Impacts of wind speed and direction on wind turbine generator fatalities

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Photo Credit: Tor Johnson

Abstract:

Fatality monitoring is a resource intensive task. In this study we aim to find correlation between wind speed and fatality distance as well as wind direction and fatality direction. A correlation between these variables would provide a basis for increasing efficiency. Ordinary least squares (OLS) and Geographic weighted regression (GWR) were used to make comparisons between the variables. A predictive shape was also generated to reduce the impact of uncertainty in time. There was a weak relationship between Fatality Direction and Wind Mean Direction. A higher proportion of carcasses were found in the Southwest quadrant, opposite the predominant wind direction. A correlation was found between the standard deviation of the wind directions and the quadrant in which the carcasses were found. Overall, the most efficient search area was found to be a 30m radius from the base of the tower. Improvements to the model could be found with more detailed data collections or with a more accurate and complex predictive shape. **Key Words: Wind Turbine Fatalities, Wind Direction, Global regression, Hawaii.**

Key terms:

OLS	Ordinary least squares
GWR	Geographically weighted regression
Mean Direction	Circular mean
Yaw angle	Direction the nacelle of the turbine is facing
WTG	Wind Turbine Generator

Variables (variables are capitalized through the paper):

Wind Mean Direction	Circular average of wind direction for the seven days preceding the date the fatality was found for which the rotor speed exceeded 2 revolutions per minute
Fatality Direction	Bearing of the fatality from the turbine
Wind Speed	Speed of the wind in meters per second as measured by the turbine
Fatality Distance	Distance from the turbine to the fatality
Standard deviation of Wind Mean Direction	Calculated in R as SD.Circular of the wind direction for the seven days preceding the date the fatality was found for which the rotor speed exceeded 2 revolutions per minute
Quadrant	0-89 degrees = Northeast 90-179 degrees = Southeast 180-269 degrees = Southwest 270-359= Northwest
Contained	Binomial variable defining if a fatality was contained by its predictive shape, 1=contained 0=not contained

Introduction:

One area of concern for the growing wind power industry is the impacts on birds and bats. Hawaii is home to 42 endangered avian species and one endangered bat (USFWS 2015). Hawaii is also the 7th smallest in state size (28,313 km^2). This combination makes Hawaii the most densely populated with susceptible species. This density has led to stringent regulation for Environmental Impact Statements, and Habitat Conservation Plans which include mitigation measures and rigorous monitoring protocols such as those described by Anderson et. al. (1999). Rigorous monitoring of turbines is a resource intensive commitment and any improvement in search protocol could prove valuable in improving the accuracy of assessments and increasing efficiency.

There have been a number of statistical analyses which attempt to model fatalities. The probability of a fatality being found decays with distance from the turbine and is influenced by turbine height and carcass size (Hull and Muir, 2010). It is predicted that the probability of collision is highest near the hub (Tucker 1996). Although many studies have looked at the impacts of tower height and carcass size on distance from a turbine (Hull and Muir, 2010, Kers and Kerlinger, 2004). No published works have looked for correlation between wind speed and carcass distance from the turbine or wind direction and carcass direction from the turbine. Search areas tend to be omnidirectional, and many sites devote a large amount of resources to the monitoring effort. If a correlation could be made, significant reduction in person hours could result by having adaptive search areas determined by weather patterns.

The wind direction in Hawaii is typically defined by “Trade winds” which blow from the northeast and are the prevailing wind direction through the summer (90%) as well as a significant proportion through the winter (50%) (NOAA 2005). For this reason we would predict that the fall direction of fatalities would show directionality and a higher proportion of carcasses would fall to the southwest. In this analysis we will look for significant predictive variables for carcass distance and direction from wind turbine generators.

Fatality searching is conducted based on the carcass retention interval. Carcass retention is measured by placing carcasses on site and monitoring daily for persistence. An average of 7 days has been found at Kawailoa Wind, LLC and this average was used as the maximum length for which statistics would be valid for prediction. Data was collected from 2 wind power facilities; on O’ahu (Kawailoa Wind, LLC) and Maui (Kaheawa Wind, LLC).

Methods:

The search effort for WTG is concentrated on 50-75% of the turbine height which extends from the base of the turbine to between 50 and 130 meters. Any carcasses found between 10 and 130 meters were included. Fatalities found within 10 meters were excluded as directionality would likely be positively correlated with wind. This is due to collision with the tower rather than the blades and the area within 10m of the turbine would always be included in a search. Data with errors in GPS location, distance, direction or missing turbine data were excluded from analysis. Because the time and date of fatalities is not known, we will look at 7 days prior to the fatality as the maximum predictive length which is equivalent to the average carcass retention time. Fatalities which had recorded distance and direction data which were different from the recorded coordinates were assumed to be located at the appropriate distance and direction. Turbine height was not used as a predictor in the analysis.

One of the largest challenges is to narrow the margin of error around the time of turbine-wildlife interaction. If the exact time were known it would provide a narrow range of values for comparison. Without this data the 7 day interval preceding the date the fatality was found, for which the rotor speed was greater than 2 revolutions per minute (RPM). Within this time frame each 10 minute average was collected and the wind mean direction was analyzed (by yaw angle at Kawailoa and wind direction at Kaheawa). The mean for wind speed were also collected. The mean angle was calculated as

$$Y = \frac{\sum_{i=1}^{N} Sin\ (a)}{n} \text{ and } X = \frac{\sum_{i=1}^{N} Cos\ (a)}{n}$$

$$r = \sqrt{(X^2 + Y^2)}$$

$$Cos\ (\bar{a}) = \frac{X}{r} \text{ and } \mathrm{Sin}\ (\bar{a}) = \frac{Y}{r}, \qquad \theta_r = \arctan\left(\frac{\mathrm{Sin}\ (\bar{a})}{Cos\ (\bar{a})}\right)$$

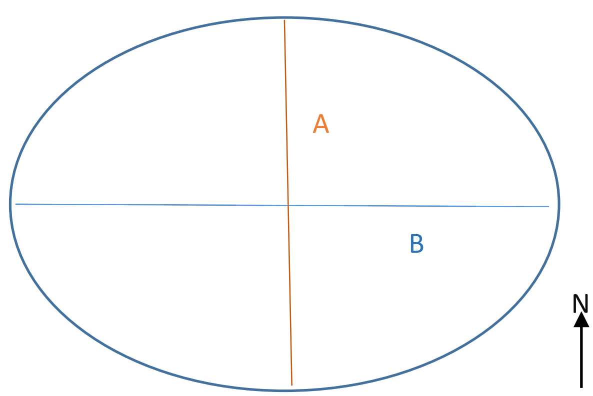
Where the quadrant is defined by the +/- of the sin/cos values.

The second analysis was a predictive shape which could potentially be used as a modified, reduced area. The predictive shape was an ellipse that would be elongated and shifted based on the wind speed. The area of the ellipse was constant at 2827.24 the long axis was based on a maximum wind speed of 17 for Kawailoa and 26 for Kaheawa and was given by the following equation:

A=30 + 12.5(Wind speed/Max Wind Speed)
B=2827/(A*pi)

The center shift was defined as:

Shift Distance = 32.5*(Wind speed/Max Wind speed)
X = Shift Distance * Sin(wind direction)
Y = -Shift Distance * Cos(wind direction)



The predictive shapes were compared with the distance and area to see if fatalities were correlated due to the distance from the turbine or if they were found because the search area was larger.

Data:

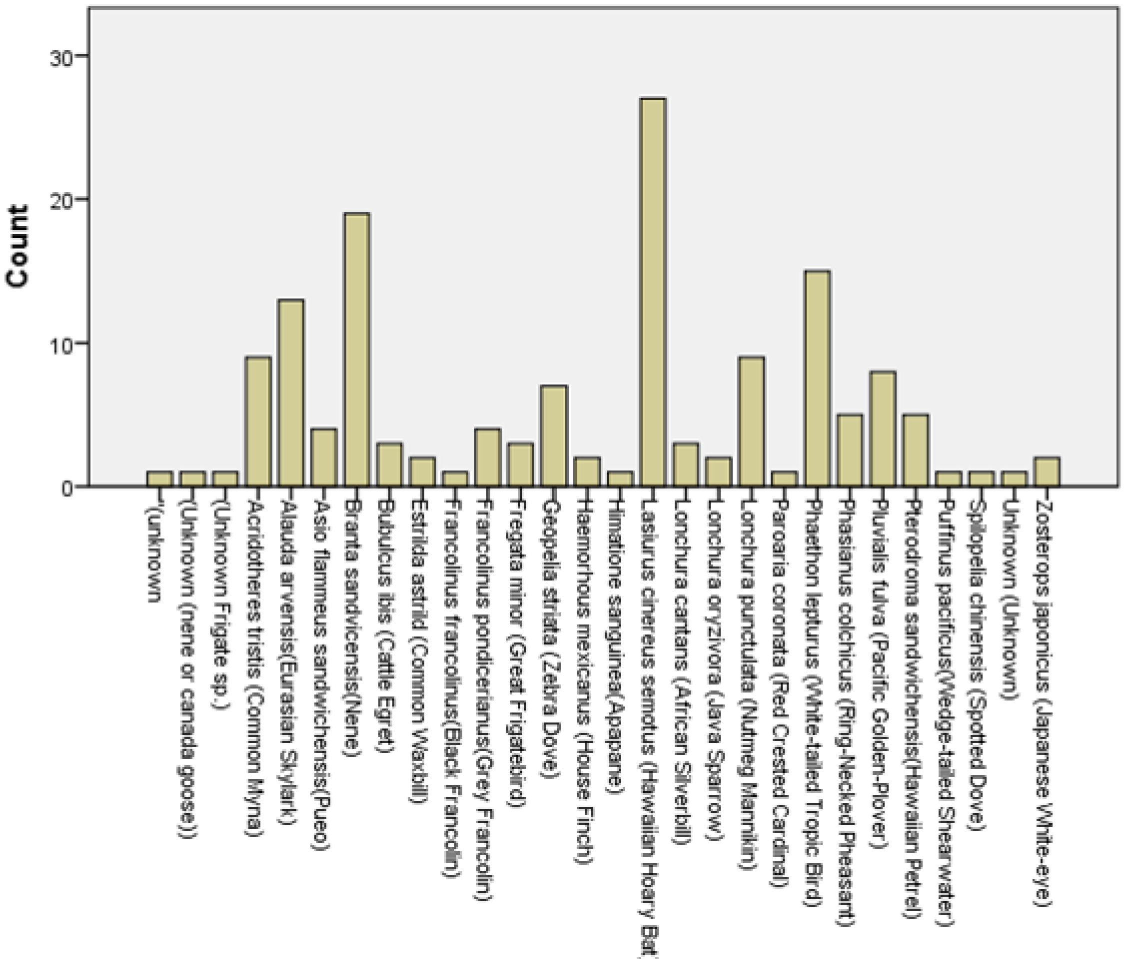
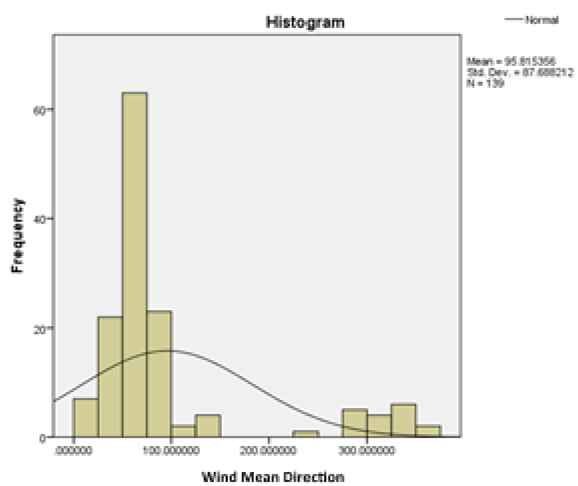
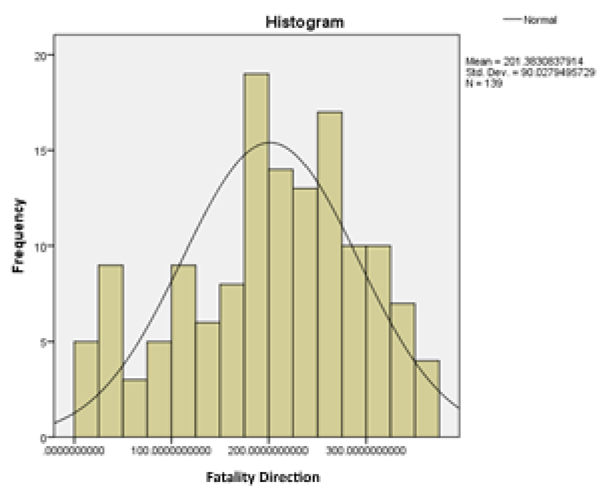


Figure 1. All species included by count of fatalities.





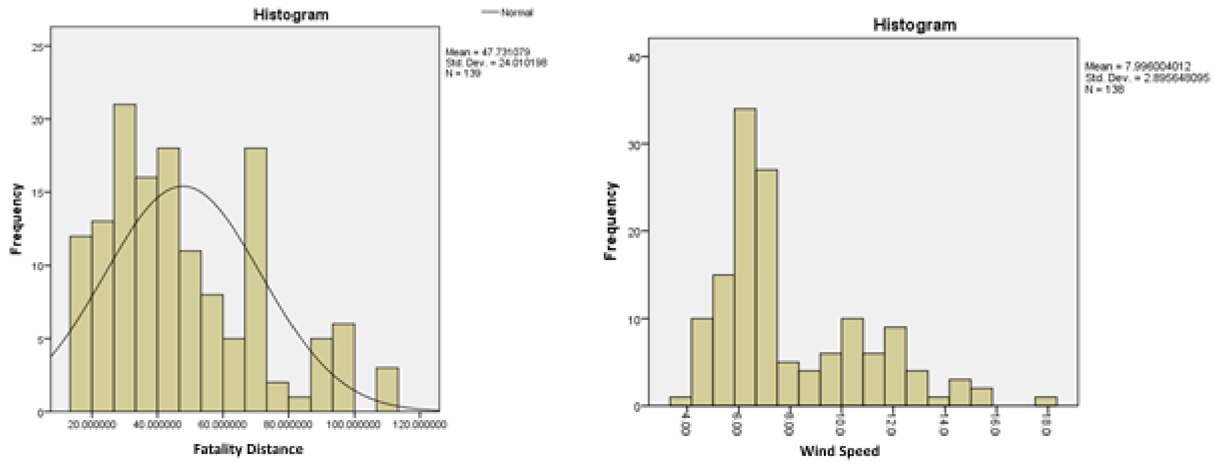


Figure 2. Histograms of variables from top right to left: Mean direction, Fatality Direction, Fatality Distance, Wind speed average.

Results:

Predictive shapes

The ellipses generated from the wind data capture 50.340 percent of the fatalities (n=139). Of the fatalities within the 75m buffer (the maximum distance for the ellipses), 56.911 percent of the fatalities were captured (n=123). This is an improvement from the 31.707 percent captured by a 30m buffer from the turbine. The combined ellipses have a mean area that is 1.89 times greater than the 30m buffer. This area equates to a circle with a radius of 41.243m, which would capture 53.659 (66/123) percent of the fatalities. If we assume that 53.659% is the base rate then a binomial distribution predicts there is 20.8 percent chance of capturing 56.911 percent (70 of 123) or more of the 123 carcasses. Making the ellipse predictive shape not a statistically significant improvement over a uniform search distance.

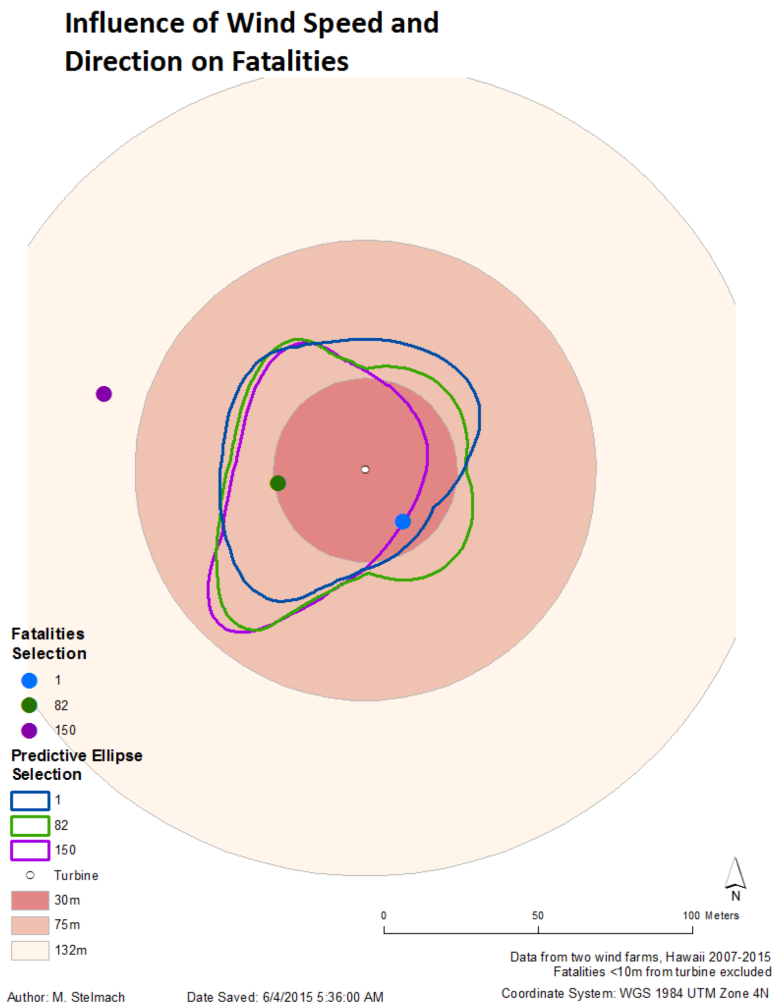


Figure 3. A sample of 3 of the predictive ellipses and the relative fatalities.

Taking the Directional Distribution of all carcasses shifts the center 10.53m south and 10.31m west for a total distance of 14.73. By buffering the mean center by the same area used by the predictive ellipses (41.243m) we capture 56.097 percent of fatalities.

Comparison of Search areas to carcasses captured:

Center	Distance	Area Searched (m^2)	Fatalities Captured	Proportion of carcasses within 75m
Turbine	30	2827.43	39	0.317073
	41.24	5343.802	66	0.536585
Mean Center	30	2827.43	37	0.300813
	41.24	5343.802	69	0.560976
Ellipse	Variable	5343.802	70	0.569106

Ordinary Least Squares

In testing how well the ellipses captured the fatalities an ordinary least squares (OLS) was run, with Contained as the dependent variable and the mode of the 7 day wind direction as the independent variable.

Adjusted R Squared	P Value	Joint Wald	BP	JB	Moran's I for Residuals
0.016	0.023	0.02	0.000	0.000	0.000

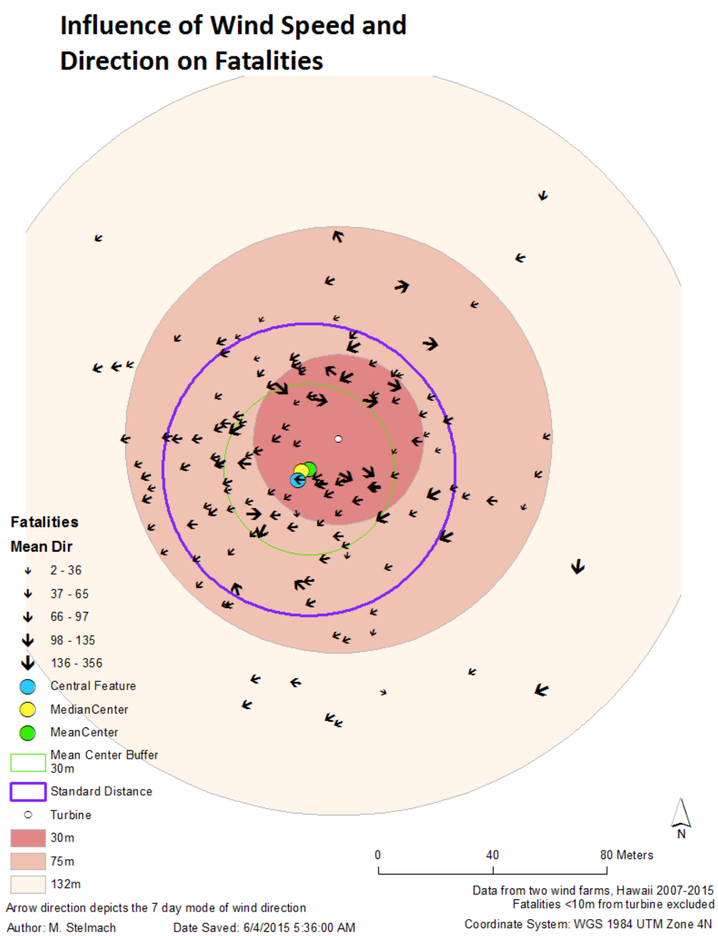


Figure 4. Measures of central tendency for the fatalities. Also included is a modified buffer location. Arrow size indicates Wind Speed and direction indicates Mean Wind Direction

Distance and wind speed:

Linear Regression:

No statistically significant correlation was found between wind speed and carcass distance.

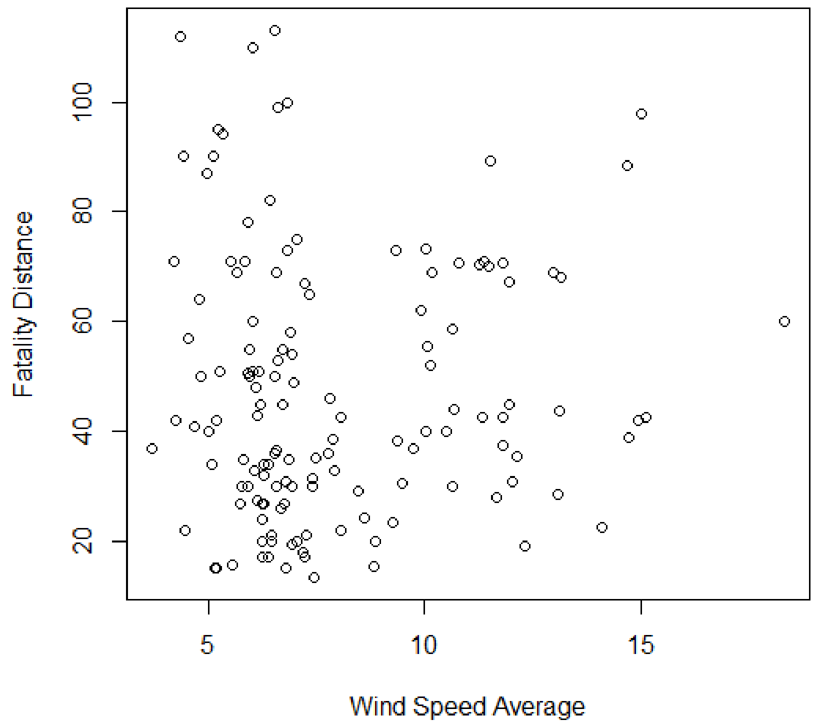


Figure 5. Scatter-plot diagram for Wind Speed Average and Fatality Distance.

Search area:

By searching out to 30m, 16% of the 75m area is searched and captures 31.7% of the fatality distribution. By searching out to 41.243m, 30.24% of the 75m area is searched and captures 53-57% of the fatality distribution (for omnidirectional to predictive shape). The highest search efficiency of the methods compared was for the 30m buffer which achieves the highest carcasses per area searched.

Fatalities per m^2				
30m turbine	41.243m turbine	30m mean center	41.243 mean center	Ellipses
0.013793	0.012351	0.013086	0.012912	0.013099

Wind Mean Direction and Fatality Direction:

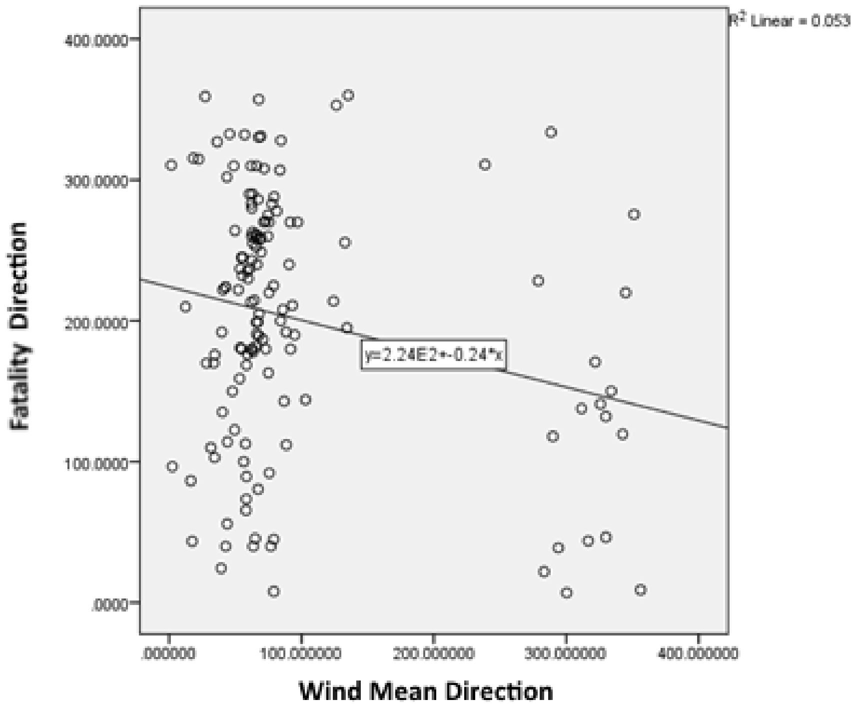


Figure 6. Scatter-plot diagram for Wind Mean Direction to Fatality Direction.

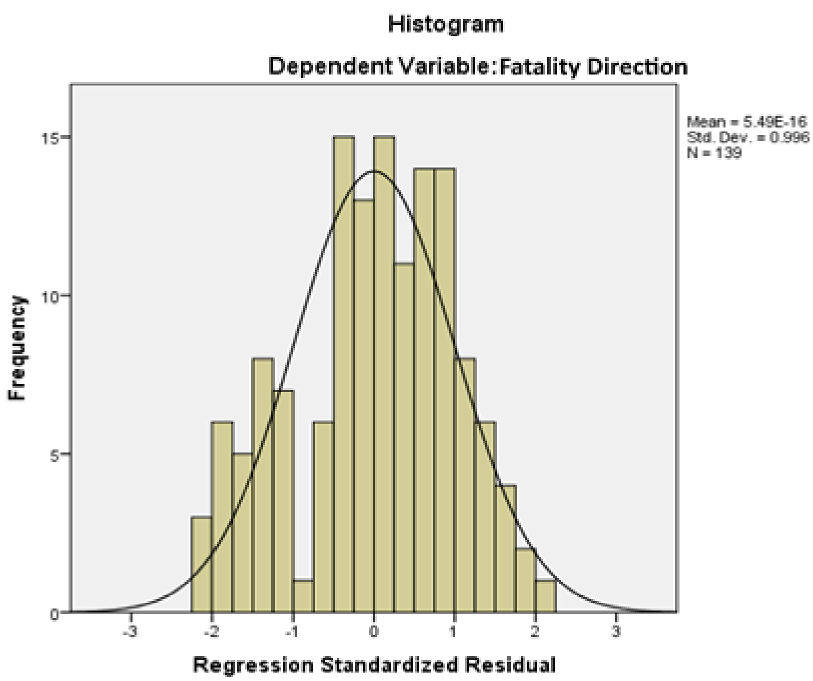


Figure 7. Standardized residuals histogram for the linear regression of Wind Mean Direction to Fatality Direction.

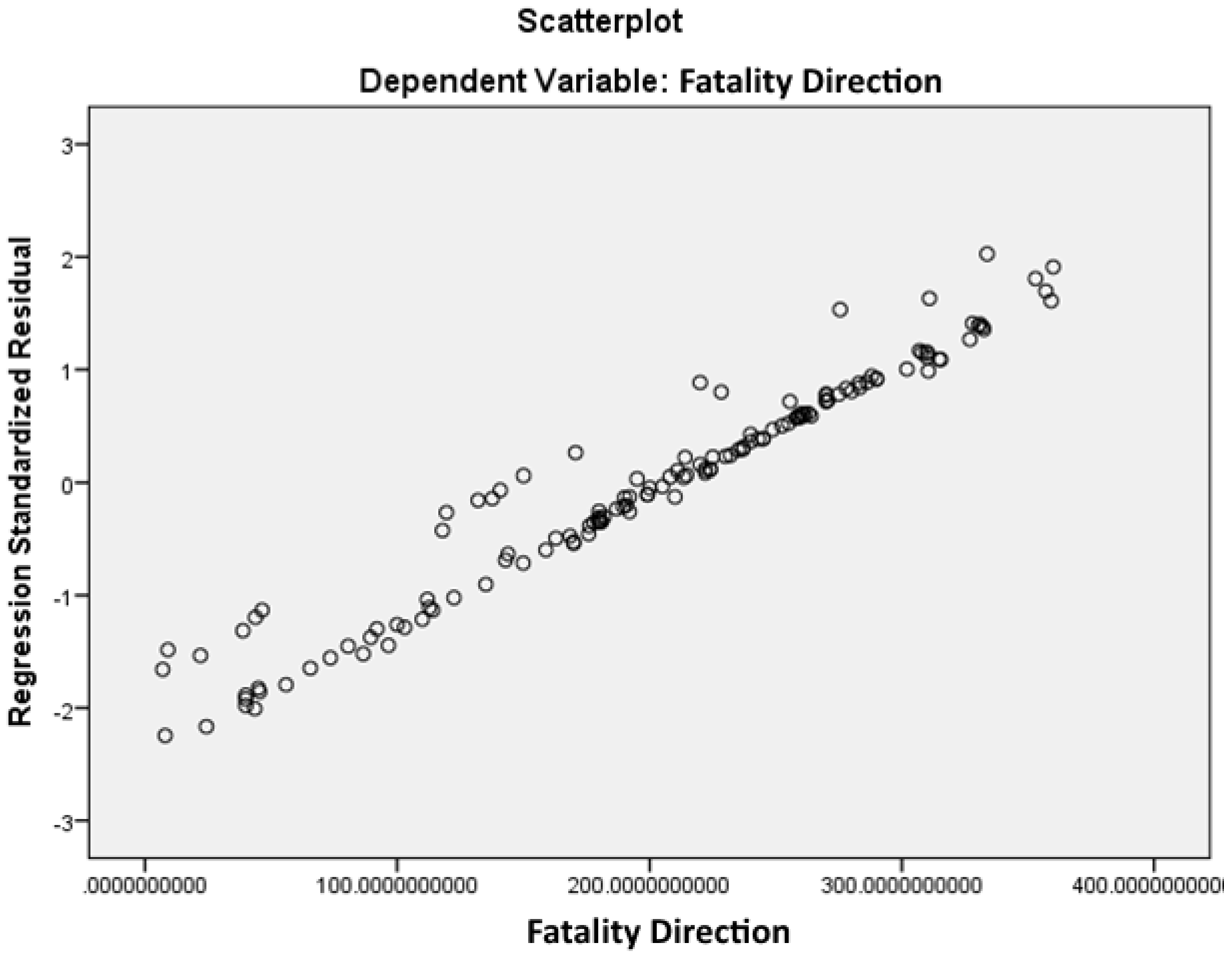


Figure 8. Standardized residuals for the linear regression of Wind Mean Direction to Fatality Direction.

Getis-Ord General-G

No statistically significant spatial clustering was found for Wind Mean Direction.

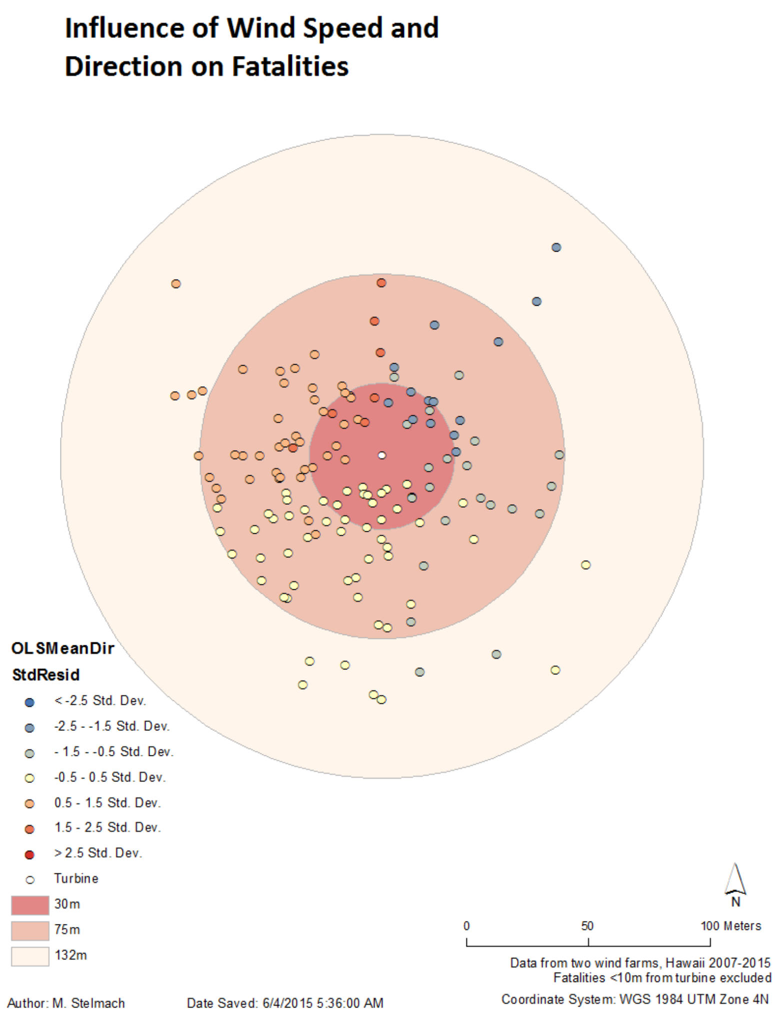


Figure 9. Ordinary least squares standardized residuals for Wind Mean Direction as a predictor of Fatality Direction.

Equation:

$$Fatality\ Direction = 224.11 - 0.237\ (Wind\ Direction)$$

R squared	P Value	Koenker (BP) Statistic	Jarque-Berra Statistic	Moran's I
0.046496	0.009867	0.57016	0.100	0.00

Fatalities by quadrant:

Quadrant	Count	Percent
Northeast	21	15.11%
Southeast	28	20.14%
Southwest	55	39.57%
Northwest	35	25.18%

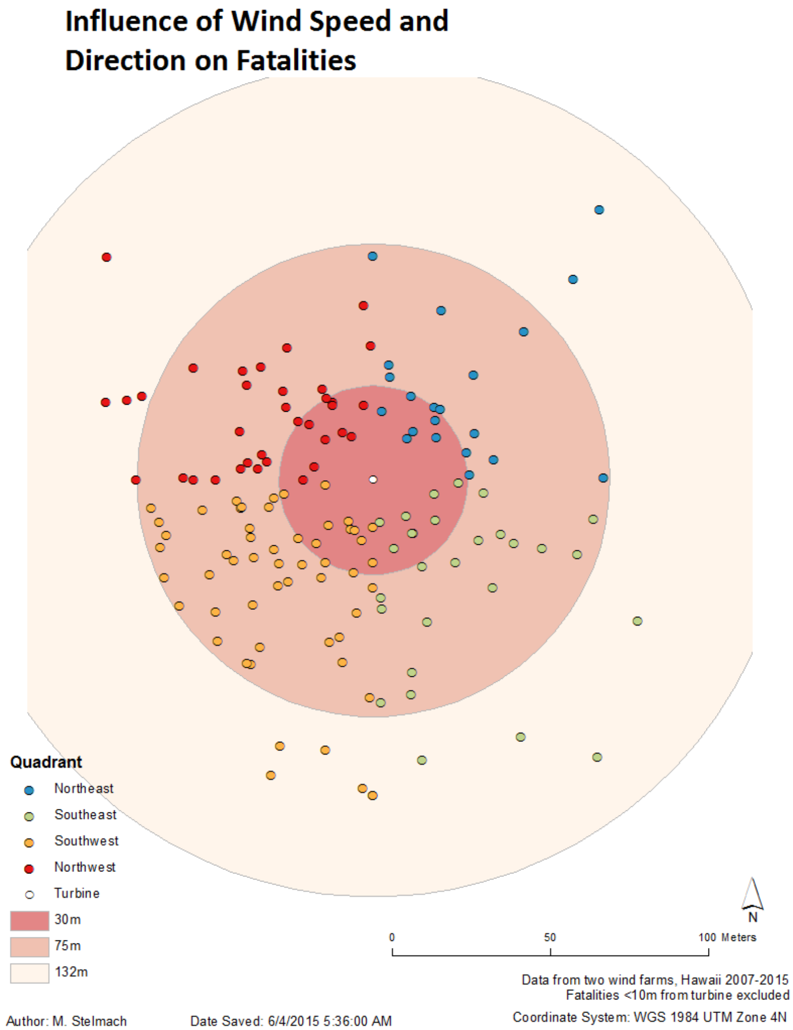


Figure 10. Fatalities by quadrant.

OLS Equation:

$$Quadrant = 3.192 - 0.008855\ (Standard\ Deviation\ of\ Yaw\ Direction)$$

R squared	P Value	Koenker (BP) Statistic	Jarque-Berra Statistic	Moran's I
0.1105	0.000	0.02500	0.3587	0.000

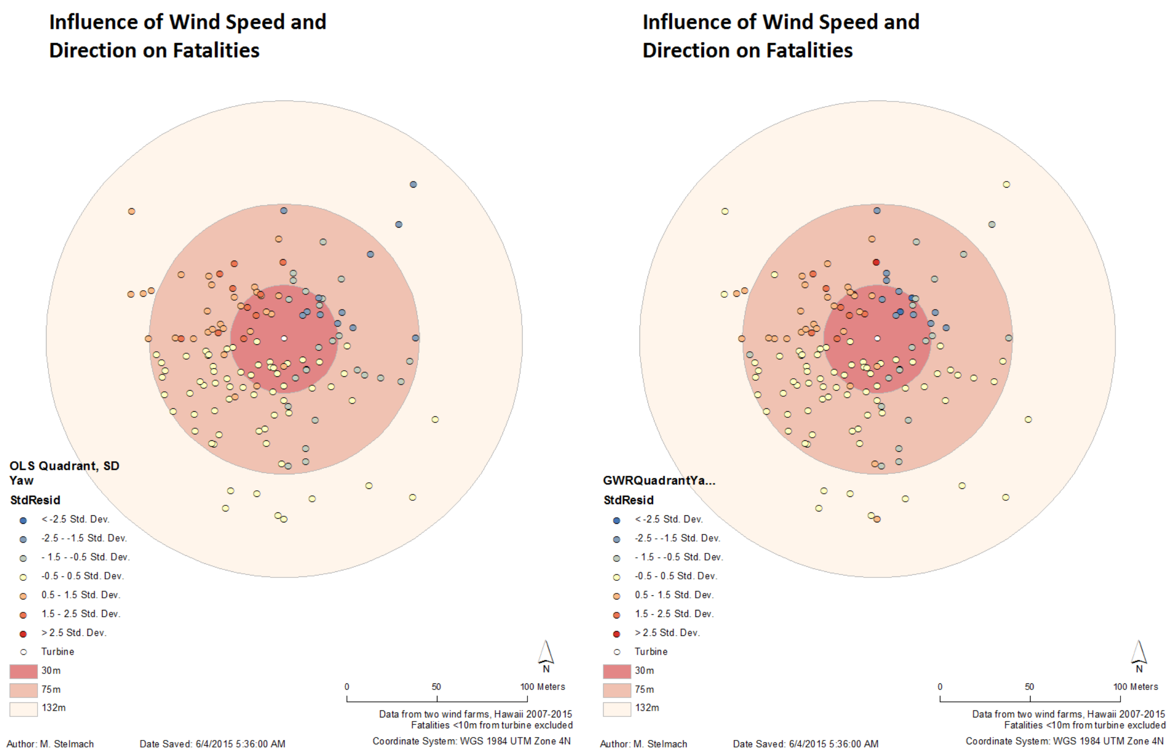


Figure 11. Standardized residuals for the Standard Deviation of Wind Direction as a predictor of Quadrant for the Ordinary Least Squares (left), and geographically weighted regression (right).

The geographically weighted regression had an adjusted R2 of 0.5499 and a bandwidth of 44.626.

Mean angle:

The mean angle for the fatality direction from the turbine is is 231.02 degrees (Rayleigh $z_{9.937}$, p <0.001) and a standard deviation of 93.06 degrees. The mean angle for wind direction was 61.55 degrees (Rayleigh Z $_{56827.683664}$, p<0.001) and a standard deviation of 41.34 degrees.

Variable	Mean	Median	Standard Deviation	Rayleigh test of Uniformity P value
Fatality Mean Direction	231.02	237.134	93.06	<0.001
Wind Direction	61.55	62.458	41.34	<0.001

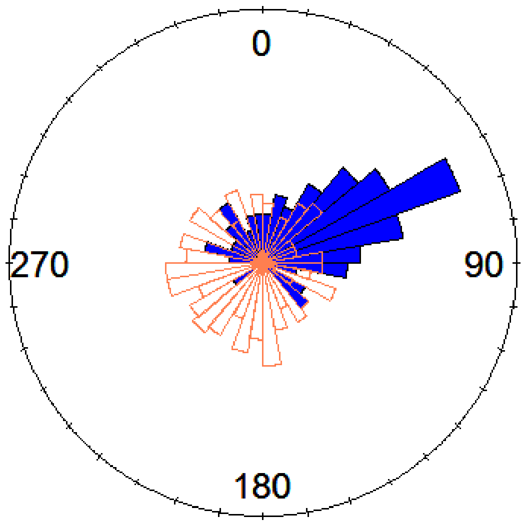


Figure 12. Rose Diagram showing the Wind Mean Direction in blue and the Fatality Direction in orange

Circular Correlation:

No statistically significant correlation was found between wind mean direction and fatality direction.

Circular Regression:

No statistically significant correlation was found between wind mean direction and fatality direction for first and second order regression.

3rd order regression:

Coefficients	Fatality Direction	Wind Mean Direction
Intercept	0.05287120	0.34318415
Cos x	-0.13244974	-0.64842429
Cos x^2	-0.10276108	0.07286978
Cos x^3	0.11858554	0.01757146
Sin x	0.31888090	0.02002215
Sin x^2	-0.15498523	-0.15498523
Sin x^3	-0.08561148	0.18354234
P value	0.0254123	0.05999396

Mean of the cosines of the circular residuals: 0.3699195

MLE of the concentration parameter: 0.7962314

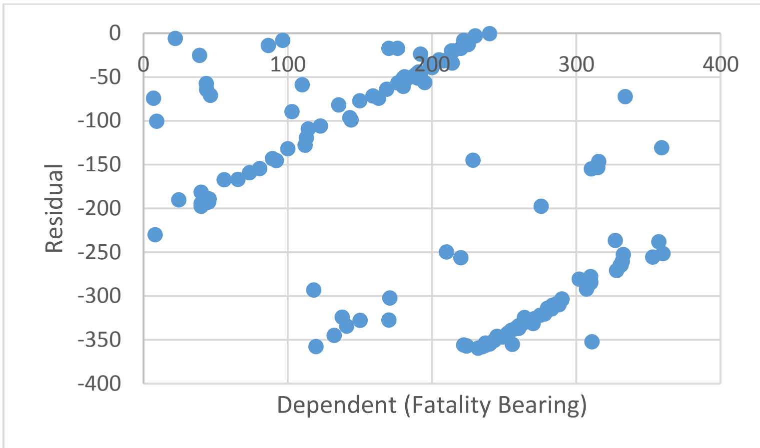


Figure 12. The residuals for the circular regression show a strong linear relationship when graphed on a linear plot.

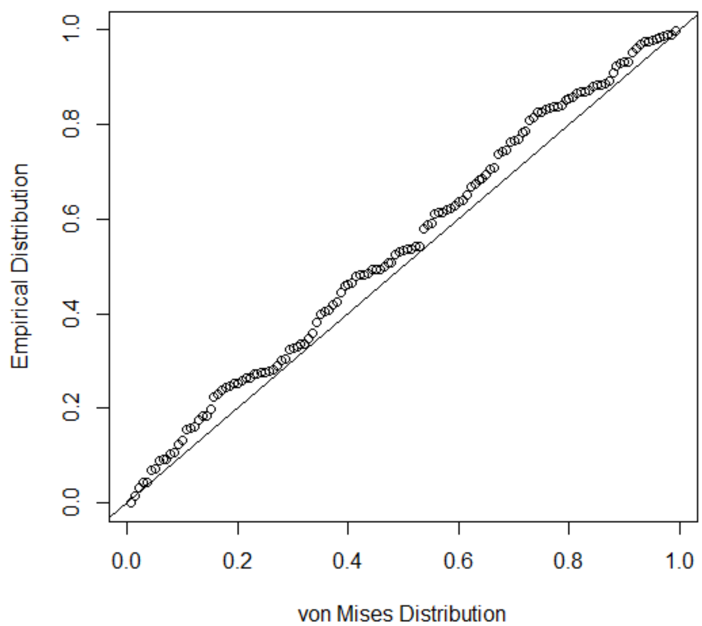


Figure 13. P-P plot for the residuals of the 3rd order circular regression relative to a von Mises distribution.

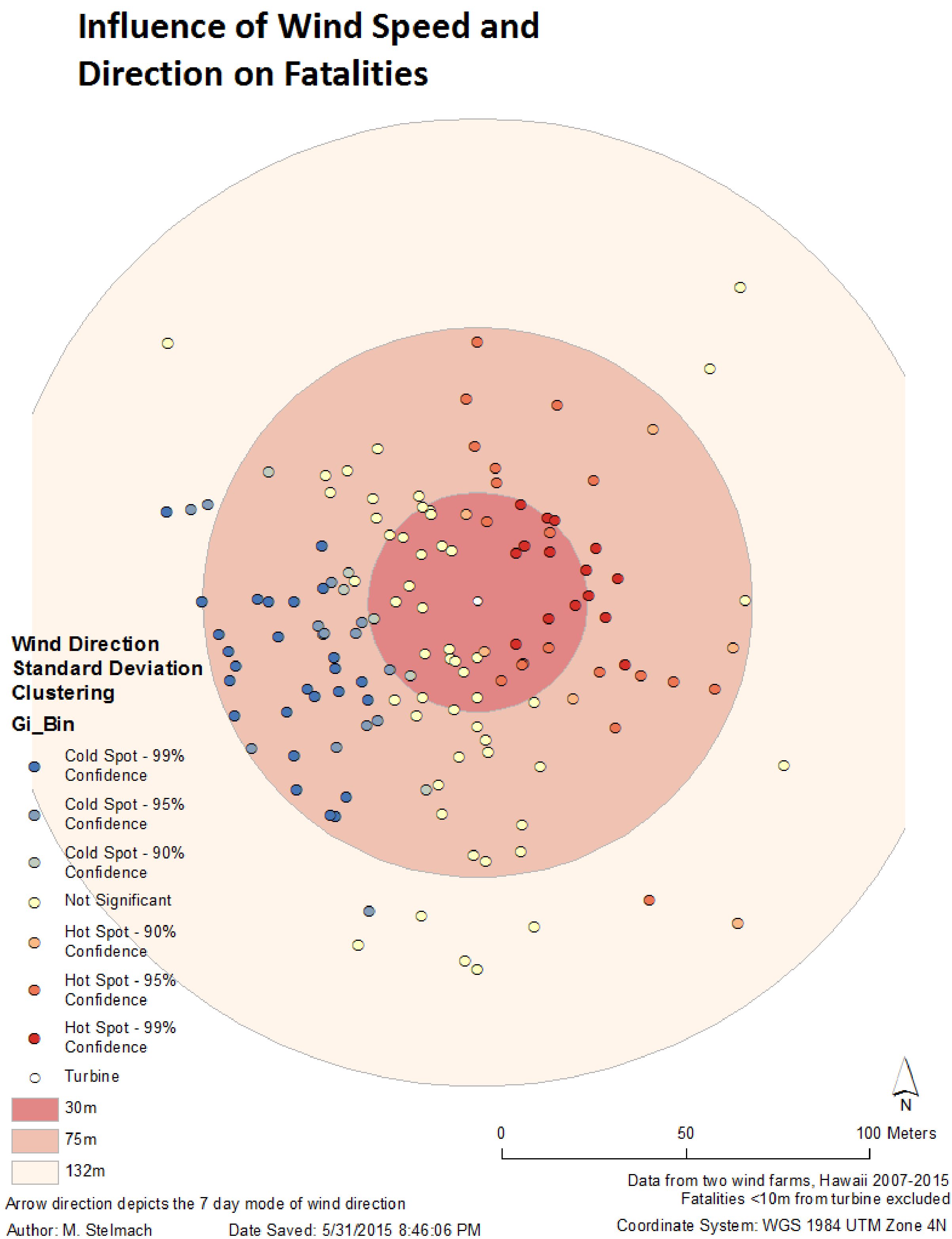


Figure 14. Getis-ord hot spot analysis for Standard deviations of Wind Mean Direction.

Discussion:

The data set itself has several inherent challenges that any analysis must overcome. The area searched under the turbine is 1.5 times the diameter of the rotor swept area and 50% of the height of the turbine. This means if an avian species was struck at the blade tip and fell straight down it's bearing from the turbine would be at 90 degrees to the direction of the wind, with a distance of 50m. Although the rotor swept area was not a significant factor in the number of animals killed per turbine (Barclay et. Al. 2007), it likely has a significant impact on where those fatalities are located. The highest probability for collision is near the hub. Carcasses which are imparted with an angular velocity in the plane of rotation could also deviate from the standard wind direction. Understanding the details of these interactions will increase the explanatory power of the model.

The uncertainty surrounding the time of the collision leads to large standard deviations for many of the Wind Mean Directions. To overcome this obstacle, all relevant timestamps for the seven days prior to the date the fatality was found were used to construct predictive ellipses. However, the predictive ellipses did not achieve a higher proportion of captured fatalities than a fixed circle either centered on the turbine or on the mean center of the fatality distribution. It is probable that a more complex shape may achieve a higher capture rate but the generation of more complex shapes was beyond the scope of this analysis. Based on the shapes analyzed, the most efficient search area is a 30m buffer centered on the turbine.

There was a significant shift of the mean center, median center, and central feature to the southwest (figure 8) indicating that there is some directionality to the fatality distribution. There was also the highest proportion of fatalities found in the southwest quadrant (figure 10). This is also inversely correlated with the Wind Mean Direction (figure 12).

The Wind Mean Direction predicts approximately 4.6 percent of the variation (figure 9) and is inversely correlated with the Fatality Direction. There is significant spatial autocorrelation in the residuals (figure 9). This is likely due to the interpretation of a circular variable by a linear method, where the values near 360 are also near 0.

There is a curvilinear response of fatality direction to wind direction with the circular-circular regression. The third order regression showed a significant result, which suggests that there is variation in the response seen based on the wind direction. This is also illustrated by the variation in figure 15. Fatalities found to the downwind of the predominant wind direction tended to have much less variation in wind direction than those found upwind. Which means upwind or fatalities found in the northeast quadrant are more likely when winds are shifting and the standard deviation of the turbine direction is high and downwind fatalities are more likely with consistent trade winds. Verification of this was found with the Standard Deviation of Wind Direction being able to predict 11 percent of the variation in Quadrant (figure 11) with the caveat again that near 0 degrees both OLS and GWR have difficulty predicting values.

Emerging technology such as blade sensors, imagery systems, and acoustic monitors may be able to increase the level of granularity of the data (EDM International, inc. 2007). This would allow precise times to be recorded and give a greater degree of accuracy to the data. Without additional technology, increasingly complex shapes may be tried as predictive shapes such as half-ellipse downwind of the turbine, T-shapes that encompass the fall zone and the blades or kernel density based shapes.

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