained. The results show a significant decrease in the westerlies and a southward shift of the storm tracks in Western Europe some weeks after an MMW occurrence, leading to an increase in precipitation in western Iberia and a slight decrease on the eastern Mediterranean fringe. The results are quite the opposite under a CE influence: the westerlies are strengthened and shifted northward due to the displacement of the Atlantic anticyclone toward Central Europe; dry conditions are established throughout Iberia, except for the Mediterranean fringe where precipitation shows a considerable increase due to the greater frequency of the northeasterly winds. Finally, an 11-year sunspot cycle – quasi-biennial oscillation (QBO) modulation might be demonstrated in Iberian rainfall in February through the occurrence of these stratospheric anomalies.

Key words: Arctic oscillation index; Circulation patterns; Iberian rainfall; Major midwinter warming; Principal component analysis; Stratosphere-troposphere coupling.

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1. Introduction

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; 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 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 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 general circulation models (GCMs) (Omrani *et al.*, 2006).

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 cold events (CE), through the 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 northern annular mode (NAM) at 150-hPa in February, which partly explains why we present an initial approach taking only February into account. We focus on the study of morphological and structural changes in circulation patterns and their effects on precipitation on the Iberian Peninsula in February following the occurrence of a stratospheric anomaly. In section 2, we define the stratospheric anomalies and detect those February months with a potential influence of the stratospheric anomaly at surface level by means of the Arctic oscillation index (AOI). In the following section, we present the results of the application of a principal component analysis (PCA) to a daily sea level pressure (SLP) grid over Europe in order to establish the main circulation patterns in February over the 1961-1990 reference period. The same analysis was subsequently conducted for those February days with a potential stratospheric anomaly influence in order to make a comparison. Finally, in section 4, we attempt to demonstrate the existence of a possible solar cycle – quasi-biennial oscillation (QBO) modulation influencing Iberian rainfall through the occurrence of these stratospheric anomalies, which is also most likely to be detected in February (Labitzke, 2005), which further justifies the selection of the month of February as an initial approach.

2. Methods and data

2.1. The MMWs and the CEs

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. Furthermore, our monthly rainfall database on the Iberian Peninsula ends in 2000; 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 anticyclone circulation over the North Pole, 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 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 midwinter warmings.

On the other hand, the CEs 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 $\leq$-75ºC or $T_{30\text{-}hPa\ N\ Pole}$ February $\leq$-70ºC and the strengthening of westerlies at 10-hPa over the high latitudes.

2.2. 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 Arctic oscillation (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. 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 CEs. 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 CE 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 NAO index (NAOI), and we therefore considered that >/0.50/ can clearly show the sign of the phase, but not extremely. The third column shows the central date of each warming at 10-hPa using ERA data as a reference (Charlton and Polvani, 2007). 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 CE 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 CE transmission is similar to the MMWs and 20 (77%) out of 26 CEs 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 CE which took place in the stratosphere that February.

Table 1.

Our 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 CE anomalies are most frequent in January, with 13 years. For February, in 10 years a CE influence was found, the same frequency as in March.

2.3. Statistical Analysis: Detection of the influence of stratospheric anomalies at regional surface circulation

The main aim of this analysis is to detect an MMW or a CE influence upon the troposphere, seeking changes in the structure and morphologies of circulation patterns, and to relate the latter to rainfall anomalies on the Iberian Peninsula. To this end we performed a daily objective classification of circulation patterns at SLP for February in two different ways: we 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, we 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 we used to identify the main atmospheric patterns was the 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). We 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., 1999; Romero et al., 1999); other options in the PCA process involve the use of the correlation matrix or rotation with the Varimax orthogonal procedure. 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 we 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 patterns are shown, but they constitute approximately 70-90% of the cases.

The February rainfall means for Iberia were calculated for the 1961-1990 period. The rainfall data were provided by 51 meteorological stations throughout the whole peninsula at a monthly resolution (Vicente-Serrano and Beguería-Portugués, 2004). Nine of these series come from the Portugese *Sistema Nacional de Informação de Recursos Hídricos*, whereas the rest were obtained from the *Instituto Nacional de Meteorología* of Spain (Fig. 1). The series were checked using a quality control process with the AnClim software (Stepanek, 2005) which identified the anomalous records, and then homogenised them according to the Standard Normal Homogeneity Test (SNHT) (Alexandersson and Moberg, 1997). Subsequently, we calculated the February rainfall anomalies according to the 1961-1990 reference period for those years under an MMW or CE influence in order to associate them with the circulation patterns obtained.

Fig. 1.

3. Results

3.1. 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 patterns with regard to the 1961-1990 reference period in February are shown in Fig. 2. The most frequent is a zonal circulation over Western Europe associated with a positive AO phase (PC1+). The second, PC2+, is a pattern showing a positive AO phase where a blocking high, between the Scandinavian Peninsula and Central Europe, shifts westerlies northward. The following one, PC3+, is a low shifted southward involving a southwesterly maritime flow over the western Iberian Peninsula. The wettest areas in February are western and northern Iberia where the maritime flows are more frequent, the eastern inland zone and the Mediterranean fringe have drier conditions.

Fig. 2.

3.2. 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 (Fig. 3). 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 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. 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 pattern under an MMW is the third one of the reference period, but in a more negative AO phase. It shows an increase in the frequency of humid southwesterly advection over the western Iberian Peninsula. The change in frequency order of these patterns is the most reliable result of the MMW influence on troposphere circulation. This Atlantic flow leads to an increase in rainfall in western Iberia, but dry conditions on the eastern fringe because the winds lose their humidity after crossing over the Iberian continental mass. That is to say that the driest Iberian area in February becomes even drier and the wettest one becomes more humid.

The blocking situation over Central Europe (PC2+ in Fig. 2) is now weakened and lies in the least frequent position. Although this second most frequent pattern in the reference period implies dry conditions throughout most of the Iberian Peninsula, wetter conditions have been seen on the eastern fringe because of the eastern and northeasterly 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 this Mediterranean area.

Fig. 3.

3.3. Under a CE influence

An analysis was conducted once again for those days under a CE 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 patterns under CE 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 (Fig. 4); it is shown by PC2+ with an obviously high AOI. 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 (Fig. 2), which match the PC1+ and PC3+ in Fig. 4 with an increased AOI, to their respective new positions, second and third. The PC3+ of the reference period (Fig. 2) does not appear among the three most frequent patterns under the influence of a CE. The rainfall anomalies map in February shows a big difference between the western Iberian Peninsula and the Mediterranean fringe. Most of the Iberian Peninsula has very dry conditions mainly due to the disappearance of the PC3+ of the reference period. There is a notable rainfall increase over the southeastern area due to the more frequent backdoor cold fronts (northeasterly winds) (PC2+ in Fig. 4). These fronts bring heavy rainfalls over the

Mediterranean fringe; consequently, the strengthening of the westerlies by a CE influence might lead to an increase in torrential events over the eastern Iberian fringe.

Fig. 4.

3.4. Stratospheric temperatures North Pole (30-hPa) and Iberian Peninsula rainfall

Fig. 5 shows those areas with a significant rainfall variation in their means between the years under an MMW and those years under a CE influence according to the Student's *t*-test (Pozo-Vázquez et al., 2005). Most of the Iberian Peninsula is significant at the 95% confidence level; precisely the western and central parts, above all, in the northwestern inland area. We detected the greatest significance over Zamora, with a 99.9% confidence level. We therefore considered an overall stratospheric winter influence on the troposphere, as we previously analysed, in a very preliminary essay, a similar transmission of the stratospheric anomalies to the troposphere in January and March (Lopez-Bustins et al., 2006). For this purpose, we conducted a simple regression between Zamora rainfall for January, February and March (JFM) and the North Pole 30-hPa geopotential height (JF) (Fig. 6), and we found a significant and positive correlation at the 99% confidence level. It should be highlighted that 11 (69%) of the 16 years with an MMW occurrence are in the top righthand quadrant, which corresponds to Zamora rainfall values above the mean. A total of 11 (58%) of the 19 years with a value above the mean for Zamora rainfall fit with an MMW occurrence. 1989 and 1973 do not fit into the general picture because the MMW did not reach the surface in its downward propagation, and 1981 and 1999 are years with a late MMW in February which mainly influenced tropospheric circulation in March. The MMW in 1991 was not considered to be well-transmitted; however, there was a weak downward propagation (Table 1) that conferred a value above the mean to Zamora rainfall. Moreover, years with an extreme cold north polar stratosphere in January or February are related to dry conditions in Zamora. It should pointed out that squares representing a very cold polar vortex are mostly in the bottom lefthand quadrant (11 (73%) out of 15). 1964, 1974 and 1996 are the only three years with positive rainfall values over Zamora with the occurrence of an undisturbed and cold polar vortex; these CEs hardly reached the surface level. A very cold polar vortex and an MMW coincided in 1981 and 1989. In short, if the geopotential height 30-hPa at the North Pole mean (JF) is below 22.1 km, a very cold vortex is certainly connected with reduced Zamora rainfall (JFM); and vice versa when geopotential height is above 22.5 km.

Fig. 5.

Fig. 6.

4. Solar cycle – QBO modulation

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, 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 Iberian 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 with a west QBO phase, would not favour an MMW occurrence; consequently, low stratospheric temperatures in the North Pole would be more probable. In Fig. 7, the 11-year solar cycles (Schwabe cycles) concerning the period studied 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).

Fig. 7.

A new analysis was performed without taking the AOI into account. We 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 (Fig. 7). 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 Fig. 8 follow the same frequency order as the one in the February analysis under an MMW influence, taking AOI into account (see Fig. 3). However, the most frequent pattern in Figure 8 does not shift southwards as in Fig. 3, 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 (Fig. 8). An 11-year solar cycle – QBO signal might be found in rainfall over the Iberian Peninsula, but it is occasionally concealed. What we highlighted was the maintenance of the PC3+ of the reference period (Fig. 2) in the second position as in Fig. 3. It means a more frequent cut-off of lows over the western Iberian Peninsula increasing precipitation over its central and western areas.

Fig. 8.

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 CE 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 Fig. 9, leading to dry conditions in the western and central areas. The increase in precipitation, however, remains over the southeastern area due to the maintenance of the frequency in the humid northeasterly winds over the western Mediterranean basin. Furthermore, the second most frequent pattern (PC2+) is the third under a CE influence (PC3+ in Fig. 4), associated with easterly winds over the Iberian Peninsula, which also contributes some precipitation to the eastern fringe. We pointed out that the PC3+ from the 1961-1990 reference period in Fig. 2 does not appear among the three most frequent patterns under these solar cycle – QBO conditions favouring a CE event. Therefore, South-North wind circulation would not be favoured over Western Europe, and this would lead to a rainfall reduction over the central and western Iberian Peninsula. This PC3+ from the 1961-1990 reference period did not appear either among the 3 most frequent circulation patterns under a CE influence taking AOI into account (Fig. 4).

Fig. 9.

Fig. 10 shows that the difference in rainfall means between both conditions are significant only in the inland northern Central Plateau and the northwest coast. The distribution of rainfall anomalies in Fig. 8 and 9, however, are quite similar to those in Figs. 3 and 4 respectively, but weakened. For instance, precipitation increases and decreases slightly over the southeastern region, but not significantly, according to the solar cycle – QBO relationship. To sum up, we concluded that the solar cycle – QBO modulation influencing Iberian rainfall through the occurrence of stratospheric anomalies is weak, but some significance is seen in those areas where the MMWs and the CEs have the strongest effect, i.e., the northwestern Iberian Peninsula (Figs. 3 and 4).

Fig. 10.

5. Discussion and conclusions

To conclude, in general terms, the results obtained in section 3 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 an increase in precipitation in the western part of the Iberian Peninsula some weeks later, and a decrease on the eastern fringe in February. On the contrary, in those February months under CE influence, the westerlies are strengthened and shifted northward over Scandinavia, and the northeasterly winds over the Iberian Peninsula are favoured, as an anticyclone is well established over Central Europe. Consequently,

after a CE occurrence we should expect a decrease in precipitation in the western and central part of the Iberian Peninsula some weeks later, and an increase on the eastern fringe. This rainfall difference over Iberia is caused by the influence of the main ranges of the eastern Central Plateau which are North-South oriented (Fig. 1); hence these constitute the border of both flows, the Atlantic and Mediterranean ones.

In February, the most frequent pattern under a CE influence, PC2+ (Fig. 4) is an anticyclone over Central Europe, which is a representative pattern of the negative phase of the Western Mediterranean Oscillation (WeMO) (Martin-Vide and Lopez-Bustins, 2006). This oscillation is negatively correlated to rainfall of a torrential nature over the eastern Iberian fringe; it might therefore account for a precipitation increase and its irregularity in this area when this pattern is more frequent after the occurrence of a CE.

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 southern Europe. Our results therefore confirm these previous studies.

The novelty of our study involves describing in detail those changes in synoptic surface circulation patterns over Western Europe between an MMW and a CE occurrence, these being consistent with the above-mentioned studies. Another new contribution of our study is to have carried out a downscaling to Iberian Peninsula rainfall of these stratospheric anomalies, where we succeeded in distinguishing precipitation differences between western and eastern Iberia.

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*". The northwestern inland area is the Iberian zone where the solar cycle – QBO modulation is most likely to be detected in late winter, because this is where we found the highest significant variation between the rainfall means (Fig. 10) and the stratospheric circulation anomalies have the greatest effect (Fig. 5). 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 Iberian Peninsula weather types by means of stratosphere-troposphere coupling, as we downscaled to the study area the spatial distribution of rainfall anomalies 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 on the western Iberian Peninsula, depending on stratospheric behaviour in late winter. Similar effects were found in other preliminary essays which we conducted for January and March, but the results were not as robust as in February (Lopez-Bustins et al., 2006). Although the results show obvious circulation patterns according to the AO phase selected, both in MMWs and CEs, our 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. Nevertheless, the close relationship between the stratospheric geopotential height (30-hPa at the North Pole) and rainfall on the Iberian Peninsula is shown, given that we found a significant correlation between these in the Zamora series, including all the years of the period. Furthermore, there is a lag in the propagation of stratospheric anomalies which has not yet been suitably established (Baldwin and Dunkerton, 2005), leading us to select the influenced month individually. 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 AOI, and the results have shown a similar, but weakened, effect on Iberian rainfall as the circulation patterns hardly change their structure or 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 was slightly negative in 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 high latitudes during midwinter. Notwithstanding, other factors, such as eruptions of tropical volcanoes or El Niño –

Southern Oscillation (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).

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Links to the different data are as follows:

FU-Berlin: http://strat-www.met.fu-berlin.de/products/cdrom

Monthly AOi Data (Thompson and Wallace, 2000): http://www.nwra.com/resumes/baldwin/nam.php

NCEP/NCAR Reanalysis Data (Climatic Research Unit): http://www.cru.uea.ac.uk/cru/data/

Solar flux, Penticton (Canada), National Geophysical Data Center, NOAA: http://www.ngdc.noaa.gov/stp/SOLAR/FLUX/flux.html

Solar Influences on Climate (SOCLI) Programme, funded by NERC (Natural Environment Research Council): http://www.see.leeds.ac.uk/research/ias/composition/current/socli.htm

References

- Alexandersson, H., Moberg, A., 1997. Homogenization of Swedish Temperature Data. Part I: Homogeneity Test for Linear Trends. International Journal of Climatology 17, 25-34.
- Azorín-Molina, C., López-Bustins, J.A. 2004. Catálogo sinóptico manual y causas atmosféricas de la precipitación en la provincia de Alicante. Boletín de la AGE 38, 279-310.
- Baldwin, M.P., 2000. The Arctic Oscillation and its role in stratosphere-troposphere coupling. SPARC Newsletter 14.
- Baldwin, M.P., Dunkerton, T.J., 1999. Propagation of the Arctic Oscillation from the stratosphere to the troposphere. Journal of Geophysical Research 104, 30937-30946.
- Baldwin, M.P., Dunkerton, T.J., 2001. Stratospheric harbingers of anomalous weather regimes. Science 294, 581-584.
- Baldwin, M.P., Dunkerton T.J., 2005. The solar cycle and stratosphere-troposphere dynamical coupling. Journal of Atmospheric and Solar-Terrestrial Physics 67, 71-82.

- Baldwin, M.P., Gray, L.J., Dunkerton, T.J., Hamilton, K., Haynes, P.H., Randel, W.J., Holton, J.R., Alexander, M.J., Hirota, I., Horinouchi, T., Jones, D.B.A., Kinnersley, J.S., Marquardt, C., Sato, K., Takahashi, M. 2001. The Quasi-Biennal Oscillation. Reviews of Geophysics 39 (2), 179-229.
- Baldwin, M.P., Stephenson, D.B., Thompson, D.W.J., Dunkerton, T.J., Charlton, A.J., O'Neill, A., 2003. Stratospheric memory and extended-range weather forecasts. Science 301, 636-640.
- Barnston, A.G., Livezey, R.E., 1987. Classification, Seasonality and Persistence of Low-Frequency Atmospheric Circulation Patterns. Monthly Weather Review 115, 1083-1126.
- Barry, R.G., Carleton, A.M. 2001. Synoptic and Dynamic Climatology. Routledge. London.
- Camara, A., Serrano, E., Ayarzaguena, B., Mechoso, C.R., 2007. Winter rainfall variability over Europe in the coupled stratosphere-troposphere system. Geophysical Research Abstracts 9, 08908.
- Charlton, A.J., Polvani, L.M. 2007. A New Look at Stratospheric Sudden Warmings. Part I. Climatology and Modeling Benchmarks. Journal of Climate 20, 449-469.
- Charlton, A.J., O'Neill, A., Stephenson, D.B., Lahoz, W.A., Baldwin, M.P., 2003. Can knowledge of the state of the stratosphere be used to improve statistical forecasts of the troposphere? Quarterly Journal of the Royal Meteorological Society 129, 3202-3225.
- Christiansen, B., 2006. On the use of stratospheric information in extended range forecasts of the near surface weather. Geophysical Research Abstracts 8, 01634.
- Esteban, P., Jones, P.D., Martin-Vide, J., Mases, M., 2005. Atmospheric circulation patterns related to heavy snowfall days in Andorra, Pyrenees. International Journal of Climatology 25, 319-329.
- Esteban, P., Martin-Vide, J., Mases, M., 2006. Daily atmospheric circulation patterns over western Europe. Anew approach using PCA and K-means Clustering. International Journal of Climatology 26 (11), 1501-1515.
- Gray, L.J., Crooks, S., Palmer, M., Pascoe, C., Sparrow, S., 2006. A Possible Transfer Mechanism for the 11-Year Solar Cycle to the Lower Stratosphere. Space Science Reviews 125, 357-370.
- Haigh, J.D., Blackburn, M., Day, R., 2005. The Response of Tropospheric Circulation to Perturbations in Lower-Stratospheric Temperature. Journal of Climate 18, 3672-3685.
- Haigh, J.D., Roscoe, H.K., 2006. Solar influences on polar modes of variability. Meteorologische Zeitschrift 8, 371-378.
- Haynes, P., 2005. Stratospheric Dynamics. Annual Review of Fluid Mechanics 37, 263-293.
- Holton, J.R., Tan, H.C., 1980. The influence of the equatorial quasi-biennal oscillation on the global circulation at 50 mb. Journal of Atmospheric Science 37, 2200-2208.
- Holton J. R., Tan, H.C., 1982. The quasi-biennial oscillation in the Northern Hemisphere lower stratosphere. Journal of the Meteorological Society of Japan 60, 140-148.
- Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. Science 269, 676-679.
- Huth, R., 1996. An intercomparison of computer-assisted circulation classification methods. International Journal of Climatology 16, 893-922.
- Huth, R., 2000. A circulation classification scheme applicable in GCM studies. Theoretical and Applied Climatology 67, 1-18.
- Julian, P.R., Labitzke, K.B., 1965. A Study of Atmospheric Energetics During the January-February 1963 Stratospheric Warming. Journal of the Atmospheric Sciences 22 (6), 597-610.
- Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetma, A., Reynolds, R., Jeene, R., Joseph, D., 1996. The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77, 437-471.
- Labitzke, K., 1987. Sunspots, the QBO, and the stratospheric temperature in the north polar region. Geophysical Research Letters 14, 535-537.
- Labitzke, K., 2005. On the solar cycle-QBO relationship: a summary. Journal of Atmospheric and Solar-Terrestrial Physics 67, 45-54.
- Labitzke, K., van Loon, H., 1988. Associations between the 11-year solar cycle, the QBO and the atmosphere. Part I: the troposphere and stratosphere in the northern hemisphere winter. Journal of Atmospheric and Terrestrial Physics 50, 197-206.
- Labitzke, K., van Loon, H., 1989. The Southern Oscillation. Part IX: The Influence of Volcanic Eruptions on the Southern Oscillation in the Stratosphere. Journal of Climate 2, 1223-1226.
- Labitzke, K. and Collaborators, 2002. The Berlin Stratospheric Data Series, CD from Meteorological Institute, Free University of Berlin.
- Labitzke, K., Kunze, M., Brönnimann, S., 2006. Sunspots, the QBO, and the Stratosphere in the North Polar Region – 20 Years later. Meteorologische Zeitschrift 9, 355-363.

- López-Bustins JA. 2006. Temperatura de la estratosfera polar y precipitación de la Península Ibérica en marzo (1958-2000). V Congreso de la Asociación Española de Climatología 5, 175-189.
- Lopez-Bustins, J.A., Esteban, P., Labitzke, K., Langematz, U., 2006. Major Midwinter Warmings and Iberian Peninsula Rainfall. Geophysical Research Abstracts 8, 03493.
- Maheras, P., Xoplaki, E., Davies, T., Martin-Vide, J., Barriendos, M., Alcoforado, M.J., 1999. Warm and cold monthly anomalies across the Mediterranean basin and their relationship with circulation; 1860-1990. International Journal of Climatology 19, 1697-1715.
- Martin-Vide, J., Lopez-Bustins, J.A., 2006. The Western Mediterranean Oscillation and Rainfall in the Iberian Peninsula. International Journal of Climatology 26 (11), 1455-1475.
- Millán, M.M., Estrela, M.J., Miró, J., 2005. Rainfall Components: Variability and Spatial Distribution in a Mediterranean Area (Valencia Region). Journal of Climate 18, 2682-2705.
- Omrani, N.E., Latif, M., Giorgetta, M.A., 2006. Troposphere-stratosphere coupling during strong stratospheric Northern Annular Mode. European Geosciences Union General Assembly in Vienna, poster communication.
- Pozo-Vázquez, D., Gámiz-Fortis, S.R., Tovar-Pescador, J., Esteban-Parra, M.J., Castro-Díez, Y., 2005. El Niño–Southern Oscillation Events and Associated European Winter Precipitation Anomalies. International Journal of Climatology 25, 17-31.
- Quiroz, R.S., 1977. The tropospheric-stratospheric polar vortex breakdown of January 1977. Geophysical research Letters 4, 151-154.
- Quiroz, R.S., Miller, A.J., Nagatani, R.M., 1975. A Comparison of Observed and Simulated Properties of Sudden Stratospheric Warmings. Journal of the Atmospheric Sciences 32 (9), 1723-1736.
- Romero, R., Sumner, G., Ramis, C., Genovés A., 1999. A classification of the atmospheric circulation patterns producing significant daily rainfall in the Spanish Mediterranean area. International Journal of Climatology 19, 765-785.
- Siegmund P. 2006. Possibilities for extended-range forecasting based on stratospheric predictors. Geophysical Research Abstracts 8, 10429.
- Stepanek, P., 2005. AnClim –software for time series analysis. Dept. of Geography, Fac. of Natural Sciences, MU, Brno. 1.47 MB.
- Thompson, D.W.J., Wallace, J.M., 2000. Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability. Journal of Climate 13, 1000-1016.
- Thompson, D.W.J., Furtado, J.C., Shepherd, T.G. 2006. On the Tropospheric Response t Anomalous Stratospheric Wave Drag and Radiative Heating. Journal of the Atmospheric Sciences 63, 2616-2629.
- van Loon, H., Labitzke, K., 1987. The Southern Oscillation. Part V: The Anomalies in the Lower Stratosphere of the Northern Hemisphere in Winter and a Comparison with the Quasi-Biennial Oscillation. Monthly Weather Review 115, 357-369.
- van Loon, H., Labitzke, K., 1994. The 10-12 years atmospheric oscillation. Meteorologische Zeitschrift 3, 259-266.
- van Loon, H., Labitzke, K., 2000. The influence of the 11-year solar cycle on the stratosphere below 30km: a review. Space Science Review 94, 259-278.
- Vicente-Serrano, S. M., Beguería Portugués S., 2004. Analysis of the spatial patterns of drought magnitude in the Iberian Peninsula by means of the Standardized Precipitation Index (SPI) and the Generalized Pareto distribution. In: EMS Annual Meeting Abstracts 1, 00180. Nice.
- Wittman, M.A.H., Polvani, L.M., Scott R.K., 2004. Stratospheric influence on baroclinic lifecycles and its connection to the Arctic Oscillation. Geophysical Research Letters 31, L16113, doi: 10.1029/2004GL020503.

FIGURE CAPTIONS

Fig. 1. Map of localization of the 51 Iberian Peninsula meteorological stations (bold dots) and the main place names.

Fig. 2. Main circulation patterns for February in the reference period 1961-1990 with their corresponding PC and sign, and the rainfall mean (mm). (The percentage of the cases included in each pattern of all cases is shown. The daily AOI (at 1000-hPa) values (Baldwin and Dunkerton, 2001) are averaged in each group in order to detect the AO phase of the pattern).

Fig. 3. Main circulation patterns with their corresponding PC and sign and the % rainfall anomaly compared with the 1961-1990 February rainfall mean, for February months under an MMW influence in the 1958-2000 period. (The percentage of the cases included in each pattern of all cases is shown. The daily AOI (at 1000-hPa) values (Baldwin and Dunkerton, 2001) are averaged in each group in order to detect the AO phase of the pattern).

Fig. 4. Idem Fig. 3, for February months under a CE influence.

Fig. 5. Detection of those areas with a significant February rainfall mean variation between the years under a MMW influence and those under a CE influence according to the Student's *t*-test. (The dotted area is significant at the 90% confidence level, light grey at 95%, dark grey at 99% and black at 99.9%).

Fig. 6. Linear regression between Zamora rainfall (JFM) and 30h-Pa geopotential height in the North Pole (JF) for the 1958-2000 period. (A very cold polar vortex is defined by $T_{30h\text{-}Pa\ N\ Pole}$ J $\leq$-80ºC or $T_{30\text{-}hPa\ N\ Pole}$ F $\leq$-75 ºC).

Fig. 7. Occurrence of MMWs (1958-2000) according to the solar activity (10.7 cm observed solar flux, Penticton, Canada, 2800 MHz, NGDC) – QBO (40-50-hPa) relationship. Dots are years in the east phase of the QBO (n=18); squares are years in the west phase of the QBO (n=25). Open 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 activity in the 11-year sunspot cycles (Labitzke et al. (2006), reconstructed).

Fig. 8. Idem as Fig. 3, but for February months in 1958-2000 under solar cycle – QBO conditions which might favour an MMW.

Fig. 9. Idem as Fig. 3, but for February months in 1958-2000 under solar cycle – QBO conditions which might favour a CE.

Fig. 10. Idem as Fig. 5, but between the years under solar cycle – QBO favouring an MMW and those ones favouring a CE.

TABLE CAPTIONS

Table 1. First column: Temperatures at the North Pole, 30-hPa (ºC). (The temperatures corresponding to MMWs are in bold and to CEs are underlined). Second Column: monthly AOI values (Thompson and Wallace, 2000). (The properly negative values (<-0.50) after a warming are in bold and those ones properly positive (>0.50) after a CE are underlined). Third Column: Central date of the warmings at 10-hPa using ERA data (Charlton and Polvani, 2007).