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Empirical Evidence for Gulf of Mexico Hurricane Landfall Dispersion

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Abstract

The clustering of hurricanes throughout the Contiguous United States (CONUS) is a poignant topic for risk carriers with interests throughout the US. Questions often asked include: *How likely are multiple hurricane landfalls throughout the US?*, and *Where would these subsequent landfalls be likely to occur?*

This study takes an empirical approach to analyse the intra-annual landfall dispersion of CONUS landfalling hurricanes throughout the Gulf of Mexico (GoM). The study finds that local GoM hurricane landfall co-occurrence is likely under-dispersed relative to what one might assume given a Poisson landfalling model. For coastal segments (termed wind gates) of length scale 556 km, this study also identifies the likely over-dispersion of hurricane landfall co-occurrence in the neighbouring wind gates. The author discusses plausible mechanisms, based on the available literature, however, promotes the need for further work into these proposed mechanisms. For insurance risk carriers the results of this study can impact underwriting decisions surrounding premium rates and risk selection, whilst also informing decisions surrounding outwards reinsurance purchasing. More fundamentally, a shift to non-Poissonian GoM hurricane landfall probabilities will likely impact long-term decisions surrounding portfolio management.

Key Points

1. Hurricanes exhibit a likely reduced landfall co-occurrence probability at the location of a previous Gulf of Mexico landfalling hurricane.
2. Hurricanes exhibit a likely elevated landfall co-occurrence probability nearby, but not at, the location of a previous Gulf of Mexico landfalling hurricane for coastal wind gates of length 556 km.
3. A Poisson distribution is likely inappropriate for modelling hurricane landfall probability throughout the Gulf of Mexico.

1. Introduction

Throughout the North Atlantic basin, environmental conditions have the capacity to modulate a changeable annual frequency of tropical cyclones, both at landfall and throughout the basin. The average annual Atlantic hurricane basin count between 1950-2024 is approximately 6.4, however individual years range from two to 14. The distribution of annual Atlantic hurricane basin frequency is positively skewed, with a prominent right-hand tail and a variance (7.16) in excess of the mean (6.42), signalling the presence of clustering in annual North Atlantic tropical cyclone frequency.

Such a signal would indicate that some years are more favourable to the development of tropical cyclones in the North Atlantic basin than others. Hurricane frequency clustering can be quantified as a case where the variance exceeds the mean in annual Atlantic basin hurricane count, otherwise termed the over-dispersion of hurricane count.

Mitchell & Camp (2021) investigated tropical cyclone dispersion throughout the Pacific and Atlantic basins. The authors found that once correcting for inhomogeneities in the historical record of tropical cyclones, spatial regions of over-dispersion (mean<variance), under-dispersion (mean>variance) and equi-dispersion (mean=variance) were identified for tropical cyclone count. To more appropriately model this, the authors leveraged a parametric distribution called the Conway -Maxwell-Poisson distribution to better represent the distribution of seasonal tropical cyclone counts, as the Conway-Maxwell-Poisson distribution can model any dispersion characteristic.

The authors found that towards the coastlines of the Northwest Pacific and Atlantic basins, there exists evidence of equi-dispersion (mean = variance), or even under-dispersion, whereas overdispersion dominated throughout offshore basin regions.

Complementary to the analysis of Mitchell & Camp (2021), Jagger & Elsner (2012) investigated the dispersion of US landfalling hurricanes throughout spatially vast Contiguous United States (CONUS) landfalling regions, namely the Gulf of Mexico (hereafter GoM) Coast, Florida and the East Coast.

For the East Coast and GoM, the authors found no evidence of over-dispersion, whilst for Florida, over-dispersion in hurricane landfall count was identified.

Jagger & Elsner (2012) find that the presence of hurricane clusters impacting Florida is related to atmospheric steering mechanisms. The authors find that the North Atlantic Oscillation (NAO), which relates to the position and strength of the Bermudan high, also termed the North Atlantic subtropical high-pressure system (NASH), is a statistically significant covariate in their hurricane cluster rate model for Florida. This is a result consistent with multiple studies on the regional clustering (over-dispersion) of hurricane landfalls (Mazza & Chen, 2023; Pérez-Alarcón *et al*., 2021; Corporal-Lodangco *et al*., 2014; McCloskey *et al*., 2013).

Temporally, synoptic systems, such as the NASH, often outlive the hurricanes caught in their currents and hence have the capacity to influence the tracks of multiple storms. Perez-Alarcon *et al*. (2021) investigated the role of the NASH on explainable variance in hurricane landfall at five US, Caribbean and Central American landfalling regions. The authors found that both the longitude and the latitude of the NASH significantly ($p<0.05$) influences landfall probability in three landfilling regions, including the GoM.

The regionality of North Atlantic hurricane landfalls was also investigated by Corporal-Lodangco *et al.* (2014), who used clustered hurricane genesis, track and decay regions to explain spatial and temporal variability in tropical cyclone tracks. The authors find large dependencies in track location on genesis region throughout the 1950-2012 period, with storms developing further south and west more likely to result in a GoM landfall. Additional studies have highlighted the importance of genesis location in determining hurricane track and eventual landfall location, with Sainsbury *et al*., (2022) and Kortum *et al*., (2024) both highlighting genesis location as the dominant covariate in describing track behaviour, specifically in relation to hurricane recurvature in the Atlantic basin. Corporal-Lodangco *et al*. (2014) also identify the importance of steering flows in dictating the regionality of hurricane landfalls.

They find that storms at higher latitudes tend to recurve away from the CONUS, whereas storms further south and westward towards the GoM are more likely to propagate towards the CONUS, Caribbean and Central American regions. This dependence of latitude on hurricane recurvature was investigated by McClosky *et al*, (2013), who calculated a recurvature index (RI), with greater values indicating a less zonal hurricane track. McClosky *et al*., (2013) identified that hurricanes not making landfall at all were associated with the greatest RI, with hurricanes making landfall to the north of the state of Georgia exhibiting the second highest RI. The dependence of RI on hurricane latitude is further emphasised with the Caribbean and GoM landfalling storms exhibiting the lowest RI values.

Beyond steering currents, in the North Atlantic, extratropical cyclones can influence one another through dynamical linkage. So called ‘serial clustering’ (Dacre & Pinto, 2020) describes how a primary cyclone may condition the atmosphere for secondary cyclones along trailing fronts of these systems.

For non-frontal tropical cyclones, the concept of hurricane-linkage becomes more tenuous. A well-studied example of tropical cyclones interacting is through the ‘Fujiwhara effect’ (Fujiwhara, 1921; Dong & Neumann, 1983), where nearby tropical cyclones can influence one another’s tracks. Aside from the Fujiwhara effect, little is understood of how tropical cyclones may influence one another’s lifecycles.

It has long been understood how tropical cyclones can influence their local environment through the medium of the ocean. Both Price (1981) and Cione & Uhlhorn (2003) demonstrated how storms can detrimentally impact sea surface temperatures (SSTs) in their wake primarily through the upwelling of cooler waters and evaporative heat loss to the atmosphere.

Through such mechanisms, Lee and Veeramony (2024) show a persistent reduction in GoM upper ocean heat and a deepening of the upper ocean mixed layer following Hurricane Katrina (2005).

They find that not only did Hurricane Katrina materially deepen the oceanic mixed layer and cool SSTs, but the suppression was found to persist such that the mixing layer depth throughout the GoM rebounded to only 84% of its pre-storm depth 18 days following storm passage.

It has also been long known how large a role upper ocean heat content plays on hurricane genesis and development (Palmen, 1948), hence any reduction of available energy could feasibly result in a reduced probability of subsequent hurricane genesis and intensification (Leipper & Volgenau, 1972).

Karnauskas *et al*., (2021) investigated the hypothesis that tropical cyclone activity is suppressed by remnant cold wakes left by previous storms (namely resimulations of hurricanes Helene and Florence in 2018).

The authors find that the frequency of low to medium intensity storms decreases as a response to cold wake interaction, whilst the frequency of subsequent very intense (category 5) events is increased. A stated potential rationale for an increase in the most intense storms is a reduction in upwelling ahead of a storm influenced by a cold wake, resulting in enhanced intensification post cold wake interaction.

It is worth noting that although the study does show evidence of dynamical linkage between the cold wakes of hurricanes Helene and Florene and a suppression of future hurricane count in proximity to the original storms (Floridian and Carolina regions), the study does not investigate this phenomenon for the GoM, which is the chosen region for this study.

The principal aim of this study is to investigate empirical signals of intra-annual dispersion in hurricane landfalls, at various spatial scales throughout the GoM. The focus of this study is to elucidate on any signals of under-dispersion, over-dispersion and equi-dispersion in hurricane landfall frequency and as such this author does not present any evidence of causal pathways. Rather, this author leverages the discussion to hypothesise potential mechanisms to explain the results of this study and emphasises the importance of further work to explain the mechanisms driving the results presented in this study, with context to an insurance risk carrier.

2. Methodology

2.1 Determining Regional Clustering at Various Spatial Scales

This study investigates whether hurricanes are more or less likely to make landfall along coastal GoM CONUS segments, termed wind gates, conditional on a storm making landfall at another wind gate within the same hurricane season, termed conditional landfall. For each hurricane within the National Hurricane Centre Hurricane Database V2 (hereafter HURDAT2) (Landsea & Franklin, 2013), the landfall location was determined as the landfall of maximum intensity, as determined by 1-minute sustained wind speed. For example, in the case of multiple-landfalling Hurricane Katrina (2005), the Louisiana landfall was retained, as opposed to the lower intensity Floridian landfall. Landfall locations were subset into 50 nautical mile (93 km) coastal wind gates throughout the entire east CONUS coastline.

This study focuses on GoM only, given the higher landfalling base rate, relative to the Atlantic Ocean facing coastline. Whilst the author acknowledges data sparsity remains an issue within the GoM, the issue is not perceived to be inhibitive to this study's conclusions in the same way as it would be along the Northeast CONUS Atlantic coastline.

This study leverages multiple aggregation levels whereby neighbouring 93 km coastal wind gates are aggregated to form less granular wind gates. Figure 1 shows two such aggregation levels for the GoM. The highest granularity leveraged within this study is a single 93 km wind gate, whilst the least granular is an aggregation of eight wind gates.

Shown in red in Figure 1 are the three gate (a) and eight gate (b) wind gate aggregations. Figure 1 also shows this study's analysed region, which is displayed as the combination of the black and red CONUS coastline, with the grey coastline omitted.

Within each wind gate aggregation, the maximum number of non-overlapping wind gates are leveraged for this study's analysis.

Therefore, for wind gates comprised of three 93 km wind gates (Figure 1a), there are eight combinations: $[WG_i{:}WG_{i+2}, WG_{i+3}{:}WG_{i+5}, \ldots, WG_{n-2}{:}WG_n]$, where n = 24.

More generally, the number of wind gates at each granularity (N) can be derived by the following equation:

$$N = \left\lfloor \frac{24}{G} \right\rfloor$$

where G stands for granularity and represents the number of 93 km wind gates within each aggregate wind gate.

This study explicitly investigates hurricane landfall probability, conditional on a landfall having also occurred that year and does so over the 172-year period 1851-2022. Between each wind gate pair within the GoM, at each wind gate granularity and each year, a binary value is obtained to indicate a conditional hurricane landfall, with 1(0) indicating co-occurrence has(not) occurred.

This study focuses on hurricane co-occurrence both within a single wind gate and between neighbouring wind gates. In many instances throughout the GoM, two neighbouring wind gates will exist for a single independent (termed local) wind gate, unless the local wind gate is positioned at the spatial extent of the GoM study region, in which case one neighbouring gate will exist. In all instances, the presence of co-occurrence at any neighbouring wind gate, regardless of whether both neighbouring gates received a hurricane landfall in that year, will result in a binary value of 1, with no values greater than 1 assigned. Furthermore, multiple conditional landfalls throughout a single wind gate would still result in a value of 1 for that given year. This author did investigate, however chose not to present, the statistics surrounding multiple conditional landfalls, with yearly co-occurrence values exceeding 1 in some cases. Following this alternative methodology, the conclusions were found to be sensitive to individual historical years, such as 2020. By assigning a maximum co-occurrence value of 1, the conclusions of this study are not sensitive to the inclusion/exclusion of any historic year.

Due to this study's design, one would expect a higher probability of a neighbouring wind gate co-occurrence than a local wind gate co-occurrence, due to the presence of one/two dependent wind gates in the local/neighbouring case. Figure 2 shows an idealised schematic of this study's wind-gate framework. In all instances, the lengths of local and neighbouring wind gates are defined by the wind gate aggregation level, with multiple aggregation length scales leveraged for this analysis.

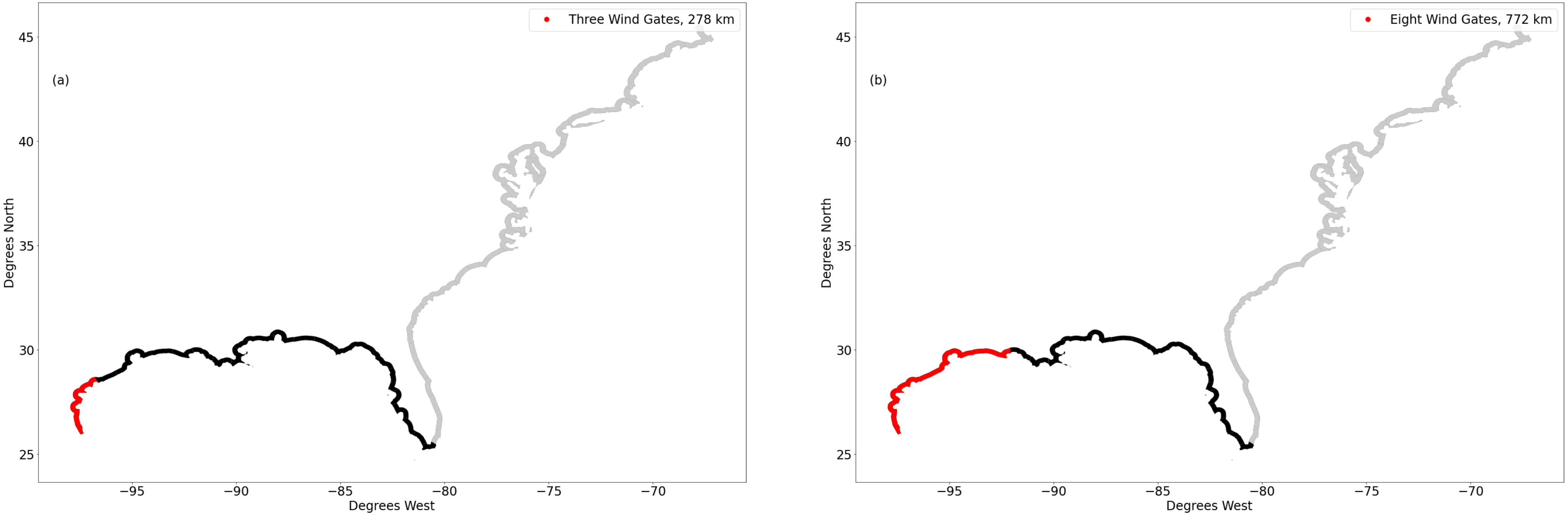

Figure 1: *Eastern CONUS coastline divided into aggregated wind gates, each of 93 km in length. Aggregations shown in red for the Gulf of Mexico coastline are for: a) three wind gates (~278 km) and b) eight wind gates (~741 km).*

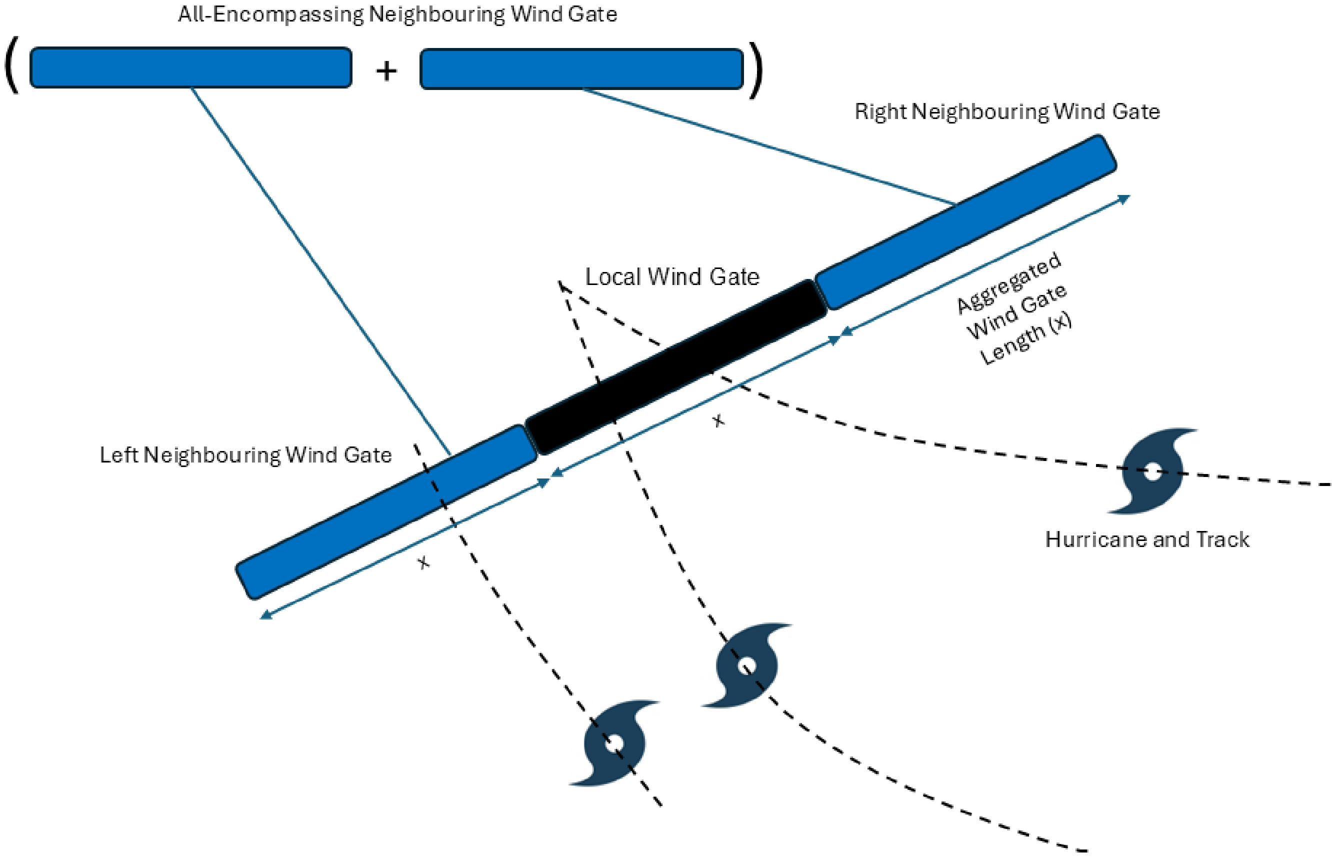

Figure 2: *Schematic illustrating a plausible scenario of hurricane landfalls throughout an active hurricane season. Three hurricane landfalls are shown, two within a local wind gate and one within the left neighbouring wind gate. Conditional on a hurricane making landfall at the local wind gate, one can state that hurricane landfall co-occurrence has occurred at both the left neighbouring wind gate and the local wind gate. An all-encompassing neighbouring wind gate is shown as the combination of the right and left neighbouring wind gates.*

If all hurricanes shown in Figure 2 were to have occurred within one hurricane season, the following would apply:

- The local wind gate would be assigned a binary value of 1 for that year, indicating local hurricane co-occurrence.
- The left neighbouring wind gate would be assigned a binary value of 1 for that year, indicating hurricane co-occurrence.
- The right neighbouring wind gate would be assigned a binary value of 0 for that year, indicating no hurricane co-occurrence.
- An all-encompassing neighbouring wind gate, which comprises of the left and right wind gates would be assigned a value of 1, as the maximum of the left and right binary values.

At each wind gate granularity, historical landfall probability was calculated for the aggregate wind gate, conditional on landfall at each other aggregate wind gate. Two statistics are subsequently derived:

1. **Local hurricane co-occurrence binary total.** For a given wind gate aggregation level, the number of years with a local wind gate co-occurrence are totalled for each of the constituent wind gates at that aggregation level. For an aggregation level of three wind gates, this would result in the sum of eight sets of 172 binary values.

2. **Neighbouring hurricane co-occurrence binary total.** This corresponds to the sum of the number of years (from 172) with a hurricane landfall occurring in a neighbouring wind gate, conditional on a landfall occurring at the local wind gate. As specified above, the right-neighbouring and left-neighbouring wind gates are assigned values of 1 for a hurricane co-occurrence, but for an all-encompassing conditional neighbouring landfalling number, the maximum of the binary value for the left and right neighbouring gates is taken.

   For the left-most and right-most wind gates, only the right and left neighbouring wind gates respectively will factor into this calculation. This statistic is calculated for each of the constituent wind gates at that aggregation level. For an aggregation level of three wind gates, this would result in the sum of eight sets of 172 binary values.

2.2 Confidence Thresholds

In addition to the calculation of historical conditional landfall probabilities, 10,000 Poisson simulations for these statistics are also calculated, where the landfalling wind gates from the HURDAT simulation were randomly shuffled (sampled without replacement) for each simulation. The results from these Poisson simulations are presented alongside the statistics derived from the historical dataset. In accordance with the confidence intervals specified in the IPCC Fifth Assessment Report Summary for Policymakers (Mastrandrea *et al*., 2010), this study uses the same terminology to determine whether landfall co-occurrence is greater or less than an equi-dispersed (Poissonian) landfall co-occurrence distribution, using two concurrent one-tailed Poisson significance tests. Shown alongside each result in this study is a figure demonstrating the corresponding percentile of the Poisson CDF (for local and neighbouring co-occurrence) and Skellam CDF (for neighbouring minus local co-occurrence) of the historical co-occurrence count.

The following definitions, in keeping with Mastrandrea *et al*. (2010) are leveraged to translate this study's CDF percentiles to confidence statements:

- virtually certain historical co-occurrence count is greater than random 99-100%
- historical co-occurrence count is very likely greater than random 90-100%
- historical co-occurrence count is likely greater than random 66-100%
- the historical co-occurrence count is indiscernible from random 33-66%
- historical co-occurrence count is likely lower than random 0-33%
- historical co-occurrence count is very likely lower than random 0-10%
- virtually certain that historical co-occurrence count is lower than random 0-1%.

The Skellam distribution is used to model differences between two Poisson models, and in this study is used to model the difference in the neighbouring and local conditional landfall binary totals. Karlis & Ntzoufras (2003) introduced this distribution for application in modelling sports data. Karlis & Ntzoufras (2003) recognised that to derive a more representative distribution for the difference of two Poisson distributions, which may be influenced by a global factor, such as the speed of the game in influencing the goals scored by two opposing teams, a bivariate Poisson model is required.

When subtracting two such distributions, the resultant Skellam distribution allows for such a correlation between two Poisson distributions. The correlation in this study's application arises from the influence of annual hurricane landfall counts on both local and neighbouring wind gates. In this analysis, the local conditional landfalling Poisson distribution is subtracted from the neighbouring conditional landfalling Poisson distribution, to result in a Skellam distribution, with probability mass function shown in Equation 1. Much like for the local and neighbouring hurricane landfall cooccurrence statistic, the results from the random Skellam distribution are presented alongside the historical neighbouring-local conditional landfall difference.

$$PMF_{Skellam} = exp\ exp\left\{-(\mu_1+\mu_2)\right\}\left(\frac{\mu_1}{\mu_2}\right)^{\frac{k}{2}} I_k\{2\sqrt{\mu_1\mu_2}\} \tag{1}$$

$$\mu_1 = \lambda_1 - \rho\sqrt{\lambda_1\lambda_2} \tag{2}$$

$$\mu_2 = \lambda_2 - \rho\sqrt{\lambda_1\lambda_2} \tag{3}$$

Where:

λ_1= Poisson mean from neighbouring conditional landfall distribution;

λ_2 = Poisson mean from neighbouring conditional landfall distribution;

ρ = correlation coefficient between neighbouring and local Poisson distributions;

k = difference in neighbouring and local hurricane conditional landfall binary total;

I_k = modified Bessel function of the first kind of order k (Abramowitz & Stegun, 1948).

2.3 HURDAT2 Data

Hurricane statistics were obtained from the National Hurricane Centre Hurricane Database V2, hereafter HURDAT2 (Landsea & Franklin, 2013), which include six hourly statistics for each identified Atlantic basin tropical storm and hurricane from 1851 to 2022.

Given limitations in historical observational networks, predominantly pre-radar era (1950s) and pre-satellite era (pre-1979), large uncertainties exist within these datasets (Vecchi, *et al*., 2021). Despite such data limitations, this study focuses on landfalling statistics, which carry far smaller uncertainties than basin statistics and as such sufficient value was obtained in leveraging all available hurricane landfall data from HURDAT2.

Table S1 in this study's appendix lists the total number of landfalling hurricanes from 1851-2022 for each wind gate. This author acknowledges data sparsity as an issue throughout this analysis, however the removal of no single historical year alters the conclusions of this study.

3. Results

3.1 Empirical Analysis of Local Wind Gate Hurricane Landfall Co-occurrence

This study's initial investigation of historical hurricane landfall co-occurrence is shown in Figure 3. This shows the relativity between the hurricane landfall co-occurrence binary total in 10,000 Poisson simulations and historical data for six wind-gate aggregations. The horizontal black markers correspond to the 10,000 Poisson simulation mean at each wind gate aggregation and the horizontal red markers correspond to the historical hurricane co-occurrence. The error bars in Figure 3a represent the 5th to 95th percentile range from the independent Poisson distributions. Figure 3b shows the percentile of the Poisson cumulative distribution function (CDF) that the historical binary total corresponds to. As detailed in Section 2.2., confidence intervals are displayed using horizontal lines.

Figure 3a shows that the historical hurricane local co-occurrence landfall count is below what one might observe if hurricane landfall co-occurrence was equi-dispersed, for all wind gate aggregations. This signal is an indication of under-dispersion, however Figure 3b demonstrates a likely reduction from the Poisson simulation set only for analysed wind gates of length scale ≥ 370 km. For analysed wind gates of length scale ≤ 278 km, whilst a consistent signal of under-dispersion is shown in Figure 3a, this is indiscernible from random noise.

3.2 Empirical Analysis of Neighbouring Wind Gate Hurricane Landfall Co-occurrence

Figure 4 presents the same analysis as Figure 3, however this compares the hurricane co-occurrence landfall in neighbouring wind gates between the 10,000 Poisson set and historical data. Like in Figure 3b, Figure 4b shows the percentile of the Poisson CDF that the historical binary total corresponds to.

Figure 4a shows that for wind gates of length 93 km – 370 km and 741 km, the historical hurricane neighbouring co-occurrence landfall count is lower than one would observe using a Poisson distribution. For wind gates of length 556 km, historical hurricane landfall co-occurrence is larger than what one might observe if neighbouring hurricane co-occurrence was equi-dispersed. For all wind gate granularities, the historical data lies within the 5th-95th percentile Poisson range. Figure 4b indicates that it is likely that neighbouring co-occurrence is under-dispersed for wind gates ≤ 185 km, with the strongest signal found for wind gates of 185 km, equating to the 16th percentile of the Poisson CDF. For wind gates of length 556 km, this study also finds the likely presence of over-dispersion.

The results in Figure 3 suggest a Poisson distribution would likely be inadequate to model the probability of two local landfalls at wind gate aggregations ≥ 370 km throughout the GoM, due to the likely presence of under-dispersion. Figure 4 indicates that for neighbouring hurricane landfall co-occurrence, there exists the likely presence of under-dispersion at wind gate aggregations ≤ 185 km, however at wind gates of length scale 556 km, overdispersion is likely.

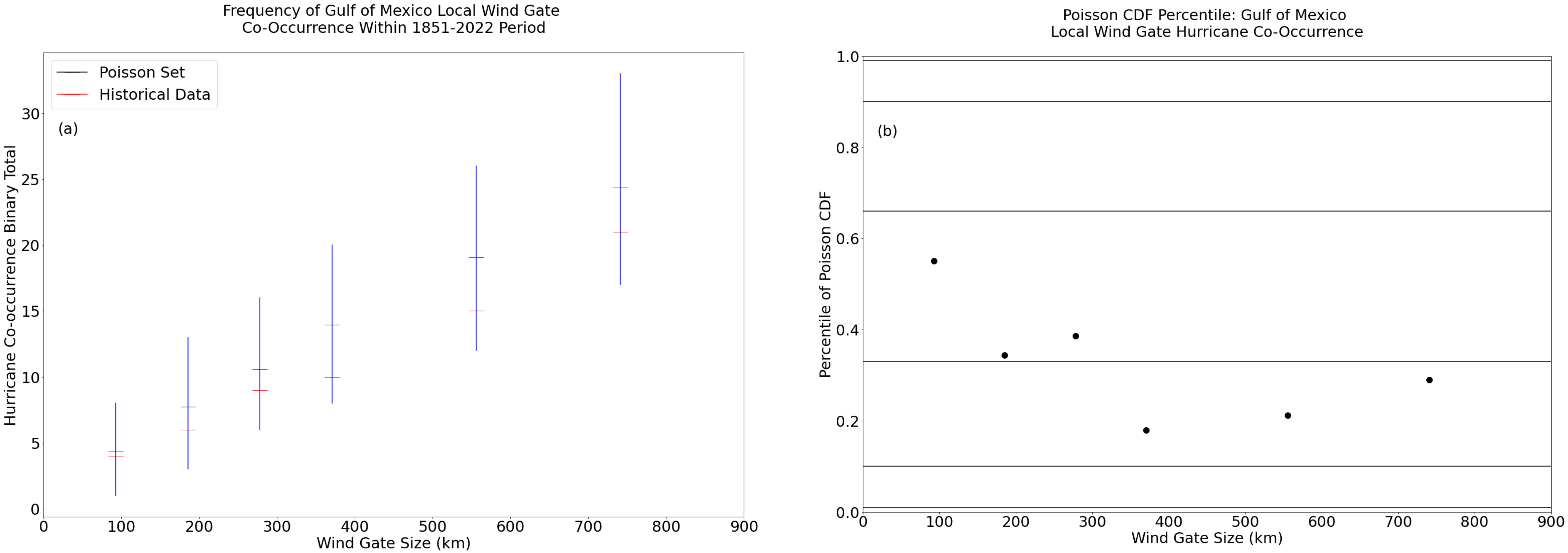

Figure 3: a (left) *mean local wind gate hurricane landfall co-occurrence binary total (red horizontal marker) and the equivalent mean co-occurrence from 10,000 Poisson simulations (black horizontal marker). Vertical blue lines represent the 5th-95th percentiles of the Poisson simulation set.* ***b (right)*** *the equivalent percentile on the Poisson cumulative distribution function (CDF) for the historical landfall co-occurrence. Horizontal lines correspond to confidence interval thresholds at 0.01, 0.1, 0.33, 0.66, 0.9 and 0.99, introduced in Section 2.2.*

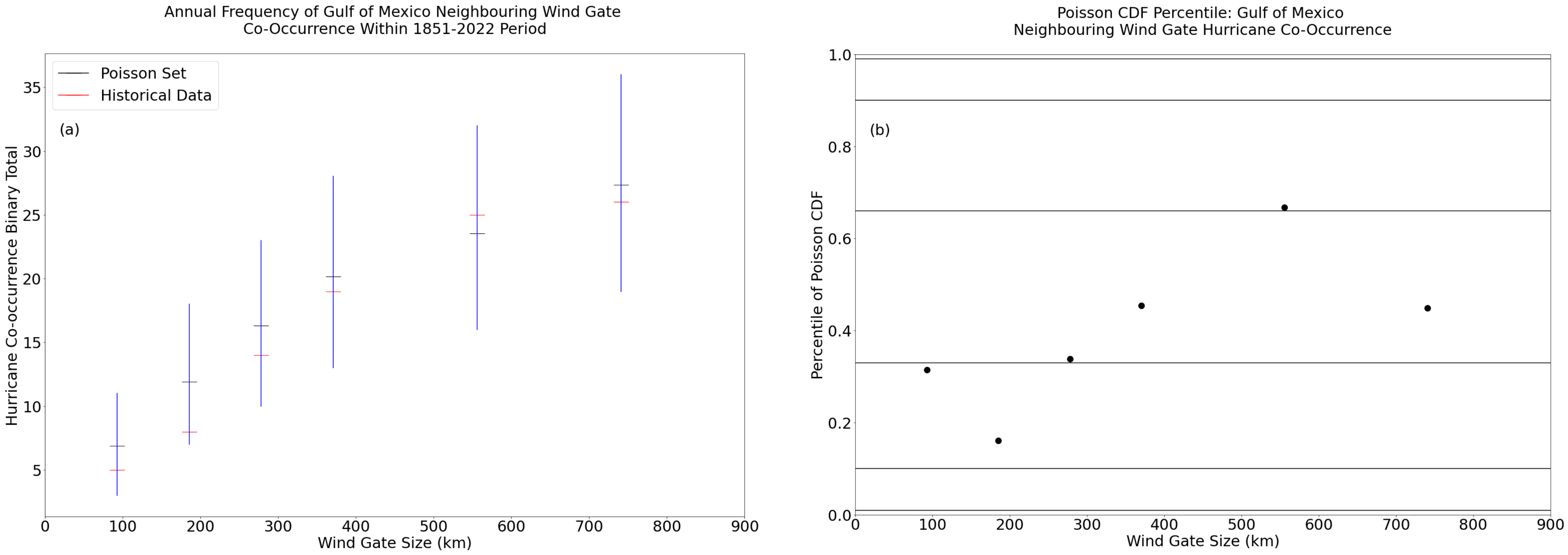

Figure 4: *As Figure 3, but for neighbouring hurricane landfall co-occurrence binary totals.*

3.3 Comparison of Neighbouring and Local Wind Gate Hurricane Landfall Co-occurrence

To further investigate this relativity between local and neighbouring landfalls, the difference between the two statistics is taken (neighbouring – local) for both the historical observations and Poisson simulations at each wind gate granularity. A similar framework is undertaken to infer confidence, as was used in Figures 3 and 4, however Figure 5 presents the historical results relative to a Skellam distribution. Figure 5b uses the same confidence thresholds as Figures 3b and 4b.

Figure 5 shows that for high wind gate granularities there exists no discernible difference between the neighbouring and local hurricane landfall co-occurrence difference and that which would be observed at random. For larger wind gates, specifically 370 km - 556 km, this study finds it likely that the difference in neighbouring and local hurricane landfall co-occurrence is greater than that which would be expected at random.

In addition to viewing the results at each wind gate aggregation level independently, one might choose to analyse the dependence of relative (neighbouring-local) co-occurrence probability on wind gate size. This study finds the presence of a wave-like feature in Figure 5b, with a nadir occurring at 185 km and peak at 556 km. This author provides a hypothesis for such a signal in the subsequent discussion section, which would infer that the results in Figure 5 are driven by the concurrent signals of over-dispersion and under-dispersion at different spatial scales.

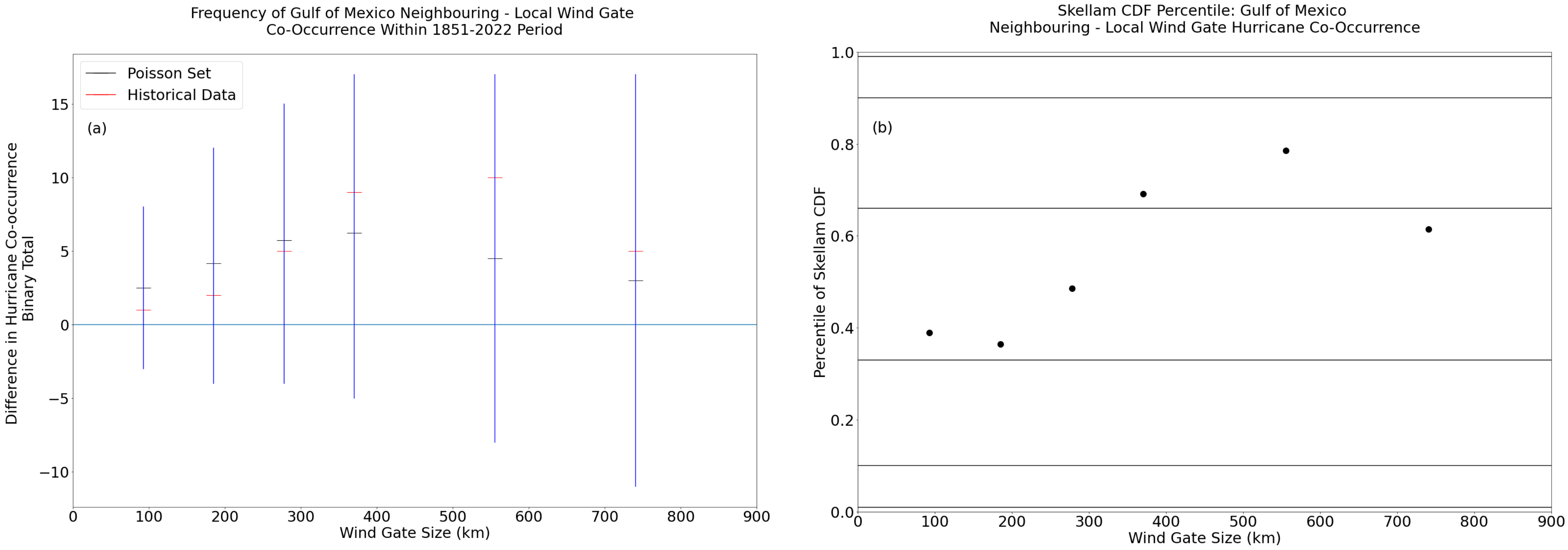

Figure 5:* *a (left) *mean neighbouring wind gate hurricane landfall co-occurrence binary total minus local wind gate hurricane landfall co-occurrence binary total (red horizontal marker) and the equivalent mean difference from two Poisson simulations, resulting in the mean of a Skellam distribution (black horizontal marker). Vertical blue lines represent the 5th-95th percentiles of the Skellam distribution.* ***b (right)*** *the equivalent percentile on the Skellam cumulative distribution function (CDF) for the historical neighbouring minus local hurricane landfall co-occurrence difference. Horizontal lines correspond to confidence interval thresholds at 0.01, 0.1, 0.33, 0.66, 0.9 and 0.99, introduced in Section 2.2.*

4. Discussion

The study exclusively investigates the conditional landfalls of hurricanes throughout the GoM and presents this in the context of regional hurricane landfall dispersion. This study finds empirical evidence for the likely under-dispersion of hurricanes making landfall in close proximity to a previous landfalling hurricane (termed local landfall co-occurrence). In the near, but not local, proximity (termed neighbouring landfall co-occurrence), this study finds signs of both likely under and over-dispersion. This study makes no attempt to demonstrate a causal pathway to explain this phenomenon, however this discussion places the results of this study in the context of existing literature and suggests potential hypotheses to explain this study's results.

For neighbouring hurricane landfall co-occurrence, this study shows that the strongest signal of over-dispersion is found for wind-gates of length scale 556 km. If one were to aggregate the entire length scale of the two neighbouring and local wind gates at this aggregation level, this would approximately equal to 1,667 km, or approximately ¾ of the coastline analysed in this study. Hurricane clustering over such a length scale could conceivably be explained by persistent steering flows (McCloskey *et al.*, 2013; Pérez-Alarcón *et al.*, 2021), or the clustering of storm geneses throughout a season (Corporal-Lodangco *et al.*, 2014).

Throughout the GoM, Perez-Alarcon *et al.* (2021) identified SST as the significant ($p<0.05$) and dominant covariant in explaining variability in GoM hurricane landfalling frequency through 1980-2019. In addition to this, Sainsbury *et al.* (2022) and Kortum *et al.* (2024) both identify genesis location as the factor most influential to explaining variability in track recurvature and eventual landfall probability. The influence of the NASH on CONUS hurricane landfall regionality must also not be overlooked, with Mazza & Chen (2023) and McCloskey *et al.* (2013) emphasising the role of the NAO in modulating tropical cyclone activity throughout the Atlantic and GoM. It is therefore plausible that mechanisms dictating the large-scale (>1500 km) clustering of tropical cyclones are linked to both the clustering of storm geneses in the GoM and phases of the NAO and NASH induced steering flows.

Despite identifying a signal of over-dispersion for neighbouring hurricane landfall co-occurrence at a wind gate length scale of 556 km, at wind gates of length scale ≤ 185 km this study identifies a likely signal of under-dispersion. Under-dispersion is also found for local hurricane landfall co-occurrence at all wind gate granularities, with the strongest signal at 370 km.

The clear disconnect between local and less granular neighbouring hurricane landfall co-occurrence, as demonstrated in Figure 5, is a somewhat curious result and one that this author believes warrants further investigation. Discussed above are potential mechanisms that would result in potential over-dispersion (clustering) of hurricane landfalls, being genesis clustering and persistent steering flows. If those were the only mechanisms influencing hurricane landfall dispersion throughout the GoM, one might expect to find the same signal for local hurricane landfall co-occurrence. Given the likely suppression of smaller scale neighbouring hurricane landfall co-occurrence and local hurricane co-occurrence at all studied wind gate granularities, this may suggest an additional mechanism driving this signal.

A plausible mechanism for this local hurricane landfall co-occurrence suppression can be found within the results of Karnauskas *et al.* (2021). Karnauskas *et al.* (2021) identified a signal of hurricane landfall suppression for the Carolinas and Floridian regions following an experiment, which simulated the response of 4,000 synthetic tracks to the SST cold-wake anomalies of two Cape Verde originating hurricanes, Helene and Florence in 2018. While Helene dissipated in the east Atlantic, Florence made landfall in North Carolina and both storms resulted in persistent cold SST wakes. These cold wakes led to a suppression, or relative under-dispersion, of hurricane count at landfall throughout localised Carolinas and Floridian regions. The results of this study suggest that the cold wake might act on a local scale within the Atlantic basin to suppress the frequency of local landfalling storms.

Lee and Veeramony (2024) indicate that cold wakes are a persistent feature of the GoM, showing the lasting impact of Hurricane Katrina on SSTs and oceanic mixing layer depth throughout a vast region of the GoM in 2005. The impact of Katrina was found to persist such that the oceanic mixing layer depth throughout the GoM rebounded to only 84% of its pre-storm depth 18 days following storm passage. Results by Landsea (1993) suggest that 82.8% of intense hurricanes throughout the GoM occur through the 62-day period of 1st August – 31st September, demonstrating a concentrated period of high activity. By comparing the temporal longevity of the oceanic mixed depth impact found by Lee and Veeramony (2024) with the temporal extent of the peak GoM hurricane landfalling season shown by Landsea (1993), one could conceive how a cold wake generated during this period of peak activity might noticeably impact seasonal GoM hurricane landfalling count.

This author must also note that the results of Landsea (1993) regarding GoM hurricane climatology may be impacted by non-stationarity in the climate system (driven by climate change, or internal modes of climate variability). Dwyer *et al*. (2015) and Kossin *et al*. (2008) both indicate a potential non-stationarity in the temporal climatology of tropical cyclone activity, with observations (Kossin, 2008) and Coupled Model Intercomparison Project (CMIP), phase 5 (CMIP5, Taylor *et al*. 2012) results indicating a tendency towards a longer hurricane season. Although both studies point to large uncertainties, any increase in the length of a hurricane season could feasibly reduce the impact of cold wake hurricane suppression on annual hurricane frequency.

The results of Figure 5 indicate likely differences in landfall probability between local and neighbouring wind gates at a length scale of 370 km – 556 km. This study finds that at these wind gate granularities, local hurricane landfall co-occurrence is suppressed relative to that in neighbouring wind gates. Through the discussion above, this author hypothesises that there may be two processes impacting this signal, one resulting in an under-dispersion of landfall frequency at the local wind gate and one resulting in an over-dispersion at neighbouring wind gates.

Mitchell and Camp (2021) identified a signal of equi-dispersion for tropical cyclone tracks throughout the GoM. Given the observed close relationship between GoM basin wide hurricane frequencies and GoM landfall frequencies (Corporal-Lodangco *et al*., 2014; Kortum *et al*., 2024; Sainsbury *et al*., 2022), this might suggest a similar result be found for GoM landfall frequency at this scale. It is plausible that the equi-dispersion in tropical cyclone frequency throughout the GoM, identified by Mitchell and Camp (2021), is supported by the results of this study. This author suggests that a less granular signal of equi-dispersion may be a result of more granular signals of both a regional clustering of storms (over-dispersion) and of more granular local suppression (under-dispersion).

Whilst the results of Mitchell and Camp (2021) would support the use of a Poisson distribution for modelling GoM hurricane landfall probability, this study would suggest that at more granular spatial scales, an alternative parameterisation would likely be preferential. Mitchell and Camp (2021) raise awareness of a parametric distribution sufficient for modelling under-dispersion, over-dispersion and equi-dispersion, the Conway-Maxwell-Poisson distribution, which this author supports the use of, for modelling GoM hurricane landfalls.

This study only hypothesises causal mechanisms driving variance in hurricane landfalling frequency dispersion, it does not demonstrate any causal pathways. Identifying causation for the local suppression and neighbouring over-dispersion of hurricane landfalls remains important for risk carriers with an interest in GoM hurricanes. Enhanced understanding of regional clustering of CONUS impacting hurricanes can help elucidate on worst case seasonal US hurricane scenarios, assisting risk managers to better understand aggregate economic and insured losses.

From an insurance risk carrier's perspective, this study's finding of a likely under-dispersion of local hurricane co-occurrence can be utilised in a multitude of ways. For risk selection in highly transactional insurance markets, the knowledge of a suppression of local hurricane co-occurrence, post an initial landfall, may motivate underwriting decisions on price and risk selection. Similarly, the likely over-dispersion of neighbouring hurricane co-occurrence may also inform underwriting decisions for these regions.

For less volatile insurance markets, whereby insurance relationships dictate a higher degree of stability in pricing and coverage for the market, it is still crucial to adequately model clustering within your risk models. The results in this study suggest that a single location is less likely to be impacted by multiple storms in a single season than would be expected at random. Such a result signifies a reduced insurance portfolio aggregation risk, relative to what would be observed in an equi-dispersed hurricane landfalling model. This relatively reduced risk is driven by large metropolitan regions, such as Tampa, Florida, being less likely to be impacted multiple times throughout a given insurance contract (typically one year). One might make the argument in such cases that property cannot be destroyed twice and hence it may be favourable from a risk carriers' perspective for two storms to make landfall at the same location, however the study of intra-seasonal vulnerability variability is highly complex and out of scope for this discussion.

Finally, one must also acknowledge that whilst high-frequency portfolio redistribution in less volatile markets might not be feasible, decisions surrounding the purchase of outwards reinsurance remain open in a fluid reinsurance market. Decisions on the purchasing of retrocession insurance for reinsurance risk carriers, or reinsurance for primary risk carriers, through traditional markets, or through insurance linked securities, are available throughout the year. The results of this study could be leveraged in discussions surrounding the mid-season purchase of protection for an insurance risk carrier.

5. Conclusion

This empirical study looks at whether any signals exist in CONUS hurricane landfall regionality clustering. Hurricane landfall co-occurrence probability for Gulf of Mexico (GoM) wind gates of length scale 370-741 km was found to be likely under-dispersed during the 1851-2022 period, relative to a Poissonian distribution of hurricane landfall. Contrastingly, conditional on a hurricane making landfall at a wind gate of length scale 556 km, the co-occurrence of hurricanes making landfall in the neighbouring wind gates of the same length scale is shown to be likely over-dispersed.

This study finds that for wind gates of length scale 556 km, there is a likely preference for hurricanes to co-occur in neighbouring wind gates, over local wind gates. The results of both likely over-dispersion and under-dispersion in intra-annual GoM hurricane landfalls suggests the possible presence of two mechanisms impacting hurricane regionality clustering at differing spatial scales.

This author stresses the need for further investigation into the physical processes hypothesised in this study to be modulating the observed signals of over-dispersion and under-dispersion in intra-annual GoM hurricane landfall. The results of this study are compelling from an insurance risk carrier's perspective, as any alteration in hurricane landfall probability following a storm landfall can be acted upon through the purchase of additional coverage and in making informed underwriting decisions.

Furthermore, any deviation away from the Poissonian hurricane landfall model might have fundamental impacts on the long-term management of an insurance portfolio.

This study suggests that regions of concentrated risk are less likely to be impacted multiple times per year, relative to an equi-dispersed hurricane landfall model.

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Declarations

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