On the dependency of Atlantic Hurricane and European Windstorm Hazards

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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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Abstract

The Atlantic Hurricane season and the European Windstorm season are found to be co-related 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 extra-tropical response in the seasonal forecast model to El Niño/La Niña provides a probable pathway for the observed co-relation 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 East Coast. In the Winter, Windstorms form in the mid-latitude regions primarily impacting Europe. These two seasons are traditionally considered to be independent of one another. Here we present evidence that the two are linked through the climate system, specifically the El Niño Southern Oscillation. 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 (Lim et al., 2018; Hallam et al., 2019) 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). While essential to understanding climate dynamics, information may be missed through this cause and effect approach by not considering the non-linear nature of the climate system. Alternatively, the interannual variability of extreme seasons may be considered as part of a network driven by interannual climate modes (Gill & Malamud, 2014, 2017; Steptoe et al., 2018). This has the advantage of providing stakeholders and policy makers with information for decision making across multiple hazards, as opposed to assessing each risk individually.

In the same 2017 season, the combined insured loss from Atlantic hurricanes and European windstorms was estimated at $100 billion, primarily due to the 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.

While it may seem counter-intuitive to investigate teleconnections between tropically-forming predominantly late summer hurricanes and extratropical winter European windstorms, there is good reason to believe they may be linked. Despite the geographical and temporal distance between the seasons, the El Niño Southern Oscillation (ENSO) has previously been associated with both. ENSO modulates the favourability of Atlantic hurricane development conditions through suppressed (La Niña) or enhanced (El Niño) wind shear (Gray, 1984; Goldenberg & Shapiro, 1996; Bove et al., 1998; Vitart & Anderson, 2001; Latif et al., 2007; Villarini et al., 2012). For European windstorms, the North Atlantic Oscillation (NAO) is well established as an important factor for development (Hurrell, 1995; Pinto et al., 2009), with more cyclones impacting Europe during the positive phase (Donat et al., 2010). The NAO is not the only influence on European windstorm variability however, with a multitude of large-scale climate drivers thought to play a role (Mailier et al., 2006; Hunter et al., 2016; Walz et al., 2018). Several authors have explored how ENSO impacts both European weather and the North Atlantic storm track.

ENSO produces an extratropical response through Rossby wave propagation (Held et al., 1989; Branstator, 2014; Stan et al., 2017). Dong et al. (2000) examined the impact of the 1997/98 El Niño and 1998/99 La Niña on Europe through this mechanism, showing a local asymmetrical circulation response to the phases of ENSO in an Atmospheric Global Circulation Model (AGCM). European temperature and precipitation anomalies associated with ENSO are spatially similar to those associated with the NAO (Pozo-Vázquez et al., 2001; Pozo-Vázquez et al., 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 to ENSO over Europe in a 500 year reconstruction, modulated by the North Pacific climate. Similarly, Li and Lau (2012a), Li and Lau (2012b) and Drouard et al. (2015) found that Sea Surface Temperature (SST) changes in the North Pacific associated with El Niño events force a stationary Rossby wave train inducing negative NAO events. Due to the establishment of ENSO events months in advance of boreal winter, this tropical to extra-tropical connection has shown predictive skill in seasonal forecasts (Toniazzo & Scaife, 2006; Scaife et al., 2014; Dunstone et al., 2016; Scaife et al., 2017), however this is complicated by the non-stationary nature of the ENSO-North Atlantic signal (Knippertz et al., 2003; López-parages et al., 2015; Rodríguez-fonseca et al., 2016). In addition to the Rossby wave train mechanism, the stratosphere has also been show to play an active role in the European response to ENSO (Ineson & Scaife, 2008; Bell et al., 2009).

Given the importance of the NAO in modulating the location of the North Atlantic storm track (Pinto et al., 2009; Donat et al., 2010), 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 and south-western Europe. Merkel and Latif (2002) successfully simulated this result using an AGCM, but stress that the opposite conditions during a La Niña could not be recreated. Schemm et al. (2018) examined the impact of ENSO phase on cyclogenesis in the North Atlantic and continental United States. Over Europe, they found competing effects 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 in southern Europe during El Niño.

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 (approximately 1980-present). Detecting a signal between the two seasons is therefore non-trivial. To address this issue, we use an Ensemble Prediction System (EPS), to increase the number of "observations" by including storms which were forecast by a multimember ensemble. Assuming the model is a reasonable representation of the climate system, this allows for a wide range of theoretically possibly storm events and a much larger sample size. An overview of this methodological approach is provided by Osinski et al. (2015).

We take this approach to establish whether co-variability exists between the North Atlantic hurricane season and the European windstorm season. We aim to answer the following questions: does an active Atlantic tropical cyclone (TC) season increase the probability of an active extratropical cyclone season over Western Europe, or vice versa? If so, how are these two seasons related dynamically?

2 Data and Methods

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 Renggli et al. (2011); Kruschke (2015); Befort et al. (2020)). 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) also show the majority of high impact TCs can be captured by this method. TCs are excluded beneath an area of 15,000km^2, while European Windstorms are excluded beneath an area of 130,000km^2. WiTRACK is otherwise applied to each season using the setup defined in Kruschke (2015).

Tracking is performed on merged 10m wind speed of both the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis ERA-interim (Dee et al., 2011) and the latest ECMWF seasonal forecast, SEAS5 (Johnson et al., 2019). For both data sets, analysis covers the period 1981-2016, with all 51 ensemble members of SEAS5 tracked. SEAS5 is initalised from ERA-interim atmospheric conditions and state-of-the-art Land and Ocean models, (Johnson et al., 2019)) on the first of every month. For this analysis, our most important consideration was maintaining a consistent model climate between the two seasons. We therefore chose each model year initalised on the first of August, covering the peak seasons for both Atlantic hurricanes (Blake et al., 2007), August-October (ASO) and for European Windstorms (Roberts et al., 2014), December to February (DJF). In total, 1836 (51x36) model years from SEAS5 were tracked. SEAS5 has a spectral horizontal resolution of T319, approximately 36km. The spectral resolution of ERA-interim is T255, approximately 79km. Additionally to the tracked 10m u and v winds, SST and 700mb Geopotential Height (GHT) from the same SEAS5 initialisation are used for further analysis.

To constrain the tracks to only TCs, a number of geographical filters were applied over the August to October period. This step was necessary to remove spurious Extra-Tropical cyclones. A similar geographical filter approach was applied successfully by Befort et al. (2020) to identify high impact Pacific Cyclones. The filters were selected to remove tracks which did not meet the observed track climatology from The International Best Track Archive for Climate Stewardship (IBTrACS) v03r10 (Knapp et al., 2010). Tracks were removed where: the origin of the track occurred in the Pacific rather than the Atlantic, 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. Constraints were also placed on European Windstorm tracks. In this case, the filters were designed to remove those storms which did not impact Europe. 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 are considered matched where the following criteria are fulfilled: a temporal overlap of at least 4 time steps, with a distance between track centres below 400km, and a mean distance of less than 1000km over the entire track. To compare track density between IBTrACS, ERA-Interim and SEAS5, the number of storms per grid cell over a 0.75x0.75 degree grid was calculated.

We calculate three separate measures of intensity for each season. The first is simply the number of tracks or events, 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 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 extreme seasons, we adopt a probability of independence approach. For a given threshold, the independent probability that the seasonal intensity of both the Atlantic Hurricane and European Windstorm season exceed that threshold is calculated, determining an expected number of model initialisation 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. To assess significance, bootstrapping (Hall & Horowitz, 1996; Horowitz, 2001; Marchand et al., 2006; Feng et al., 2011) is applied to generate 1000 random samples from the seasonal intensities within the full model ensemble of August initalisations. A 95% confidence value is drawn from the bootstrapped random sample distribution, and relationships are considered significant where this value is exceeded.

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; Renggli et al., 2011; Kruschke, 2015; Osinski et al., 2015; 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°N-40°N, 90°W-30°W. There are clear track density differences in the main development region (MDR, 10°N-20°N, 80°W-20°W) and north of 40°N in the cyclolosis 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 US East Coast (difference of approximately 1 cyclone per year) gives us confidence that the climatology of mature cyclones is well represented. Track Density is averaged 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). 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, 85% of hurricanes which reached category 3 on the Saffir-Simpson Scale and 61% of hurricanes which reached category 2 were matched successfully. Lower intensity TCs are matched 33% of the time, while only 6 of 58 tropical depressions (6%) were matched.

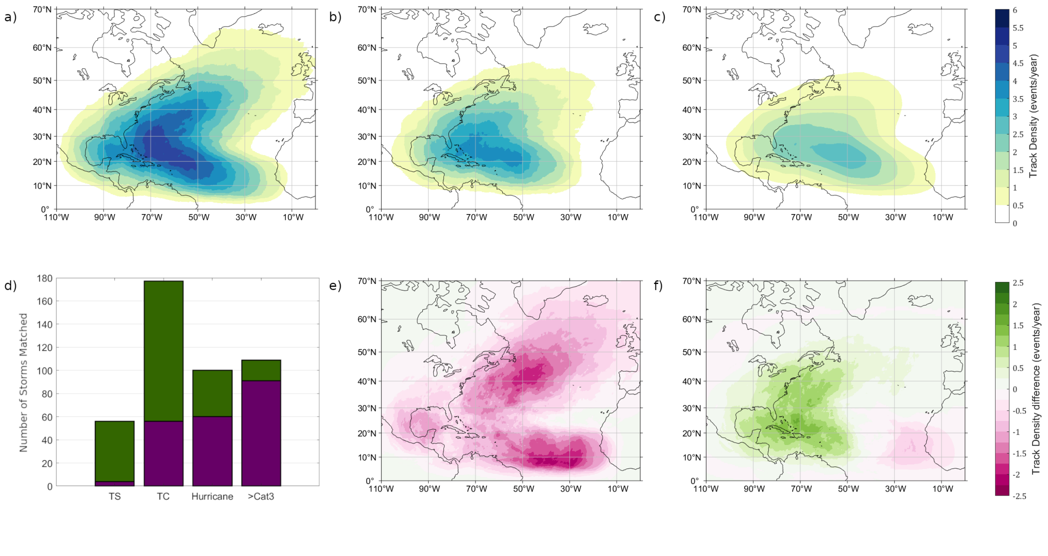

Figure 1. Track Density per year of TC events in a) IBTrACS, b) WiTRACK ERA-interim c) WiTRACK SEAS5. d) Matched events between IBTrACS and WiTRACK ERA-interim for Tropical Depressions (TS), Tropical Cyclones (TC), Category 1-2 Hurricanes (Hurricane) and Category 3-5 Hurricanes (Cat3). All categorizations 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.

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 excellent agreement with those of Befort et al. (2020), who found an overall hitrate of 62% and an intense storms hitrate of 85%. The performance of WiTRACK for Atlantic TCs is therefore very similar to the performance in tracking Pacific TCs, with clear skill representing higher category storms.

3.2 Atlantic Hurricane and European Windstorm co-relation

3.2.1 Assessment of Independence

For all three intensity measures (nStorms, SSSI, LiSSSI), we find statistically significant differences from independent probability. Intensity distributions are first calculated for each hazard season independently. For a wide range of seasonal intensity thresholds, the independent probability that the number of Hurricane seasons and the number of European Windstorm seasons will fulfil that threshold is then compared to the observed number of SEAS5 model years which actually fulfil the threshold (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 represents an intense Hurricane season and weak European Windstorm season, top right the case where both are more intense than the mean, bottom left where both are weaker than the mean, bottom right where European Windstorms are more intense and Hurricanes less intense. Coloured boxes indicate where more (green) or less (pink) seasons meeting this threshold occurred in the SEAS5 ensemble. For example, of the 1836 model years we find 11 or more TC events in 151 cases, (8.22%). We find 16 or more European Windstorms in 210 model years (11.4%). If the two seasons are independent, we would therefore expect both 11 or more TCs **and** 16 or more European windstorms in the same model year .94% of the time, or in 17.25 model years. The dark pink shading indicates that the true value lies between 30 and 45% less than that (actually 11 model years). This is statistically significant at the 95% confidence interval based on a bootstrap of 1000 random samples.

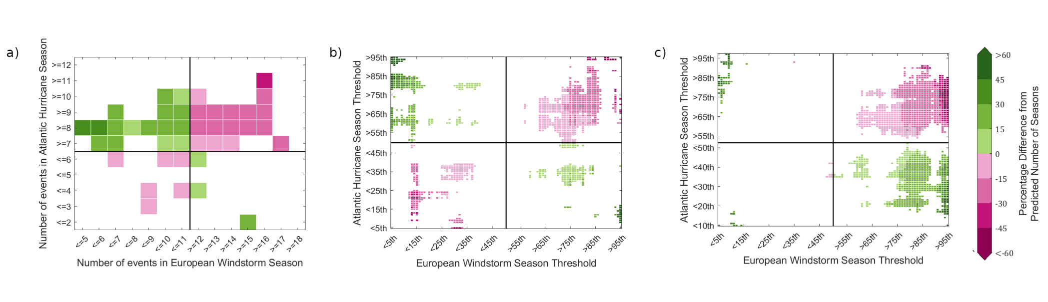

Figure 2. Percentage difference between number of seasons which meet the shown thresholds and the expected statistically independent value for a) nStorms b) SSSI c) LiSSSI. Grid cells shown where the difference from independent predicted value exceeds the 95th% confidence interval, derived from a random sample of 1000 independent seasons.

There is a clear pattern in figure 2 of fewer seasons than predicted where the sign of intensity agrees and more seasons than predicted where the sign of intensity disagrees. 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 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 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 the response of the North Atlantic storm track to the NAO, with similar centres of action (Walz et al., 2018).

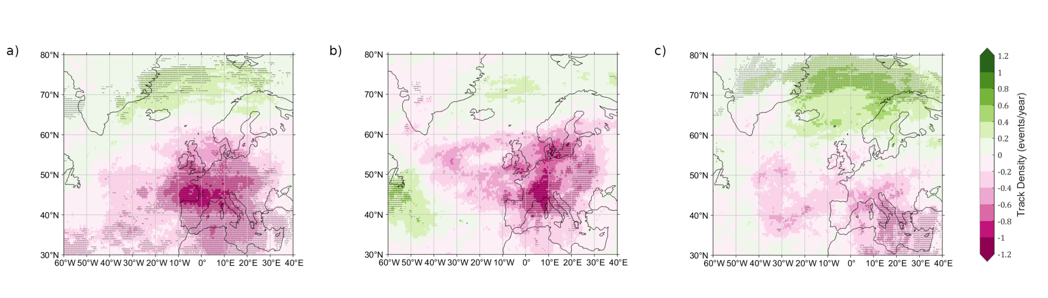

Figure 3. European Windstorm Track Density difference between model years with top 10% hurricane intensity and bottom 10% hurricane intensity for a) nStorms b) SSSI c) LiSSSI. Stippling represent where the difference from independent predicted value exceeds the 95th% confidence interval, derived from a random sample of 1000 independent seasons.

3.2.2 Physical mechanism explaining dependence

ENSO is the dominant SST pattern associated with the SSSI Hurricane-Windstorm hazard co-relation (Figure 4). A persistent La Niña pattern in both ASO and DJF is associated with the high-hurricane, low-windstorm phase of the relationship (Figure 4a,b) while El Niño is associated with the opposite low-hurricane, high-windstorm phase (Figure 4d,e). 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 Extra-Tropical Rossby wave like response (Figure 4c,f) 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-Extra Tropical responses over Europe, similar to the pattern 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 is replicated across all three intensity measures (nStorms and LiSSSI not shown).

4 Conclusions and Discussion

Where previously the Atlantic hurricane and European windstorm season had been considered independent, we show here that the two hazards 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 (Gray, 1984; Goldenberg & Shapiro, 1996; Bove et al., 1998), influences Atlantic hurricane seasonal intensity. The ENSO phase frequently persists from ASO to DJF. Through an extra-tropical response (Branstator, 2014; Scaife et al., 2017), ENSO excites an NAO-like modulation of the location and intensity of the North Atlantic storm track (Figure 4c and f).

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 is reliable. It is worth noting however that the limited evidence from observations supports the conclusions of this study. Lloyd's (2016) find a small but significant negative correlation between US TC risk and EU flooding, of the same magnitude as the correlation between IBTrACS and WiTRACK ERA-interim over

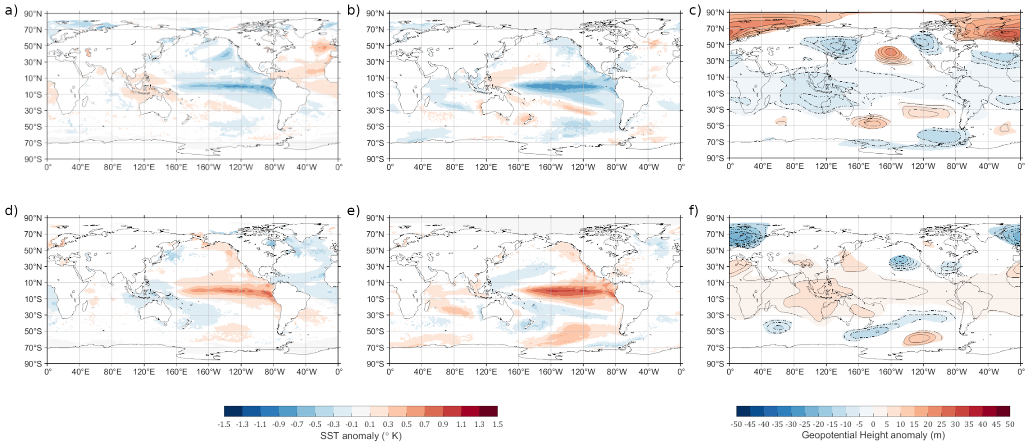

Figure 4. a) SST Composite of top 10% ranked difference between Hurricane SSSI and Windstorm SSSI during ASO (above average hurricane season, below average windstorm season). b) as in a), during DJF d) and e) as in a) and b), for bottom 10% ranked difference (below average hurricane season, above average windstorm season). c) and f) corresponding 700mb GHT composite during DJF. Grid cells shown where the difference from independent predicted value exceeds the 95th% confidence interval, derived from a random sample of 1000 independent seasons.

1981-2016 (-0.2). While conclusions should not be drawn from such a limited sample size, it is nevertheless encouraging that the sign of the correlation supports our findings.

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 extra-tropical response (Figure 4c-f). 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 northwards 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.

El Niño events have previously been shown to co-relate with the negative NAO phase (Brönnimann et al., 2007; Li & Lau, 2012a, 2012b; Drouard et al., 2015), 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 700mb GHT response in SEAS5 shown in figure 4 remains consistent throughout December-February. The exact nature of the non-stationary (Knippertz et al., 2003; López-parages et al., 2015; Rodríguez-fonseca et al., 2016) ENSO-NAO relationship is a subject for further study. The results presented here do agree well with the shift in storm track towards southern Europe associated with El Niño, previously found by Fraedrich and Müller (1992), Merkel and Latif (2002) and Schemm et al. (2018).

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. 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 co-variability 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.

Acknowledgments

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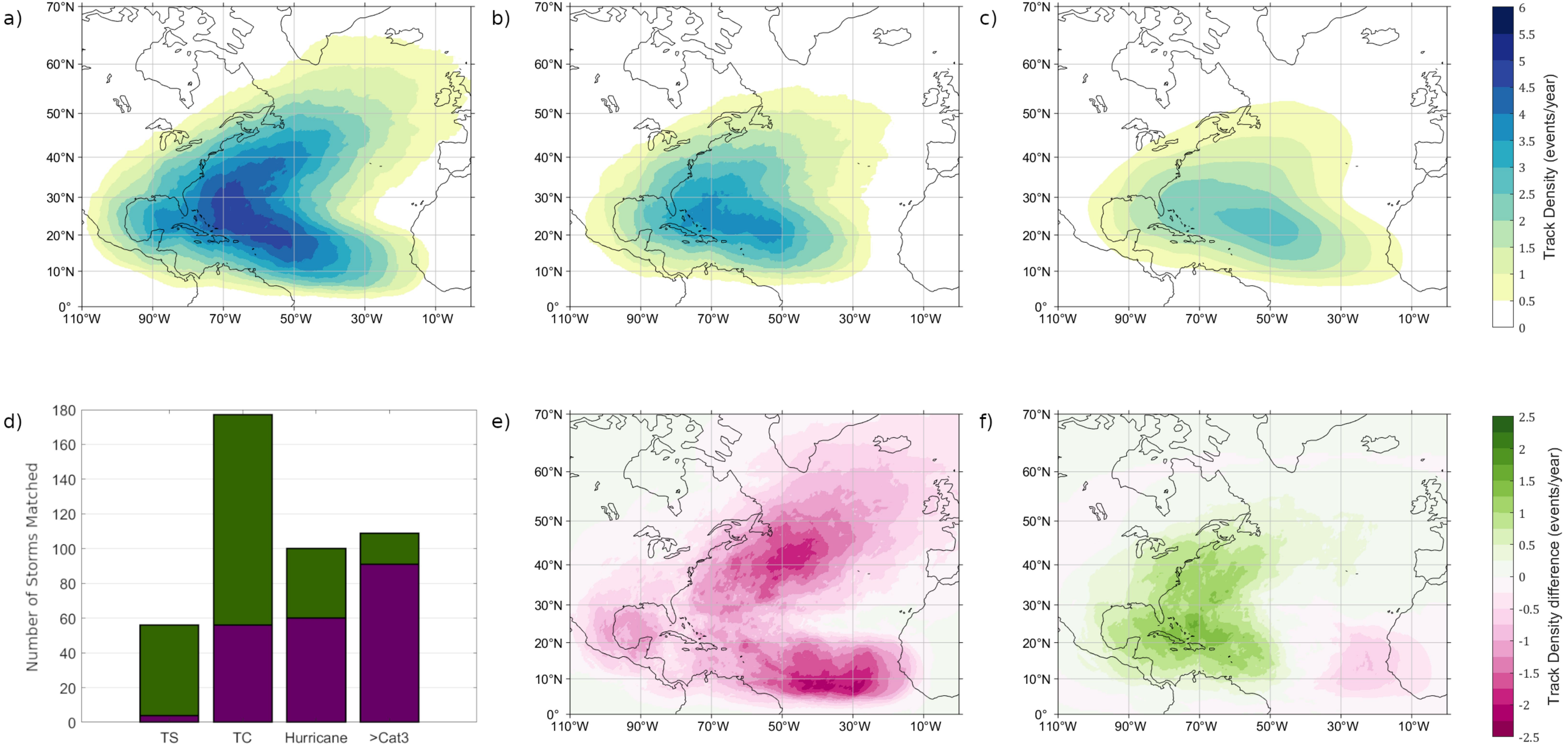
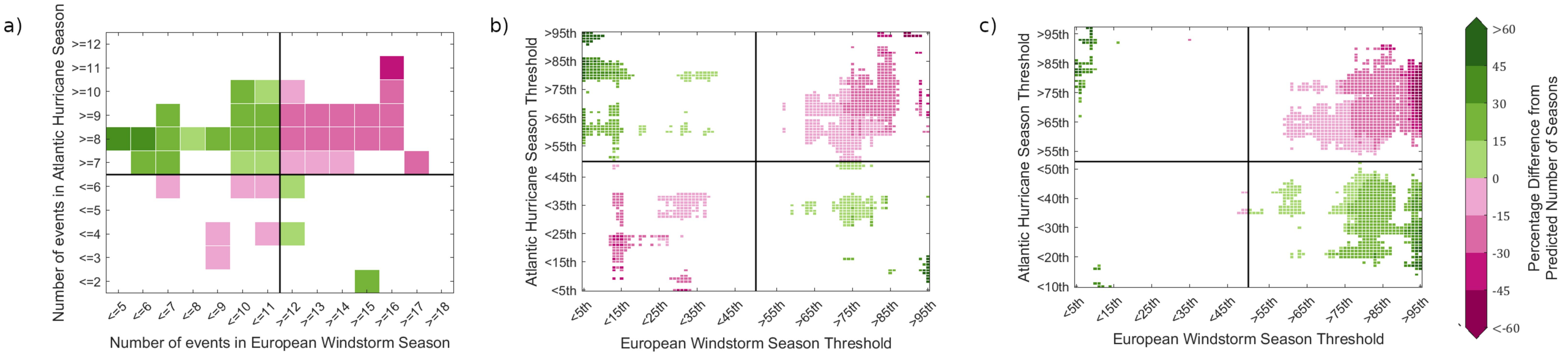
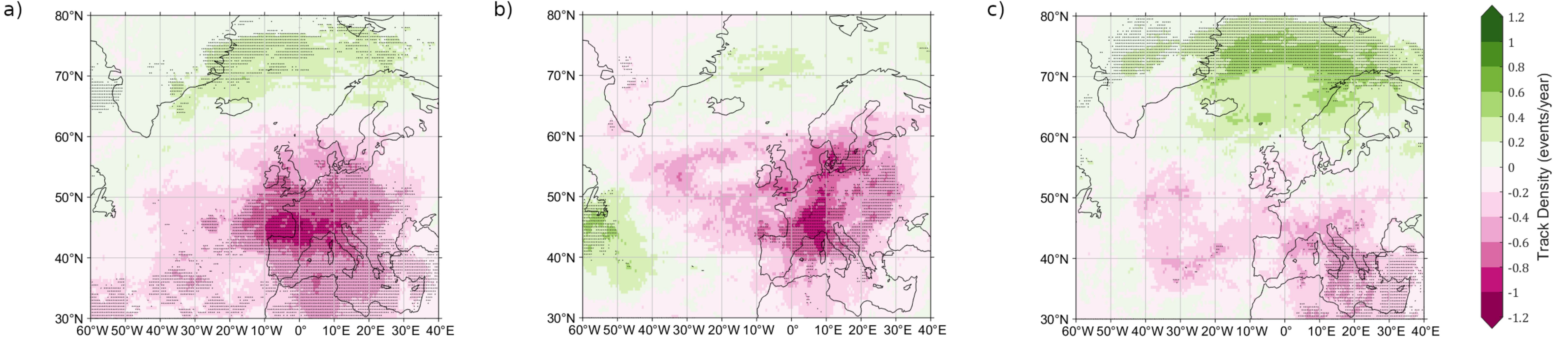
TC_ETC_D1_fig1.png.


a)
b)
c)
d)
e)
f)
70°N
60°N
50°N
40°N
30°N
20°N
10°N
0°
110°W
90°W
70°W
50°W
30°W
10°W
Track Density (events/year)
Track Density difference (events/year)
Number of Storms Matched
TS
TC
Hurricane
>Cat3

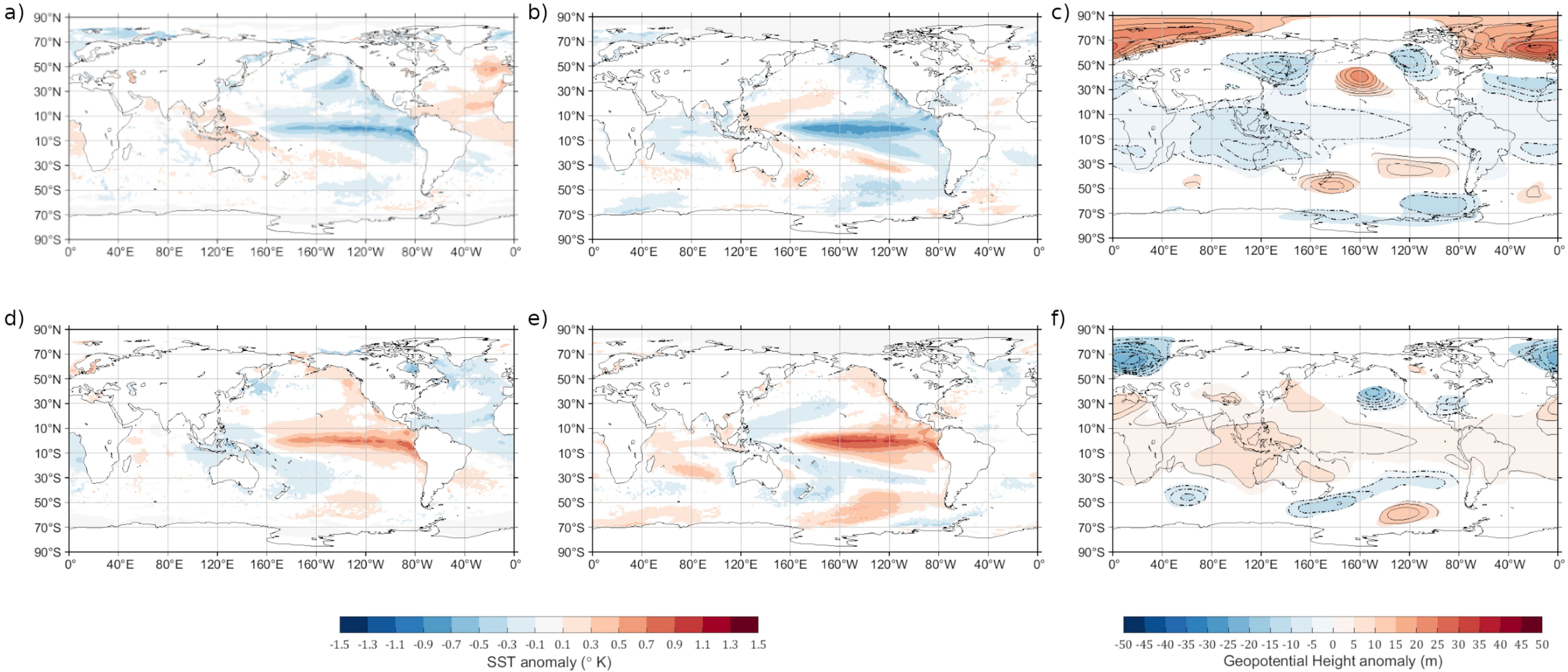
TC_ETC_D1_fig3.png.


a)
Number of events in Atlantic Hurricane Season
>=12
>=11
>=10
>=9
>=8
>=7
<=6
<=5
<=4
<=3
<=2
<=5
<=6
<=7
<=8
<=9
<=10
<=11
>=12
>=13
>=14
>=15
>=16
>=17
>=18
Number of events in European Windstorm Season
b)
Atlantic Hurricane Season Threshold
>95th
>85th
>75th
>65th
>55th
<45th
<35th
<25th
<15th
<5th
<5th
<15th
<25th
<35th
<45th
>55th
>65th
>75th
>85th
>95th
European Windstorm Season Threshold
c)
Atlantic Hurricane Season Threshold
>95th
>85th
>75th
>65th
>55th
<50th
<40th
<30th
<20th
<10th
<5th
<15th
<25th
<35th
<45th
>55th
>65th
>75th
>85th
>95th
European Windstorm Season Threshold
>60
45
30
15
0
-15
-30
-45
<-60
Percentage Difference from Predicted Number of Seasons

TC_ETC_D1_fig4.png.


a)
b)
c)
80°N
70°N
60°N
50°N
40°N
30°N
60°W 50°W 40°W 30°W 20°W 10°W 0° 10°E 20°E 30°E 40°E
Track Density (events/year)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2

TC_ETC_D1_fig5.png.


a)
b)
c)
d)
e)
f)
90°N
70°N
50°N
30°N
10°N
10°S
30°S
50°S
70°S
90°S
0°
40°E
80°E
120°E
160°E
160°W
120°W
80°W
40°W
0°
-1.5 -1.3 -1.1 -0.9 -0.7 -0.5 -0.3 -0.1 0.1 0.3 0.5 0.7 0.9 1.1 1.3 1.5
SST anomaly (° K)
-50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50
Geopotential Height anomaly (m)