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# On the development of strong ridge episodes over the eastern North Atlantic

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[1] The occurrence of strong and persistent mid-latitude anticyclonic ridges over the Eastern North Atlantic is a major contributor to the occurrence of severe winter droughts over Western Iberia. We analyze the development of strong and persistent ridge episodes within 40–50°N; 40°W–5°E, which are defined as 300 hPa geopotential height anomalies above 50 gpm that persist for at least 10 consecutive days. Results suggest that the generation and maintenance of these episodes, with positive stratospheric geopotential anomalies over the North American continent and the adjacent North Pacific, are associated with an intensified polar jet. Such positive anomalies tend to detach from the main stratospheric anomaly and propagate eastwards and downwards as Rossby tropospheric waves. Furthermore, the Eastern North Atlantic ridge is generated and repeatedly reinforced until the stratospheric anomaly dissipates. Results also show evidence for waves breaking anticyclonically during the episodes, which is dynamically coherent with their persistency and quasi-stationarity. **Citation:** Santos, J. A., J. G. Pinto, and U. Ulbrich (2009), On the development of strong ridge episodes over the eastern North Atlantic, *Geophys. Res. Lett.*, *36*, L17804, doi:10.1029/2009GL039086.

## 1. Introduction

[2] Recent decades have been characterised by an enhanced frequency of heat waves and droughts over Europe [*Trenberth et al.*, 2007]. Both precipitation deficits and increased temperature lead to water deficits (hydrological droughts). One area particularly vulnerable to such changes is southern Europe, which features high climate sensitivity and has been identified as a climate change "hot spot" [*Giorgi*, 2006]. Southwestern Europe has experienced a number of droughts in recent decades, e.g., in the summer of 2003 [e.g., *Stott et al.*, 2004; *Schär et al.*, 2004] and in the winter 2004/2005 [*Garcia-Herrera et al.*, 2007; *Santos et al.*, 2007]. Such events are associated with anomalous large-scale atmospheric circulation typically enduring several months. Among the main large-scale atmospheric factors related to winter rainfall deficits, a positive phase of the North Atlantic Oscillation (NAO) [e.g., *Hurrell*, 1995] has often been recognised as an important forcing pattern [e.g., *Ulbrich et al.*, 1999]. In recent years, the development of the NAO phases has been regarded from the Rossby wave perspective, particularly in how far NAO phases are associated with wave breaking [e.g., *Feldstein*, 2003; *Benedict et al.*, 2004; *Kunz et al.*, 2009] and the occurrence/absence of blocking events over the North Atlantic [e.g., *Woollings et al.*, 2008]. Here, we analyse tropospheric and stratospheric anomalies related to the development of strong anticyclonic ridges over the Eastern North Atlantic (ENA), which are specifically associated with winter precipitation deficits over Western Iberia.

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## 2. Data

[3] Data from the National Centers for Environmental Prediction reanalysis [*Kistler et al.*, 2001] is used for the period 1958–2008. The analyses are based on 6-hourly data defined over the regular 2.5° latitude × 2.5° longitude grid at 17 isobaric levels (1000–10 hPa) over the Northern Hemisphere. As the focus of this study is on winter conditions, the analysis is restricted to the period from 1st December–28/29th February (DJF). Daily anomalies are obtained by subtracting the corresponding calendar daily mean values for the period 1961–1990.

## 3. Results

[4] Previous studies have documented that the strength and persistence of a mid-latitude ridge over the ENA plays a key role in triggering extremely dry episodes over Western Iberia, which ultimately may lead to the establishment of droughts in subsequent months [cf. *Santos et al.*, 2007]. Results by *Santos et al.* [2007, 2009] suggest that the 300 hPa geopotential height within a sector delimited by 40–50°N; 40°W–5°E (herein referred to as ridge sector; RS) is particularly suitable in modeling the occurrence of anomalous winter precipitation over Western Iberia; a significant anti-correlation ($\sigma = -0.91$) exists between winter precipitation and the RS-mean 300 hPa geopotential height. The latter time series shows considerable interannual variability (Figure S1 of the auxiliary material) and features an upward trend in recent decades.[4] Strong ridge days are then defined as days when the area-mean 300 hPa geopotential height is at least 50 gpm (60-th percentile of the geopotential anomalies) above its winter-mean value. A sensitivity analysis showed that lower thresholds are too permissive (includes episodes that do not feature a strong ridge) and higher thresholds are too restrictive (few episodes). A strong ridge episode (SRE) is defined as a non-interrupted sequence of strong ridge days. Results showed that most SRE display lengths within the synoptic timescales: about 63% of the SRE last 5 days or less.

[4]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039086.

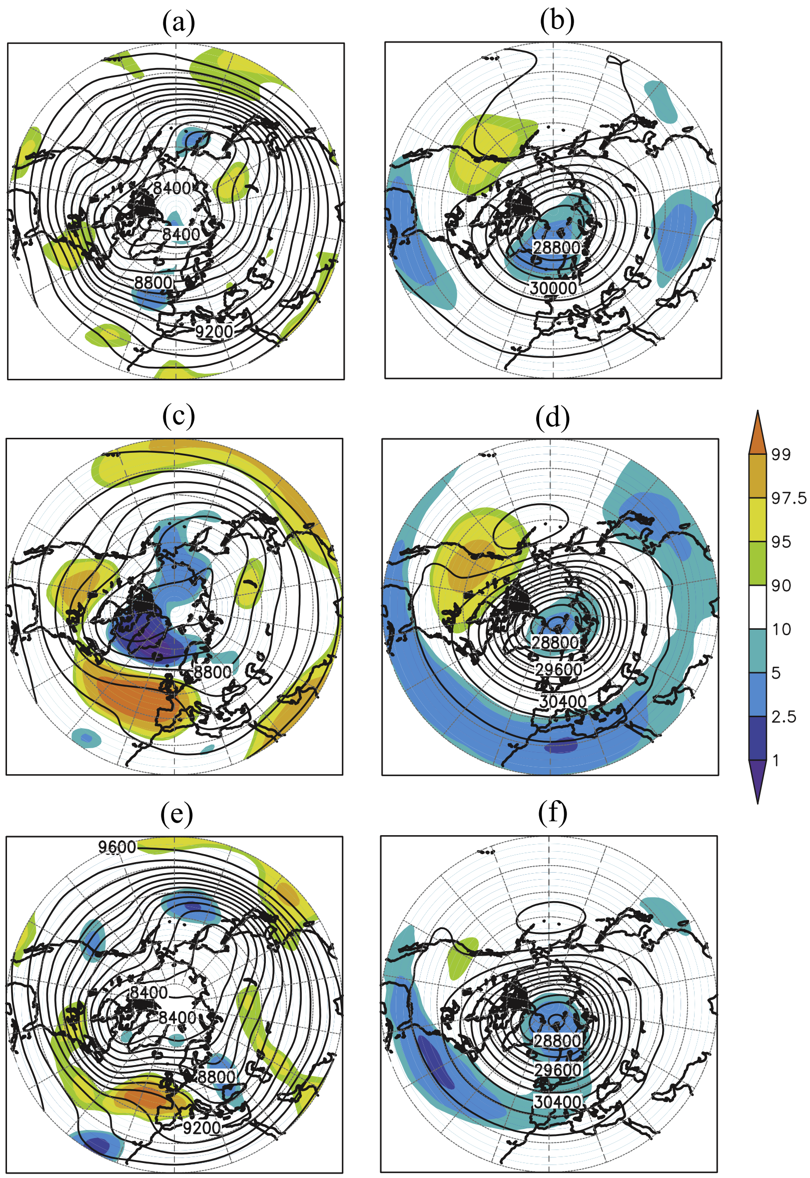


**Figure 1.** Mean geopotential fields at (left) 300 hPa and (right) 10 hPa for (a–b) onset−3 (c–d) first 10 days of the episodes and (e–f) decay. Shading: significance levels of the Student's t-test.

[5] As our focus lies on the most persistent episodes (typically associated with extremely dry winters in Western Iberia), a further restriction was added: only SRE lasting at least 10 consecutive days were chosen as being strong and persistent ridge episodes (SPRE), which corresponds to 50 episodes out of a total of 298 SRE identified between 1961 and 2008 (roughly 17% of all SRE). Nevertheless, some of these SPRE are separated from other episodes by very short interruptions (1 or 2 days), suggesting that they could be part of a single longer SPRE. As we aim at analysing the mechanisms underlying the generation and maintenance of SPRE, only well-defined onsets and decays are considered here: onsets (decays) must be preceded (followed) by at least three non-episode days. Using this criterion, 24 (32) well-defined onsets (decays) were identified. Changing this criterion to five non-episode days, the number of onsets (decays) decreases to 18 (27), but no significant differences were found in the results (not shown). The same methodology was applied to the linearly detrended 300 hPa geopotential height (Figure S1), resulting in exactly the same sample of SPRE, with only minor changes in their length. Since SPRE are commonly related to a strengthening of the Azores high (and not to high-latitude blocking highs), they are typically associated with a positive NAO phase (78% of all episode days occurred in a positive NAO phase compared to a daily NAO-index obtained from the Climate Prediction Center at http://www.cpc.ncep.noaa.gov/products/precip/CWlink/).

[6] Compositing geopotential height anomalies for onsets and decays at all vertical levels revealed that 300 hPa and 10 hPa anomalies are particularly informative. Three days before onset, only unclear anomalies can be found at 300 hPa (Figure 1a). Simultaneously, a positive anomaly in a sector over Western North America (WNA) is already recognised at 10 hPa, accompanied by negative anomalies over the Arctic and mid-latitudes (Figure 1b). During SPRE (first 10 days),

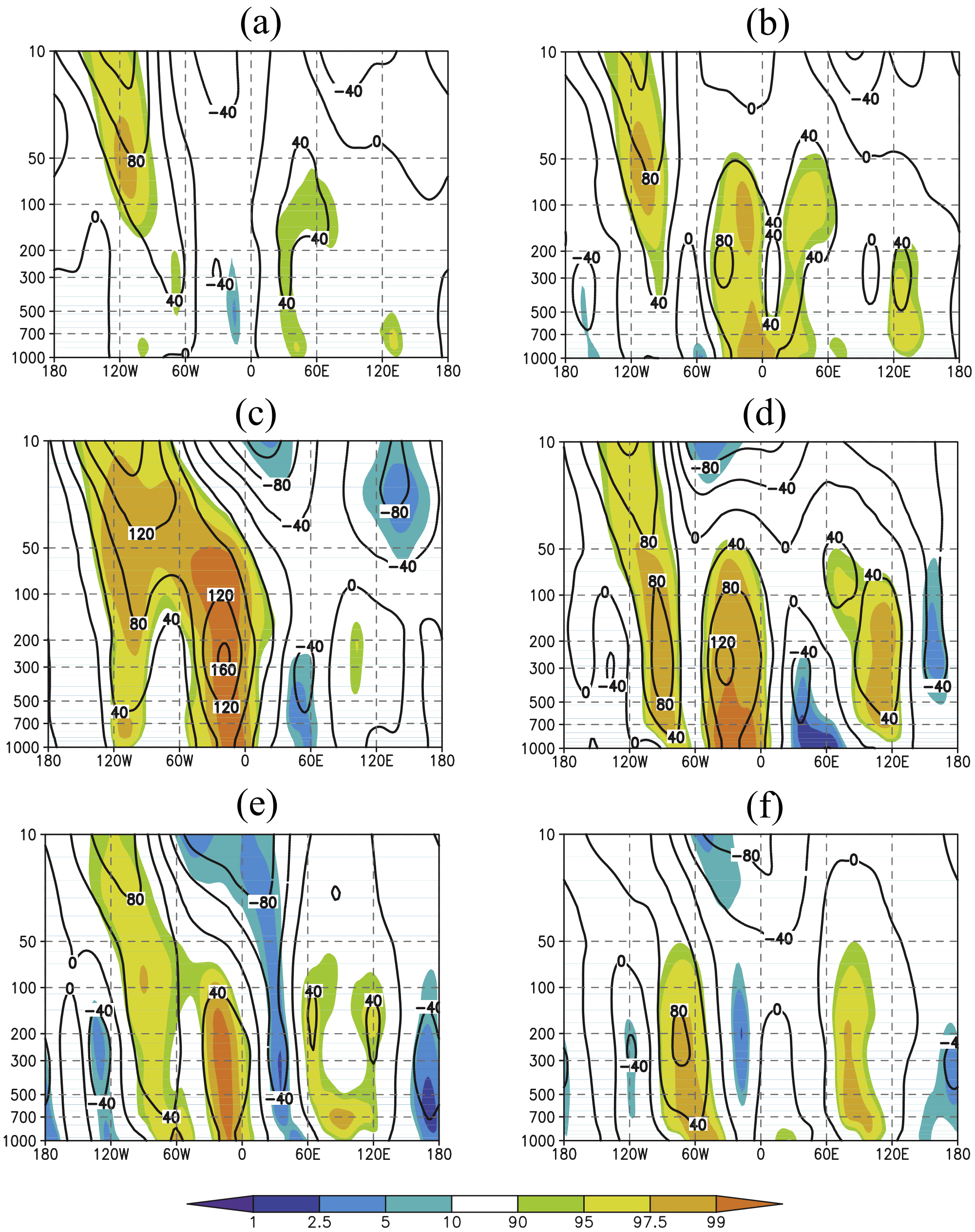

**Figure 2.** Zonal cross-sections (1000–10 hPa) of the meridionally averaged (35°–55°N) geopotential height anomalies for all winters (DJF) in the period 1961–2008. (a) onset−3 to −1; (b) onset; (c) onset+5; (d) onset+10; (e) decay; (f) decay+1 to +3 days. Shading: significance levels of the Student's t-test.

the expected maximum is found at 300 hPa over the ENA (Figure 1c). Further, a secondary positive anomaly is identified over North America, almost underneath the stratospheric positive anomaly, while a negative anomaly is recognised near Iceland. The stratospheric anomalies preceding onset (Figure 1b) undergo a significant enhancement during SPRE (Figure 1d). In fact, a reshaping and a strengthening of the stratospheric polar jet pattern are observed during SPRE, particularly over North America (Figure S2), while during decay the stratospheric jet tends to recover its climate-mean pattern (not shown), and both the stratospheric and tropospheric anomalies significantly weaken (Figures 1e and 1f). Hence, these fields suggest a link between the anomalies in the stratospheric jet and the tropospheric anomalies associated with SPRE. The Hovmöller diagrams of 300 hPa geopotential height anomalies composited for all episodes also reveal the quasi-stationarity of the tropospheric North Atlantic ridge (60°W–0°), which is accompanied by a secondary positive anomaly over North America. At the 10 hPa level, strong stratospheric anomalies precede the onset, which strengthen and persist throughout the episode (Figure S3). The stratospheric anomalies can thus be assumed as a dynamical precursor of SPRE.

[7] We test this hypothesis by analysing zonal cross-sections of the meridionally-averaged (35°–55°N) geopotential height anomalies during the different stages of SPRE (Figure 2). During the three days preceding the onset, a westward tilted core of positive anomalies can be found

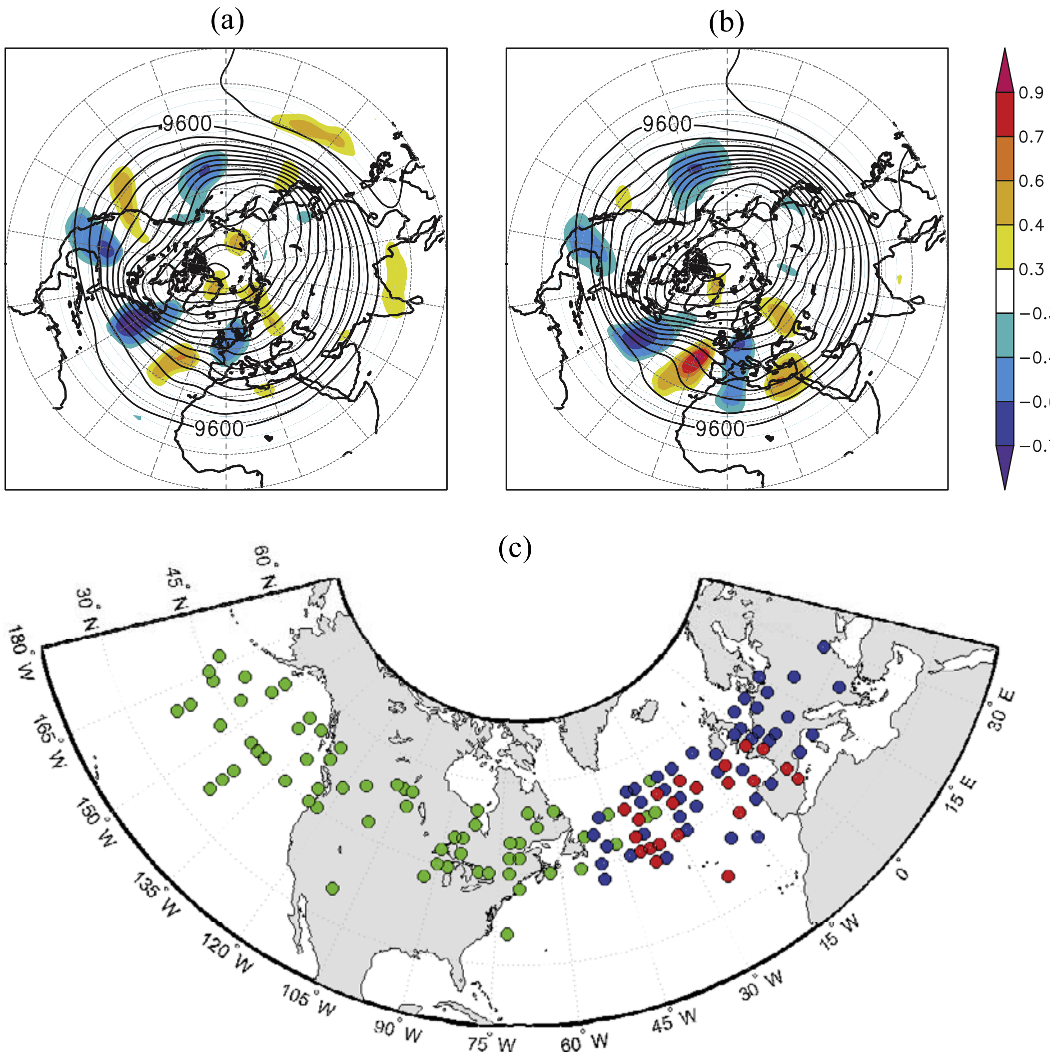


**Figure 3.** Correlation patterns between the 12 UTC 300 hPa geopotential heights at a grid point (45°N; 17.5°W) for all onsets in the period 1961–2008 and the corresponding hemispheric (a) one day lagged field; (b) simultaneous field. The respective composite of the 300 hPa geopotential height is also displayed. (c) Locations of 300 hPa geopotential height anomaly maxima for the three days before the onsets (green circles), during the onsets (red circles) and for four, seven and ten days after onset (blue circles).

near 120°W, extending from the stratosphere down to the upper troposphere (Figure 2a). Further, a weak tropospheric wave pattern can also be identified over the North Atlantic and Europe (90°W–60°E). However, due to wave transiency, there is a phase offset in the composite cross-sections (averages of different SPRE with different wave speeds). However, analysis of individual SPRE clearly reveals the presence of eastwardly propagating tropospheric waves over the North Atlantic (Figure S4). This propagation can be more clearly highlighted by considering correlation patterns between the 300 hPa geopotential height within the RS and its corresponding 1-day lagged and simultaneous hemispheric values. Figures 3a and 3b show the results for 45°N; 17.5°W and clearly depicts a wave train extending from the North Pacific towards Eastern Europe. Eastward shifts in the location of the cores over the North Atlantic emphasise the eastward propagation of the wave phase, while the enhancement (weakening) of cores downstream (upstream) are a manifestation of the eastward energy propagation. The corresponding correlation patterns using days after onset show a large stationarity in the core positions (not shown), which is in agreement with the SPRE stationarity.

[8] The positions of the maxima in the 300 hPa geopotential height anomalies at various stages also support the previous results. The maxima for the three days before onset (green dots on Figure 3c) are typically located upstream of the RS. During onset the maxima are evidently located within RS (red dots in Figure 3c), while after onset they are spread across the Euro-Atlantic sector, documenting the quasi-stationarity of SPRE (blue dots in Figure 3c). Therefore, an eastward propagation of the anomalies from WNA towards the Euro-Atlantic sector clearly precedes the onsets, while they become quasi-stationary during SPRE. This interpretation is in line with *Feldstein* [2003], which showed evidence that wave train propagation from the North Pacific to the North Atlantic tends to precede the NAO positive phase. This phase also tends to be

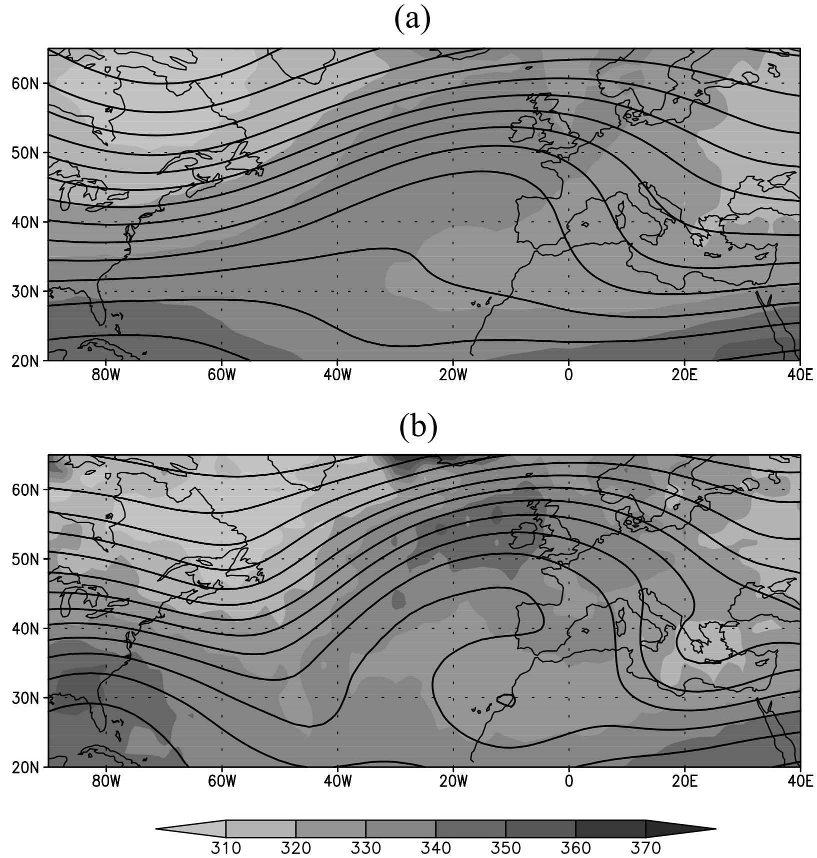


**Figure 4.** Mean potential temperature (in K) at the dynamical tropopause (2-PVU surface) for (a) all episodes and for (b) a specific episode (26 December 1974–8 January 1975). Note the different scales in figures. Corresponding mean 300 hPa geopotential heights (interval of 100 gpm) are also displayed.

generated and maintained by waves breaking anticyclonically over WNA and over ENA [*Benedict et al.*, 2004], which is plainly coherent with the secondary positive anomaly found over North America (Figure 1c) and with the SPRE quasi-stationarity.

[9] During onset, the tropospheric ridge is already established around 30°W, while the stratospheric anomaly remains almost unchanged (Figure 2b). During the episode (illustrated for 5 and 10 days after onset), the tropospheric ridge strengthens and stays quasi-stationary (Figures 2c and 2d), presenting a nearly equivalent barotropic structure, which is in clear agreement with the dynamical properties of the winter-mean North Atlantic ridge for dry winters in Western Iberia [*Santos et al.*, 2009]. During SPRE, the stratospheric anomaly strengthens and its extension into the troposphere is evident (Figures 2c and 2d). During decay, both the stratospheric anomaly and the tropospheric ridge are significantly weakened (Figure 2e), whereas during the following days these anomalies disappear and are replaced by an entirely different wave train (Figure 2f).

[10] These results strongly suggest that the stratospheric positive anomaly over WNA plays a key role in generating and maintaining the SPRE. In particular, our results suggest that its generation is related to the presence of a persistent stratospheric positive anomaly over WNA that extends downward (westward tilted) into the troposphere. A SPRE can then be thought of as a tropospheric Rossby wave train triggered by a downward propagating stratospheric anomaly over North America, which tends to break anticyclonically over the ENA. Its persistence depends both on the length of the wave breaking event and on the state of the polar vortex. Its decay is mostly related to the absence of a strong stratospheric feeding anomaly and of a sustained propagation of positive anomalies from North America towards Europe.

[11] This direct modulation of tropospheric baroclinic waves by the lower stratospheric polar vortex has been proposed as one of the relevant mechanisms underlying the stratosphere-troposphere coupling [e.g., *Baldwin and Dunkerton*, 2001; *Wittman et al.*, 2004; *Kunz et al.*, 2009]. During the winter half of the year, downward propagation of zonal mean zonal wind anomalies from the stratosphere into the troposphere were also shown to play a key role in triggering the NAO positive phase [*Christiansen*, 2001]. Furthermore, a strong polar vortex is also associated with more frequent anticyclonic wave breakings over the North Atlantic [*Kunz et al.*, 2009]. In fact, during SPRE, the 300 hPa geopotential height and the potential temperature at the dynamical tropopause (2 PVU) also show some evidence of wave-breaking mechanisms close to Iberia (Figure 4a). In fact, there is a reversal in the potential temperature meridional gradient over the ENA. This is in accordance with *Woollings et al.* [2008], where a wave-breaking increase is found over Iberia during the NAO positive phase. Since there is a high

case-to-case variability in the wave-breaking location, their structure is much clearer for individual episodes (Figure 4b).

## 4. Conclusions

[12] Following the analysis by *Santos et al.* [2009] on the relationship between the occurrence of SPRE and precipitation deficits over Western Iberia, we have here analysed the generation, maintenance and decay of the SPRE. Positive anomalies over North America propagate eastwards over the North Atlantic and contribute to the generation/onset of these SPRE. However, results also suggest that anomalously strong and vertically extended stratospheric ridges over the North America/North Pacific maintain the SPRE by feeding anomalies propagating as Rossby wave trains. The maintenance of a persistent ridge has already been related to eddy transports of momentum and enthalpy over the North Atlantic [*Santos et al.*, 2009]. Here, results suggest that the quasi-stationarity of the ridge is related to both persistent stratospheric anomalies and anticyclonic wave breaking. In fact, the dynamical structure over the North Atlantic during SPRE (quasi-stationary equivalent barotropic ridge associated with the NAO positive phase and with a distorted and strong lower stratospheric polar vortex) has been previously related to an increase in the occurrence of anticyclonic breakings over the North Atlantic [e.g., *Benedict et al.*, 2004; *Kunz et al.*, 2009]. The occurrence of SPRE plays a key role in triggering precipitation extremes in Western Iberia (e.g., the 1980/81 and 2004/05 winters are characterized by a sequence (clustering) of strong ridge episodes and are simultaneously among the driest winters on record). Therefore, the assessment of their frequency and intensity under human-induced climate change is of major interest. In a next step, model data will be analysed to infer possible changes in the frequency and persistence of SPRE under future climate conditions.

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