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Interannual variability of cut-off low systems over the European sector: The role of blocking and the Northern Hemisphere circulation modes

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With 14 Figures

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Summary

An earlier developed multidecadal database of Northern Hemisphere cut-off low systems (COLs), covering a 41 years period (from 1958 to 1998) is used to study COLs interannual variability in the European sector (25°–47.5° N, 50° W–40° E) and the major factors controlling it. The study focus on the influence on COLs interannual variability, of larger scale phenomena such as blocking events and other main circulation modes defined over the Euro-Atlantic region. It is shown that there is a very large interannual variability in the COLs occurrence at the annual and seasonal scales, although without significant trends. The influence of larger scale phenomena is seasonal dependent, with the positive phase of the NAO favoring autumn COL development, while winter COL occurrence is mostly related to blocking events. During summer, the season when more COLs occur, no significant influences were found.

1. Introduction

Cut-off lows (COLs) are synoptic-scale low pressure systems formed as a result of meridional shifts of the jet streams (Palmén and Newton, 1969; Winkler et al, 2005) near 200 hPa. They show a closed circulation on upper-level topographies of isobaric maps. In terms of their dynamics, COLs are isolated regions of potential vorticity that affect both the stratosphere and the troposphere. Their meteorological characteristics have been investigated (e.g., Palmén and Newton, 1969; Price and Vaughan, 1992) and a brief summary of them has been included in the Appendix.

The main climatological characteristics of COLs (Kentarchos and Davies, 1998; Nieto et al, 2005) are summarized below:

– There are three preferred areas of COL occurrence in the Northern Hemisphere: Southern Europe and Eastern Atlantic coast, the Eastern North Pacific, and the North China to Siberian region extending to Northwestern Pacific coast. The European area shows the highest occurrence of COLs.
– COLs formation shows a higher occurrence during summer than during winter. Further-

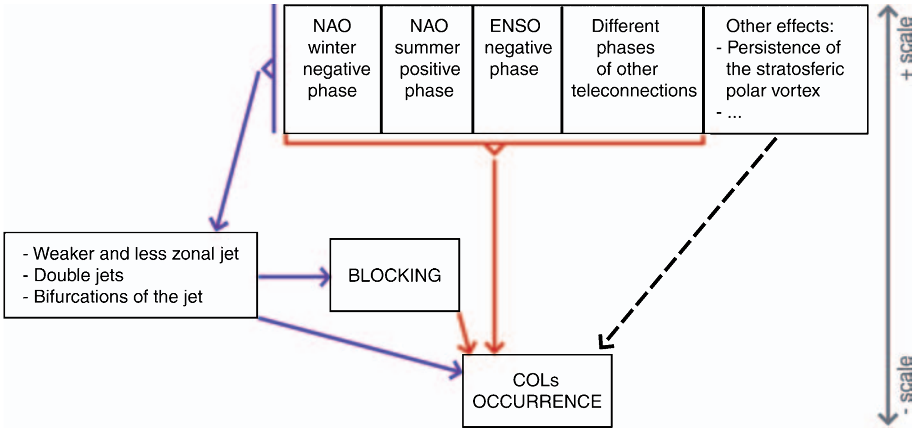

Fig. 1. Proposed physical mechanism that links the cut-off low systems with larger-scale phenomena. The blue lines indicate the relationships found in previous studies. The relations analyzed in this paper are indicated with red arrows. Dashed black line denotes other possible influences on COL occurrence

more COLs tend to occur more frequently at higher latitudes.
– Most COLs last few days (2–3 days and very few last more than five days).
– In general terms, COLs tend to be of a transient nature during their life cycle, and less than 20% are stationary.

However, several aspects of COLs are not well understood, such as their interannual variability and the larger scale phenomena controlling them. This is in part due to the lack of a multidecadal COL database. The studies by Price and Vaughan (1992) and Kentarchos and Davies (1998) were limited to five years, therefore lacking the required length to extract more robust conclusions. However despite their small record length they have found significant variability in the annual number of COLs; Price and Vaughan obtained a maximum of occurrence in the year 1994 with 275 cases and a minimum in 1991 with 181. There are also objective reasons to presume that blocking episodes and other major teleconnections modes such the NAO or El Niño-Southern Oscillation (ENSO) might bear a relevant influence on COL occurrence. The proposed physical mechanism that links the cut-off low systems with these larger-scale phenomena is illustrated in Fig. 1.

Both blocking events and COLs are associated with the occurrence of upper tropospheric jets, with strong meridional components and even with the bifurcation of the jet and the appearance of double jets. The relationship of the different phases of the NAO and ENSO with the intensity and zonality of the jet flow is well-known. During winter, strong (weak) jets extend over the western Atlantic for positive (negative) phases of the NAO (Hurrell, 1995), so negative phases of wintertime NAO should favor both COLs and blocking occurrence. In their work, Shabbar et al (2001) found that when the NAO is in the negative phase, there is an amplified meridional wave-like flow (favorable for block formation), with the average 500 hPa trough axis located in the band 70–90° W (region of intense COL occurrence). Using a theoretical approach based on the envelope soliton block-eddy interaction model, Luo (2005) found also that winter negative NAO phase provides a favorable environment for the frequent occurrence of blocking episodes. On the other hand, from mid-spring to mid-fall the subtropical jet shifts its position poleward, and the polar jet becomes weaker. During negative phases of NAO the high-latitude jet is very weak or absent and there is a single jet structure close to our region of study that does not favor COL occurrence. On the contrary, the positive phase of NAO is associated with an area of strong westerlies surrounding the Arctic Ocean and with the existence of a double jet structure that spans between Eurasia and North America, which is more evident during summer (Ogi et al, 2004). This double jet, consisting of two separated polar and subtropical jet streams, is formed and maintained by wave forcing and tends to favor COLs development and to cause atmospheric blocking that supports long-lasting weather anomalies (Ogi et al, 2004).

During El Niño events, anomalies in convection and in large-scale overturning producing subsidence in the descending branch of the local Hadley circulation strengthen the jets in each hemisphere, turn them more zonal and shift them equatorward (Trenberth et al, 1998). Thus, positive phases of ENSO are not associated with the jets conditions that favor both COL and blocking occurrence. On the contrary weaker and less zonal jet during negative phases of ENSO should favor their development. Watson and Colucci (2002), examining cold season NH (Northern Hemisphere) blocking, found that blocking is suppressed in the Atlantic region during El Niño years. They have also demonstrated that in La Niña years blocking is enhanced over the Atlantic Ocean Basin. The effect of other teleconnection patterns affecting the European region over the jet strength and zonality has been less studied but it could also be important to explain the occurrence of COLs and blocking.

The fact that both blocking events and COLs develop during similar conditions of the jet streams and that blocking has been statistically and dynamically related to modes of climate variability such as the NAO or ENSO as expected according to their effects on the jet, suggests that the relationship between major circulation modes and COLs might be modulated by the occurrence of blocking events.

The aim of this paper is to study COLs interannual variability in the European sector and the major factors controlling it. The multidecadal database for the whole Northern Hemisphere obtained by Nieto et al (2005), covering a 41 years period (from 1958 to 1998) was used. Section 2 describes the data and summarizes the methodology of research. Trends and seasonal variations in the number of COLs are analyzed in Sect. 3. The relationship between COLs occurrence and the main modes of Northern Hemisphere climate variability is presented in Sect. 4. The relationship with blocking events is presented in Sect. 5. Finally, Sect. 6 summarises the main results and conclusions.

2. Data and methodology

The different datasets used in this study are reported below.

COL data: The daily COL multidecadal dataset from Nieto et al (2005) detected at 200 hPa was used. It was constructed by using 41 years (1958–1998) of National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) reanalysis data with a 2.5° by 2.5° resolution. The box from 25° to 47.5° N, 50° W to 40° E, hereafter called European sector, was chosen. A summary of the method to extract COLs used by Nieto et al (2005) can be found in the Appendix.

Blocking data: Dates of occurrence of blocking events, their positions and intensities were obtained from the dataset derived by Barriopedro

Table 1. Summary of the research methodology followed in this paper

Action	Analysis tool	Objectives
Interannual variability of COLs occurrence	– Linear regression (trends) – MTM analysis (significant oscillations in the whole studied period) – Wavelet analysis (significant oscillations in any part of the studied period)	– To know if COLs occurrence has increased (decreased) in the last decades – To check if COLs occurrence exhibits trend or oscillations similar to those of the main modes of climate variability (possible relation)
Association of COLs with modes of climate variability and teleconnections	– Correlations between COLs occurrence and teleconnection indices – Composites of geopotential height fields associated with COL occurrence	– To explore possible associations, rejecting those in which correlations are not significant – To check the physical mechanism, testing if the signs of significant correlations match the expected ones, according to the relation of the modes with the jet structure – To give physical sense to the statistical connection, looking for height patterns similar to those that characterize the different phases of the modes and teleconnections
Association with blocking events	– Objective identification of blocking events linked to COLs – Comparison of monthly frequencies – Comparison of geographical distributions	– To estimate how many COLs occur linked to blocking events – To estimate when and where is more probable this linked occurrence

et al (2006). Brief details of the method to identify and characterize blocking events are summarized in the Appendix.

Indices of climate variability modes were obtained from the NOAA/CPC database. These are available at the following web pages: *http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml* for Northern Hemisphere teleconnection patterns and *http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices* for ENSO. The procedure used to identify NH teleconnection patterns is briefly described in the Appendix.

The methodology of research is summarized in Table 1. The first step consists of looking for significant trends and oscillations in the annual occurrence of COLs. Such analysis has not been done before due to the absence of a multidecadal COL database. The straightforward comparison with trends and significant oscillations found with the main modes of climate variability may provide us a first idea of which modes could have any influence on COL occurrence. Correlation analysis between COLs occurrence and teleconnection indices provides a first approach to possible associations of COLs with climate variability modes (second step of our methodological design). This statistical connection will acquire physical sense if a) it is confirmed by an agreement with the connections expected due to the variations in the structure of the jets, and b) coherence exists between height anomaly patterns associated with COLs occurrence and those

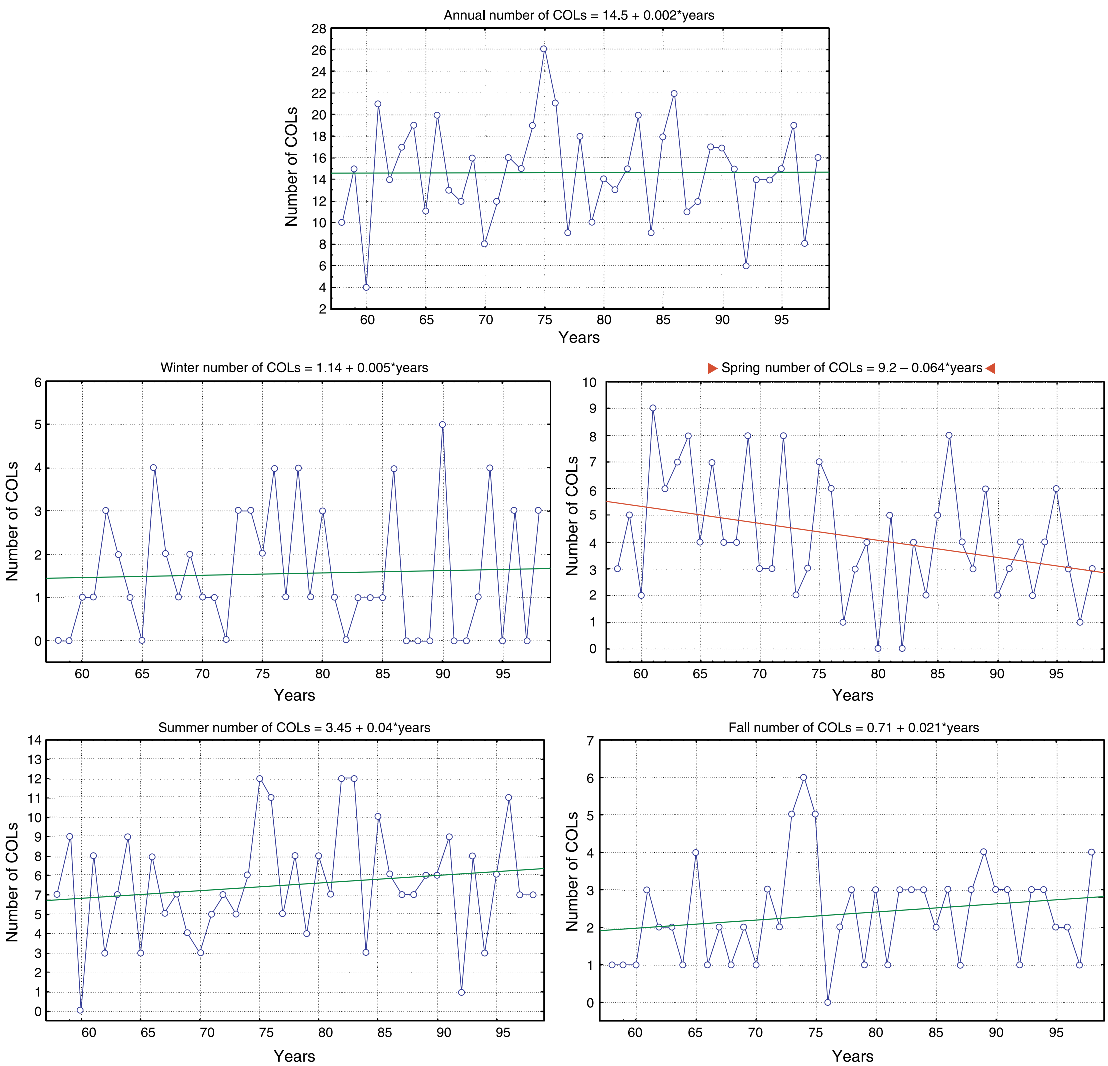

Fig. 2. Annual and seasonal series of COLs occurrence in the European sector and their trends (red line notes significant trend at 95%)

associated with different phases of the climatic modes. As the development of blocking events and COLs share many characteristics related to jets structures and have similar connections with any teleconnection, we estimate when and where this concurrent occurrence is more probable (third step).

3. Trends and oscillations in the occurrence of COLs

The yearly series of annual and seasonal occurrence of COLs and their trends, calculated by means of linear regression, are displayed in Fig. 2. Seasons are defined as winter (JFM), spring (AMJ), summer (JAS) and fall (OND). We can observe strong interannual variability. Thus, the annual number of COLs varies from only four cases in 1960 up to 26 events in 1975, with an average of about 15. This interannual variability is also observed for seasonal occurrence. However, it has not been detected any significant trend in the annual number of COLs throughout the period of study – 1958 to 1998 – and only during spring there is a decreasing tendency in COLs occurrence (significant at 95%).

To find possible significant oscillations in COLs occurrence we applied the MTM analysis (Multi-Taper Method – multiband method – Ghil et al, 2002, for details) to the five different series (the annual and the four seasonal ones). MTM has been chosen over classical methods of spectral estimation, such as conventional periodogram, because it possesses better spectral estimation properties. Moreover because MTM is a non-parametric method (since it does not use an "a priori" parameter dependent model of the process that generated the time series under analysis) it provides better spectral estimation than other sophisticated methods, such as MEM (Maximum Entropy Method).

Table 2. Significant periods (in years) found in the COLs occurrence by means of MTM analysis (the significant level is indicated in brackets)

Annual	Spring	Summer	Fall	Winter
2.5 (95%)		2.63 (95%)	2.27 (90%)	2.12 (95%)
2.63 (90%)		3 (90%)	2.43 (95%)	4.54 (90%)
			2.63 (90%)	

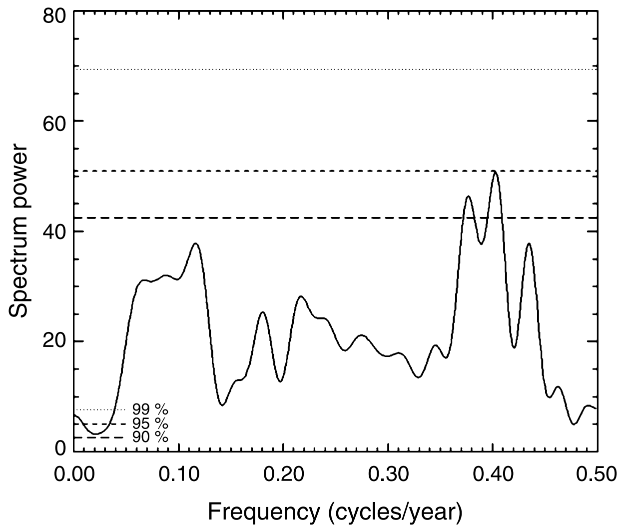

Fig. 3. Power spectrum of MTM analysis for the annual series of COLs occurrence; and levels of significance at 99%, 95% and 90%

Results are summarised in Table 2 highlighting all peaks that are significant (at least at the 90% significance level), revealing that a significant oscillation is found in all cases, except for spring within the 0.33–0.47 cycles/year frequency band (periods between 2.12 and 3 years). Figure 3 shows the complete power spectrum for the annual series. An oscillation with this period can be related to the Quasi-Biennial Oscillation (QBO), but also to the NAO or even ENSO, since oscillations with peaks of periods close to 2.4 years have been found in many spectral analyses of these modes (Gamiz-Fortis et al, 2002 for NAO; Ghil et al, 2002; Ribera and Mann, 2002 for ENSO). The significant oscillation of 0.22 cycles/year (period of 4.54 years) found in winter might be related also with NAO (Gamiz-Fortis et al, 2002; Ghil et al, 2002) and ENSO (Ribera and Mann, 2002).

4. Association of COLs with major modes of climate variability

The first step to assess if COLs occurrence is affected by the major modes of atmospheric circulation consisted in computing correlation coefficients between the indices of these circulation modes and the series of COLs frequency of occurrence. The main modes that affect the region of study – European sector – are those that have been identified over the European and North

Table 3. Correlation coefficients between major modes of climate variability and COLs number. Italic values are statistically significant at a 95% confidence level and bold ones at a 90%

	Months with signal	COLs period	Winter	Spring	Summer	Autumn
NAO	DJFMAMJJASON	*0.36*	0.11	**0.29**	0.16	**0.28**
EA	DJFMA- - - -SON	0.01	0.09	X	X	0.25
EA-JET	- - - -AMJJA- - - -	−0.13	X	−0.21	−0.13	X
EA-WR	DJFMAM- - -SON	−0.12	−0.06	**0.30**	X	−0.04
SCAN	DJFMAM- - -ASON	−0.01	−0.01	0.02	0.03	−0.10
QBO	DJFMAMJJASON	0.21	0.08	0.04	**0.29**	−0.06
NIÑO 3.4	DJFMAMJJASON	**−0.26**	−0.21	−0.13	−0.06	*−0.32*
NIÑO 4	DJFMAMJJASON	**−0.29**	−0.13	−0.16	−0.10	*−0.39*

Atlantic sector (Barnston and Livezey, 1987; Trigo et al, 2006) namely the North Atlantic Oscillation (NAO), East Atlantic pattern (EA), East Atlantic-JET pattern (EA-JET), East Atlantic/Western Russia (EA-WR) and Scandinavia pattern (SCAND). The time-series of occurrence were also correlated with modes of variability that affect the whole globe, like El Niño-Southern Oscillation (ENSO) and the Quasi-Biennial Oscillation (QBO) and the results are summarized in Table 3. Firstly, the correlations were calculated for the whole temporal domain of occurrence of every mode. For instance, if the EA-JET pattern is active since April to August, an annual index and the corresponding COLs frequencies are calculated for this sub-set of months. A second analysis consisted in correlating the COLs occurrence for every season of the year with the seasonal values of the indices. Only those seasons that included at least two months with signal of the mode were considered in the analysis. Correlation coefficients values are significant at 90% and 95% whenever superior to 0.26 and 0.31 respectively taking into account the total number of years (41) and considering negligible the autocorrelation.

When the whole active period was considered, only NAO and ENSO indices correlated significantly with COLs occurrence. The positive value of the correlation with NAO suggests that the positive phases of NAO favor the occurrence of COLs in the European sector. The seasonal correlations between NAO and COLs occurrence were lower than those for the whole year (only statistically significant at a 90% confidence level for spring and autumn, while significant at 95% for the annual series). The low (non-significant) correlation values obtained in winter between NAO and the number of COLs is especially remarkable, due to the high influence of NAO on the wintertime circulation over the European region. A significant correlation at 90% was also found for the EA-WR mode in spring (also positive, as for NAO). Global modes seem also to have a moderate influence in the occurrence of COLs. Thus, there is a significant positive correlation (at 90%) between QBO and COLs occurrence in summer and significant negative

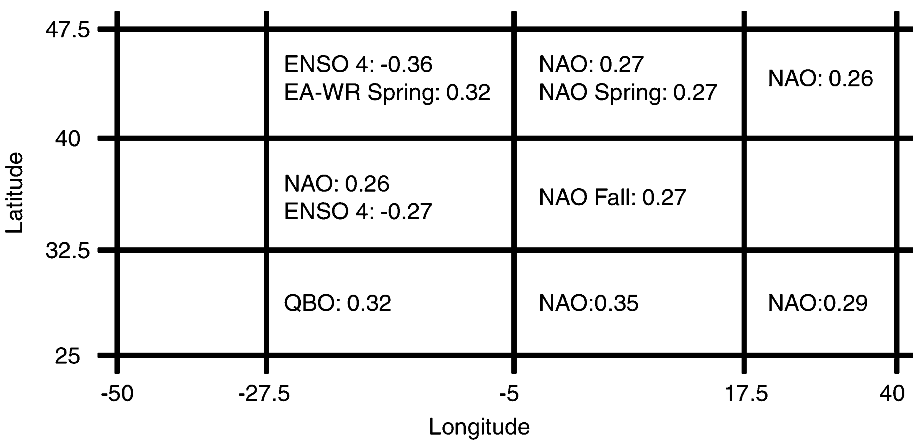

Fig. 4. Correlation coefficients (exceeded the 90% confidence level) between the COLs occurrence in the European sector divided in boxes of 22.5° × 7.5° and modes of climate variability (only those modes and periods in which correlations were significant at least at 90% for the whole European sector)

correlations between ENSO (Niño 3.4 and Niño 4) and COLs occurrence for the whole year (at 90%) and for autumn (at 95%).

A more detailed correlation analysis, calculating COLs occurrence in boxes of 22.5° of longitude and 7.5° of latitude, was done for those modes and periods with correlations significant at least at 90% showing that there is no clear spatial pattern (Fig. 4). The NAO mode seems to be important in the annual occurrence of COLs over the African zone, west of Gibraltar strait and over the northern Mediterranean Sea, and in the spring over the northwestern Mediterranean Sea. The EA-WR pattern does not provide a significant role on the spring occurrence of COLs in the Northwest of Iberian Peninsula. The influence of the QBO is limited to the summer occurrence over the region of the Canary Islands while ENSO has influence in the annual occurrence over the South European Atlantic coast. There are only two regions with significant influence of two modes. The simultaneous occurrence of positive (negative) phases of NAO (ENSO) favors COLs occurrence over the Atlantic coast of southwestern Iberian Peninsula and Northern Africa, in agreement with previous studies on the frequency of synoptic disturbances (done by Gallego et al, 2001; García et al, 2001). Positive phases of EA-WR in spring and negative phases of ENSO favor occurrence over the Atlantic coast of northwestern Iberia.

The correlation analysis can only be considered as an exploratory way to show that the occurrence of COLs can be influenced by some of the major modes of climate variability that affect the European sector. To give physical sense to these statistical results we analyzed the composites of the height fields in the middle troposphere connected with the occurrence of COLs. In this way we might be able to identify spatial patterns that favor the occurrence of COLs and to verify their compatibility with the major modes of climate variability. We calculated the difference of composites in 500 hPa geopotential height field for days in which there is occurrence of COLs (COL days) and for those in which there is not (not-COL days). This analysis was done for all the months although it is only displayed (Fig. 5) for four months (January, April, May and November) when patterns differ more. In general, a dipolar spatial structure of the anomalies centred in the North Atlantic is observed, with

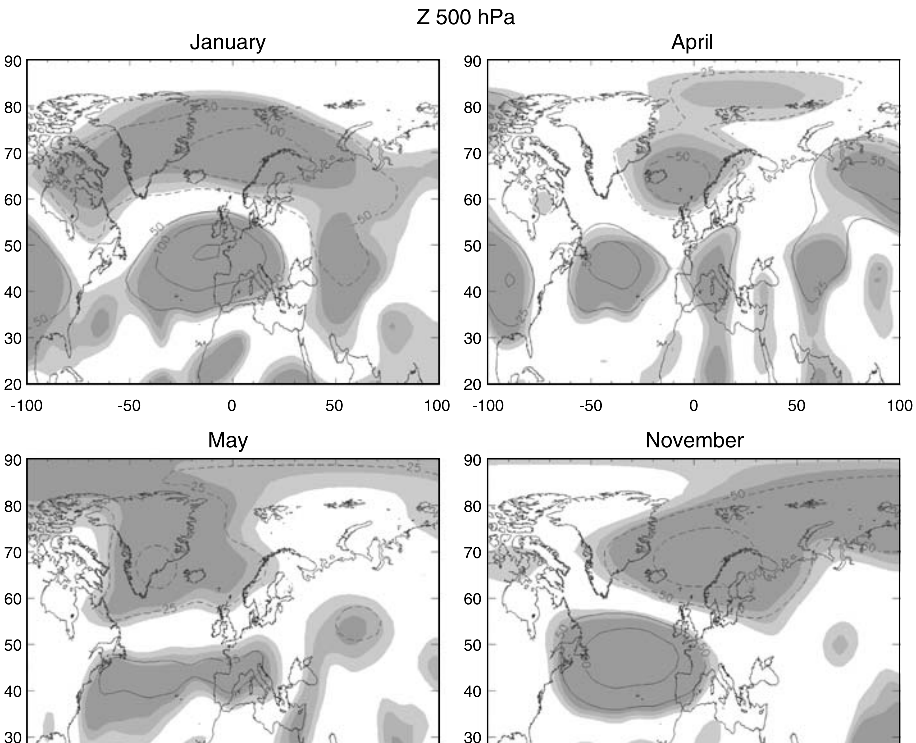

Fig. 5. Geopotential height composites differences (in gpm) at 500 hPa for "COL-days" and "not-COL days" in January, April, May and November. Shading indicates confidence levels (dark grey 99%, intermediate grey 95% and light grey 90%

a band of positive anomalies centred between 40° N and 60° N and another centre of negative anomalies situated to the north of 60° N. This North–South dipolar structure of height anomalies resembles the typical distribution of the anomalies in the NAO pattern but slightly displaced to North. There are not many variations of the pattern from one month to another, although intensity and position of the dipole centres can vary. During winter (e.g., January in Fig. 5) the dipole is stronger with a difference between the centres of anomalies up to 200 gpm. According to the position of the anomalies dipole during winter, the positive phases of NAO do not favor the occurrence of COLs in the European sector, what is concordant with the result obtained through the calculation of correlations. Although the dipole continues being the dominant pattern for the remaining months, the distribution of the centres of anomalies is modified slightly and their intensities are reduced. The best example of this occurs during April, May and November (Fig. 5). In April the negative anomalies centre diminishes in size and is displaced eastward in comparison with the previous months and the positive anomaly centre. However, it maintains its latitudinal position. It is weakened taking the form of a band, with four centres of anomalies smaller than those for the winter months. One of these centres is situated over Northern Africa and over the Mediterranean Sea. This structure, with a centre of negative anomalies displaced toward the east of North Atlantic Ocean and the centre of positive anomalies over the Mediterranean region resembles to the structure of the EA-JET pattern. The negative phase of this mode is associated with a strong division of the circulation over the eastern North Atlantic Ocean and over a large part of Europe, many times in association with long-term blocking anticyclones in the vicinity of Greenland and the United Kingdom. Although it is not significant, the correlation of the EA-JET index with the occurrence of COLs has a negative signal (Table 2). This fact can indicate light favorable conditions in the occurrence of COLs during negative phases of this mode of variability.

During May the small centre of negative anomalies which appears over Russia (centred in 60° E–55° N, Fig. 5), jointly with the centre of positive anomalies over Western Europe resembles the typical structure of the EA-WR pattern, which explains the sign of the correlation between this mode and COLs over the European sector. This suggests that positive phases of this mode favor the occurrence of COLs over the studied region. During November the dipole centres are closer to the typical centres of the NAO positive phase, suggesting that this phase favors the occurrence of autumn COLs in the European sector, as indicated by the positive correlations. The analysis was also done at 200 hPa with almost identical results to those with 500 hPa.

5. Association with blocking events

The recent long-term climatology of blocking events by Barriopedro et al (2006) shows that there are four preferred areas where blocking events occur: the Atlantic sector, the European sector, the West-Pacific sector and the East-Pacific sector – downstream of the primary storm tracks. These events are more frequent over continents during the warm season; however the long-lasting episodes with the largest spatial extensions and intensities usually occur over the Euro-Atlantic sector during the cold season. The dynamic forcing mechanisms that contribute to the occurrence and maintenance of blocking events have been partitioned into synoptic-scale, planetary-scale, and interaction processes (e.g., Tsou and Smith, 1990; Nakamura et al, 1997; Marques and Rao, 1999; Colucci, 2001; Burkhardt and Lupo, 2005). Several studies have suggested that blocking occurs as the result of interactions between amplifying synoptic-scale waves and a quasi-stationary planetary-scale wave (e.g., Frederiksen, 1982; Shutts, 1983, 1986; Mullen, 1986, 1987) although the importance of synoptic and planetary-scale forcing may be different for the occurrence of North Atlantic and North Pacific blocking events, with North Atlantic blocking events being primarily determined by interactions between synoptic and planetary-scale processes (Nakamura et al, 1997; Lupo and Smith, 1995; Colucci, 2001). Furthermore, additional studies (e.g. Tsou and Smith, 1990; Alberta et al, 1991; Lupo et al, 1997) suggested that temperature advection plays an important role as well.

On the other hand, the sustaining of blocking events is primarily maintained by the influx of anticyclonic vorticity advection into the blocking region by an amplifying synoptic-scale wave. Previous studies have found that extratropical activity of high-frequency perturbations enhances (weakens) northward and southward of the blocking center (blocking area) (Blackmon et al, 1986; Dole, 1986a, b; Liu, 1994). Based on these ideas, Konrad and Colucci (1988) suggested that surface cyclogenesis occurring downstream of a mid-troposphere trough moving northeastward with the planetary flow may constitute a potential precursor of blocking occurrence. Following this hypothesis blocking formation and development over Euro-Atlantic and Pacific sectors, which are frequent over the main oceans, have been dynamically linked to the storm-tracks occurring downstream of North America and Asia, respectively. Shutts (1983, 1986), Colucci (1985) and Tsou and Smith (1990) proposed a conceptual model based on the barotropic interaction between the planetary waves and the potential vorticity advection downstream of surface cyclonegenesis. According to that, blocking formation and sustainment is favored by the anomalous planetary flow advection of anticyclonic potential vorticity from the upstream cyclone.

Since COLs are indicative of well developed cyclones, they are likely to influence dynamical block development and/or maintenance. In fact, the region with major occurrence of COLs is also coincidental with that of the major occurrence of blocking events (Barriopedro et al, 2006; Trigo et al, 2004). Quite often the concurrent development of surface cyclones and COLs intensify the potential vorticity transport as well. An issue that has not been addressed before is whether COLs, in addition to surface cyclones, could also favor blocking occurrence. The aim of this section is to analyse the relationship between COL occurrence and situations of blocking, identifying when COLs are associated to blocking situations and in which way COLs associated with blocking events differ from those not related to blocking episodes. To analyse this relationship we used the blocking database by Barriopedro et al (2006) previously described in the data section.

In order to define which COLs are associated with situations of blocking, we have imposed two conditions based on the time and space scale of both events: (1) the beginning of a COL must occur in the period situated between 5 days

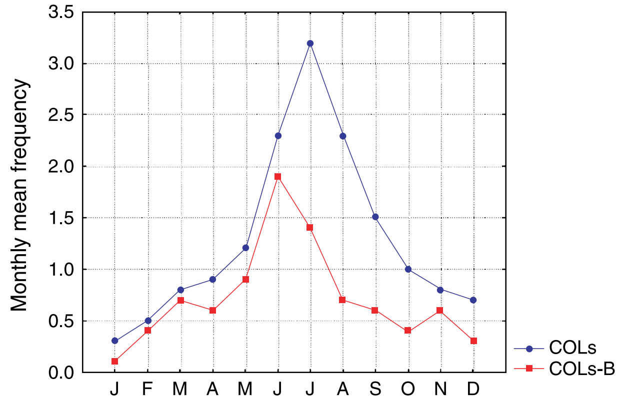

Fig. 6. Monthly mean distribution of COLs (blue line) and COLs-B (red line) for the European sector

before the beginning of a blocking event and 5 days after it; (2) the COL must be located in a region between – 50° and 50° of longitude from the centre of the blocking. Under these conditions we observed that 55.3% of COLs detected in the European sector were associated with blocking episodes situations of blockes flow. Figure 6 shows the monthly average distribution for the set of COLs over the European sector -blue line- and for those COLs associated with blocking events (hereafter known as COLs-B) -red line-. The shape of the distribution is similar, though the maximum of COLs-B's occurrence is obtained in June, while for the total COLs occurred in July. A seasonal counting indicates that winter (JFM) and spring (AMJ) are the seasons when COLs are more frequently associated with blocking, with 73.9% (76.1%) of winter (spring) COLs being associated with blocking events. It should be stressed that blocking situations are more frequent during these seasons over the Euro-Atlantic region.

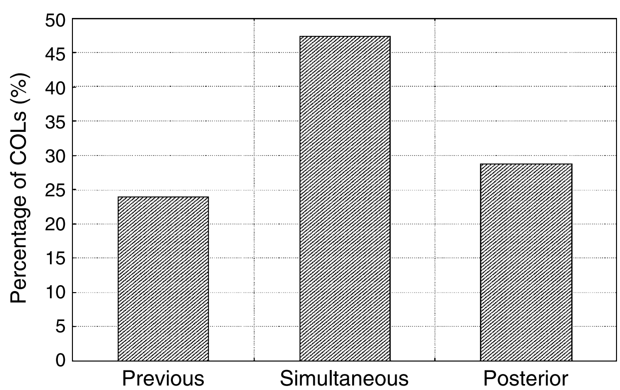

Fig. 7. Frequency of COLs-B attending to if they are "previous", "simultaneous" or "posterior" to blocking events

The average duration of blocking events (around 8–9 days) (Barriopedro et al, 2006) is higher than that for COLs, with an average duration of 2.4 days (Nieto et al, 2005). Consequently, COLs-B can occur entirely within a period of a single blocking; nevertheless they may occur either before or after the blocking

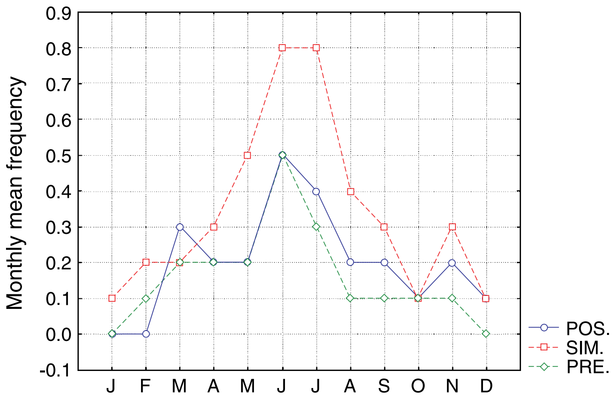

Fig. 8. Monthly mean frequency of COLs-B number attending to their occurrence with regard to blocking events. The blue line indicates the posterior COLs-B, the red one the simultaneous COLs-B and the green one the previous COLs-B

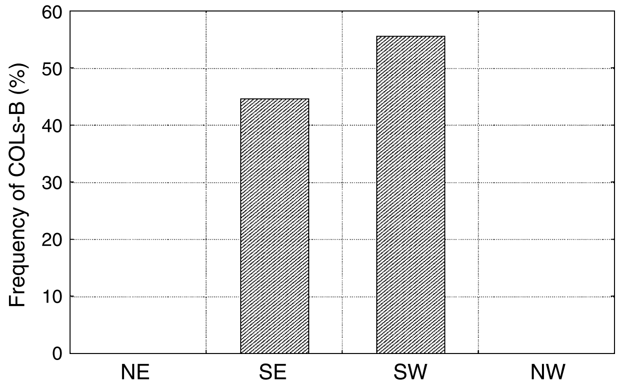

Fig. 9. Relative situation of COLs-B (in percentage) when the reference point is the centre of the correspondent blocking event

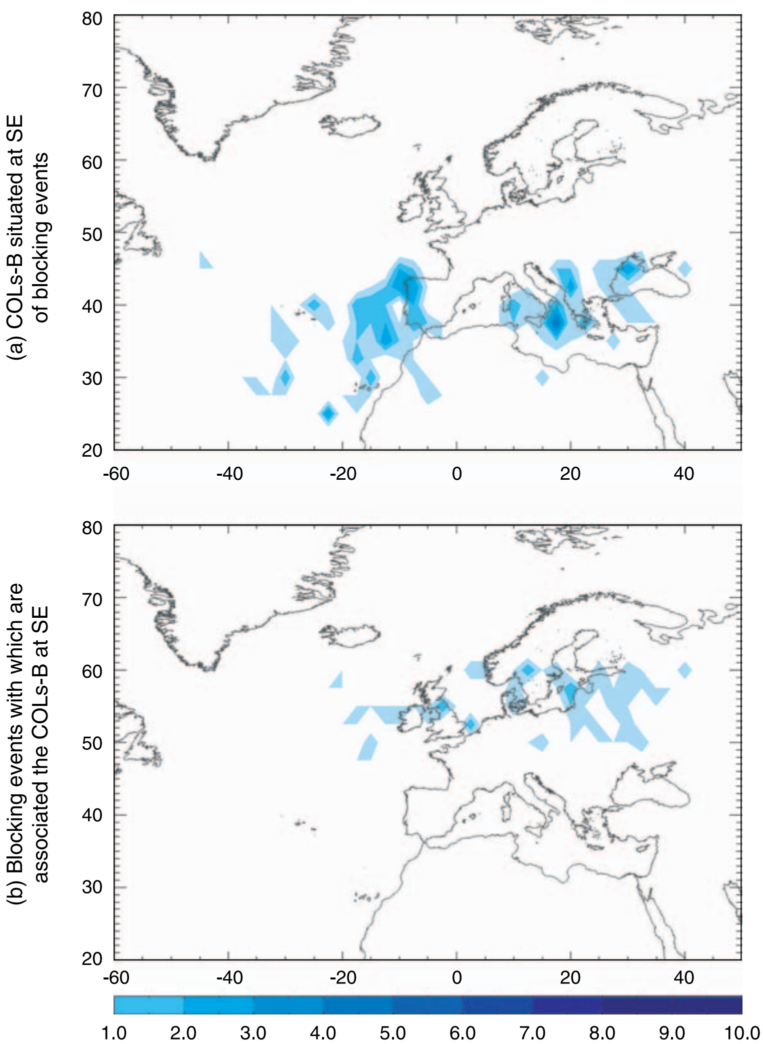

Fig. 10. Total number of (**a**) COLs-B placed at SW of blocking events, and (**b**) blocking events which are associated with SW COLs-B by grid point (2.5° × 2.5°) for the period 1958–98

event. In fact, Lupo and Smith (1995) demonstrated that all blocks of a 3-year period were preceded by surface cyclones within 36 hours before the blocking onset and generally westward of the block. Thus, we classified COLs-B depending on whether they occur before, during or after a blocking event because we wanted to assess if COLs (a) preceded the blocking onset, then being able to favor blocking formation, (b) occurred simultaneously with the block, contributing then to the blocking maintenance, (c) or developed after the blocking, being then a resulting feature of blocking occurrence. According to the life cycle of blocking events [0, d], being "0" the first day of occurrence and "d" the last one, we classified COLs-B as "previous" to a blocking event if their beginning occurred from 1 to 5 days before the beginning of the blocking event. They were classified as "posterior" if they began after the end of the blocking event (d + 1 to d + 5). Finally COLs were labelled "simultaneous" if occurred within the period [0, d]. The percentages of COLs-B that occur in each of these three situations are displayed in Fig. 7. We can observe that most COLs-B are simultaneous to a blocking event (47.38% of the cases), 28.75% occur after the event and only 23.87% occur before, suggesting that most of the COLs could play a significant role in the blocking maintenance and/or be the result of blocking signatures. A seasonal analysis (Fig. 8) shows that the highest occurrence is reached in June for the three COLs-B classes, maintaining the preference for the simultaneous ones except for March when posterior COLs are the most frequent.

Another interesting aspect of the relationship between COLs-B and blocking events is the position that COLs-B occupy with regard to the

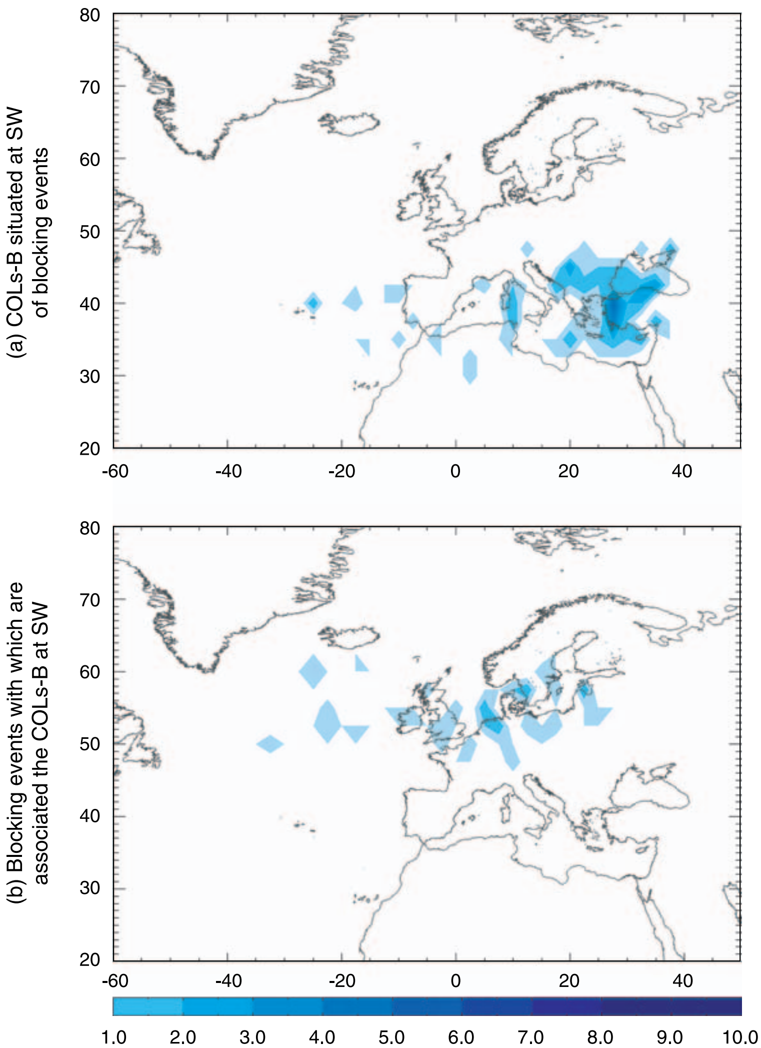

Fig. 11. Total number of (**a**) COLs-B situated at SE of blocking events, and (**b**) blocking events which are associated with SE COLs-B by grid point (2.5° × 2.5°) for the period 1958–98

location of the blocking centre. We classified COLs-B depending on if these were located in the NorthWest, SouthWest, NorthEast or SouthEast quadrants of the blocking centre with which they are associated. According to Fig. 9, COLs-B only occur to the south of blocking; 55.52% to the Southwest (SW) and 44.48% to the Southeast (SE). These results are in agreement with those of Liu (1994) who reported a northward and southward displacement in the

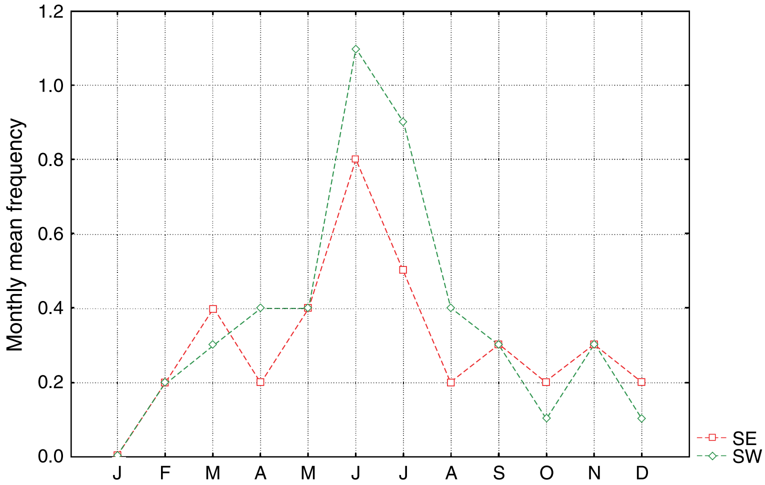

Fig. 12. Monthly mean frequency of the number of COLs-B according to the spatial classification with regard to the centre of blocking events (red line: SE COLs; green line: SW COLs)

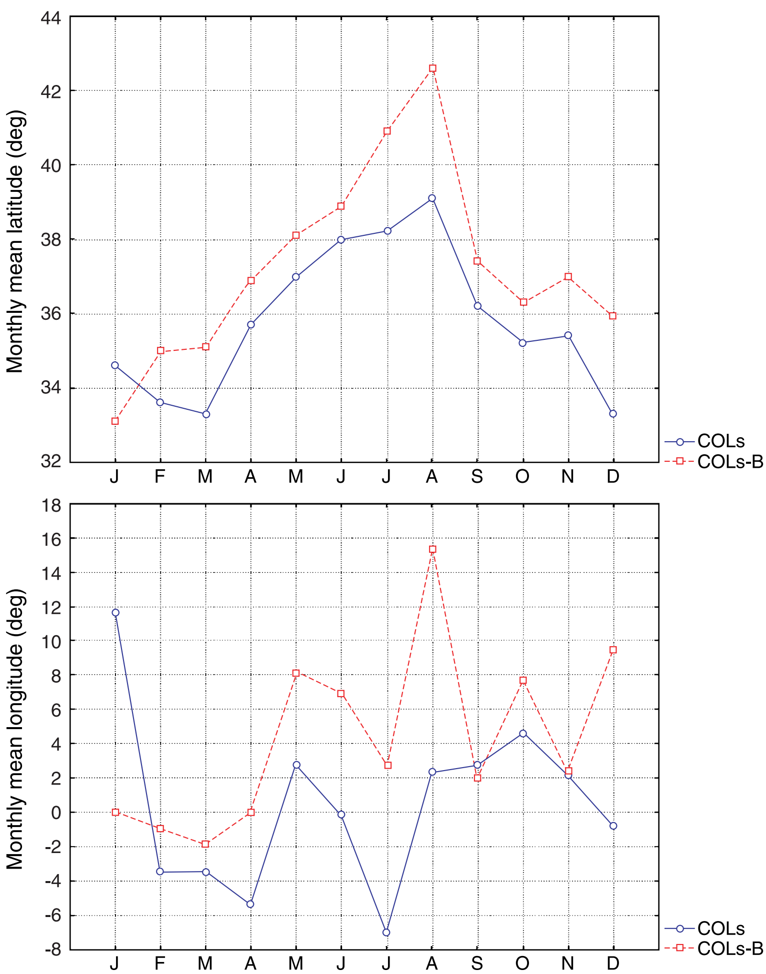

Fig. 13. Monthly distribution of the mean longitude (top) and of the mean latitude (bottom) for the all the COLs over the European sector (blue line) and for the subset of these that are associated with situations of blocking (dotted red line). The negative (positive) values for the longitude indicate positions towards the west (east) of the Greenwich meridian

activity of high-frequency perturbations relative to the blocked region. Since blocking is a typical feature of mid and high latitudes, COLs formation northward to blocking events is clearly inhibited. Figure 10 displays the spatial distribution of COLs-B located to the SW of the centre of blocking events (top) and the spatial distribution of these blocking events (bottom). Figure 11 displays the same as Fig. 10 but for COLs-B placed to SE. The color range in blue indicates the absolute number of cases of COLs and blocking. It is observed that there are two maxima of occurrence for COLs-B located to SW. These maxima are coincident with the dipole of occurrence detected for this region by Nieto et al (2005) when the density of COLs is analyzed, although the concentration (total number of COLs-B by grid point (2.5° × 2.5°)) is slightly higher over the Atlantic Ocean area for COLs-B than for total COLs. On the other hand, there is only one maximum of COLs-B when they are formed SE of the blocking events (the Eastern Mediterranean region). In general terms, COLs-B located SW of the blocking events are more frequent than those to the SE in the growing seasons (from April to September) (Fig. 12) which is in agreement with the usual climatological position of anticyclones over the European sector. Also, these results suggest that Atlantic COLs could contribute to the Euro-Atlantic blockings through the transport of low potential vorticity from the upstream COL into the blocked region, while Mediterranean COLs could be the result of blocking signatures downstream of the blocked region. It should be noted here that the spatial maxima of COLs-B located SW is almost coincident with the surface storm-track bands which develop over the Atlantic Ocean and the Mediterranean Sea, respectively (Whittaker and Horn, 1981).

Finally, we compared the differences (if any) in the geographical positions of COLs-B with respect to the total COLs. Along the whole year, COLs associated with blocking events are

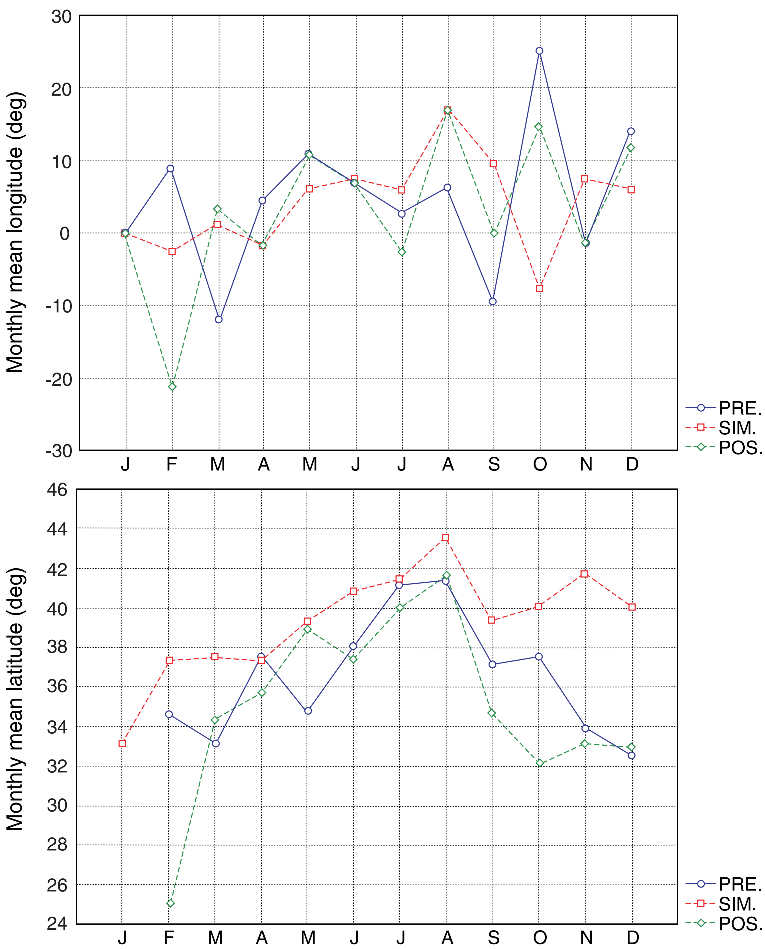

Fig. 14. Monthly distribution of the mean longitude (top) and the mean latitude (bottom) for COLs-B that happen in a "previous" (PRE, in blue), "simultaneous" (SIM, in red) or in a "posterior" (POS, in green) position with regard to blocking events to which they are associated

displaced eastward and northward with regards to the total set of European COLs (Fig. 13). ‘‘Simultaneous’’ COLs-B occur over higher latitudes than ‘‘previous’’ and ‘‘posterior’’ ones during the whole year and are displaced eastwards during summer (Fig. 14).

6. Conclusions

Based on the first multidecadal database of cut-off low systems over the Northern Hemisphere (Nieto et al, 2005) we analyzed the interannual variability of these systems over the European sector, the area with the highest occurrence concentration of COLs in the world, and the influence that larger scale phenomena, such as blocking events or main circulation modes, could have on their occurrence. Results obtained here prove that there is large interannual variability in the COLs occurrence and that it is partially modulated by larger scale phenomena. The main specific results and conclusions can be summarized as follows:

– The annual occurrence of COLs over the European sector presents a large interannual variability that is also observed for seasonal occurrence; however there is only a significant and negative trend for spring series. This lack of additional significant trends contrasts with the negative trends found in overall cyclone population in the Azores-Mediterranean band (Trigo, 2005), thus highlighting the different cyclogenesis mechanisms of COLs vs other cyclones. An oscillation with a period of about 2.5 years appears for annual and seasonal COL occurrence and another one of period about 4.5 years appears only for winter.
– Correlation analyses results are in moderate agreement with those expected according to the structure of the jet stream. ENSO negative (positive) phases are related to weaker (stronger) jets and higher (lower) probability of COL occurrence. Correlation analysis suggests that the NAO has the highest influence in COLs occurrence; positive phases of NAO favor the annual occurrence of COLs in the European sector. These results are difficult to interpret completely in terms of the tropospheric jet structure because positive correlations found for spring and fall are in agreement with jets variations, but there is neither a significant negative correlation between NAO and COLs during winter nor a significant positive one during summer, as expected.
– The difference in 500 hPa height fields between composites of COL-days and non COL-days has a dipolar structure. This structure resembles the positive phase of the NAO throughout the year. The dipole is displaced to the north with respect to NAO pattern during spring and especially during winter. It matches the NAO dipole during autumn and not so clearly during summer, in agreement with the previous conclusion. During spring the structure of the height fields associated to COLs is closer to the EA-JET spatial pattern than to NAO.
– More than half of the COLs found in the European sector are associated to blocking events, the association being higher in spring and winter when blocking events are more frequent. Almost half of the COLs associated to blocking occur simultaneously with blocking events. Most of the blocking centres associated to COLs are placed northward of 50° N and eastwards of 0°, what permits the COLs development in the European sector.
– Even though the association between blocking and cyclones has been widely discussed in the literature, the linkage with COLs remained unexplored. These results show that most of the COLs were associated with blocking, especially during the life cycle of the block, suggesting that, in addition to surface cyclogenesis, COLs may also play a significant role in blocking maintenance. Also, these results are indicative of the blocking influence in COLs development, with a significant number of COLs being located SE and, hence, influenced by the potential vorticity influx of the block.

In conclusion, there are three important reasons that suggest that NAO is not a major influence factor in the development of winter COLs: the low correlation between COL occurrence and NAO, the lack of trend in COL occurrence whereas NAO has shown a significant positive trend during the analyzed period and the lack of coincidence in the geographical position of the height anomalies dipole associated to COLs and NAO. However the occurrence of winter

COLs seems to be closely related to blocking events and there is a solid theoretical study that shows that blocking events must be influenced by NAO (Luo, 2005). An explanation for this paradox could be the difference found in the NAO dipole for strong and weak polar vortex. Walter and Graf (2005) have recently found a two dipole structure for weak vortex and only one for strong vortex. They found that only the negative upper tropospheric "NAO" during strong polar vortex has similar structure to blocking height situations over Europe and could be important in explaining the occurrence of both blocking and COLs. More relevant seems to be the NAO influence during autumn, as supported by correlation analysis and 500 hPa height anomalies associated with COLs; positive phases of NAO favor COLs development in this season. During spring the connection between COLs and NAO is not as clear as during autumn, and the correlation analysis supports the relationship, but the negative trend in COLs occurrence is in clear disagreement with the positive trend found in NAO indices. In addition, the dipole structure in height fields associated with COLs continues being displaced to North. These two results suggest that COLs occurrence during spring could be more influenced by variations in the occurrence of the spring onset (Black et al, 2005), which has a similar spatial structure, than by NAO. Of particular relevance is the lack of significant results during summer, the season when most COLs occur. Neither NAO, nor blocking events seem to have an important role in the development of COLs, neither other relevant modes such as EA-JET seem to play an important role. Only QBO seems to have a weak relevance during this season. The recently referenced "Recurrent circumglobal teleconnection pattern – CGT-" (Ding and Wang, 2005) that is a relevant mode during summer in the upper troposphere with a zonal wave number-5 structure could be responsible for part of the interannual variability in the summer COL occurrence and merits further study.

Appendix

COLs data: The COL dataset was constructed by using 41 years (1958–1998) of National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) reanalysis data with a 2.5° by 2.5° resolution. For this study Nieto et al (2005) used geopotential height, zonal wind, and temperature daily data from 200 and 300 hPa. The analysis is based on an identification of COLs by means of three consecutive steps based on physical characteristics of the conceptual model of COLs for the extratropical Northern Hemisphere in a band from 20° N to 70° N. These three steps are: a) Height minimum and cut-off circulation at 200 hPa. In this step, two characteristics of COLs were considered, the condition of a minimum of height field at 200 hPa and the isolation of the system from the westerlies general circulation in the upper troposphere. b) Equivalent thickness. In a COL, this field is characterized by a thickness ridge in front of the low. The pressure levels chosen to calculate this field were 200 and 300 hPa. c) Thermal front parameter (TFP). TPF is the change of temperature gradient in the direction of the temperature gradient. The temperature used in the TFP was computed at 200 hPa. One of the two baroclinic zones in a COL is placed in front of the low, which is connected with a frontal-like cloud band. So, the grid point eastward of a COL point must have TFP values higher than this to continue considering this point a COL point. For all the steps they also followed the following rules to consider that the points of COL were from a same COL: the grid points belonged to the same COL when these points were adjacent and they considered that a COL was the same in two consecutive days when any of the grid points that fitted the COL condition had, in the following day, at least one contiguous grid point fitting the condition. When several adjacent points fitted these criteria on the same day, the northernmost and westernmost grid point was used as the representative position of the COL. This choice permits to identify the closest point to the general circulation where the circulation is cut-off.

Blocking data: The blocking index by Barriopedro et al (2006) has been obtained from an adapted version of the TM90 index (Trigo et al, 2004). This new version is based on the 2.5° × 2.5° resolution of the NCEP/NCAR gridded data and the latitudinal frequency distribution of blocking episodes. This methodology computed simultaneously two 500 hPa geopotential height gradients (GHGN and GHGS) for each 2.5° longitude and for each day of study over the Northern Hemisphere according with the following expression:

$\mathrm{GHGS} = [Z(\lambda, \phi_O) - Z(\lambda, \phi_S)]/(\phi_O - \phi_S)$ and $\mathrm{GHGN} = [Z(\lambda, \phi_N) - Z(\lambda, \phi_O)]/(\phi_N - \phi_O)$ where $\phi_N = 77.5^\circ \mathrm{N} + \delta$, $\phi_O = 60^\circ \mathrm{N} + \delta$, $\phi_S = 40^\circ \mathrm{N} + \delta$, $\delta = -5^\circ$, -2.5°, 0.0°, 2.5°, 5.0°; where $Z(\lambda, \phi)$ is the geopotential in 500 hPa at longitude λ and for latitude ϕ. GHGS is proportional to the zonal geostrophic wind component while GHGN gradient is imposed in order to exclude those non-blocked flows.

A longitude is considered as blocked when both, GHGN and GHGS, verify $\mathrm{GHGN} < -10$ gpm/°latitude and $\mathrm{GHGS} > 0$, at least for one of the five δ values.

A blocking event is detected when at least five consecutive longitudes (12.5°) verify the conditions during at least five days, but allowing one non-blocked longitude between two blocked longitudes. This additional condition is imposed in order to include those blocking patterns presenting non-blocked longitudes under the anticyclone area. To detect the centre of blocking, a longitude and latitude box centred within the blocked region was constructed. The box is defined by a longitude that extends from 5° eastern (western) of the first (last) blocked longitude. The latitude thresholds were selected as those northward (southward) of the maximum (minimum) value of ϕ_S (ϕ_N). They select those grid points where the averaged height is the maximum in the box. The longitude centre is chosen as that longitude with maximum height latitudinally averaged for box limits. Once the blocking longitude is detected, the latitudinal centre is that for the selected longitude centre, displaying the highest longitudinal averaged height value within the box.

Indices of Northern Hemisphere Teleconnection Patterns: The Rotated Principal Component Analysis – RPCA (Barnston and Livezey, 1987) – is the method to identify the Northern Hemisphere (NH) teleconnection patterns (TP) and their indices. The primary TP for all months is identified with this method, and it permits to construct the time series of the patterns. To obtain the TP the RPCA procedure is applied to monthly mean standardized 500 hPa height anomalies for the extratropical region (20° N–90° N) from 01/01/1950 to 31/12/2000. The ten leading unrotated EOFs are determined from the standardized monthly height anomaly fields in the 3-month period centred on that month for each of all months of the year. Then a Varimax rotation is applied to these ten leading unrotated modes. In the Varimax rotation method, the indices for the ten leading rotated modes are calculated simultaneously for each month in the record. These indices are the solution to the Least Squares system of equations. They reflect the combination of modes which explains most of the spatial variance of the standardized height anomaly field in that month. Ten dominant TP are observed in the twelve sets of rotated modes. Among these ten TP are those that affect the European region and that we use in this paper (the North Atlantic Oscillation (NAO), the East Atlantic pattern (EA), the East Atlantic/Western Russia pattern (EA-WR), the East Atlantic-Jet pattern (EA-Jet) and the Scandinavia pattern (SCAND)). The solution to this system of equations produces the resulting teleconnection indices, which represent the combination of TPs that indicates the most spatial variance of the observed standardized anomalies in each month.

Synoptic description of a cut-off low system (COL): COLs are closed cyclonically circulating eddies isolated from the main western stream. These lows are upper and midtropospheric features and consequently they do not need to have a corresponding low in the lower levels of the troposphere. However, sometimes a cut-off low may start as an upper-level trough extending to the surface once it has developed. Their meteorological characteristics are represented by some physical parameters.

- Height contours at 200 hPa: During the initial stage of a COL the absolute topography at 200 hPa shows an upper-level trough. During the different stages of development the trough forms an inverse omega shape that leads to a closed cyclonic circulation in the southern part of the trough.
- Height contours at 1000 hPa: Sometimes no distinct low-level features can be observed in this field. The gradient of the height contours is generally weak. Some weak cyclonic circulation may appear, initiated by the circulation from aloft, during the later phases of a cut-off.
- Equivalent thickness: This field is characterized by a thickness ridge in front of the low and a trough or a distinct minimum behind or in the center of the low.
- Thermal front parameter (TFP): There are two baroclinic zones, one in front of the low, which is connected with a frontal-like cloud band, and another one behind the low, connected with a baroclinic boundary.
- Temperature at 500 hPa: The air within the cut-off low is colder than in the surroundings. The temperature field shows a life cycle similar to that of the upper height field.

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