A dynamical link between deep Atlantic extratropical cyclones and intense Mediterranean cyclones

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1. Introduction

Potential vorticity (PV) streamers correspond to high-PV stratospheric air that intrudes into lower atmospheric levels in a filamentary structure during Rossby wave breaking (Appenzeller and Davies, 1992, Wernli and Sprenger, 2007). PV streamers are widely recognized as upper-tropospheric precursors for Mediterranean cyclogenesis, and they play a primary role in the development and intensification of these cyclones (Tafferner, 1990, Fita et al., 2006, Funatsu et al., 2007, Homar et al., 2007, Tous and Romero, 2013). Flaounas et al. (2015) recently analyzed the baroclinic life cycle of the 200 most intense Mediterranean cyclones in a 20-year climatology and confirmed that PV streamers systematically precede cyclogenesis. In fact, their results showed that the streamers correspond to the downstream, southward, deflection of the polar jet, similarly to the anticyclonic wave breaking (e.g. Thorncroft et al., 1993). This type of upper-level wave breaking is also of key relevance for heavy precipitation events in the region (Massacand et al., 1998, Martius et al., 2006, 2007, Raveh-Rubin and Wernli, 2015).

The synoptic scale conditions related to the 200 most intense Mediterranean cyclones (as identified in Flaounas et al., 2015) are shown in Figure 1(a) as composite averages of pressure at sea level and of PV and wind on the 330-K isentropic surface. Composites are centered at the time when the Mediterranean cyclones reach their maximum intensity. In addition, Figure 1(b) shows the composite fields as monthly anomalies (deviations from the 20-year monthly climatology). A coherent structure of anticyclonic wave breaking is shown in Figure 1(a), characterized by a ridge over the eastern North Atlantic and a trough over Western Europe. The ridge is associated with negative PV anomalies, while the streamer is associated with positive PV anomalies (Figure 1(b)). The latter are centered over the Mediterranean, to the northwest of the cyclone centers [negative sea-level pressure (SLP) anomalies over the central Mediterranean Sea in Figure 1(b)], consistent with the downstream deflection of the polar jet (Figure 1(a), at the eastern flank of the ridge).

Despite the importance of PV streamers for the genesis of intense Mediterranean cyclones, our knowledge lacks a systematic analysis on the atmospheric mechanism that contributes to the wave breaking, and in turn, the intrusion of PV streamers over the Mediterranean. In a numerical case study of a Mediterranean cyclone and PV streamer which caused Alpine flooding, Massacand et al. (2001) showed that an upstream Atlantic cyclone and its associated diabatic heating contributed to the upper-tropospheric Rossby wave breaking. This was achieved by the cross-isentropic transport of low-PV air to the upper troposphere, thereby enhancing the upper-level ridge and forming the elongated PV streamer downstream. In a case study in September 2008, Rossby wave breaking was provoked by the extratropical transition of hurricane Hanna over the North Atlantic (Grams et al., 2011). The wave breaking was similar to the one shown in Figure 1 and was...
The motivation of this study is thus to investigate whether the aforementioned mechanism dynamically relating two cyclones via wave breaking due to ridge amplification by the WCB of the first cyclone is systematically present whenever intense cyclogenesis takes place in the Mediterranean basin.

2. Methodology

2.1. Data and approach

Our methodology is designed to trace the dynamical link between North Atlantic cyclones and those developing downstream in the Mediterranean. Therefore, an objective feature-based approach has been developed and applied to the 200 most intense Mediterranean cyclones for the years 1989–2008, taken from Flaounas et al. (2015). The set of intense cyclones was determined based on their 850-hPa relative vorticity, and their occurrence frequency peaks in winter, while still significant in autumn and spring (Flaounas et al., 2015). These cyclones have been identified in a regional climate simulation forced at its boundaries and nudged within its domain by the ERA-Interim reanalysis of the European Centre for Medium-range Weather Forecasts (Dee et al., 2011). Consistently, in this study, the dynamical conditions that lead to these Mediterranean cyclones are analyzed with 6-hour ERA-Interim atmospheric fields, interpolated to a regular 1° × 1° horizontal grid.

Our methodology follows a three-component feature-based approach, applied to each of the 200 cases. Given the time and location of the mature stage of each cyclone (i.e. the time when cyclones reach their maximum intensity), we first track the associated ridge that formed upstream of the wave breaking, i.e. the PV streamer typically northwest of the center of the Mediterranean cyclone (Figure 1(b)). Then we identify the WCB that is potentially associated with the amplification of the tracked ridge (if there is any), and finally, we detect the cyclones that go along with these WCBs. In more detail, the analysis is based on the following three atmospheric features:

1. Tracked ridges: At the time when Mediterranean cyclones reach their maximum intensity (time 0 h hereafter), we locate the associated ridge that is located at a cyclone northwest side. The ridge is defined by enclosed contours of negative PV anomalies of less than −2 PVU (PV units) on the 330-K surface. The ridge is then tracked backwards in time up to 1 week prior to time 0 h, or until 120°W. Tracking is achieved first by detecting closed contours of −2 PVU anomalies on 330 K every 6 hours until −168 h, followed by connecting the PV anomalies enhanced by an upstream ridge, which was amplified due to rising moist air masses (see their Figure 4), similar to the case in Massacand et al. (2001). Such transport of low-PV air has been achieved through warm conveyor belts (WCBs; strongly ascending airstreams along the warm sector of extratropical cyclones), which undergo significant latent heating (Browning, 1990, Wernli and Davies, 1997). The wave breaking formed a PV streamer over the Mediterranean basin which, in turn, instigated Mediterranean cyclogenesis south of the Alps. A similar scenario of intense Mediterranean cyclogenesis has been shown by Chaboureau et al. (2012), Pantillon et al. (2015) and noted as well in other regions (Pomroy and Thorpe, 2000, Grams and Archambault, 2016).

The case studies demonstrate the concept of downstream development of baroclinic waves (Simmons and Hoskins, 1979, Chang, 1993, Orlanski and Chang, 1993, Orlanski and Sheldon, 1993, Wernli et al., 1999). These idealized studies, which employ dry primitive equations, explain the development of a downstream cyclone by the export of energy from the primary system via the ageostrophic flux divergence. Recently, in an idealized moist baroclinic channel setup, Schemm et al. (2013) have suggested that moist diabatic processes related to WCBs enhance the downstream development. Madonna et al. (2014b) quantified climatologically the co-occurrence of Rossby-wave breaking and WCB outflows and found that 60% of the WCBs occur together with a PV streamer, but less than 15% of PV streamers are accompanied by WCBs. Once occurring together, the most prevalent situation (35% of the cases) is for WCBs to be followed by PV streamers downstream. A common feature to the studies incorporating moist dynamics and the case studies described above is a primary cyclone with associated WCB outflow which enhances the upper-tropospheric ridge downstream, causing eventually Rossby-wave breaking and downstream cyclogenesis.
that overlap at consecutive time steps. If more than one PV anomaly overlaps at consecutive time steps, we retain the one with the largest overlapping area. Tracking the ridges provides a dataset of the location and extent of the negative PV anomalies that eventually favor the wave breaking.

2. *Warm conveyor belts:* WCBs are identified objectively in a Lagrangian framework as airstreams ascending at least 600 hPa in 48 h in the vicinity of a cyclone (Madonna *et al.*, 2014a). This dataset includes all identified WCB trajectories in the ERA-Interim data period, their three-dimensional position, potential temperature, and ice water content traced along the trajectories from the starting time of the vertical ascent, to the end of the ascent after 48 h and beyond. For the purpose of this study, both the WCB ascent and outflow phases are important to identify. The ascent phase of a WCB is defined as the time of the first appearance of ice water content along the WCB trajectory. This methodology to define WCBs ascent has been previously applied in Flaounas *et al.* (2016). The outflow portion of the WCB trajectory is of particular interest, as it is the outflow of the WCBs which might amplify the PV ridges and thus influence wave breaking (e.g., Massacand *et al.*, 2001, Madonna *et al.*, 2014b). Performing several sensitivity tests, a suitable approach to identify WCB outflow is to consider the section of a WCB trajectory from 36 to 72 h (i.e., last 12 h of the ascent and the subsequent 24 h) with potential temperature higher than 310 K. The choice of the potential temperature threshold is consistent with the fixed isentropic level used to track the negative PV anomalies (see above) and ensures that only outflows reaching the highest levels are considered.

3. *Cyclone tracks:* cyclone tracks are extracted in ERA-Interim by applying the method of Wernli and Schwierz (2006). In this method, cyclones are identified as SLP local minima within enclosed SLP contours from a standard 0.75° × 0.75° grid in longitude and latitude.

Our methodological approach has two steps and is applied separately for each of the 200 intense Mediterranean cyclone cases, providing a meaningful connection among the three datasets: In a first step, at every 6-h time step that precedes a Mediterranean cyclone’s maximum intensity (time 0 h), WCB outflow positions are matched with the tracked negative PV anomalies. This is done by counting how many WCB trajectory outflows are located in the area of the tracked ridge. These trajectories are ‘tagged’, to allow the identification of the North Atlantic cyclones they are associated with in the second step. The association is valid if the WCB ascent is closer than 10° from a cyclone center.

### 2.2. Two illustrative examples

Figure 2 shows two examples of intense Mediterranean cyclones which are consistent with the chain of events described in the introduction. In our first example, a Mediterranean cyclone reaches its mature stage over northwest Africa at 0000 UTC 10 November 2001 (0 h, left panels). The cyclone is clearly formed alongside an elongated stratospheric PV streamer, located northwest of the cyclone, having a southwest-northeast direction and corresponding to the eastern side of an eastwards tilted ridge (outlined by blue contour at 0 h). This configuration is similar to the composite presented in Figure 1(a), as well as to the anticyclonic wave breaking scenario LC1 in Thorncroft *et al.* (1993). The evolution of the wave breaking is shown in the left panels of Figure 2, from −60 to 0 h. Strong negative PV anomalies (blue contour) tend to propagate and progressively extend toward the east from the central North Atlantic (blue contour at −60 h) until forming the ridge over the eastern North Atlantic (blue contour at 0 h). In parallel, the outflows of WCBs reach the flanks of the ridge (magenta dots) potentially contributing to its amplification and eventual wave breaking due to advection of low PV air masses from the lower troposphere. Several North Atlantic cyclones have been found to be associated with this series of WCBs (shown in green line).

In the second example, a deep cyclone occurred over Italy at 0600 UTC 13 December 1990 (0 h, right panels in Figure 2), also associated with a trough and a PV streamer. The trough itself was stationary over the region until being amplified and deformed into a narrow PV streamer. The ridge amplification took place from −60 to −12 h, again supported by WCB outflow of air with low PV. However, the clear ridge and PV streamer shape broke down by the time the Mediterranean cyclone attained maximum intensity. Here, two North Atlantic cyclones were found to produce the WCBs leading to the ridge-streamer pattern, with tracks that, unlike the first example, are confined to the western North Atlantic.

These two case studies exemplify a considerable case-to-case variability concerning the Mediterranean cyclone itself, the location and shape of the upper-tropospheric wave breaking, the WCB outflow locations and the associated Atlantic cyclone tracks, as well as the dynamical evolution and the mutual interactions of these atmospheric features.

### 3. The climatological connection between North Atlantic and intense Mediterranean cyclones

Performing our methodology for all 200 intense Mediterranean cyclones, we found that a vast majority, 181 cases (90.5% of Mediterranean cyclones) were dynamically associated with upstream North Atlantic cyclones. For the rest of the cases, the mechanism was not confirmed. In fact, an average of 4.3 North Atlantic cyclones have been identified as being related to the Mediterranean cyclones with a standard deviation of 2.1 cyclones. This indicates that a series of cyclones and their associated WCBs, rather than a single primary
cyclone, build up the North Atlantic ridge required for the downstream formation of the PV streamer instigating the Mediterranean cyclone, during the 168-h period prior to maximum intensity. However, not all the identified cyclones contribute equally in terms of associated WCB trajectories that reach the ridge. To distinguish those cyclones that contribute significantly to the WCB outflows, we filter out cyclones with less than 25% of the total associated WCBs count for that event. This reduces the number of associated cyclones by almost a factor of two.

All associated extratropical cyclone tracks are presented in Figure 3(a). Despite the large variability of their tracks, there is a high track density between 40

Figure 2. Sea-level pressure (contours with 5-hPa intervals, red contours depict values of less than 1015 hPa), PV on the 330-K isentropic surface (PVU, shaded), WCB outflow positions (magenta dots), and tracked negative PV anomaly on 330-K surface (−2 PVU in blue contour) for different times relative to 0000 UTC 10 November 2001 (left panels) and 0600 UTC 13 December 1990 (right panels). The associated North Atlantic cyclones tracks are plotted in green (only the associated cyclone tracks are plotted), and the position of the cyclone at the corresponding time is marked by a green circle. The downstream Mediterranean cyclone is marked with a green star at time 0 h.
and 60°N, where cyclones also tend to attain their deepest central SLP. This is consistent with the climatology of winter cyclones in the region (Wernli and Schwierz, 2006) and thus no different areas of occurrence are favored for Atlantic cyclones associated with Mediterranean cyclogenesis. It is also evident that five cyclones underwent extratropical transition, including the event at 0000 UTC 10 November 2001 (Figure 2, left column). From a composite perspective, Figure 3(b) shows the spatial variability of the WCBs ascent and outflow positions. Consistent with the cyclones’ location at their time of maximum intensity (Figure 3(a)), the WCBs tend to start their ascent over the western North Atlantic and to reach the upper troposphere further northeast near 50°N/40°W where they amplify the PV ridges. Outflow locations are indeed collocated with the average ridge location in the composite PV at 330 K (Figure 1(b)). WCB densities are located consistently with their climatological distribution (Figure 4 in Madonna et al., 2014a).

The mechanism identified and explained in this study suggests a series of processes that stem from North Atlantic cyclones and result in intense Mediterranean cyclogenesis, with a certain degree of diabatic contribution to the wave breaking via WCBs. The preferred location of the associated group of Atlantic cyclones, and their key contribution for the downstream development, suggests that relatively strong extratropical cyclones are more likely to play such a role. This hypothesis is addressed by comparing the intensification rates of the associated North Atlantic cyclones to a climatological reference, formed by 20 random samples of North Atlantic cyclones. The random samples were chosen by maintaining the same seasonality of the 200 Mediterranean cyclones and the same number of associated Atlantic cyclones. In addition, the random cyclones were bounded to attain their minimum SLP within the area 70°–5°W, and 30°–70°N, where the associated Atlantic cyclones attain their deepest SLP. Figure 3(c) shows the probability density function of the cyclones intensification in Bergeron units for the randomly selected cyclones (solid line), compared with the one of the North Atlantic cyclones that are dynamically related to the 200 most intense Mediterranean cyclones (dashed line). This metric refers to the cyclones maximum deepening rate within 24 h, taking into consideration their latitudes (Sanders and Gyakum, 1980). There is a fair shift of the associated cyclones distribution to faster deepening cyclones, with respect to the random cyclones dataset. Our results are in line with Binder et al. (2016), who analyzed the cyclones deepening rate to show a climatological correlation between cyclone intensification and WCB air mass (see their Figure 1). Indeed, it is the strongly deepening North Atlantic cyclones that we found to contribute significantly to downstream Rossby wave breaking. However, a large variability of the cyclone intensification-WCB relationship is governed by dynamical interactions between the low-level diabatic PV production in the WCB, the cyclone, and the upper-tropospheric jet. Therefore, it would be misleading to draw a direct conclusion that it is only the strongest Atlantic cyclones that provoke Mediterranean cyclogenesis. Finally, we found that the WCBs of the North Atlantic cyclones ascend, on average, 4 days before the Mediterranean cyclones’ mature stage (with a standard deviation of 2 days). This time lag is fairly consistent with the time lags of about 5 days, reported both the idealized simulations by Scherm...
et al. (2013) and the real case study analyzed by Grams et al. (2011).

4. Summary and discussion

The key role of WCB air as a dynamical link between intense North Atlantic and Mediterranean cyclones is demonstrated in this study. The vast majority (90.5%) of intense Mediterranean cyclones have been found to be associated with upstream North Atlantic cyclones, which are accompanied by ascending WCBs transporting low-PV air to the upper troposphere. This amplifies the upper-level ridges, which in turn contribute to the downstream Rossby wave breaking and cyclogenesis in the Mediterranean. In fact, it is the strongly deepening Atlantic cyclones, located between Newfoundland and Iceland that are particularly favorable for initiating the mechanism of downstream genesis of intense Mediterranean cyclones, presumably because these cyclones develop substantial WCB airstream flow compared with all North Atlantic cyclones.

The examination of the upstream development of the 200 intense Mediterranean cyclones is challenging due to the large spatiotemporal variability among the cases. For instance, Figure 2 shows two examples where Rossby wave breaking leads to downstream Mediterranean cyclogenesis. However, the ridges evolve, amplify, and propagate differently. A sophisticated feature-based approach, as outlined in this study, has been successful in highlighting a coherent mechanism that is common to more than 90% of all cases, and to provide a quantification of its occurrence. The high relevance of the mechanism to the climatological set is robust with respect to the Mediterranean cyclone identification and tracking technique. We have carried out the methodological procedure for a set of the 200 most intense Mediterranean cyclones in the ERA-Interim dataset, based on the identification and tracking technique of Wernli and Schwierz (2006). This set of 200 Mediterranean cyclones has only 39 overlapping events with the set analyzed in this study, yet, the mechanism is relevant for a comparable percentage of events (88%). Nevertheless, our methodology failed to associate North Atlantic with Mediterranean cyclones in 19 cases out of 200. This is partly due to uncertainties in our feature tracking procedure or due to the absence of WCBs in cases when Rossby wave breaking occurs without a strong diabatic contribution. While WCBs and cyclone tracks are defined by specific physical criteria, the definition of ridges and PV streamers may present considerable uncertainties, especially when tracking these features in time. In our current study, the areas of interest are relatively close, taking into account the characteristic lengths of the tracked features and hence our methodology provided meaningful results. It would be of great interest to identify the relation of cyclone tracks to wave breaking in the whole Northern Hemisphere. In this context, it is for future work to investigate the statistical relationship between cyclone intensity, latent heating within WCBs and downstream ridge amplification, wave breaking, and secondary cyclogenesis. Understanding the chain of atmospheric processes that lead to the formation of Mediterranean cyclones may significantly contribute to the improvement of medium-range (of the order of 3–5 days) efficient forecasting of extreme weather in the Mediterranean.

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