

# On the Dependency of Atlantic Hurricane and European Windstorm Hazards

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# Geophysical Research Letters

## RESEARCH LETTER

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### Key Points:

- Above average Atlantic hurricane seasons are followed by above average European windstorm seasons less often than if they were independent
- The El Niño–Southern Oscillation is a consistent factor for both seasons, several months ahead of the European windstorm season
- This has important predictability implications for both the actuarial and seasonal forecasting communities

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## On the Dependency of Atlantic Hurricane and European Windstorm Hazards

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**Abstract** The Atlantic hurricane season and the European windstorm season are found to be negatively correlated in a seasonal forecast model. The probability of extremes occurring in both seasons is compared to the probability of extremes in each season being independent of one another. An above average Atlantic hurricane season is followed by an above average European windstorm season less often than if they were independent, consistent across three intensity measures. The El Niño–Southern Oscillation is found to be in the positive (negative) phase when hurricane activity is suppressed (enhanced) and European windstorm activity is enhanced (suppressed). A clear extratropical response in the seasonal forecast model to El Niño/La Niña provides a probable pathway for the observed correlation between the extreme event seasons. This result has important predictability implications for both the actuarial and seasonal forecasting communities.

**Plain Language Summary** On both sides of the Atlantic Ocean storms with extremely high wind speeds are a natural hazard, resulting in billions of dollars in damages and loss of life. During the late summer and autumn, hurricanes which form in the tropical ocean impact the Caribbean and United States. In the winter, windstorms form in the midlatitude regions primarily impacting Europe. These two seasons are traditionally considered to be unrelated. Here we present evidence that the two are linked through the climate system, specifically the El Niño–Southern Oscillation. An active Atlantic tropical cyclone season precedes an active European windstorm season less often than if the two seasons were independent. Future efforts to predict how damaging the upcoming European windstorm season may be should take this into account, and the insurance industry should be aware that these two risks are not independent.

## 1. Introduction

Following an extreme weather season, focus naturally turns to the climate conditions which preceded it, especially if such conditions may be predicted. Taking for example the 2017 hurricane season, multiple explanatory climate factors were observed prior to the historically high hurricane count, including high ocean heat content in both the tropical Atlantic (Hallam et al., 2019; Lim et al., 2018) and Gulf of Mexico (Trenberth et al., 2018), as well as low wind shear in the western Atlantic due to a developing La Niña event (Camp et al., 2018). In the same 2017 season, the combined insured loss from Atlantic hurricanes and European windstorms was estimated at \$100 billion, primarily due to this extremely active hurricane season (Halverson, 2018; Klotzbach et al., 2018; SwissRe, 2018). These two hazards accounted for around 70% of the total global insured losses for the year and were the primary cause of insured loss in North America and Europe, respectively (SwissRe, 2018). Clarifying the relationship between these two leading natural hazard seasons is therefore crucial for estimates of potential yearly loss. Lloyd's (2016), in an examination of global hazard relationships, finds a small but significant negative correlation between U.S. tropical cyclone (TC) risk and EU flooding, further motivating a thorough analysis of their combined risk potential.

Both European windstorm and Atlantic TC frequency is influenced by the El Niño–Southern Oscillation (ENSO). ENSO modulates the favorability of Atlantic TC development conditions through suppressed (La Niña) or enhanced (El Niño) wind shear in the tropical Atlantic (Bove et al., 1998; Goldenberg & Shapiro, 1996; Gray, 1984; Latif et al., 2007; Villarini et al., 2012; Vitart & Anderson, 2001). Over Europe, several authors have explored how ENSO impacts the North Atlantic storm track. ENSO produces an extratropical response through Rossby wave propagation (Branstator, 2014; Goss et al., 2018; Held et al., 1989; Mezzina et al., 2020; Soulard et al., 2019; Stan et al., 2017), influencing atmospheric hazards globally (Steptoe et al., 2018). European temperature and precipitation anomalies associated with ENSO are spatially similar to those

associated with the North Atlantic Oscillation (NAO) (Pozo-Vázquez et al., 2001, 2005), attributed to a predominantly positive phase relationship between the two indices during November to December and a negative phase relationship during January to March (Huang et al., 1998; Moron & Gouirand, 2003). Focusing on this late winter signal, Brönnimann et al. (2007) found a consistent response of European temperature and precipitation to ENSO. Similarly, Li and Lau (2012a, 2012b) and Drouard et al. (2015) found that sea surface temperature (SST) changes in the North Pacific associated with El Niño events induce negative NAO events. Due to the establishment of ENSO events months in advance of boreal winter, this tropical to extratropical connection has shown predictive skill in seasonal forecasts (Dunstone et al., 2016; Scaife et al., 2014, 2017; Toniazzo & Scaife, 2006); however, this is complicated by the nonstationary nature of the ENSO-North Atlantic signal (Knippertz et al., 2003; López-parages et al., 2015; Rodríguez-fonseca et al., 2016).

Given the associations between NAO conditions and the North Atlantic storm track location (Donat et al., 2010; Pinto et al., 2009), the ENSO-NAO relationship has clear implications for interannual variation in European windstorm climatology. Fraedrich and Müller (1992) found that during El Niño events, cyclones occurred further south, leading to a precipitation increase over western Europe. Merkel and Latif (2002) agree but stress that the opposite conditions during La Niña could not be recreated. Schemm et al. (2018) found competing effects over Europe, with gulf stream cyclogenesis enhanced (suppressed) during El Niño (La Niña) events and Greenland cyclogenesis suppressed (enhanced). This is in good agreement with the results of Fraedrich and Müller (1992) and Merkel and Latif (2002), with an increase of cyclones over mainland Europe during El Niño.

Here we seek to establish whether covariability exists between the North Atlantic TC season and the European windstorm season. We aim to answer the following questions: Does an active Atlantic TC season increase the likelihood of an active European windstorm season over western Europe, or vice versa? If so, how are these two seasons related dynamically?

## 2. Data and Methods

We track TCs and European windstorms using merged 10 m wind speed of the latest European Centre for Medium-Range Weather Forecasts (ECMWF) seasonal forecast, SEAS5 (Johnson et al., 2019). All 51 ensemble members of SEAS5 are tracked, for the period 1981 to 2016. SEAS5 is initialized from ERA-interim (Dee et al., 2011) atmospheric conditions and state-of-the-art land and ocean models, on the first of every month. The ensemble is created by perturbing the initial conditions of multiple fields across multiple levels in the atmosphere, as discussed in Johnson et al. (2019). We tracked storms for each model year initialized on the first of August, covering the peak seasons for both Atlantic hurricanes (Blake et al., 2007; Stockdale et al., 2018), August–October (ASO), and for European windstorms (Roberts et al., 2014), December to February (DJF). In total, 1,836 ( $51 \times 36$ ) model years from SEAS5 were tracked. The ensemble is physically consistent in reproducing the location of the European storm track, and the climatology of European windstorms has been validated and found to be physically consistent with both reality and previous iterations of the seasonal forecast (Befort et al., 2019). SEAS5 has a spectral horizontal resolution of T319, approximately 36 km, and has previously been shown to skilfully recreate the location of TCs globally, although the frequency and intensity of TCs are underestimated in the Atlantic (Klotzbach et al., 2019). Additionally to the 10 m  $u$  and  $v$  winds required for tracking, SST and 700 mbar geopotential height (GHT) from the same SEAS5 initialization are composited to analyze the dynamical conditions associated with the hypothesized TC/European windstorm relationship. We also track European windstorms and Atlantic TCs in ERA-interim for verification, and the climatology of Atlantic TC tracks is provided by the International Best Track Archive for Climate Stewardship (IBTrACS) v03r10 (Knapp et al., 2010).

SEAS5 provides an ideal test data set for comparison between the two hazard seasons as it fulfills two key criteria. First, a fundamental requirement for assessing the relationship between two extreme seasons is a high temporal resolution. A 1 in 10 North Atlantic hurricane season occurring during the same year as a 1 in 10 European windstorm season would be a 1 in 100 year event, assuming independence. Reliable measures of seasonal activity such as best track data only cover a short period of time (with low uncertainty only for the satellite era, 1980 to present). Detecting a signal between the two seasons is therefore nontrivial. By assessing the relationship between European windstorms and Atlantic TCs in a seasonal forecast system such as SEAS5, this issue is addressed by increasing the number of “observations” (Osinski et al., 2015). This methodology assumes that each model initialization represents an independent realization of the climate

system. In SEAS5, mean storm track position and European windstorm count are both found to be independent of calendar year, providing confidence that this assumption is valid. Second, each model run includes both seasons driven by the same initial climate conditions, allowing for analysis of any dynamical factors which relate the two seasons.

For both European windstorms and TCs, events are classified by identifying and tracking clusters of wind speed exceeding a local threshold. Classification is performed using the algorithm WiTRACK (introduced by Leckebusch et al., 2008, applied in Befort et al., 2020; Kruschke, 2015; Renggli et al., 2011). For the local threshold, the 98th percentile is chosen because of its association with extratropical cyclone-related damage over Europe (Klawa & Ulbrich, 2003). Befort et al. (2020) show the majority of high-impact TCs can also be captured by this method. TCs are excluded beneath a wind speed exceedance area of 15,000 km<sup>2</sup>, while European windstorms are excluded beneath a wind speed exceedance area of 130,000 km<sup>2</sup>. WiTRACK is otherwise applied to each season using the setup defined in Kruschke (2015).

As WiTRACK does not distinguish between extreme windstorms caused by tropical or extratropical cyclones, postprocessing is required to select only the tracks of TC origin within SEAS5 over the August to October period. Tracking is performed on 6-hourly fields, but midlevel temperature is available at only 12-hourly intervals, precluding dynamical identification of warm core and cold core storms. Instead, we apply geographical filters to exclude tracks which do not form in the tropical Atlantic. The filters were designed by examination of IBTrACS. By design, therefore, no Atlantic, Gulf of Mexico, or Caribbean categorized event within the IBTrACS climatology would be removed by the application of these filters, resulting in a climatology of SEAS5 tracks which are physically consistent with observed TCs. A similar geographical filter approach was applied successfully by Befort et al. (2020) to identify high-impact Pacific cyclones. Tracks were removed in the following: where the track originated in the Pacific; where the track's central location remained either south of 10°N, north of 40°N, or east of 40°W; and where the track's central location was at any time both north of 35°N and west of 85°W. To remove windstorms which did not impact the European continent, the following constraints were placed on European windstorm tracks: All tracks were removed where the central location remained west of 30°W and/or where the storm remained north of 70°N.

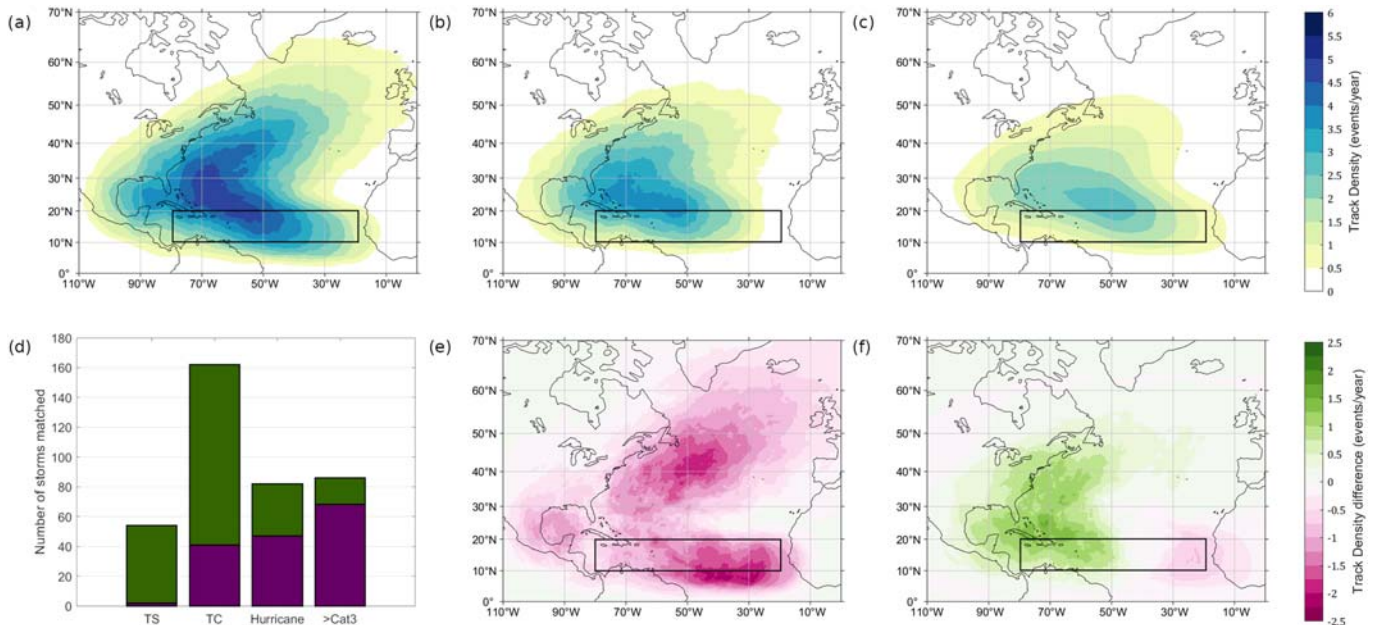
Tracks identified by WiTRACK in ERA-interim were matched to IBTrACS. Following Befort et al. (2020) tracks fulfilling the follow criteria are considered matched: a temporal overlap of at least four time steps, with a distance between track centers below 400 km, and a mean distance of less than 1,000 km over the entire track. To compare track density between IBTrACS, ERA-Interim, and SEAS5, the number of storms per grid cell over a 0.75 × 0.75° grid was calculated.

We calculate three separate measures of intensity for each season. The first is simply the number of tracks, referred to subsequently as nStorms. The second is a Seasonal Storm Severity Index (SSSI), a measure of the total “storminess” throughout a given ASO or DJF period. Storm Severity Index (SSI) is calculated as a normalized value of the 98th percentile exceedance in the wind field, following Leckebusch et al. (2007). SSSI is the summation of the individual SSI value for each track over a complete ASO or DJF season. The third intensity measure is Land impacting Seasonal Storm Severity Index (LiSSSI). LiSSSI is determined by calculating the SSSI of the WiTRACK cluster points which occur over land.

To classify the relationship between the two seasons, we adopt a probability of independence approach. For a given threshold, the independent probability that the seasonal intensities of both the Atlantic hurricane and European windstorm season exceed that threshold is calculated, determining an expected number of model initialization years. We test the hypothesis that the two seasons are independent by comparing the true number of model years which meet a given threshold to this predicted independent value. If the two seasons are independent, both seasons will exceed thresholds independently of one another, and no consistent difference will be observed between seasonal threshold exceedance within and without the same ensemble member model year. The advantage of this approach over other test of covariability, such as correlation coefficient, is that it allows us to determine if a relationship exists across the distribution of observed seasons simultaneously. It is therefore a better tool for assessing hazard dependence where the tails of the distribution are crucial. Additionally, it does not assume the relationship to be symmetrical.

To assess significance, bootstrapping (Feng et al., 2011; Hall & Horowitz, 1996; Horowitz, 2001; Marchand et al., 2006) is applied to generate 1,000 random samples with replacement from the seasonal intensities within the full model ensemble of August initializations. A 95% confidence value is drawn from the





**Figure 1.** Track Density per year of TC events in (a) IBTrACS, (b) WiTRACK ERA-interim, and (c) WiTRACK SEAS5 ensemble mean. (d) Matched events (purple) between IBTrACS and WiTRACK ERA-interim for tropical depressions (TS), tropical cyclones (TC), Categories 1–2 hurricanes (Hurricane), and Categories 3–5 hurricanes (>Cat3). All categorizations from IBTrACS. (e) Difference between (b) and (a), with pink indicating greater IBTrACS track density. (f) Difference between (b) and (c), with green indicating greater ERA-interim track density. Difference in spatial structure (e) attributable to comparison of wind and pressure-based tracking schemes.

bootstrapped random sample distribution, and relationships are considered significant where this value is exceeded.

Data generated in this study are publicly available from Angus and Leckebusch (2020), and we encourage researchers to make use of this resource.

### 3. Results

#### 3.1. Evaluation of WiTRACK Performance in SEAS5

WiTRACK was primarily developed for assessing damage potential of European windstorms (Leckebusch et al., 2008) and has been validated extensively for this application (Donat et al., 2010; Kruschke, 2015; Osinski et al., 2015; Renggli et al., 2011; Walz et al., 2018). Befort et al. (2020) has recently demonstrated the skill of WiTRACK in tracking TCs in the West Pacific, and we apply it here for the first time to Atlantic hurricanes so that the damage potential from both seasons can be compared directly.

The climatology of hurricanes in IBTrACS (Figure 1a), WiTRACK ERA-Interim (Figure 1b), and WiTRACK SEAS5 (Figure 1c) broadly share the same features, with a clear maxima at 20–40°N, 90–30°W. There are clear track density differences in the main development region (MDR, 10–20°N, 80–20°W) and north of 40°N in the cyclolysis region (Figure 1e). This is an expected result of comparing a central pressure-based tracking scheme (IBTrACS) to the wind speed clustering methodology (WiTRACK). As the TC becomes more organized, consistent regions exceeding the minimum cluster size with >98th percentile wind speed are more likely. This is a recognized advantage of the application of WiTRACK rather than a minimum pressure or vorticity tracking scheme; however, the well-matched track density pattern over the Caribbean and U.S. East Coast (difference of approximately one cyclone per year) gives us confidence that the climatology of mature cyclones is well represented. Track density here is the mean value over all ensemble members for SEAS5 (Figure 1c), resulting in the smoother spatial pattern. In the peak maxima region, there are 0.5–2 more storms per year in ERA-interim than in the SEAS5 ensemble (Figure 1f), consistent with the findings of Klotzbach et al. (2019). The number of tracks in individual SEAS5 model years exceeds the number of tracks in ERA-interim only 26.8% of the time, confirming the negative bias observed in the track density pattern. The spatial pattern is otherwise qualitatively similar.

Increasing skill in the tracking of higher category storms is also observed by matching IBTrACS events to the ERA-interim WiTRACK events (Figure 1d). Dividing by TC strength, 79% of hurricanes which reached Category 3 on the Saffir-Simpson Scale and 57% of hurricanes which reached Category 2 were matched successfully. Lower-intensity TCs are matched 25% of the time, while only 2 of 53 tropical depressions (4%) were matched. No Category 5 event was unmatched. Again, this is an expected result of the WiTRACK approach where fewer overall tracks of shorter duration and higher average damage potential are found in the surface wind field. Our results are in good agreement with those of Befort et al. (2020), who found an overall hit rate of 62% and an intense storms hit rate of 85%. The performance of WiTRACK for Atlantic TCs is therefore similar to the performance in tracking Pacific TCs, with clear skill representing higher-category storms.

## 3.2. Atlantic Hurricane and European Windstorm Correlation

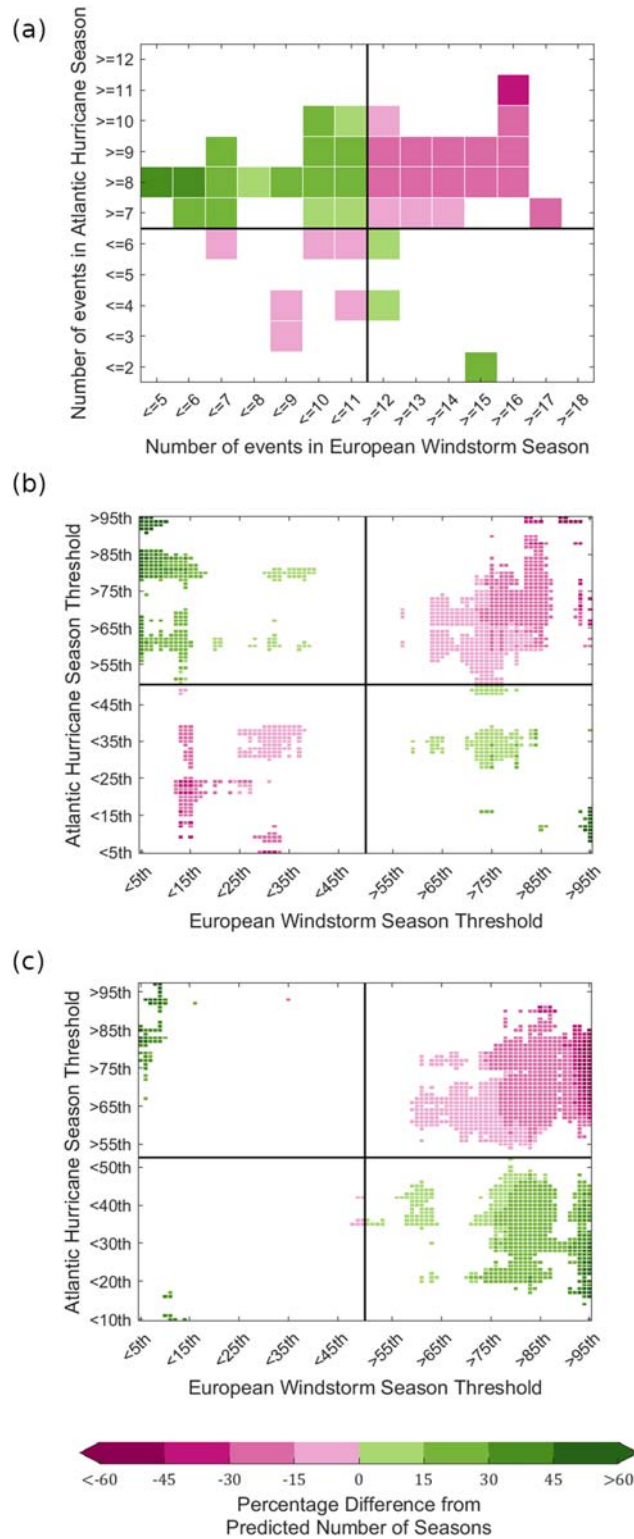
### 3.2.1. Assessment of Independence

For each intensity measure (nStorms, SSSI, and LiSSSI), empirical distributions are derived for each hazard season (hurricane and windstorm) independently. For a wide range of seasonal intensity thresholds within these distributions, the independent probability that the number of hurricane seasons and the number of European windstorm seasons will fulfill that threshold is then calculated. For example, of the 1,836 model years we find 11 or more TC events in 151 TC seasons (8.22%). We find 16 or more European windstorms in 210 European windstorm seasons (11.4%). If the two seasons are truly independent, we would therefore expect both 11 or more TCs *and* 16 or more European windstorms in the same ensemble member model year 0.94% of the time, or in 17.25 of 1,836 model years. Finally, the number of SEAS5 ensemble model years where the given threshold is met for both seasons is calculated and compared to the theoretically independent value.

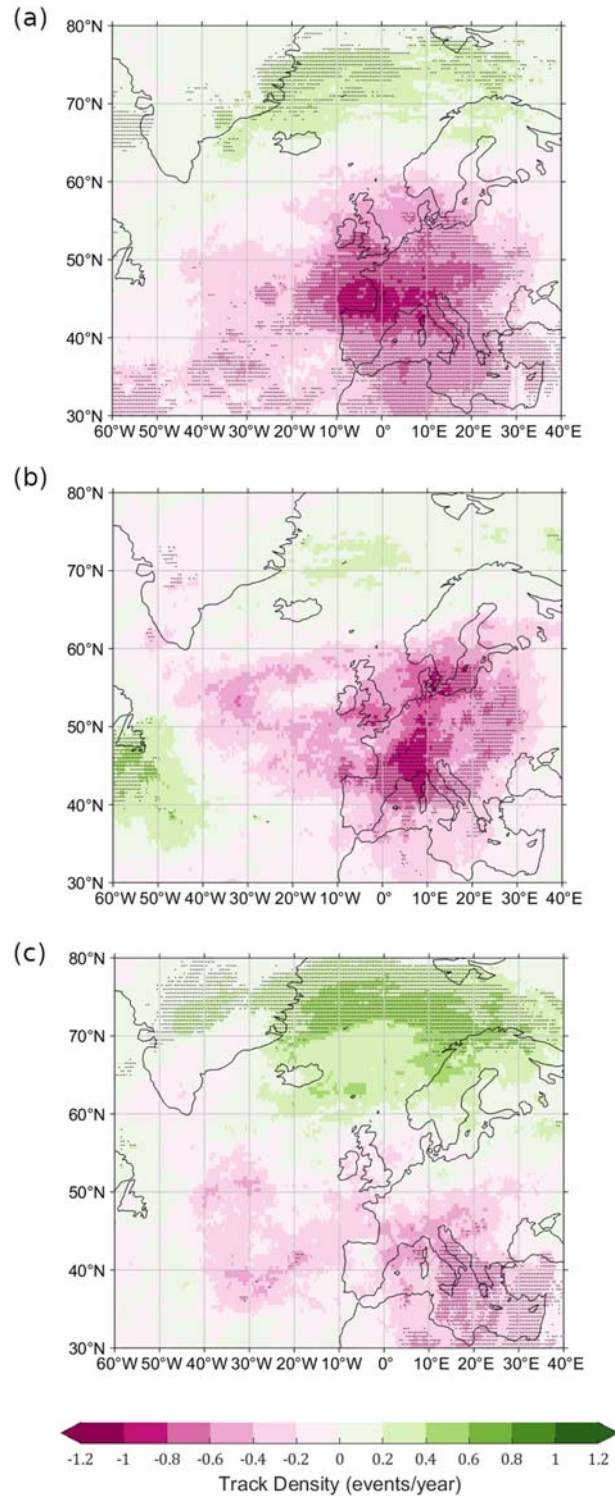
For all three intensity measures, we find statistically significant differences from the independent probability that the two hazard seasons are unrelated (Figure 2). Figure 2 should be interpreted as follows: for each panel (a–c), the four separated quadrants represent a different relationship between the extreme seasons. The top left quadrant represents an intense hurricane season and weak European windstorm season, top right quadrant the case where both are more intense than the mean, bottom left quadrant where both are weaker than the mean, and bottom right quadrant where European windstorms are more intense and hurricanes less intense. Colored boxes indicate where the number of ensemble model years exceeded (green) or were fewer than (pink) the theoretically independent number. Returning to the example above, the dark pink shading in the more than 11 TCs and more than 16 European windstorms box (Figure 2a) indicates that the true value lies between 30% and 45% less than the theoretically independent 17.25 model years (actually 11 model years). This is statistically significant at the 95% confidence interval, based on a bootstrap of 1,000 random samples.

There is a clear pattern in Figure 2 of fewer seasons than predicted where both seasons are above or below average and more seasons than predicted where one is above average and the other below. In very few cases across all intensity measures is there a significant threshold met where this relationship is reversed. This indicates that an above average Atlantic hurricane season is followed by a below average European windstorm season less often than if they were independent and vice versa. In the case of nStorms (Figure 2a) the relationship is most prevalent when the hurricane season is above normal, with little to no relationship observed for below normal hurricane seasons. Depending on threshold, the difference ranges from a 0% to 45% change from the predicted seasonal count. For SSSI (Figure 2b), the relationship is broadly symmetrical, although most consistent in the case of an above average hurricane season and below average windstorm season. The intensity measure LiSSSI (Figure 2c) is consistent with the other intensity measures for above average European windstorms, particularly above the 75th percentile threshold, where the magnitude of the percentage change in seasonal count is persistently between 15% and 30%. However, the relationship is not observed for weaker than average European windstorms, indicating little difference between normal and less than average hurricane seasons in terms of direct damage potential in Europe the following winter.

European windstorm track density was calculated for the most and least intense hurricane season model years (Figure 3). For nStorms (Figure 3a) and SSSI (Figure 3b) derived hurricane seasonal intensity there is a significant difference in European windstorms across much of western Europe. This is not replicated for LiSSSI, with the spatial pattern shifted to the southeast and weaker overall. North of 60°N, the sign of the relationship is reversed with a positive signal indicating more European windstorms following an above

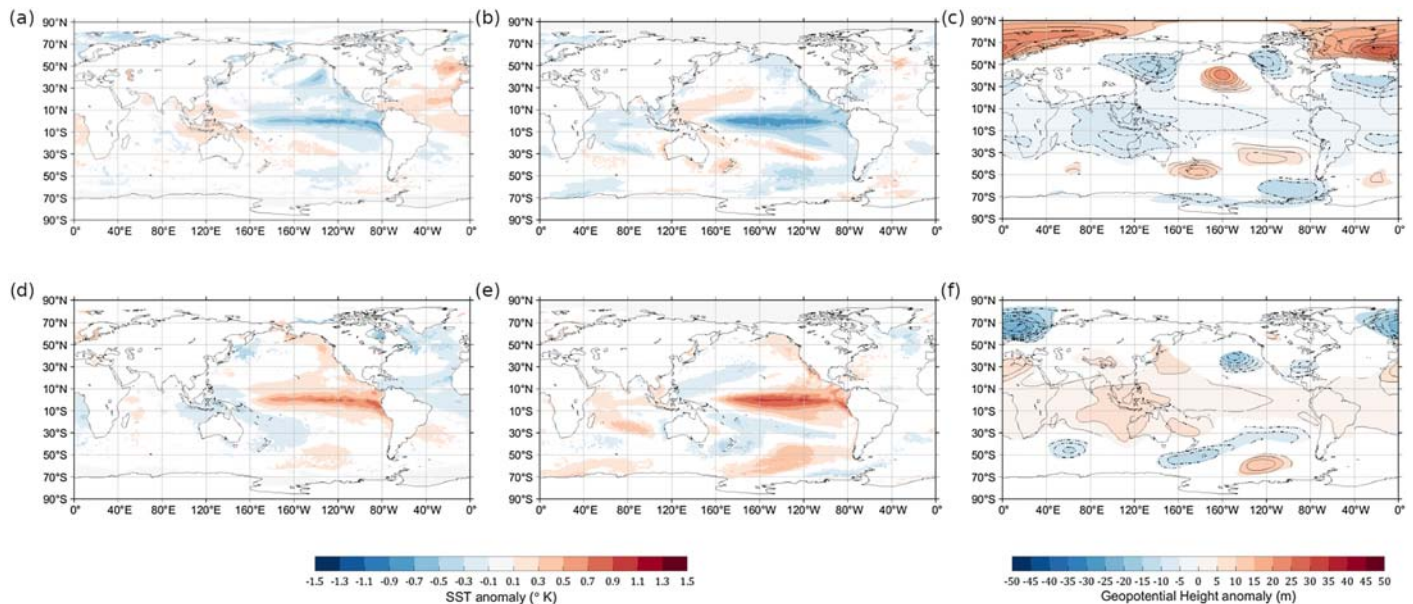


**Figure 2.** Percentage difference between number of seasons which meet the shown thresholds and the expected statistically independent value for (a) nStorms, (b) SSSI, and (c) LiSSSI. Grid cells shown where the difference from independent predicted value exceeds the 95th percentile confidence interval, derived from a random sample of 1,000 independent seasons.



**Figure 3.** European windstorm track density difference between model years with top 10% hurricane intensity and bottom 10% hurricane intensity for (a) nStorms, (b) SSSI, and (c) LiSSI. Stippling represents where the difference from independent predicted value exceeds the 95th percentile confidence interval, derived from a random sample of 1,000 independent seasons.





**Figure 4.** (a) SST composite of top 10% ranked difference between hurricane SSSI and windstorm SSSI during ASO (above average hurricane season, below average windstorm season). (b) As in (a), during DJF. (d and e) As in (a) and (b), for bottom 10% ranked difference (below average hurricane season, above average windstorm season). (c and f) Corresponding 700 mbar GHT composite during DJF. Grid cells shown where the difference from independent predicted value exceeds the 95th percentile confidence interval, derived from a random sample of 1,000 independent seasons.

average Atlantic hurricane season, significant in the nStorms and LiSSSI composite. The SSSI composite is qualitatively similar but not significant. This north/south track difference is reminiscent of shifts in the storm track location associated with the NAO, with similar centers of action (Walz et al., 2018).

### 3.2.2. Physical Mechanism Explaining Dependence

ENSO is the dominant SST pattern associated with the SSSI hurricane-windstorm hazard correlation (Figure 4). A persistent La Niña pattern in both ASO and DJF is associated with the high-hurricane, low-windstorm phase of the relationship (Figures 4a and 4b), while El Niño is associated with the opposite low-hurricane, high-windstorm phase (Figures 4d and 4e). Weak SST anomalies in the Pacific resembling the SST tripole (Peng et al., 2003) are observed in ASO but do not persist to the DJF season. An extratropical response (Figures 4c and 4f) is observed in DJF, particularly in association with the high-hurricane, low-windstorm La Niña composite. Johnson et al. (2019) note the ability of SEAS5 to recreate tropical-extratropical responses over Europe, as observed here. An anomalous high and associated low over the Atlantic region, similar in structure to the NAO, provides a direct pathway between climate influences on the two seasons. The SST pattern and associated atmospheric response described here are replicated across all three intensity measures (nStorms and LiSSSI not shown).

## 4. Conclusions and Discussion

We show here that the the Atlantic hurricane and European windstorm seasons are related in a seasonal forecast model. Probabilistically, an above average Atlantic hurricane season is followed by an above average European windstorm season less often than if they were independent. This finding is confirmed for three separate measures of seasonal intensity. During La Niña (El Niño), enhanced (suppressed) hurricane activity during ASO is followed by suppressed (enhanced) European windstorm activity during DJF. The following pathway is proposed to explain this co-hazard relationship: ENSO, through the well-established modulation of wind shear in the MDR during ASO (Bove et al., 1998; Goldenberg & Shapiro, 1996; Gray, 1984), influences Atlantic hurricane seasonal intensity. The ENSO phase frequently persists from ASO to DJF. Through an extratropical response (Branstator, 2014; Scaife et al., 2017), ENSO excites an NAO-like modulation of the location and intensity of the North Atlantic storm track (Figures 4c and 4f).

To assess this co-hazard relationship, we expand the number of observed storms by employing the seasonal forecast SEAS5. This is a necessary step due to the small number of years for which track data are reliable. It is worth noting, however, that the limited evidence from observations supports the conclusions of this

study (Lloyd's, 2016). Although the relationship was observed in three separate intensity measures, some asymmetries were observed in the nStorms and LiSSSI response. The number of observed European windstorms following an above average hurricane season is more significantly related than following a below average season. This implies the response of European windstorms is more strongly influenced by La Niña than El Niño, supported by the difference in extratropical response (Figures 4c–4f). Conversely, the intensity of European windstorms over the continent is only impacted during above average years. This may be explained by the location of the storm track (Figure 3). During lower than average European windstorm seasons, the storm track is shifted northward, and the total accumulated SSI over Europe is not statistically different from normal. During above average years, however, the storm track is shifted south over continental Europe demonstrated by the clear hurricane-windstorm LiSSSI co-hazard relationship. This agrees well with the findings of Schemm et al. (2018), who attribute decreased cyclogenesis over the Gulf Stream region to La Niña, accompanied by increased cyclogenesis further north near Greenland, as observed in Figures 3a and 3c.

El Niño events have previously been shown to correlate with the negative NAO phase (Brönnimann et al., 2007; Drouard et al., 2015; Li & Lau, 2012a, 2012b), which would imply the opposite co-hazard relationship to our findings. We explain this apparent contradiction by referring to Moron and Gouirand (2003), who show that the phase of the ENSO-NAO relationship is dependent on whether early (November–December) or late (January–March) winter is used to calculate the NAO. The prior findings are based on this late winter period, whereas the 700 mbar GHT response in SEAS5 shown in Figure 4 remains consistent throughout December–February. The exact nature of the nonstationary (Knippertz et al., 2003; López-parages et al., 2015; Rodríguez-fonseca et al., 2016) ENSO-NAO relationship is a subject for further study.

The pathway we propose explaining the observed numerical relationship between the two hazard seasons is defined post hoc by examining the associated climate of those model years exhibiting the strongest signal. One possible source of bias is the Atlantic SST in SEAS5 during DJF, which is significantly too warm in the Gulf Stream exit region (Johnson et al., 2019). Baroclinic instability introduced through an unrealistic SST Atlantic gradient may impact the location and intensity of the SEAS5 North Atlantic storm track, biasing the frequency and location of observed European windstorms. While the ENSO response observed is robust, further work will focus on replicating the co-hazard relationship in SST prescribing numerical models. This would also address the impact of ENSO intensity unaccounted for here. The covariability of the two extreme wind hazards has important implications for both the actuarial and seasonal forecasting communities, and we encourage further study of the predictive implications.

### Data Availability Statement

Data sets for this research are available in Knapp et al. (2010), (IBTrACS freely available from <https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C01552>), Dee et al. (2011), and Johnson et al. (2019) (both ERA-interim and SEAS5 available with academic license from the ECMWF Meteorological Archival and Retrieval System). Data created in the results section are available at the University of Birmingham eData repository (<https://doi.org/10.25500/edata.bham.00000569>).

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