EXPLOSIVE CYCLONES IN THE NORTH ATLANTIC: NAO INFLUENCE AND MULTIDECADAL VARIABILITY

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ABSTRACT

In this study we have analyzed the variability of explosive cyclones affecting Europe at different timescales. Cyclones have been identified and tracked through an automatic algorithm that has been applied to the MSLP NCEP reanalysis data. Subsequently, explosive cyclones affecting Europe have been selected from the whole climatology of extratropical North Atlantic cyclones (406 total cases from Oct-Mar 1950-2010).

In the first part of the work, the general circulation conditions that appear to be beneficial for the development of explosive cyclones affecting Europe have been assessed through the North Atlantic Oscillation (NAO) characteristics. By using a Daily NAO Index (DNI), results have shown that a positive NAO phase seems to foster such events over Europe. Under this phase, events become more frequent and more intense. This fact can be partially explained by a more intense, northeastwardly displaced and zonally elongated (compared to climatology) Jetstream, which is characteristic of a NAO positive phase.

In the second part of the work, multidecadal variability of explosive cyclones has been studied in January through their basic characteristics (average latitude, frequency and intensity). Preliminary results suggest that the Pacific Decadal Oscillation (PDO) might be modulating the average latitude of explosive cyclones affecting Europe. Additionally, a significant correlation was also found at multidecadal scales between the cyclone count and the Atlantic Multidecadal Oscillation (AMO).

Key words: Explosive Cyclones, Europe, North Atlantic Oscillation, Jetstream, Cyclone's properties, Multidecadal Variability.

RESUMEN

En este estudio se ha analizado la variabilidad en diferentes escalas temporales de las ciclogénesis explosivas que afectan Europa. La identificación y seguimiento de ciclones se ha realizado a través de la utilización de un algoritmo automático aplicado sobre los datos de MSLP del reanálisis de NCEP. En total, 406 casos de ciclogénesis explosivas que han afectado Europa han sido seleccionados (Oct-Mar 1950-2010).

En la primera parte de este estudio, las condiciones de circulación general que podrían favorecer el desarrollo explosivo de ciclones sobre Europa se han estudiado a través de las características de la Oscilación del Atlántico Norte (NAO). Mediante la utilización de un índice NAO diario, los resultados muestran como bajo una fase positiva de la NAO las ciclogénesis explosivas aumentan tanto en frecuencia como en intensidad sobre el continente Europeo. La existencia de una corriente en chorro más intensa, zonalmente estirada y desplazada hacia el NE (característica de una fase NAO positiva), comparada con el Jet climatológico, sería capaz de explicar parcialmente este comportamiento.

En la segunda parte de este trabajo se ha estudiado la variabilidad multidecadal de las propiedades básicas asociadas a las ciclogénesis explosivas en enero (latitud media, frecuencia e intensidad). Nuestros resultados preliminares sugieren que la Oscilación Pacífica Decadal (PDO) podría estar modulando la latitud media de estos eventos. Asimismo, también se ha encontrado correlación significativa a escala multidecadal entre la frecuencia de ocurrencia de estos eventos y la Oscilación Atlántica Multidecadal (AMO).

Palabras clave: Ciclogénesis Explosiva, Europa, Oscilación del Atlántico Norte, Corriente en Chorro, Propiedades de Ciclones, Variabilidad Multidecadal.

1. INTRODUCTION

Extratropical cyclones are one of the most important features of the climate in the mid-latitudes of both hemispheres. Over the North Atlantic, extratropical cyclones develop near the North American East Coast, undergo a strong intensification over the ocean, move eastward and reach Europe. There, they are one of the main factors influencing local weather (e.g. Trigo, 2006; Dacré & Gray, 2009). Intense cyclones are often associated with extreme weather conditions, in terms of wind and precipitation, and they are among the most severe natural hazards affecting Europe (e.g. Klawa & Ulbrich, 2003; Della-Marta *et al.*, 2009).

Explosive cyclones are among the most intense extratropical cyclones (Sanders & Gyakum, 1980). Their main characteristic is that they possess large deepening rates (i.e. a pressure fall greater than 24 hPa over 24 hours at latitude of 60ºN) during their evolution. In the recent past, two explosive cyclones have hit southwestern Europe (Klaus in JAN-2009 and Xynthia in FEB-2010) leading to very strong impacts (Liberato *et al.*, 2011). Hence, a better understanding of the characteristics of such events is crucial to prevent their catastrophic effects.

At seasonal and interannual timescales, cyclones are linked to precipitation patterns, with increased rainfall along their trajectories. In the North Atlantic sector, many studies have shown that stormtracks are influenced by the North Atlantic Oscillation (NAO) (van Loon & Rogers, 1978; Wallace & Gutzler, 1981; Chang, 2009). The NAO (Walker, 1924) is the most prominent pattern of variability in the North Atlantic region and it is characterized by the redistribution of mass between subpolar and subtropical latitudes. A positive NAO phase is associated with a poleward shift of cyclone trajectories, leading to wetter and warmer weather over Northern Europe, while a negative phase is associated with drier and colder conditions over the same region (Hurrell *et al.*, 2003). However, only a few studies have analyzed the relation between very intense extratropical cyclones and the NAO. Pinto *et al.* (2009) and Nesterov (2009) analyzed the influence of the NAO on the development of explosive cyclones with intensification rates exceeding 1.0 hPa (deg.lat.)$^{-2}$ over 24h in the vicinity of Europe. Donat *et al.* (2010) studied the influence of the NAO on the occurrence of storm days with very intense winds over central Europe. In this work we present a more complete statistical analysis using a climatology that includes 406 explosive cyclones affecting Europe from 1950 to 2010, compared with the more limited studies of Nesterov (2009) (21cases) and Pinto *et al.* (2009) (62 cases).

Likewise, only a few studies have investigated the possible relations between the low frequency Sea Surface Temperature patterns and the characteristics of cyclones impacting Europe at multidecadal timescales. Polonskii (2008) noted that the Atlantic Multidecadal Oscillation (AMO) (Knight *et al.*, 2005) influences the frequency and predominant direction of cyclones over the Black Sea Region. More recently, Voskresenskaya and Maslova (2012) have shown that the joint action of the Pacific Decadal Oscillation (PDO) (Mantua and Hare, 2002) and AMO affects cyclone characteristics in the same region. In this work, we will assess the possible connections between AMO/PDO and the characteristics of explosive cyclones affecting Europe at multidecadal scales.

In the next section the methodology of this study is described. Results are provided in section 3 and a brief summary and conclusions follow in section 4.

2. METHODOLOGY

An automatic tracking method was applied to describe the complete life cycles of cyclones from NCEP reanalysis. For this purpose, an algorithm originally developed by Murray & Simmonds (1991) was utilized. The algorithm was adapted and evaluated for Northern Hemisphere cyclone properties (Pinto *et al.* 2005). Cyclones are identified using Laplacian of the MSLP as proxy for their relative geostrophic vorticity (cf. Murray & Simmonds 1991). Subsequently, a tracking algorithm is applied, taking into consideration the most probable displacement of a cyclone under the given large-scale conditions, previous path and speed. The method provides characteristic variables (e.g. core pressure, intensity and propagating velocity) at each stage of the systems' life-cycle. Further details on the method and settings can be found in Murray & Simmonds (1991), Simmonds *et al.* (1999) and Pinto *et al.* (2005).

As a first step before cyclone's selection, an intensity index has been calculated for each cyclone in the dataset. This index, the so-called Normalized Deepening Rate (1), provides information on how fast extratropical cyclones strengthen with time.

(1) $$NDR = (\triangle P/24)*(\sin 60^{\circ}/\sin\Phi) \text{ Bergeron}$$

Where $\triangle P$ is the pressure fall in the cyclone's surface center during the 24 hours of maximum intensification and Φ is the averaged latitude of the cyclone's center within this time period.

Using the cyclone climatology and the calculated NDR, the following selection criteria have been applied in this work:

1) Maximum intensification period (24 hours) of cyclones must lie in the time interval: October-March 1950-2010 (i.e. 60 extended winter seasons).
2) Spatial coverage: The trajectory during the maximum intensification period must fall inside the longitude-latitude box [20W-40E, 30N-65N]. This criterion is used to select cyclones that affect Europe during their maximum intensity stage.
3) Lifecycles (LCs) of cyclones must be longer than 24 hours and not superior to 12 days in order to filter out possible spurious and not physically coherent tracks.
4) Pressure minimum during LC must be lower than 1000 hPa at least at one time step in order to get rid of weak low pressure areas.
5) All cyclones must have positive NDRs. Cyclones with $NDR \geq 1$ Bergeron are considered as Explosive cyclones (Sanders & Gyakum, 1980). Cyclones with $0 < NDR < 1$ are considered as Non-explosive ones.

In the first part of this study, explosive cyclones affecting Europe have been analyzed (Oct-Mar 1950-2010). The possible connections between the NAO and explosive cyclones have been studied using the Daily NAO Index (DNI) provided by NCAR CGD's Climate Analysis Section (http://www.cgd.ucar.edu/cas/jhurrell/indices.html). This index was constructed by projecting the z500 daily anomalies at 00 UTC onto the loading NAO pattern since 1950 (first EOF of montly z500 anomalies in the North Atlantic from 1950 to 2010 for the full year). Based on the DNI values, five different NAO phases have been defined as follows: NAO++ (strong positive; DNI≥1.5), NAO+ (positive; 1.5>DNI≥0.5), NAO-0 (neutral; 0.5>DNI>-0.5), NAO- (negative; -0.5≥DNI>-1.5) and NAO) - - (strong negative: DNI≤-1.5).

When analyzing the multidecadal variability in the second part of the study, an additional time constraint is applied: only January cases are included to prevent confusion arising from the seasonal variability in the mean flow. Information on the average latitude (avlat), the number of cases (Ncases) and cyclone intensity (NDR) has been extracted from all cyclones in this subpopulation. Time series for these 3 variables were created for the time period extending from 1951 to 2010 and an 11 year running mean (RM-11Y; centered) filter was applied to these series to isolate low frequency variability. All cyclones laying inside each 11-Y time window were considered for the calculations. While the average latitude and NDR were calculated as means, number of cases was computed as an absolute frequency. For example, the avlat and NDR values for the first year in the series (1956) represent the mean value of the average latitude and NDR for all cyclones occurring within the time window of January 1951 to 1961. In contrast, the number of cases at the same time step represents the number of cyclones that occurred in the same time interval. This methodology takes into account that cyclones are not homogeneously distributed in time. Grouping the cyclones according to their time of occurrence, which implies using a different number of events for each data point, is necessary to relate changes in the cyclone properties to low frequency changes in the general circulation. The number of data points used to construct the avlat and NDR averages in the RM-11Y series range from 10 to 32 cases, depending on how many cyclones lay in each time window. This is deemed large enough to make these means representative of the properties of all cyclones within any given time window. After computing the RM-11Y timeseries for average latitude, number of cases and NDR, linear trends were subtracted from all series, which were subsequently standardized. This eliminates a possible anthropogenic climate change signal and keeps only multidecadal natural variability signal with periodicity lower or equal to 60 years. Finally, we have used correlation analysis to relate changes in the cyclone's properties with patterns of SST known to have long periodicity. In this study we have assessed the impact of the AMO and PDO on cyclone characteristics. The AMO variability is described using the NCEP unsmoothed index (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/) while for the PDO we used the index computed by JISAO (http://jisao.washington.edu/pdo). Correlations were assessed at 95 and 99% confidence levels using a double tailed t-test method.

3. RESULTS

3.1. Explosive cyclones affecting Europe and the NAO

The full trajectories of the selected 406 explosive cyclones that fulfill the criteria introduced in the methodology are shown in Fig. 1. We also show in the same figure the fraction of the trajectory in which the cyclones undergo explosive development (in green).

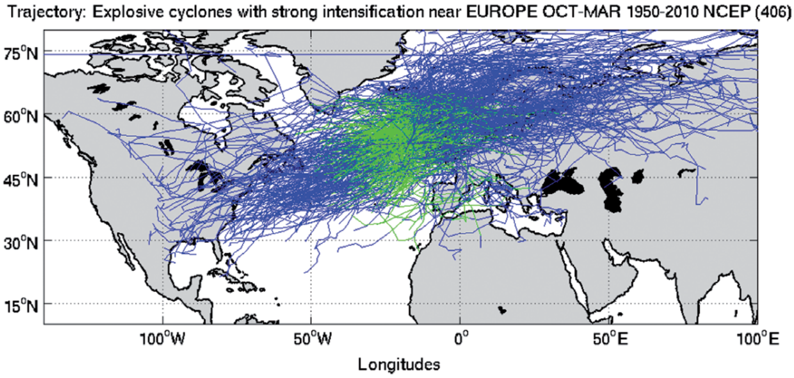

FIG. 1: *Trajectories of explosive cyclones affecting Europe (406 cases), with the 24h period of explosive development emphasized in green. NCEP.*

As we can see, explosive cyclones that develop in the vicinity of the continent present trajectories mostly in the SW-NE direction. These trajectories are consistent with previous studies of the North Atlantic stormtrack of Trigo (2006) and Dacré & Gray (2009).

To analyze the large scale mean circulation conditions that are present during the development of explosive cyclones affecting Europe, we have computed a composite of the daily z500 anomalies (geopotential height at 500 hPa) on the dates in which the explosive development for each cyclone started (Fig. 2).

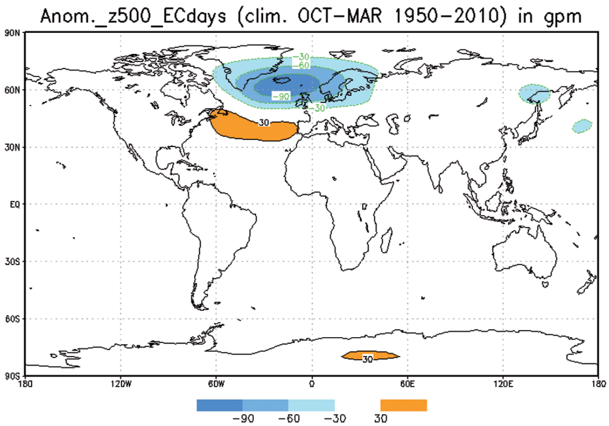

FIG. 2: *Composited anomalies of z500 on days in which explosive development started for each cyclone. Anomalies are computed by subtracting the mean of Oct-Mar from 1950 to 2010 to the z500 field at the time step (i.e. 00, 06, 12, 18 UTC) when explosive cyclogenesis started.*

From Fig. 2, two areas of anomalies can be observed in the North Atlantic: a negative one centered on Iceland and a positive one over the subtropical North Atlantic. This pattern highly resembles the NAO positive phase, suggesting that this phase might be beneficial for the development of explosive cyclones affecting Europe. We provide in Table I the frequency of occurrence of the different NAO phases at the time of explosive development for all 406 cases in our climatology.

NAO phase	NAO- -	NAO-	NAO-0	NAO+	NAO++
Freq. (%)	1.48	10.59	46.80	38.18	2.95

TABLE 1: *Frequency of the NAO phase under which explosive cyclones developed (406 cases).*

This calculation has been done by taking the DNI on the dates of explosive development as described in the methodology. As expected, results show that under positive NAO phases (NAO+ and NAO++) there are a higher number of explosive and more intense (not shown) cyclones affecting Europe compared to the negative phases (NAO- and NAO—). The neutral phase (NAO-0) has the largest frequency of occurrence but this is not surprising because this is also the phase most frequently observed in the full climatology (extremes are less frequent, by definition). To take this into account, we have compared in Fig. 3 the frequency of each DNI value during the period of explosive development (yellow area) to the frequency of that DNI value for all days during the period of study. We can conclude from this figure that NAO positive phases appear to favor the development of explosive cyclones affecting Europe. For positive DNIs, the dashed line (climatological frequency) lies below the yellow area (frequency at time of explosive development), while the reverse is true for negative DNI values.

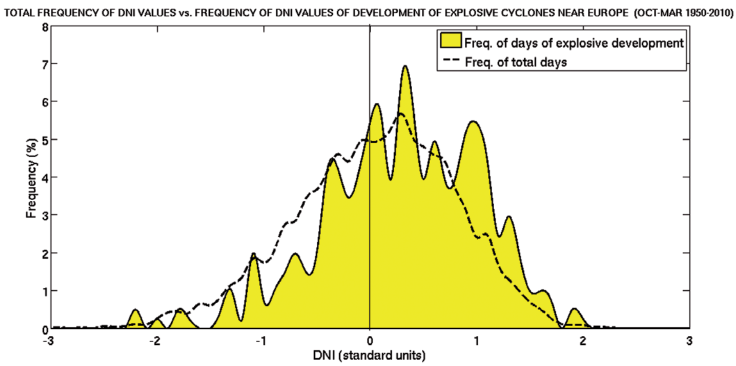

FIG. 3: *Frequency of DNI values on days of explosive development (yellow area) and frequency of DNI values over the total days in the time period of study (dashed line). Oct-Mar 1950-2010. NCEP.*

Finally, we have analyzed possible dynamical conditions that could trigger the development of explosive cyclones downstream in the North Atlantic under positive NAO phases. It is well known in the synoptic literature that a very local intense Jetstream (Jetstreak) situated above the region of cyclogenesis usually triggers the explosive development of the surface low (Bosart & Lin, 1984; Reed *et al.*, 1993). One important factor is the relative position of the Jetstreak entrance/exit regions relative to the surface cyclone (Schulz *et al.*, 1998). In Fig. 4, we have represented the composite of the wind intensity at 250 hPa on the days of explosive development (shaded) overlaid to contours of the climatological Jet during the period of study.

The figure shows that during the days of explosive cyclogenesis a more intense extratropical Jestream is present. Additionally, this Jetstream is more elongated to the East, pointing towards

Europe. The existence of such intense Jetstreams, which are characteristic of a NAO positive phase (Pinto *et al.*, 2009), could be one of the dynamical precursors that lead to the development of explosive cyclones affecting Europe.

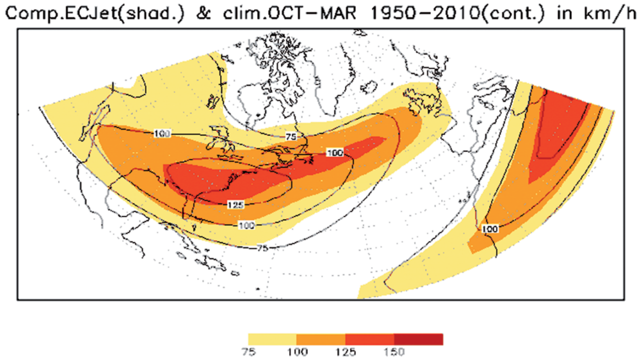

FIG. 4: *Composite of wind intensity on days of explosive development (shaded) and climatological Jet (contours). Oct-Mar 1950-2010. NCEP.*

3.2 Multidecadal variability of North Atlantic cyclones

In this second part of the study, changes in the main properties of explosive cyclones affecting Europe in January (110 cases selected from the total 406 cases in the period Oct-Mar 1950-2010) have been studied from a decadal to multidecadal perspective. To tackle this task, we first calculated the RM-11Y series of average latitude, number of cases and NDR of the cyclones. These three series are provided in Fig. 5.

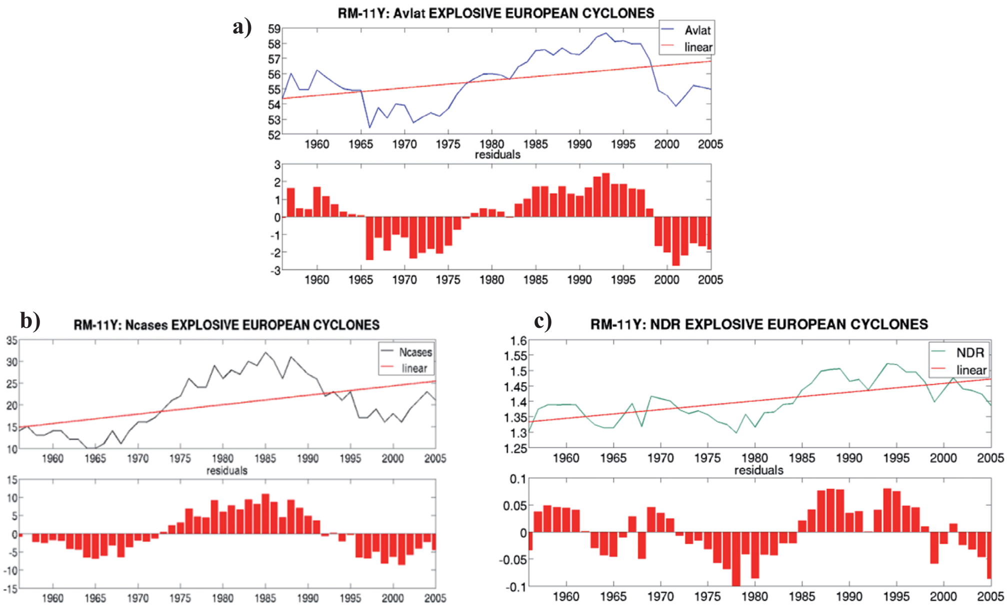

FIG. 5: *RM-11Y of avlat (a), Ncases (b) and NDR (c) of explosive cyclones in the vicinity of Europe (lines). Residuals (non standardized) after subtracting the linear trend are plotted below (bars). January 1956-2005. NCEP.*

The linear trend for the three variables shows that explosive cyclones in the vicinity of Europe are becoming more frequent and more intense (Figs. 5b, c) in the second half of the 20th century and first decade of the 21st. There is also an upward trend in the mean latitude of their tracks (Fig. 5a). These results are consistent with previous studies by Wang *et al.* (2006), Ulbrich *et al.* (2008) and Pinto *et al.* (2009), giving us confidence on the appropriateness of our methodology. Nevertheless, the time window considered is too short to unambiguously attribute these trends to anthropogenic global climate warming (this is not the objective of this work, in any case).

To analyze the possible modulation of explosive cyclone's characteristics during multidecadal variability (shorter or equal than 60 years), the linear trends have been substracted from the timeseries in Fig. 5 (lower panels in the figure) and the series have also been standardized. Then, linear correlations have been computed with the AMO and PDO indexes. This analysis is motivated by the apparent long periodicity observed in the timeseries of avlat, Ncases and NDR, similar to the characteristic timescale of variability of the AMO and PDO SST patterns. This suggests that AMO and PDO might be modulating the basic characteristics of explosive cyclones affecting Europe at multidecadal timescales. The correlations between our timeseries and the AMO-PDO indexes are given in Fig. 6 and Table 2 (only the correlations that lie above the 95% significance level using a double tailed t-test).

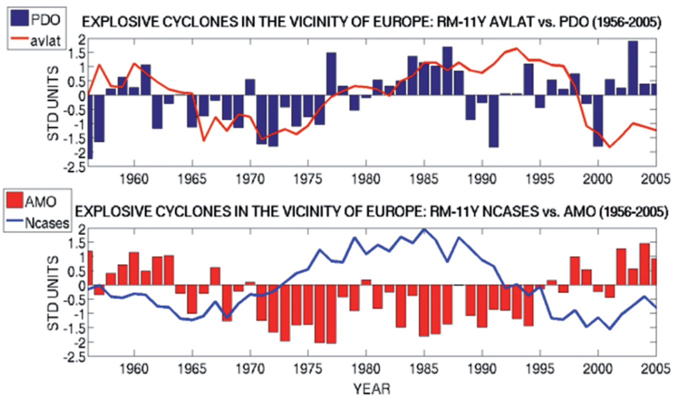

FIG. 6: *Explosive cyclones in the vicinity of Europe. Top: RM-11Y of avlat (red line) vs PDO index (blue bars). Bottom: Ncases (blue line) vs AMO index (red bars). January 1956-2005.*

Correlation	**avlat**	**Significance (t-test)**
PDO	0.2812	95%
Correlation	**Ncases**	**Significance (t-test)**
AMO	-0.4967	99%

TABLE 2: *Correlations and confidence level of avlat, ncases and PDO/AMO indexes.*

According to these preliminary results, it appears that the PDO is modulating the average latitude of explosive cyclones downstream in the North Atlantic at multidecadal timescales, while the AMO might be affecting the number of cases in the region.

As a first step, in order to understand the underlying physics of these modulations, anomalous z500 and zonal wind at 250 hPa (u250) have been regressed onto the 11 running means of AMO and PDO (Fig. 7).

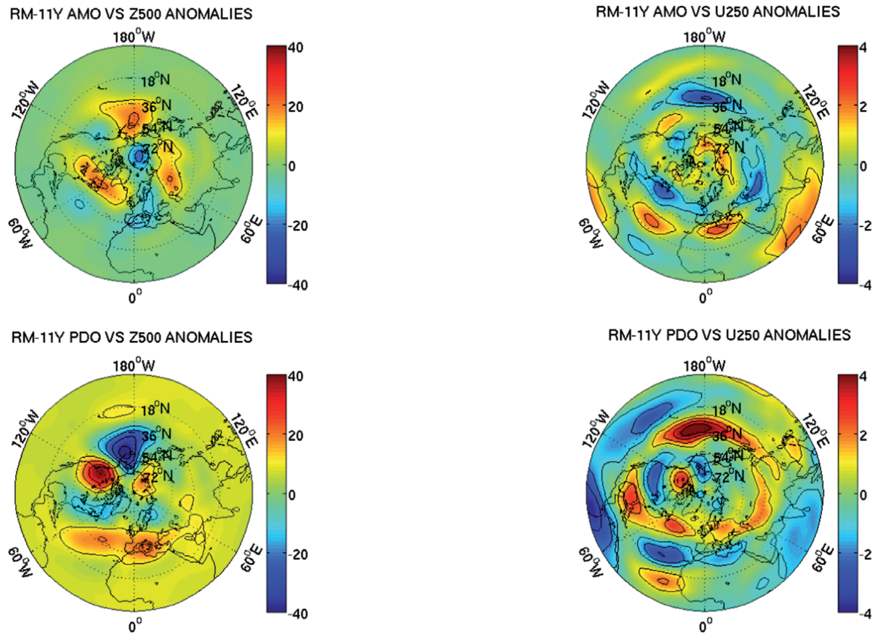

FIG. 7: *Shadings and contours - Anomalous z500 (left) and u250 fields (right) regressed onto the 11 year running means of AMO (top) and PDO (bottom). Contour interval 10 mgp (left) and 4 m/s (right). Jan 1948-2003. NCEP.*

As it can be observed from Fig. 7, a positive standard deviation of the AMO phase is related to positive z500 (top-left) and negative u250 (top-right) anomalies that span over the North Atlantic's stormtrack region [80-10W, 40-60N]. Under these conditions, it is expected that the frequency of cyclones is reduced, as the factors for cyclone growing appear to be unfavorable under a positive AMO phase (and vice versa). Concerning to the PDO, an anomalous z500 dipole, similar to a NAO positive phase pattern, arises in the North Atlantic (bottom-left). Additionally, the Jet downstream in the North Atlantic is displaced to the North (bottom-right). Thus, a positive PDO (through a teleconnection mechanism still to be determined) might be shifting in some manner the cyclone trajectories to the north (and vice versa), modulating their average latitude at multidecadal timescales through the Jetstream's mean latitude.

Nevertheless, this study is still at a preliminary stage and a deeper analysis is needed to confirm the robustness of these results. Also, the physical connection between the AMO/PDO SST patterns and the large scale circulation conditions that appear in Fig. 7 still needs to be elucidated. Finally, a wider population of cyclones with different characteristics would be necessary to give us more confidence in these results.

4. SUMMARY AND CONCLUSIONS (provided in the abstract)

Acknowledgements

This study has been partially supported by the Spanish National projects DE VIAJE (CGL2009-06944), TRACS (CGL2009-10285) and the UCM-BSCH GR58/08 "Micrometeorology and Climate variability" group. We would like to thank Joaquim G. Pinto for the automatic tracking dataset, his help and comments. Thanks also to the NCEP and JISAO for the data that has made possible this study.

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