How important are post-tropical cyclones for European windstorm risk?

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Key Points:
- Post-tropical cyclones are significantly more intense than midlatitude cyclones at their maximum intensity over Europe
- The fraction of post-tropical cyclones impacting northern Europe with storm force winds is 10 times higher than that for midlatitude cyclones
- A disproportionately large fraction of high-impact European windstorms forming in hurricane season are caused by post-tropical cyclones

Supporting Information:
- Supporting Information S1

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How Important Are Post-Tropical Cyclones for European Windstorm Risk?

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Abstract Post-tropical cyclones (PTCs) extend many hazards associated with tropical cyclones (TCs) to the midlatitudes. Despite recent high-impact cases affecting Europe such as Ophelia, little research has been done to characterize the risk of PTCs. Here we compare the climatologies and intensity distributions of midlatitude cyclones (MLCs) and PTCs in the North Atlantic and Europe by tracking cyclones in the ERA5 reanalysis. Considering hurricane season cyclones impacting Northern Europe, PTCs show a significantly higher mean maximum intensity than MLCs, but make only a small contribution to total windstorm risk. Our results show that a disproportionately large fraction of high-intensity cyclones impacting Europe during hurricane season are PTCs. The fraction of PTCs impacting N Europe with storm force (>25 m s^{-1}) winds is ~10 times higher than that for MLCs. Less than 1% of cyclones impacting Northern Europe are identified to be PTCs. This rises to 8.8% when considering cyclones which impact with storm force winds.

Plain Language Summary Ex-hurricanes (post-tropical cyclones; PTCs) can bring hazardous weather such as damaging winds and extreme precipitation to the midlatitudes. The importance of these cyclones for European wind and flood risk is still an open question. By tracking cyclones through 39 years of data, we show that on average, the maximum intensity of PTCs over Europe is significantly higher than that for European windstorms (midlatitude cyclones, MLCs). The difference between the maximum intensity of PTCs and MLCs is larger across Northern Europe than Southern Europe. Our results show that a disproportionately large fraction of high-intensity cyclones impacting Northern Europe during hurricane season are PTCs. The fraction of PTCs impacting Northern Europe with storm force winds is ~10 times greater than for MLCs. Less than 1% of cyclones impacting Northern Europe during the North Atlantic hurricane season are PTCs. This rises to 8.8% when only considering cyclones which impact Northern Europe with storm force winds.

1. Introduction

The post-tropical stage of a recurving tropical cyclone (TC) can result in hazardous weather such as high winds and heavy precipitation in the midlatitudes, exposing areas which infrequently see such events (Evans et al., 2017; Jones et al., 2003). Recurving TCs and their interaction with the upper-level midlatitude flow can also have severe consequences for downstream predictability of the midlatitude flow (Grams et al., 2015; Grams & Blumer, 2015; Keller et al., 2019). They have also been shown to increase the likelihood of downstream extreme weather (Pohorsky et al., 2019), posing challenges for risk management.

Recent papers have investigated how post-tropical cyclone (PTC) impacts and frequency may change as a result of climate change (Baatsen et al., 2015; Haarsma et al., 2013; Liu et al., 2018; Michaelis & Lackmann, 2019; Semmler et al., 2008a, 2008b). Baatsen et al. (2015) and Haarsma et al. (2013) show that the number of severe autumn European windstorms is likely to increase in near-future and future climates, with the majority of the increase due to PTCs. Liu et al. (2018) and Semmler et al. (2008a, 2008b) find that the fraction of TCs which undergo extratropical transition is likely to increase in the North Atlantic under RCP 4.5, the SRES-A2 emission scenario, and a 1 K increase in SSTs, respectively. Michaelis and Lackmann (2019) find that the number of extratropical transition events may increase by 40% by the year 2100 under RCP 8.5. Without an understanding of the risks posed by PTCs for Europe in the current climate, it is difficult to deduce the consequence of a future change in PTC frequency or intensity.

High-impact European events such as the PTCs Debby (Laurila et al., 2020), Floyd (Atallah & Bosart, 2003), and Ophelia (Rantanen et al., 2020; Stewart, 2018) have revealed the potential risk associated with PTCs in Europe. In particular, Ophelia attracted widespread scientific and public attention after impacting Ireland in October 2017 as Ireland's most damaging storm in over 50 years (Stewart, 2018). Climatologies of North Atlantic TCs suggest that between 46% (Hart & Evans, 2001) and 68% (Studholme et al., 2015) undergo extratropical transition, with other climatologies falling within this range (Bieli et al., 2019; Zarzycki et al., 2017). Further to this, Hart and Evans (2001) suggest that over half of these PTCs reintensify in the midlatitudes.

How important PTCs are for European windstorm risk is still an open question. It has been shown that TCs which undergo extratropical transition and develop a warm seclusion obtain the lowest pressure values over Europe of all cyclones which form in the tropics. These cyclones also reach their maximum intensity a day after reaching Europe, increasing the risk that they pose (Dekker et al., 2018). While this result highlights the potential risk tropical-origin systems pose for Europe, these risks also need to be considered in the context of overall European storm risk.

Here we present a systematic comparison between PTCs and midlatitude cyclones (MLCs) for the first time, looking particularly at the risk, in terms of surface winds, that PTCs and MLCs pose for Europe. A more quantitative understanding of the risks associated with PTCs is obtained by investigating both the absolute risk posed by PTCs (such as the frequency of high-impact PTCs compared to high-impact MLCs) and also the relative risk posed by PTCs (i.e., how likely is a given PTC to be impactful, and how does this compare with a given MLC), paying particular focus to wind speed. The specific questions we answer are as follows:

- How does the intensity distribution of PTCs compare to that of MLCs over Europe?
- Do the intensity distributions vary spatially across the European domain?
- What fraction of high-impact wind events are caused by PTCs?

Section 2 contains a description of the data, the cyclone-tracking algorithm used to identify the cyclones and a description of the PTC identification procedure. Section 3 contains the results of a climatological comparison of PTC and MLC maximum intensities for Europe, and section 4 contains the discussion and conclusions.

2. Data Sets and Methodology

2.1. Data Sets

The ERA5 reanalysis is used to provide vorticity fields for tracking, along with the wind and pressure fields. Data from 1979–2017 is used. ERA5 has a resolution of T639 L137 and uses a 4D-Var assimilation system provided by cycle 41R2 of the ECMWF Integrated Forecasting System model. The ERA5 reanalysis is chosen due to its high horizontal resolution and improved data assimilation scheme, which are likely key drivers of improvements in the representation of location and intensity of TCs in reanalyses (Hodges et al., 2017; Murakami, 2014).

Additional information on the tracks of TCs from the IBTrACS v03r10 best track data set, a description of which can be found in Knapp et al. (2010), is also used in this study. For the North Atlantic, IBTrACS contains quality-controlled TC data from the National Hurricane Center. It should be noted that cyclone intensity and identification in IBTrACS are not homogeneous, particularly in the post-tropical stages due to forecaster subjectivity and changes in observational capabilities over time.

2.2. Cyclone Detection and Tracking

Cyclone detection and tracking is performed using the tracking scheme developed by Hodges (1994, 1995, 1999). This method has been used in many studies of both TCs (Strachan et al., 2013; Studholme et al., 2015; Yanase et al., 2014) and extratropical cyclones (Froude, 2010; Hoskins & Hodges, 2002, 2005, 2019). Tracking is performed on the vertically averaged 6-hourly relative vorticity fields using the 600, 700, and 850 hPa pressure levels. Features with a vorticity maximum exceeding $0.5 \times 10^{-5}\ \mathrm{s}^{-1}$ at T63 resolution are tracked. Tracks with a lifetime exceeding 2 days are then retained as cyclones. For more information on the configuration used in this study, see Hodges et al. (2017). For this study, all cyclone tracks which at some point in their lifetime enter a domain defined as 10°W to 30°E; 36–70°N, hereafter referred to as the European domain, are retained for further analysis.

Maximum 10 m wind speeds, 925 hPa wind speeds, and mean sea level pressure (MSLP) values are sampled along the cyclone tracks from full T639 resolution ERA5 fields. For MSLP the nearest pressure minima within a 5° radius spherical cap of the vorticity center is determined. For winds, a direct grid point search for the maximum winds in a 6° cap is used (Hodges et al., 2017). The 10 m wind speed in cyclones is underestimated in ERA5, even in the midlatitudes (Figure S1 in the supporting information).

2.3. PTC Identification Methods

In this study we do not explicitly diagnose the extratropical transition process, but instead define PTCs as cyclones which were TCs at some point in their lifetime prior to impacting the European domain. Three methods are used to identify PTCs. The first method, and the focus of this paper, identifies PTCs using spatiotemporal matching between the cyclones tracked in the reanalysis and the observed TCs present in the IBTrACS data set. A reanalysis track matches that of an IBTrACS track if over the time period for which the tracks overlap there is a mean separation distance of less than 4° (geodesic). If more than one track satisfies this criterion then the track with the smallest mean separation distance is chosen (Hodges et al., 2017; Hodges & Emerton, 2015). This has the benefit of obtaining the complete life cycles of the observed TCs, which is crucial for the study of PTCs. All tracked cyclones not captured in IBTrACS data (and therefore are not identified as PTCs) are considered MLCs. Over 95% of all Northern Hemisphere TCs recorded in IBTrACS are found in ERA5 using track matching, comparable to the reanalyses investigated in Hodges et al. (2017). The 5% of cyclones which are not identified tend to be weaker, shorter-lived TCs.

Two other objective methods are also used to identify PTCs by determining which cyclone tracks had a TC stage prior to impacting Europe. The first of these methods uses T63 vorticity fields to identify cyclone tracks which, while equatorward of 30 N, had characteristics associated with TCs—such as a warm core and a coherent vertical structure. This is achieved using the identification criteria in Hodges et al. (2017). The second objective method uses thresholds on the cyclone phase space (Hart, 2003) parameters to identify the cyclone tracks containing a warm core throughout the depth of the troposphere which also have symmetric properties. In future work we will investigate how PTC impacts may change across Europe using high resolution climate models. For this, observational data will not be available and objective methods will be utilized. The work presented here is used to verify the effectiveness of these objective methods at tracking and identifying PTCs and to better understand their limitations. See page 1 of the supporting information for more information.

2.4. Statistical Maps and Analysis

Cyclone statistics are produced showing the spatial distribution of storm tracks over Europe, using the spherical kernel method described in Hodges (1996). This allows for spatial statistics to be calculated directly on the sphere without the inherent problems associated with histogram type approaches—namely biases, arising due to distortion associated with grid box binned data on a projection (Hodges, 1996). Track and genesis densities are expressed as cyclones per year per unit area (within a 5° radius centered on the cyclones), where genesis is defined as the position of the cyclone at the first time step for which it is tracked through the reanalysis.

A 95% confidence interval is constructed and shown in Figure 4. This is calculated as

$$p \pm Z\sqrt{\frac{p(1-p)}{n}}, \tag{1}$$

where p is the proportion of cyclones in a given intensity bin which are identified as PTCs, $Z = 1.96$ for a 95% confidence interval from a standard normal distribution, and n is the total number of cyclones in a the intensity bin (i.e., PTCs + MLCs).

3. Results

3.1. Cyclone Track Density and Cyclogenesis

In this section we first compare MLCs and PTCs impacting Europe, considering cyclones forming in all months of the year. A large fraction of high-intensity MLCs impact Europe during the winter months, and it is therefore necessary not only to compare MLCs and PTCs during North Atlantic hurricane season (during which the majority of PTCs impact Europe, Figure S2) but also to investigate how PTCs compare to MLCs throughout the year, including during the seasons (autumn and winter) typically associated with the highest risk for Europe. Figure 1a shows the track and genesis density for all MLCs impacting Europe in the ERA5 reanalysis from 1979–2017. There are two clear regions of MLC genesis and highest track density—one over the North Sea and Scandinavia, associated with the midlatitude storm track, and another over the Mediterranean Sea. Cyclone tracks in both regions have different trajectories and associated impacts. Unlike MLCs, PTCs tend to occur in one region over Europe rather than two (Figure 1b). The western side of the European domain, particularly over the UK and Ireland, sees the highest PTC activity. On average, this region experiences 1 or more PTC impacts per year, the highest density over land within the European domain. PTC activity is considerably lower toward the east of the domain.

The highest track density of PTCs occurs inside the main development region for North Atlantic TCs, the region climatologically associated with high TC genesis density. PTC genesis density maxima are close to the west coast of Africa and over the Caribbean. Genesis areas to the west of Africa (and over Africa) are the result of the vorticity-based algorithm tracking the systems in the reanalysis and identifying the genesis of precursor systems (see section 2.2).

3.2. Contribution of PTC Intensity to Annual European Windstorm Risk

We split the European domain into two subdomains: The Mediterranean (S Europe), 10°W to 30°E, 36–48°N, and central and northern Europe (N Europe) extending from 10°W to 30°E, 48–70°N. This separation is based on the two centers of maximum MLC track density (Figure 1a) and allows us to investigate the difference in risk associated with PTCs and the MLCs with characteristics specific to each region. Figure 2 shows the distributions of all PTCs and MLCs impacting Europe by considering the maximum intensity attained by each system inside the European subdomains, represented by maximum 10 m wind speed, 925 hPa wind speed, and minimum MSLP. The distribution of PTCs is skewed toward higher intensities when compared to MLCs, particularly in the N Europe domain (Figures 2d–2f). This can be seen for all three intensity metrics. PTCs are also present in high-intensity bins in the tail of the distribution, suggesting that some PTCs are among the strongest windstorms in the climatology. Taking the mean of all tracked cyclones, PTCs have a maximum 10 m wind speed 2.1 m s^{-1} higher (17.5 m s^{-1} vs. 15.4 m s^{-1}), and minimum MSLP 10.2 hPa lower (990.8 hPa vs. 1001.0 hPa) than MLCs inside the whole European domain on average. PTCs also have a considerably higher median maximum 10 m wind speed (17.0 m s^{-1} vs. 15.0 m s^{-1}) and highest decile intensity (for other specific values, see Table S1). A two-sample Kolmogorov-Smirnov (K-S) test indicates that the distributions are different, significant to 99.9% for all three intensity metrics used in N Europe, and for MSLP in S Europe ($p = 0.05$ and 0.13 for 10 m and 925 hPa wind speed in S Europe, respectively). Significant differences are also found between the distributions of PTCs and MLCs when PTCs are instead identified using thresholds on the cyclone phase space parameters and using T63 relative vorticity fields (see section 2.3), with the largest separation between the distributions apparent in N Europe (Figure S3).

3.3. Contribution of PTC Intensity to Hurricane Season European Windstorm Risk

The focus of this section is on cyclones forming during the operationally defined North Atlantic hurricane season (1 June to 30 November). Figure 3 also shows that the distribution of PTCs is skewed toward more intense cyclones. This is true for both subdomains, however, results in S Europe should be treated with caution due to a limited sample size of high intensity PTCs (26 PTCs in total, seven of which have maximum 10 m wind speeds in excess of 17 m s^{-1}). For N Europe, both the mean and median maximum intensity of PTCs is more than 3 m s^{-1} greater than for MLCs. In S Europe, PTCs have a mean and median maximum intensity 2.3 and 2.6 m s^{-1} higher than MLCs respectively. The mean maximum wind speeds for the MLC distributions is lower in S Europe, and the intensity distribution is narrower than in N Europe, with few cyclones attaining wind speeds exceeding of 25 m s^{-1}. The differences between PTC and MLC mean maximum intensity is largest when considering the strongest 10% of cyclones. The strongest decile of PTCs have 10 m wind speeds 4.2 and 3.9 m s^{-1} higher than the strongest decile of MLCs in N and S Europe, respectively. Of all PTCs impacting N Europe 8.2% are accompanied by storm force winds (Beaufort scale 10, >25 m s^{-1}). For MLCs, this fraction is much lower at 0.8%, suggesting that the fraction of PTCs impacting N Europe with storm force winds is 10.1 times higher than MLCs (95% confidence interval: 1.3–25.6). with the data used in the construction of Figure 2, a two-sample K-S test also shows that the distributions are significantly

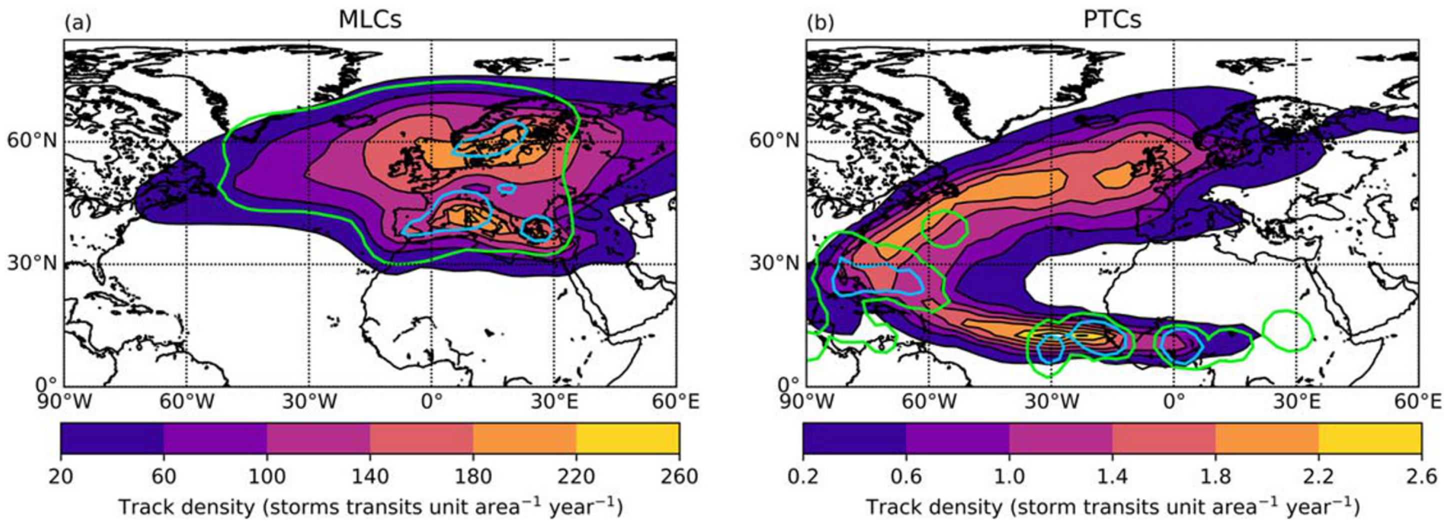

Figure 1. Track density (filled contours) and genesis density (open contours) of MLCs (left) and PTCs (right) impacting the European domain (10°W to 30°E, 36–70°N) tracked in the ERA5 reanalysis from 1979–2017, all year round. Genesis contours are 8 (green) and 32 (blue) MLCs per year (left) and 0.04 (green) and 0.12 (blue) PTCs per year (right). Densities are expressed as the number of cyclones per year in a cap with a 5° (geodesic) radius.

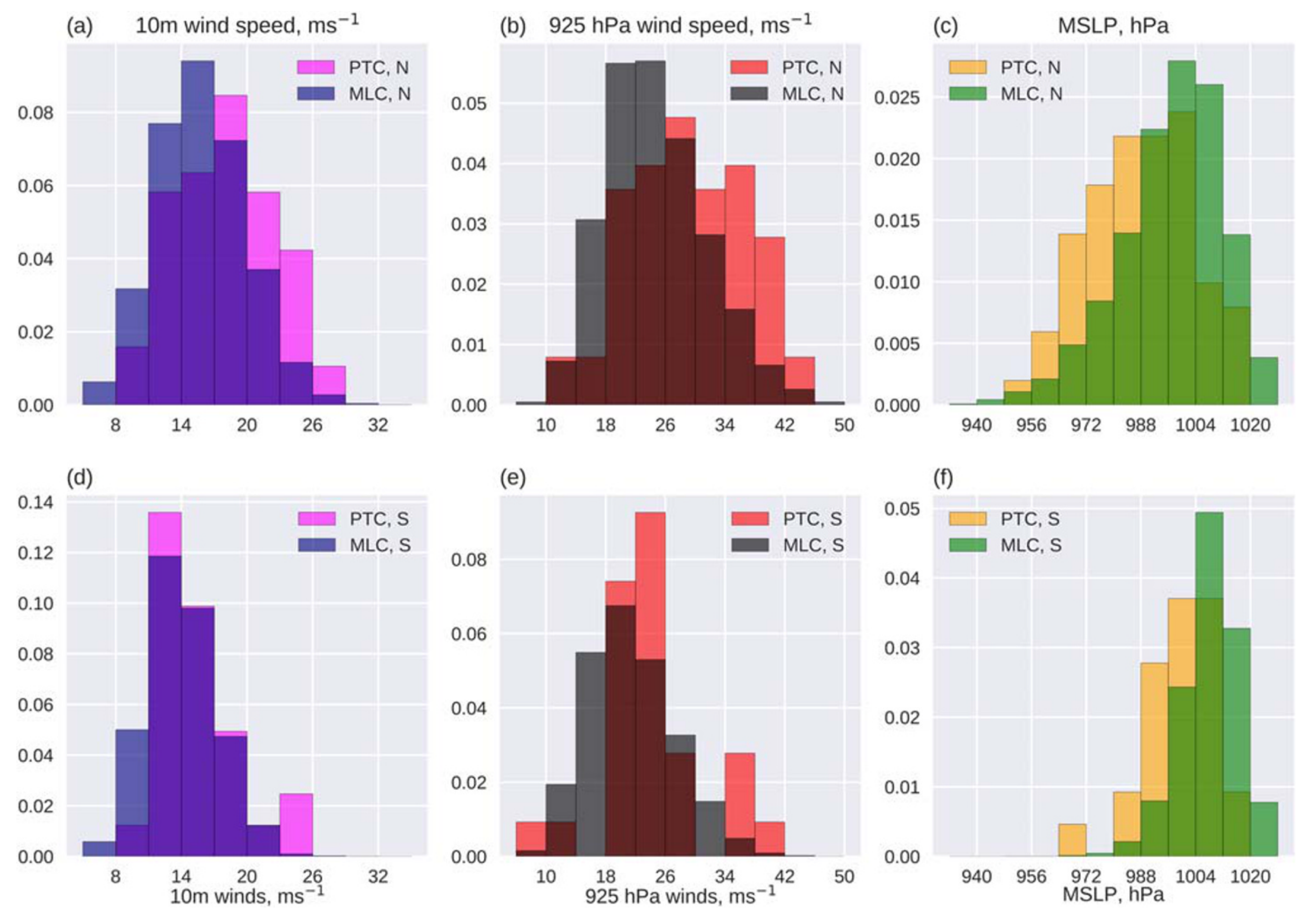

Figure 2. Distributions of the maximum intensity (maximum wind speed, minimum MSLP) attained by each PTC and MLC inside (a–c) the north European subdomain (10°W to 30°E, 48–70°N) and (d–f) the south European subdomain (10°W to 30°E, 36–48°N), using cyclones tracked through the ERA5 reanalysis all year round, 1979–2017.

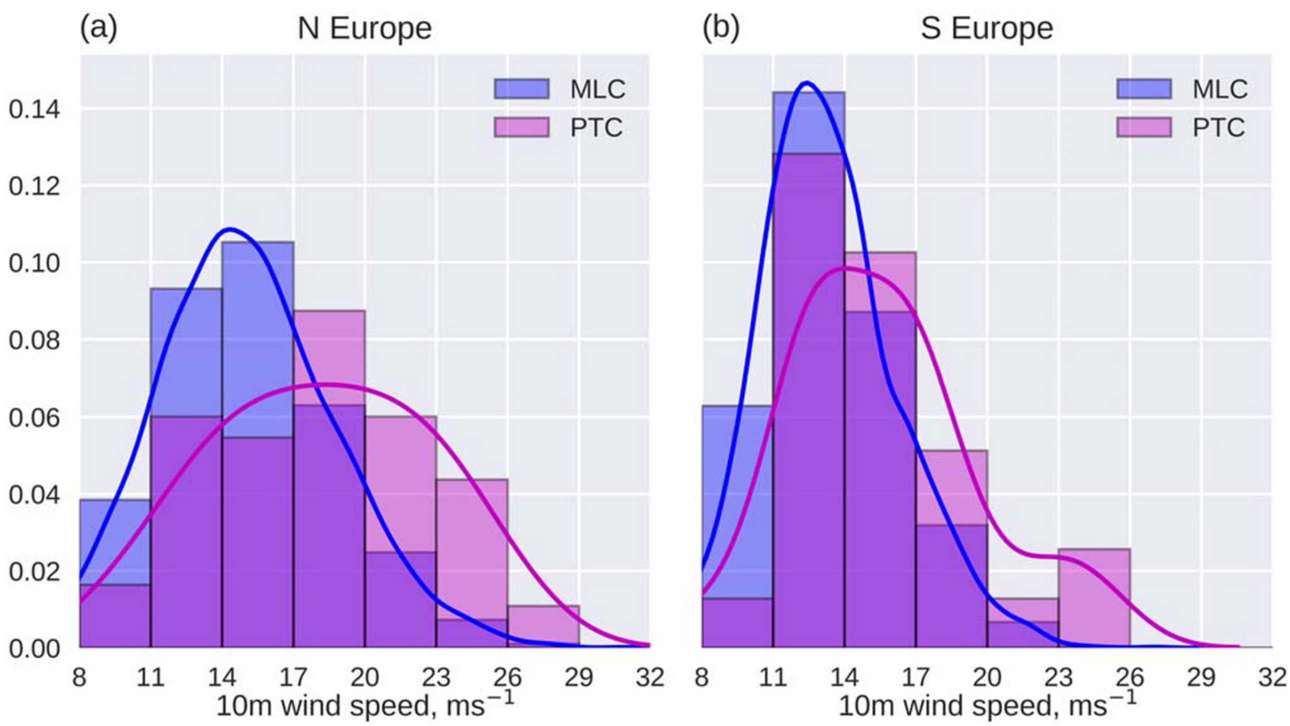

Figure 3. Distributions of the maximum intensity attained by each PTC and MLC inside the North Europe subdomain (10°W to 30°E, 48–70°N) (left) and the South Europe subdomain (10°W to 30°E, 36–48°N) (right). Gaussian kernel density estimate is overlaid for PTC and MLC distributions in both panels. All cyclone tracks forming during the North Atlantic hurricane season (1 June to 30 November) are used.

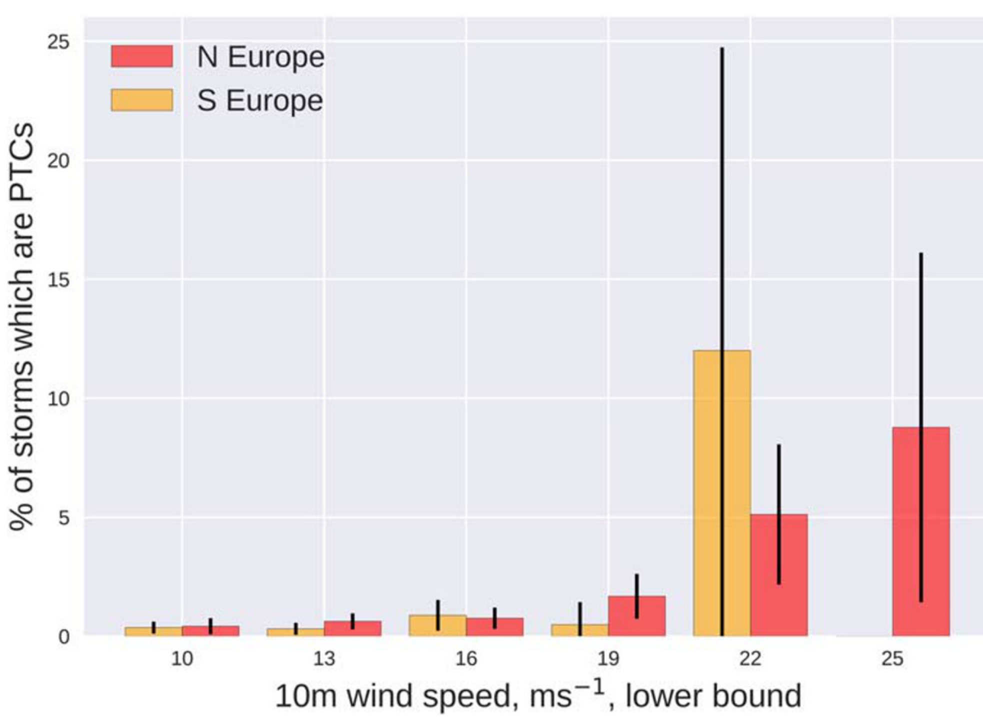

Figure 4. The fraction of cyclones impacting Europe which are PTCs as a function of their maximum 10 m wind speed in their respective domain. Lower bound of wind speed is shown on the *x* axis, bin width = 3. Error bars show the 95% confidence interval. All cyclone tracks forming during the North Atlantic hurricane season are used.

different. The two additional PTC identification methods yield similar results as shown in Figure 3, showing a large difference between the PTC and MLC distributions in N Europe and a smaller but still significant difference in S Europe (Figure S4).

Figure 4 shows the percentage of wind events occurring in a given subdomain which are associated with PTCs. In S Europe, <1% of wind events in the lowest four intensity bins are associated with PTCs. This fraction increases to 12% for cyclones with a wind speed >22 m s^{-1} (shown as the yellow bars). The sample size is small for this bin, with only 25 total cyclones recording windspeeds >22 m s^{-1} in S Europe between 1979 and 2017, three of which are PTCs. This is reflected by the large range of values within the 95% confidence interval. In N Europe, the fraction clearly varies with maximum cyclone intensity inside the subdomain. Less than 1% of cyclones which form during hurricane season and impact N Europe are PTCs overall; however, 8.8% of all hurricane season forming cyclones which impact N Europe with storm force winds are PTCs (Figure 4, red bar at 25 m s^{-1}). The difference between the distribution of PTC and MLC maximum intensities when considering the entire European domain (not shown) is very similar to that shown for N Europe for Figures 2–4. Despite large uncertainty as shown by the error bars, the lower bound for the 22 and 25 m s^{-1} intensity bins still exceed the upper bound for the lowest three intensity bins. The results of Figure 4 are supported by the alternative PTC identification methods described in section 2.3, which both show that ~1% of cyclones impacting N Europe during hurricane season are PTCs, but 7% of storm force cyclones are PTCs. For S Europe, <1% of cyclones impacting the subdomain are PTCs for all cyclones with wind speeds below 22 m s^{-1}. This rises to 8% for PTCs identified using thresholds on the cyclone phase space parameters, and to 20% for cyclones identified using T63 vorticity fields (Figure S5). The variation between the three PTC identification methods in S Europe for high-intensity cyclones is an indication of the small sample size; however, all three methods agree that a disproportionately large fraction of high-impact events occurring in Europe during hurricane season are the result of PTCs.

4. Discussion and Conclusions

The aim of this paper was to quantify the importance of PTCs when assessing European windstorm risk. This has been achieved by tracking all cyclones impacting Europe through the ERA5 reanalysis from 1979–2017 and identifying the PTCs using objective track matching with the IBTrACS best track data set. The main conclusions of this study are as follows:

- At their maximum intensity across Europe, PTCs are on average significantly more intense than MLCs. This holds true when comparing PTCs and MLCs impacting Europe overall, and also when comparing cyclones which impact Europe and form during hurricane season.
- 8.2% of all N Europe impacting PTCs which form during hurricane season impact the region with storm force winds. This fraction is only 0.8% for MLCs, suggesting that the fraction PTCs impacting N Europe with storm force winds is ~10 times greater than MLCs.
- PTCs are responsible for less than 1% of all cyclones impacting N Europe during hurricane season from 1979–2017. This rises to 8.8% when considering cyclones which impact N Europe with storm force winds, showing that high-impact wind events during hurricane season are disproportionately caused by PTCs.

The difference in intensity between PTCs and MLCs is largest for N Europe—In this region, the differences between the distributions of PTC and MLC maximum intensities are statistically significant for all three intensity metrics used. For cyclones impacting S Europe, they are significant for the distributions of MSLP when considering all cyclones, and for the distribution of 10 m wind speeds when considering cyclones forming in hurricane season.

This study has used three different methods to identify PTCs, with the results from one method—objective track matching with IBTrACS, presented. Identification methods which use T63 relative vorticity fields and thresholds on the cyclone phase space parameters to identify PTCs support the analysis shown here and yield very similar results, highlighting the robustness of the results presented in this paper. The objective PTC identification methods show statistically significant differences between the maximum intensity distributions of PTCs and MLCs over Europe, with the largest differences between the distributions over N Europe. Both of these methods show that 7% of all hurricane season forming cyclones which impact N Europe with storm force winds are PTCs, despite PTCs only contributing 1% of the total cyclones to impact the region.

While this paper shows that PTCs are, on average, more intense than MLCs at their maximum intensity over Europe, the question still remains as to why this is the case. Warm-seclusion storms (Shapiro & Keyser, 1990) post extratropical transition have been shown to have the fastest rates of reintensification (Kofron et al., 2010) and typically have the lowest sea level pressure upon impacting Europe (Dekker et al., 2018). Given the climatological track that PTCs often take over the warm waters of the Gulf stream (Figure 1), along with the contribution of both baroclinic instability and latent heat release for warm-seclusion development (Baatsen et al., 2015), future work will assess whether PTCs are more likely to develop warm seclusions than the broader class of MLCs, potentially explaining the disproportionate impacts they cause across Europe.

Despite PTCs disproportionately impacting Europe with high intensities, they are a relatively small component of the total cyclone risk in the current climate. However, only small changes are expected in MLC activity—the CMIP5 multimodel mean cyclone number over the North Atlantic basin decreases by 3.6% in December–February and 1.9% in June–August under RCP 4.5 by the end of the century, with a reduction in the number of cyclones attaining wind speeds greater than the present-day 90th percentile (Zappa et al., 2013). Conversely, the number of hurricane force (>32.6 m s^{-1}) storms impacting Norway, the North Sea, and the Gulf of Biscay increases by a factor of 6.5, virtually all of which originate in the tropics (Haarsma et al., 2013). While the absolute contribution of PTCs to hurricane season windstorm risk is currently low, PTCs may make an increasingly significant contribution to European windstorm risk in a future climate.

Data Availability Statement

All ERA5 reanalysis fields used in cyclone tracking (relative vorticity) and analysis (MSLP, 10 m wind speed, 925 hPa wind speed, geopotential) are freely available at the Copernicus C3S Date store (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). IBTrACS data are available from this site (https://www.ncdc.noaa.gov/ibtracs/index.php?name=ib-v4-access). TRACK is available for use with permission (see http://www.nerc-essc.ac.uk/~kih/TRACK/Track.html, version 1.5.2 used).

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