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Characterization of synoptic conditions and cyclones associated with top ranking potential wind loss events over Iberia

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Abstract

Intense extra-tropical cyclones are often associated with strong winds, heavy precipitation and socio-economic impacts. Over southwestern Europe, such storms occur less often, but still cause high economic losses. We characterize the large-scale atmospheric conditions and cyclone tracks during the top-100 potential losses over Iberia associated with wind events. Based on 65 years of reanalysis data, events are classified into four groups: (1) cyclone tracks crossing over Iberia on the event day ('Iberia'), (2) cyclones crossing further north, typically southwest of the British Isles ('North'), (3) cyclones crossing southwest to northeast near the northwest tip of Iberia ('West'), and (4) so called 'Hybrids', characterized by a strong pressure gradient over Iberia because of the juxtaposition of low and high pressure centres. Generally, 'Iberia' events are the most frequent (31–45% for top-100 *vs* top-20), while 'West' events are rare (10–12%). Seventy percent of the events were primarily associated with a cyclone. Multi-decadal variability in the number of events is identified. While the peak in recent years is quite prominent, other comparably stormy periods occurred in the 1960s and 1980s. This study documents that damaging wind storms over Iberia are not rare events, and their frequency of occurrence undergoes strong multi-decadal variability.

Keywords: **windstorms; Iberia; cyclones; impacts; potential wind losses; multi-decadal variability**

1. Introduction

Extra-tropical cyclones are determinant for the weather conditions in the mid-latitudes. Embedded in the westerly flow, cyclones typically undergo a strong intensification over the North Atlantic Ocean while travelling towards Europe. Intense cyclones are often associated with strong winds and heavy precipitation (Pfahl, 2014), thus often leading to large socio-economic impacts (Swiss Re, 2008). Over southwestern Europe, such intense cyclones occur less often (Trigo, 2006; Pinto *et al.*, 2009). This can be explained by the cyclone track climatology (Figure 1(a)), which features a reduced number of systems near Iberia. Intense cyclones affecting Iberia typically cause high amounts of precipitation and flooding in that area (Ramos *et al.*, 2014). Still, recent storms like 'Klaus' (cyclone names after Freie Universität Berlin database, www.met.fu-berlin.de/adopt-a-vortex/historie/) (Liberato *et al.*, 2011) were primarily characterized by very strong winds, leading to €541 m insured losses in Spain because of wind gusts (CCS, 2015). In winter 2013/2014, several storms affected the Iberian Peninsula, including storm 'Dirk' [20131224 (all dates in yyyymmdd)], which caused €30.3 m insured losses in Spain because of both wind gusts and floods (CCS, 2015). While previous studies analysed single storms (e.g. 'Klaus' and 'Xynthia'; Liberato *et al.*, 2011, 2013), a climatological assessment is missing. Based on 65 years of reanalysis data, we characterize the large-scale atmospheric conditions and cyclone tracks associated with the top-100 potential losses over Iberia because of strong wind events (windstorms).

2. Data

The analysis of potential wind loss events over Iberia is performed based on the National Centre for Environmental Prediction/National Centre for Atmospheric Research reanalysis (hereafter NCEP; Kistler *et al.*, 2001). As no gust wind speed is available for this dataset, 6-hourly instantaneous 10 m-wind speeds (hereafter wind) are analysed. NCEP reanalysis is provided on a T62 resolution (Figure 1(b); 1.875°). For each grid point *ij*, daily maximum wind speeds (largest values for each day between 00, 06, 12 and 18

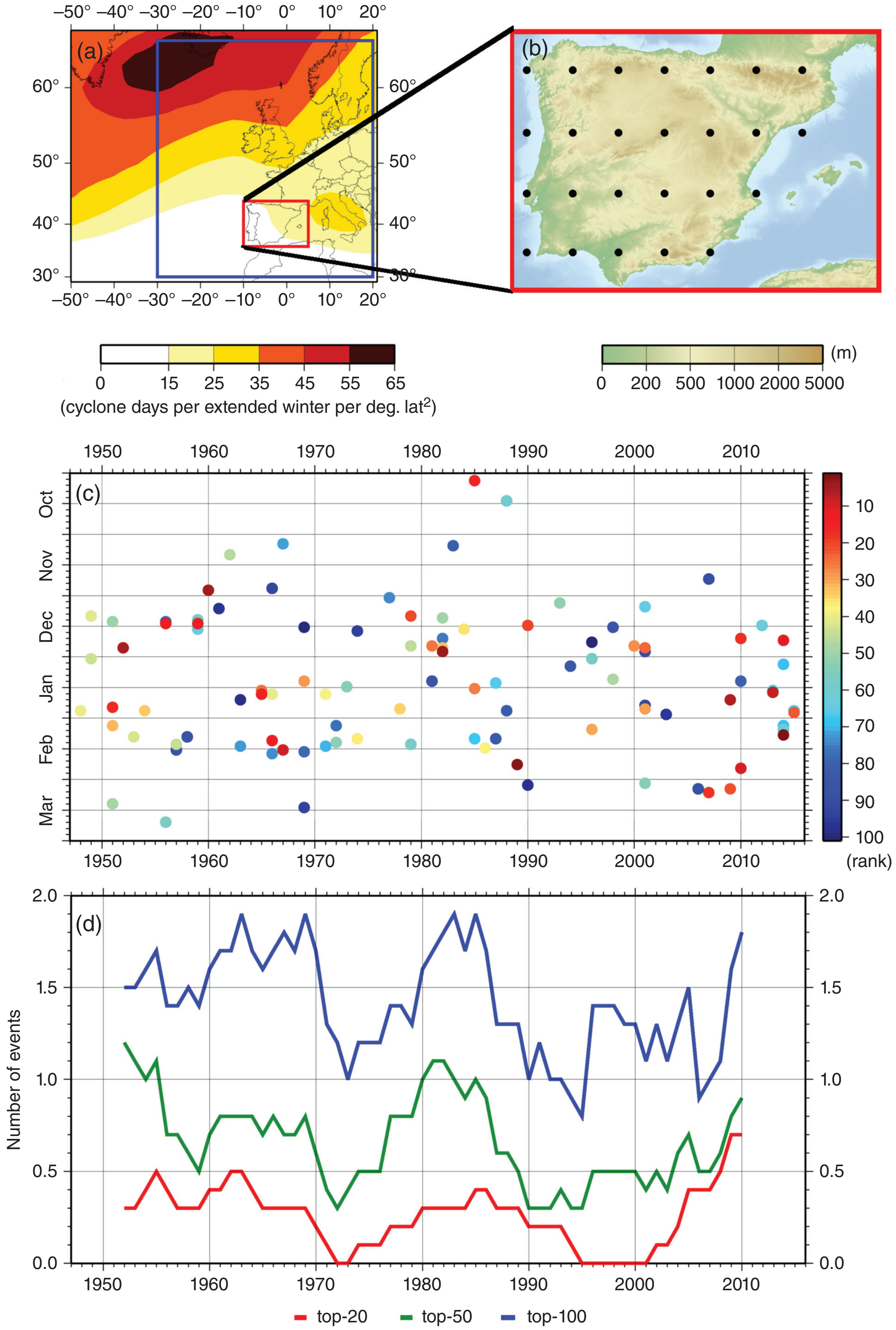

Figure 1. (a) Cyclone track density [cyclone days per extended winter season per deg. lat^2]; red box: geographical location of Iberian Peninsula; blue box: area for identification of cyclone tracks, (b) orography and NCEP grid points of investigated region, (c) time distribution of top-100 potential wind loss events for winters 1949–2015. Year corresponds to January, e.g. 1990: winter 1989/1990. Colours: rank of event (d) 10-year running mean of the number of events for each winter; red: top-20 potential wind losses; green: top-50, blue: top-100 wind loss events; e.g. 1953: running mean of 1949–1958. Average number of events per winter: top-100 potential wind losses: 1.5; top-50: 0.75; top-20: 0.3.

UTC, denoted v_{ij}) for the extended winter (October to March) 1948/1949 to 2014/2015 are selected. Winters are named by the second year, e.g. winter 2014/2015 is named 2015. Based on the climatology, 98th wind percentiles ($v_{98_{ij}}$) are calculated, and are used as a threshold for the loss model. The 6-hourly mean sea level pressure (MSLP) data are used for cyclone tracking and computation of the MSLP gradient over Iberia [10°W–2.5°E; 35°–45°N].

Potential loss event rankings may differ between reanalysis datasets (Karremann *et al.*, 2014a). This is also true for cyclone characteristics (Trigo, 2006). A preliminary analysis revealed a similar list of top events for NCEP and ERA-Interim (cf. Table S1, Supporting Information). Our focus on NCEP is motivated by the longer time series, which enables a better representation of long-term variability of events affecting Iberia.

3. Methodology

3.1. Event identification

This study uses a simplified approach of previous empirical models (Klawa and Ulbrich, 2003; Pinto *et al.*, 2012; Karremann *et al.*, 2014a) considering only meteorological parameters to estimate potential losses based on gridded data. The main assumptions are: (1) a critical wind speed needs to be exceeded to cause any loss. In most parts of Europe, this threshold corresponds to $v_{98_{ij}}$ (Klawa and Ulbrich, 2003), (2) a strong non-linearity in the wind – loss relation is assumed as the kinetic energy flux is proportional to the cube of wind speed (Mills, 2005). Following Pinto *et al.* (2012), the potential wind loss (MI) over Iberia (Figure 1(b)) per day is defined as:

$$\mathrm{MI}\ (\mathrm{day}) = \sum_{i=1}^{N}\sum_{j=1}^{M}\left(\frac{v_{ij}}{v_{ij}^{98}}\right)^{3} \times I\left(v_{ij}, v_{ij}^{98}\right) \quad (1)$$

$$I\left(v_{ij}, v_{ij}^{98}\right) = \begin{cases} 0 & v_{ij} < v_{ij}^{98} \\ 1 & v_{ij} > v_{ij}^{98} \end{cases}$$

The number of analysed grid points in the longitudinal and latitudinal directions is given by M and N, respectively. Based on all identified MI events, a ranking is established. The top-100 MI events between October 1948 and March 2015 are selected for detailed analysis.

3.2. Cyclone tracking

Cyclone tracks are derived with a cyclone tracking algorithm (Murray and Simmonds, 1991; Pinto *et al.*, 2005). The Laplacian of MSLP is used as proxy for the relative geostrophic vorticity and is used for cyclone identification. Cyclone tracks are compiled by considering the most probable trajectory of the systems between subsequent time frames (estimated from MSLP gradients, past cyclone speed and intensity).

3.3. Assignment of top loss events with cyclone tracks

The top-100 MIs are characterized in terms of large-scale atmospheric conditions and the presence of low pressure centres using NCEP data and weather charts (Berliner Wetterkarte, 2009, 2011, 2014). If cyclone tracks are located on the event day within 30°W–20°E, 30°N–65°N (blue box in Figure1(a)), they are preliminary assigned to the event. These cyclone tracks and associated windstorm footprints are analysed: the cyclone which matches best with the windstorm footprint in terms of timing and overlap with Iberia is subjectively selected as potentially responsible for MIs over Iberia.

If potential loss event days are identified on subsequent dates and both events are associated with the same cyclone, the dates are combined as one event. In this case, MI is recalculated by summing up the maximum exceedance of the 98th percentile within these subsequent days at each grid point *ij*. Thus, the following MI events (below top-100) are added to the list until the top-100 is complete again. The final list of top-100 MIs is shown in Table S1.

4. Analysis of the top-100 events

The time distribution of top-100 MIs over the 65-year period is displayed in Figure 1(c). About 84% of the events occurred between December and February, and only 2% in October, 6% in November and 8% in March. Colours indicate the ranking of storms. A clear dependency between the ranking of events and the seasonality is not found (Figure 1(c)). On the one hand, the number of events changes strongly from year to year. The largest number of events is identified for 2001 (six events) and 2014 (five events), while for other periods a maximum of two events per winter is found, e.g. in most of the 1970s, 1990s and 2000s. Decadal variability is analysed using a 10-year running average of the number of events per winter for different intensities (Figure 1(d)). Periods with a reduced number of events include 1957–1960, the 1970s and 1994–2004, while periods in the 1960s, 1980s and after 2005 display more events than average. While this result is largely independent from the intensity of events (colours in Figure 1(d)), the peak in recent years is very prominent for the top-20 MIs (red curve). Longer periods with a low number of top-20 MIs are identified in the 1970s, 1990s and early 2000s. Thus, decadal variability in the number of events is identified for all intensities.

For each event, synoptic conditions and associated cyclone tracks are characterized following the methodology described in Section 3. The location of the pressure minima for the top-100 events is depicted in Figure 2(a). The pressure minima of the top-20 MIs (red colours in Figure 2(a)) are mostly identified close to the north of Iberia, roughly between 15°W–5°E and 38°–58°N. For lower ranking events,

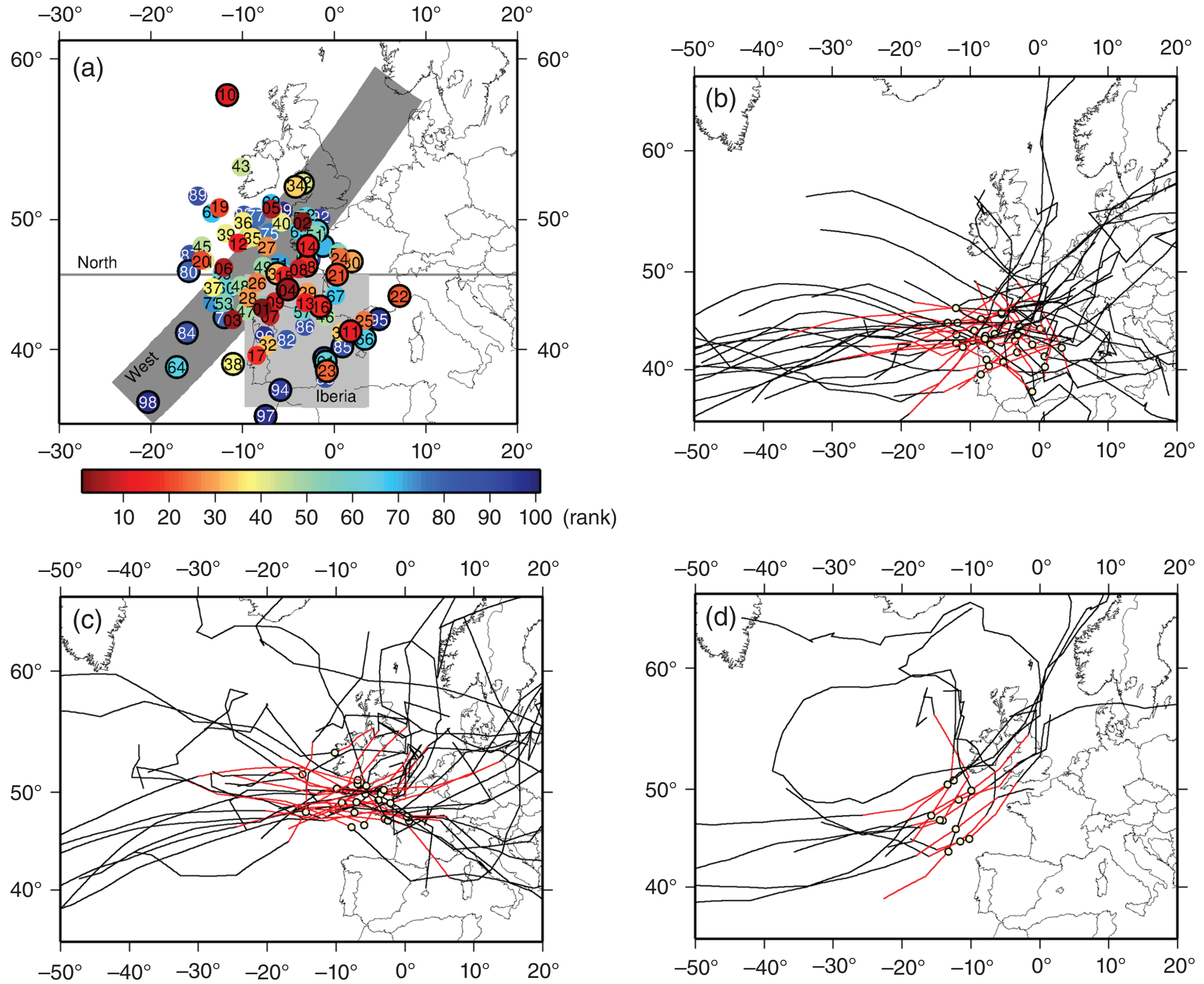

Figure 2. (a) Position of minimum pressure of identified cyclones responsible for potential wind losses over the Iberian Peninsula at the event day. Colours/numbers: rank of event; black circle: cyclones associated with Hybrid type. Identification of regions of the different groups: Iberia (light grey shaded region): cyclones crossing this area during the event day; North: cyclones crossing from west to east in a zonal path within this region during the event day; West (dark grey shaded region): cyclones crossing from southwest to northeast along the dark grey shaded region. (b) Cyclone tracks of group *Iberia* (31 events). (c) Cyclone tracks within *North* (28 events). (d) Cyclone tracks for *West* group (11 events). (b)–(d) red: cyclone track during the event day; circles: corresponding to (a).

the region is wider. It is notable that only four events from the extreme windstorms database [XWS; Roberts *et al.*, 2014; their Table 1 (cf. http://www.europeanwindstorms.org for updates on the XWS database)] are present in our event list, revealing that the top events for Iberia (Table S1) are largely different from those affecting other parts of Europe (cf. also Karremann *et al.*, 2014b).

The identified cyclones were grouped based on their characteristics. Seventy percent of the analysed events are strongly influenced by cyclones:

1. Cyclone tracks crossing over Iberia at the event day (box 'Iberia' in Figure 2(a)) and thus with a direct influence (group '*Iberia*', cf. Figure 2(b)).
2. Cyclone tracks crossing north of Iberia on a zonal track, mostly southwest from the British Isles (region 'North' in Figure 2(a)), and influencing Iberia primarily because of their extended fronts (group '*North*', Figure 2(c)).
3. Cyclone tracks crossing from southwest to northeast, but west of Iberia (cf. grey area 'West' in Figure 2(a)) and not intersecting the *Iberia* box (group '*West*', Figure 2(d)).

In some cases, the cyclone was not found to be determinant *per se* for the windstorm footprint from the selected event, but rather its co-occurrence with a high pressure centre on the opposite side of Iberia, which led to a strong pressure gradient over the region and consequently strong winds (cf. also Pfahl, 2014). Thus, a final category is defined as follows:

4. Synoptic situation with the juxtaposition of a cyclone and an anticyclone, leading to a pronounced MSLP gradient over Iberia and thus strong winds (group '*Hybrid*', cyclone tracks shown in

Table 1. Number of events [%] per group and intensity.

	Iberia	North	West	Hybrid
Top-20	45	15	10	30
Top-50	36	24	12	28
Top-100	31	28	11	30

Top-20, top-50 and top-100 potential wind loss events between October 1948 and March 2015.

Figure S1). Events are marked with a black circle in Figure 2(a).

The assignment of events into the four groups is shown in Table S1, and composite MSLP fields in Figure S2. For the top-100 MIs, most events are classified as *Iberia* (31%), closely followed by *Hybrid* (30%), *North* (28%) and *West* (11%, Table 1). The relative importance of the *Iberia* group increases with intensity of MI, reaching 45% for top-20 MIs. Conversely, the percentage of *North* storms decreases with intensity, reaching 15% for top-20 MIs. Top ranking events typically affect a larger area (more grid points; Table S1), although the relationship is not strong. While all four groups show a dichotomous pattern with a high and a low pressure system (cf. Pfahl, 2014), the analysis provides evidence that in 70% (all but *Hybrid* group), the cyclones are primarily responsible for the strong winds over Iberia and thus the MI event.

5. Characterization of the four groups

The general characteristics of each group are presented in this section including a representative case study. Like many East Atlantic cyclones, most of the systems considered here are secondary cyclones, which develop on the trailing cold fronts of 'parent' cyclones located further north (Dacre and Gray, 2013).

5.1. Group *Iberia*

The cyclones in this group cross over Iberia (Figure 2(b)), leading to a direct impact. This group includes named storms like 'Klaus' (20090123), 'Xynthia' (20100227) and 'Gong' (20130119). Storm 'Stephanie' (Top#1, 20140209) is selected as representative example. A high pressure at 500 hPa is identified over the subtropical North Atlantic, and a low pressure system north of Scotland (not shown). The corresponding surface low pressure centre ('Ruth', Figure 3(a)) is below 970 hPa, and the Azores high is above 1025 hPa, leading to an intense westerly flow towards West- and Central Europe. 'Stephanie' is a secondary low developing in this strong westerly flow, and is located over the Bay of Biscay on 10 January, 00 UTC (Figure 3(a)). The associated windstorm footprint affected the whole Iberian Peninsula (Figure 3(b)). Hurricane-force winds, snow and rain were reported, causing the strongest damage in western regions where wind uprooted numerous trees, broke windows and blew roofs away while high waves and flooding disrupted roads.

5.2. Group *North*

This group is characterized by cyclones crossing north of Iberia in a zonal track, typically over the British Channel (Figure 2(c)). Such cyclones usually feature extended cold fronts, leading to strong winds further south over Iberia. This group includes named storms 'Martin' (19991227) and 'Anne' (20140104). Storm 'Joachim' (Top#62, 20111216) is selected as representative case. High pressure at 500 hPa is identified over the subtropical North Atlantic, while the mid-level low pressure system is located west of Iceland (not shown). The corresponding surface low pressure centre ('Hergen', Figure 3(c)) is below 970 hPa, and the Azores high is above 1030 hPa. Strong westerly flow dominates at upper levels, in which cyclone 'Joachim' is embedded (not shown). Beside the difference of air masses, a short wave trough influenced its explosive development. The core pressure deepened from 1008 to 980 hPa within 24 h bringing severe wind gusts and heavy rainfall to many parts of northern Iberia, causing numerous incidents such as falling trees, fences and streetlights or landslides.

5.3. Group *West*

This group is characterized by cyclones crossing from the southwest to the northeast, typically close to the northwestward tip of Iberia (Figure 2(d)), and includes storms like the 'Great Storm of 1987' (19871015). Storm 'Qumaira' (Top#59, 20140206) is selected as a representative example. A blocking high pressure system is located over the subtropical North Atlantic and mid-level low pressure centres are located between Greenland and Scotland (not shown). The surface steering low 'Petra' is located over Scotland (Figure 3(e)), while the secondary pressure system 'Qumaira' (980 hPa) moves northeastward towards southern England. 'Qumaira' led to important disruption to all forms of transport in Iberia, together with power cuts and building and tree damage.

5.4. Group *Hybrids*

This group is characterized by a co-occurrence of a high and a low pressure centre on opposite sides of Iberia, leading to a pronounced MSLP gradient and strong winds over the region. A prominent example is 20090305 (Top#21). A low pressure system is located north of Scotland, while a blocking high is found over the North Atlantic (not shown). The juxtaposition of both systems is associated with an intense jet stream from southern Greenland towards Iberia (not shown). At lower levels, the surface high pressure system is above 1040 hPa, while cyclone 'Andreas' located between Scotland and the Faroese has a core pressure of 975 hPa (Figure 3(g)). Further south, over the English Channel, an unnamed low below 985 hPa is found. This example shows that the cyclone over southern England cannot be primarily responsible for the

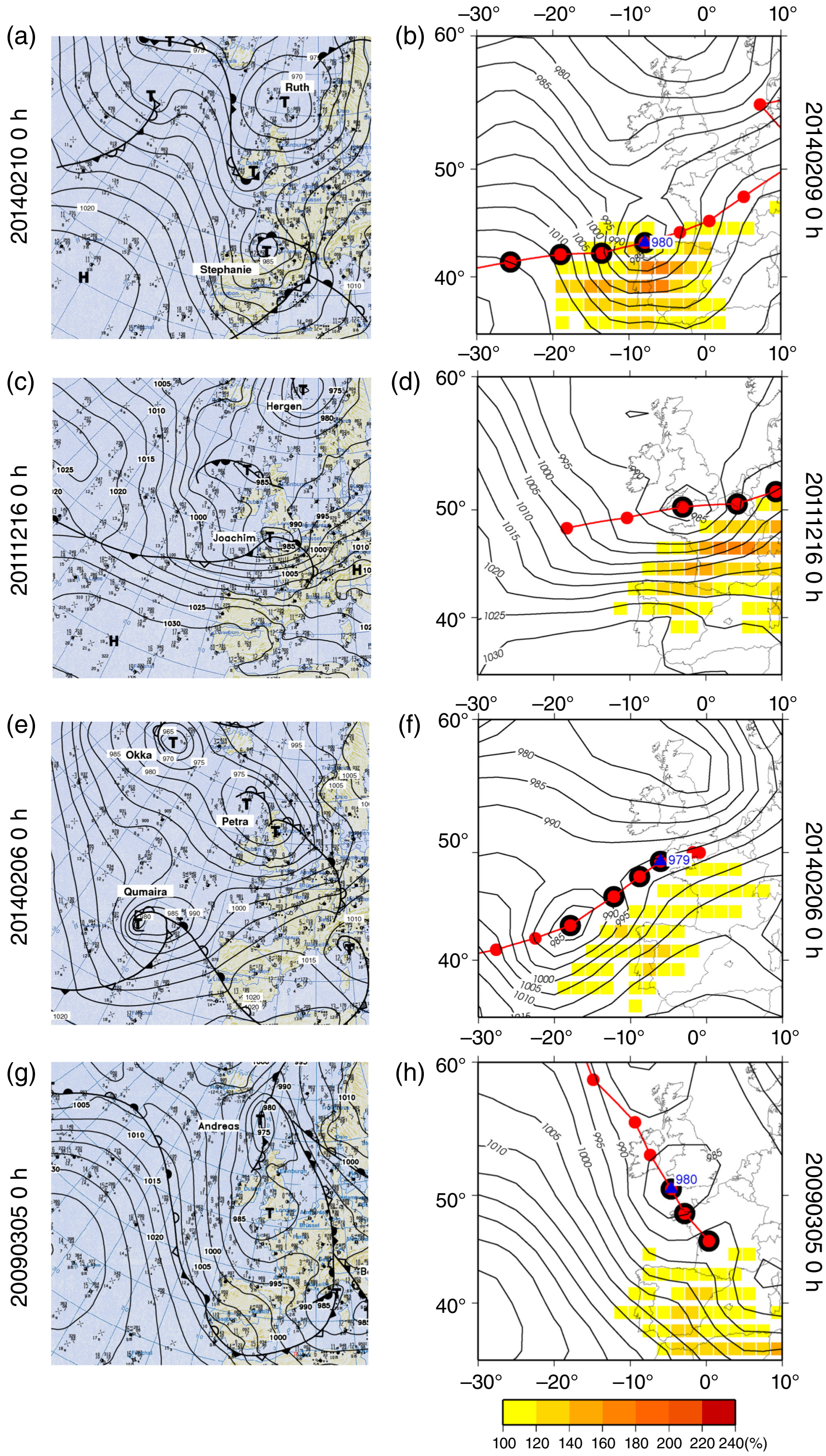

Figure 3. Case study for (a, b) group *Iberia*, (c, d) group *North*, (e, f) group *West*, (g, h) group *Hybrid*. Left panels: surface weather charts adapted with courtesy of Berliner Wetterkarte e.V.; right panels: windstorm footprints and responsible cyclone tracks; black circle: time frames corresponding to event day, blue triangle: pressure minimum at event day [for (d) outside shown area]; colours: exceedance of $v_{98_{ij}}$ in (%); date: yyyymmdd time in UTC.

potential loss event over Iberia; only the combination of the different systems led to a strong pressure gradient and thus strong surface winds. The impacts were severe: many trees were uprooted and a great number of buildings were damaged, also in southern Spain and even Morocco.

6. Comparison of cyclone characteristics

The difference of cyclone characteristics between the groups is now explored. In terms of the minimum core pressure, the lowest minimum mean value for the event day (±1 day) was found for *West* (966 hPa),

Table 2. Mean value and standard deviation for different characteristics for the four groups: pressure minimum at the event day (hPa); Laplace maximum at the event day (hPa deg.lat^{-2}); MSLP gradient at the event day (hPa/100 km); pressure evolution (hPa/24 h) and Laplace evolution (hPa deg.lat^{-2}/24 h) within 24 h.

	Iberia	North	West	Hybrid
Pressure minimum (event day)	983 ± 9.31	976 ± 13.1	966 ± 13.3	983 ± 15.8
Laplace maximum (day)	1.63 ± 0.68	1.51 ± 0.67	1.95 ± 0.95	1.28 ± 0.76
MSLP gradient (day)	1.64 ± 0.46	1.83 ± 0.39	1.81 ± 0.44	1.72 ± 0.44
Pressure evolution (24 h)	13.5 ± 8.46	14.8 ± 8.26	12.7 ± 9.46	13.2 ± 8.93
Laplace evolution (24 h)	0.95 ± 0.60	0.84 ± 0.51	1.13 ± 0.64	0.84 ± 0.64

followed by *North* (976 hPa), *Iberia* and *Hybrid* (both 983 hPa; Table 2). Given the small samples and large spread, the differences between groups are not statistically significant at the 90% significance level. Results are similar for the maximum vorticity, with largest values found for *West* and the lowest for *Hybrid* (1.95 and 1.28 hPa deg.lat^{-2}, respectively). The intensification rates per 24 h, in terms of vorticity, are highest for *West* and *Iberia* [1.13 and 0.95 (hPa deg.lat^{-2}) day^{-1}] and lowest for *North* and *Hybrid* [both 0.84 (hPa deg.lat^{-2}) day^{-1}], while core pressure evolution is highest for *North* (14.8 hPa day^{-1}) and lowest for *West* (12.7 hPa day^{-1}). Results are similar when analysing the 24 h peak intensity change irrespective of the event day (not shown). Unlike other types, the deepening cyclone phase associated with *Hybrid* events does not often coincide with the event day ($\pm$1 day). This indicates that cyclones contributing to *Hybrid* events are not necessarily very intense and their development does not always have a clear impact on the events. The mean MSLP gradient around Iberia is lowest for *Iberia* (1.64 hPa/100 km) and largest for *North* and *West* (1.83 and 1.81 hPa/100 km, respectively). The gradient for *Hybrid* is in between (1.72 hPa/100 km). This confirms that despite the weaker cyclones in the *Hybrid* group, the co-occurrence of a high pressure centre on the opposite side of Iberia effectively creates a strong pressure gradient leading to strong winds.

7. Summary and conclusions

The top ranking potential wind loss events affecting Iberia were classified into four groups based on cyclone tracks and large-scale atmospheric conditions: (1) cyclone tracks crossing Iberia on the event day (*Iberia*), (2) cyclones crossing further north, mostly southwest of the British Isles (*North*), (3) tracks crossing southwest to northeast to the northwest of Iberia (*West*), and (4) so called *Hybrids*, days with a large pressure gradient over Iberia because of the juxtaposition of a low and a high pressure centre. Generally, *Iberia* events are the most frequent, ranging from 31% (top-100 MIs) to 45% (top-20 MIs). However, other types like *North* and *Hybrid* are also frequent (28 and 30%, respectively, for top-100 MIs). The number of *North* storms decreases considerably with intensity (15% for top-20 MIs). *West* type storms are rare (10–12%). Seventy percent of the MIs can be primarily attributed to cyclones. Cyclones associated with *Hybrid* events (30%) are typically weaker than for other cases, but the mean MSLP gradient over Iberia is comparable to other types. Although we have focussed on a single reanalysis dataset, the results would be comparable for others given our focus on large-scale features like MSLP gradients, cyclone tracks and windstorm footprints. Multi-decadal variability of events is identified for all intensities. The peak in recent years is quite prominent in terms of the number of top-20 MIs. Other periods with a large number of storms occurred in the 1960s and 1980s. This study documents that windstorms affecting Iberia may have different characteristics, they are not rare events, and their frequency of occurrence undergoes strong multi-decadal variability.

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Supporting information

The following supporting information is available:

Appendix S1. Supplementary material on event selection and assignment to the four groups.

Figure S1. As Figure 2(b) but for group *Hybrid*.

Figure S2. MSLP composites for (a) group *Iberia* (31 dates) (b) group *North* (28 dates) (c) group *West* (11 dates) (d) group *Hybrid* (30 dates). All four MSLP fields (00, 06, 12, 18 UTC) of each event day were included in the composites. For a list of dates see Table S1.

Table S1. List of top-100 potential wind loss events including information on the date, the number of grid points exceeded (GP), the rank (rk) and the corresponding group (G): *Iberia* (I), *North* (N), *West* (W), *Hybrid* (H) for NCEP data. Date format is yyyymmdd. The top-20 events are in bold and italic. Rank of events also featured in the ERA-Interim top-50 (rE) for the period 1979–2014 are added in the last column for comparison. '-' indicates the event was not found within the top-50 for ERA-Interim. 'x' indicates date outside the analysed ERA-Interim period.

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