ATSC 448-Directed Studies Project

The Linear Gust and Mean Wind Relationship along Three BC Ferry Routes

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Abstract

The study computed linear regressions of mean wind and gust speeds for three ferry routes with data collected at twelve weather stations from April 1st 2011 to February 29th 2012. Ferry route 1 and 2 connected across the Georgia Strait, and route 3 connected across the Hecate Strait. The wind speed represented the average wind of 1 to 2 minute intervals occurring at the time of record, and the gust speed was the peak reading on the anemometer lasting for 3 to 5 seconds. An annual relationship was established for the region covering the Strait of Georgia and Hecate Strait: gust(km/hr)=1.1986820*mean wind speed(km/hr)+0.7696146. The relationship could be used to forecast gust speeds from mean wind speeds for the West Coast region. The seasonal variation and the influence of wind speed on the wind and gust relationship were also investigated. Lastly, to examine the specific conditions at each of the three ferry route, linear regressions were obtained for each route and comparison between the wind and gust relationships of route 2 and 3 showed that at route 3 (Hecate Strait), the wind and gust were much stronger than at route 2 (Georgia Strait).

Introduction

BC Ferry is the ferry service provider for the West Coast of British Columbia, and with its fleet of 35 vessels and 25 ferry routes connecting to 47 terminals, BC Ferry transported over 20.7 million passengers and 8.1 million vehicles in 2011.("About BC Ferries," 2012) The current weather forecasts mainly focused on mean wind speed, which was defined by Environment Canada as the average wind speed recorded over a 1 or 2 minutes period at a height of 10 metres above ground, but no gust forecast was provided. ("Environment Canada Glossary," 2011) Wind is the horizontal flow of air and the driving force for the weather, which impacts may aspects of our daily lives, but a strong gusty condition could also be dangerous to the BC ferry vessels sailing across various straits. On January 22 of 2012, a high wind episode forced the cancellation of many ferry services and extreme gust speed of 110km/h was expected in parts of the coast and Vancouver Island. (Duggan, 2012)

Gust was defined as the sudden rapid change in wind speed that fluctuated between peak and lull speeds, but the peak gust speed was the one of more concern due to its greater magnitude comparing to the mean wind, so the gust speed mentioned in this study represented the peak gust speeds only. Peak gust speed is the instantaneous maximum wind speed that usually lasts for 3 to 5 seconds. (“Environment Canada Glossary,” 2011) Due to its small temporal and spatial scales, gust was a difficult variable to predict. (Friederichs et al., 2009)

Atmospheric scientists worldwide have long studied the relationship between gust speed and mean wind speed, and different methods were devised in attempt to determine the possible gust speeds from a known mean wind speed. For example, a 1999 study investigating the maximum daily gust related to mean daily wind speed utilized a new definition of the gust factor, which changed from being the ratio of peak gust to mean wind to the ratio subtracted by one. With this new gust factor and several manipulations of the gust factor equation combined with statistical transforms, the study was able to determine the exceedance probability of the gust surpassing a certain magnitude when the mean wind speed was known. (Weggel, 1999) Furthermore, many research studies suggested that potential factors influencing the wind and gust relationship included height, averaging time of the mean wind speed, wind strength, atmospheric stability. (Deacon, 1965)(Davis & Newstein, 1968) (Weber et al., 2001) In addition, the gust itself also exhibited interesting characteristics, such as a diurnal trend with afternoon maxima, which were shown by a research study analyzing the time and magnitude of daily maximum wind gust. (Hewston & Dorling, 2011)

However, studies focusing on the gust and wind relationships of the West Coast region were sparse. Therefore, the goal of this study was to determine a linear relationship between the mean wind and gust along three BC ferry routes across the Strait of Georgia and Hecate Strait: Route 1 is at Georgia Strait South from Swartz Bay to Tsawwassen; route 2 is at Georgia Strait Central from Nanaimo (via Departure Bay) to Horseshoe Bay; lastly, route 3 is from Prince Rupert to Skidgate. (“About BC Ferries,” 2012) The locations of the three ferry routes were marked by black lines in Figure 1 below. With a wind and gust relationship more specific to our region, better and more accurate gust forecasts could be provided to the public.

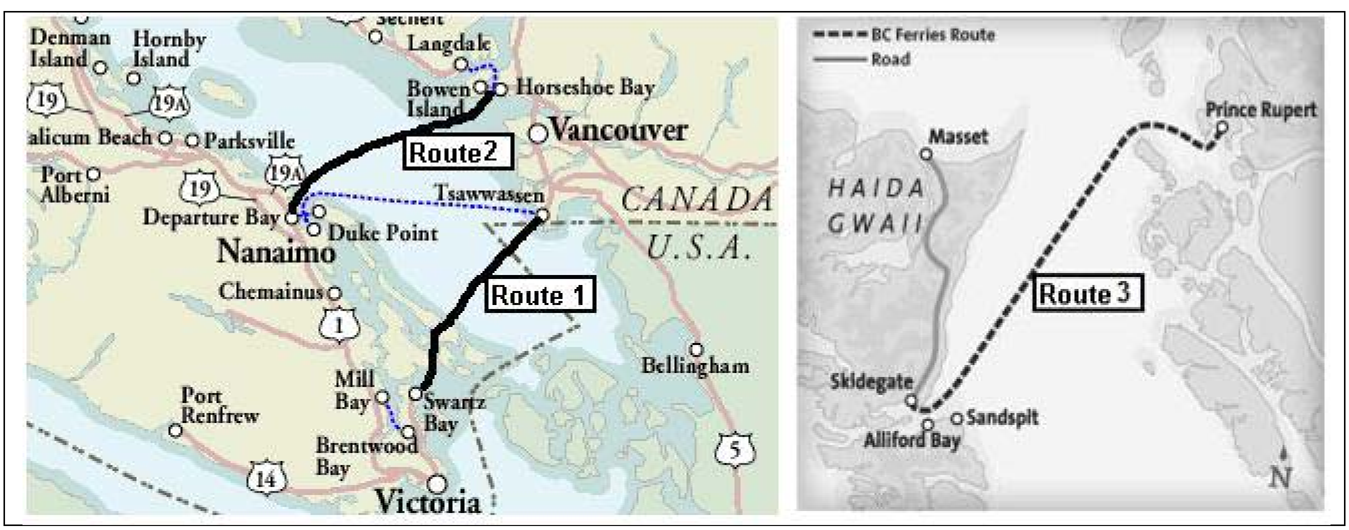

Figure 1. BC ferry route 1 and 2 are marked with solid black lines on the map on the left side: Route 1 is from Swartz Bay, Victoria to Tsawwassen terminal, Vancouver; route 2 is from Nanaimo to Horseshoe Bay, West Vancouver. Route 3, which is from Prince Rupert to Skidgate located in Haida Gwaii, is marked by a black dashed line on the map on the right side. (“About BC Ferries,” 2012)

Methods

This study analyzed the mean wind and gust data reported at weather stations adjacent to the three BC ferry routes to determine a linear regression relationship in the form of the equation for a straight line:

$$y=a*x+b,$$

where a represented the slope, b represented the intercept, x was the mean wind speed in km/hr and y was the gust in km/hr. The linear regression relationship could provide a general description of the complex correlation between wind and gust speeds and help predict the potential gust speed associated with a known wind speed. Davis and Newstein also applied a linear regression model in their study on the effect of mean wind speed and height on gust factor, and Weber's analysis on surface wind gust statistics employed a linear regression model as well. (Davis & Newstein, 1968) (Weber et al., 2001)

Mean wind and gust speed data were collected from weather stations nearby the three BC ferry routes. The wind speed represented the average wind of 1 to 2 minute intervals, and the gust speed was the peak reading on the anemometer lasting for 3 to 5 seconds. ("Environment Canada Glossary," 2011) Due to the time constraint of this study, eleven month of data were collected from April 1st 2011 to February 29th 2012.

Table 1. Table detailing the Weather stations used in the study.

Weather Station Name (**ID**)	Latitude	Longitude	Elevation(m)
Route 1-Swartz Bay to Tsawwassen			
Tsawwassen Terminal (**Westshore-1**)	49.01	-121.47	47
Route2- Nanaimo to Horseshoe Bay			
DISCOVERY ISLAND CS (**WDR**)	49.42	-121.57	15
POINT ATKINSON CS [AU8] (**WSB**)	49.33	-121.6	35
Halibut Bank (**46146**)	49.34	-122.036	-
Ballenas Island [AU8] (**CWGB**)	49.35	-122.476	5
Route3- Prince Rupert to Skidgate			
Central Dixon Entrance (**46145**)	54.38	-130.736	-
Hecla Island (**CWHL**)	54.17	-128.676	5
HOLLAND ROCK [AU8] (**WHL**)	54.167	-128.683	3
Lucy Island (**WLC**)	54.3	-128.93	26
ROSE SPIT [AU4] (**WRO**)	54.167	-130	7
North Hecate Strait (**46183**)	53.617	-129.41	-
SANDSPIT ARPT [AU5] (**CYZP**)	53.25	-130.15	6

Furthermore, only a limited number of weather stations recorded gust speed, so a total of twelve weather stations in the west coast region could be used in the analysis. The names and locations of the weather stations used in the study to determine the wind and gust relationship are shown in the Table 1 and Figure 2. There was only one weather station reporting gust speed near route1, and for route 2, there were four weather stations. Lastly for route 3, seven weather stations were available.

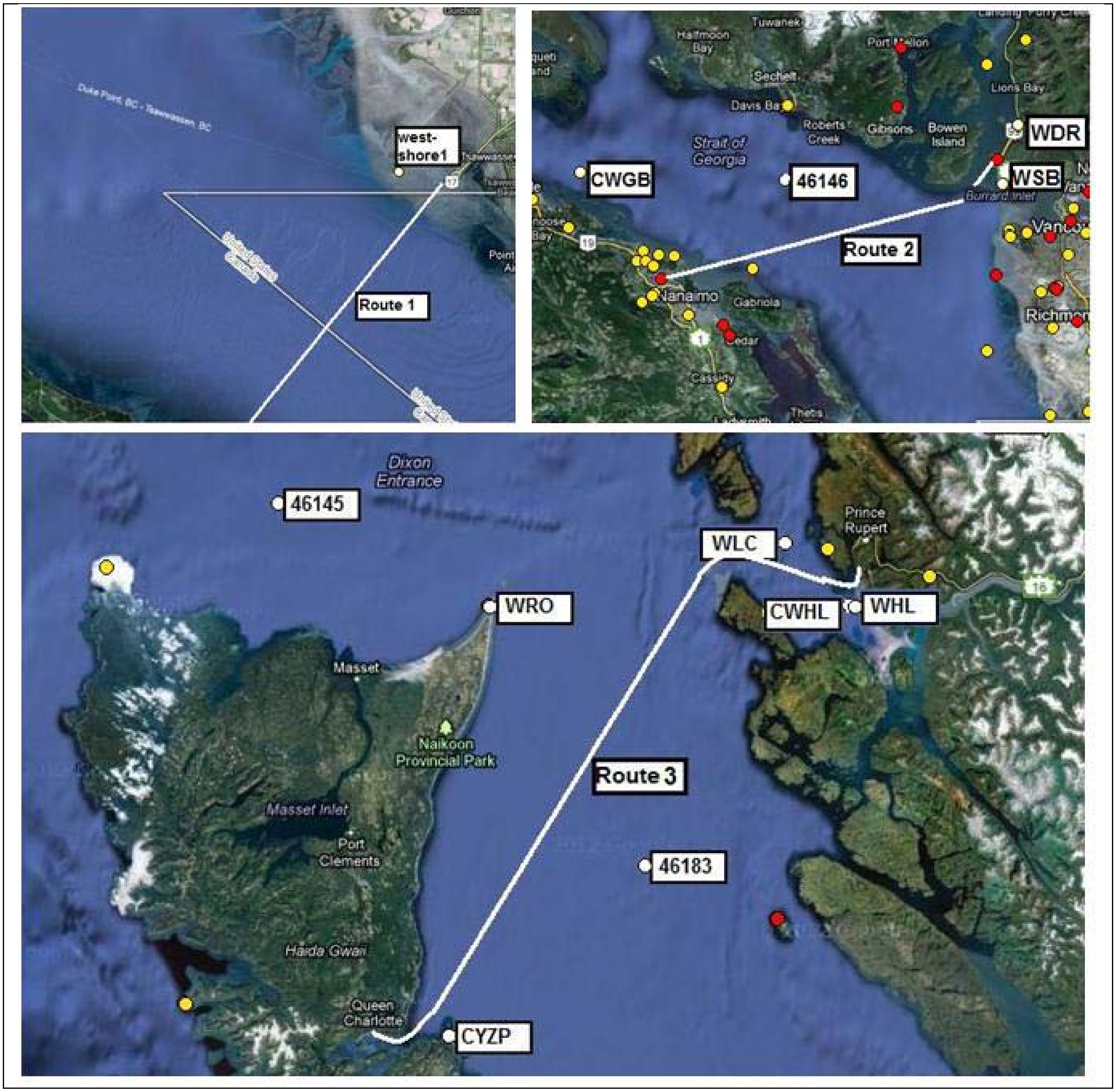

Figure 2. Weather stations utilized in the study were shown by white dots with the corresponding station ID's in boxes, and ferry routes were marked by white lines on the map acquired from Emergency Weather Net website maintained by the Geophysical Disaster Computational Fluid Dynamics Centre at the University of British Columbia (UBC). ("Emergency Weather Net", 2012)

After closely examining the data, it was discovered that some stations reported gust speeds that were less than mean wind speeds, and these data were removed because the goal of this study was to estimate the dangerous peak gust that was faster than the mean wind.

Different subsets of the mean wind and gust data were graphed to produce various linear regression relationships, which provided a description of the general wind and gust relationship in the region as well as the specific conditions along each ferry routes:

First, the complete wind and gust dataset from April 2011 to February 2012 was plotted and fitted with a linear regression model to obtain an annual wind and gust relationship for the general region of the Strait of Georgia and Hecate Strait, where the three ferry routes were located.

Secondly, an analysis on daily maximum gust speed in the United Kingdom suggested that extreme gusts occur more often in winter, so to test if there existed a difference in the wind and gust relationship due to seasonality, the data were divided in to two subsets, with the April to September 2011 data representing spring and summer conditions and October 2011 to February 2012 data representing fall and winter conditions. (Hewston & Dorling, 2011)

Thirdly, wind and gust relationship graphs were produced for each of the three ferry routes to verify if there was a significant difference between the conditions along each route.

Fourthly, to examine the influence of different wind speeds on the wind and gust relationship, three wind classes were established and the linear regression relationship was obtained for each wind class and compared: The first class was medium to strong wind ranging from 30 to 50 km/hr; the second class was very strong wind to gale with the range of 51 to 75 km/hr; the third wind class was storm to violent storm with wind speed from 76 to 102 km/hr. The wind classification was adapted from Cvitan's study which also analyzed how gust factor varied with different wind class. (Cvitan, 2003)

Lastly, it was intended to use the forecast mean wind data extracted from the Ensemble Model operated by the Geophysical Disaster Computational Fluid Dynamics Centre at UBC to validate the linear regression relationships obtained in this study. The original plan was to apply the wind and gust relationship to the forecast mean wind along the three BC ferry routes, calculate the forecast gust speed at each ferry route and compare the forecast gust speed to observed gust speed reported at weather stations adjacent to the ferry route. Specifically, the 24hr forecast mean wind produced on Day 1 would be multiplied with the wind and gust relationship to obtain the 24hr forecast gust, which would be compared to the observed gust at 00hr on Day 2.

However, several problems arose: Many weather stations did not report gust speed at regular time intervals nor at the 00hr of the day, which made it difficult to systematically code a script to perform the validation test. Secondly, for the stations reporting gust speed regularly at 00hr, such as stations 46146 and 46183, the forecast wind speed provided by the ensemble model were significantly less than the actual wind speed observed at the station, which might be due to the weather stations being at a distance from the ferry routes, so it was not beneficial to compute the forecast gust speed based on forecast wind speed that did not represent the observed wind speed at the weather stations, and then compare the forecast gust with observed gust . As a result, the validation test could not be performed for the wind and gust dataset.

Results & Discussion

Linear regressions of the mean wind and gust were obtained by fitting a straight line through the graphed data, and the six fitted graphs were shown in Figure 3 on the next page. All of the six linear regression relationships possessed significant P-values and R-squared values above 0.9. The intercept, slope, the corresponding standard deviations and adjusted R-square values were shown in Table 2.

Table 2. Summary table of wind and gust relationship coefficients for different subsets of data (The complete summary statistics could be found in the "R script output" PDF document)

Data Subsets	**Intercept**	Std. Deviation (Intercept)	**Slope**	Std. Deviation (Slope)	**Adjusted R^2**
Annual Relationship (Apr 2011-Feb 2012)	0.7696146	0.0255370	**1.1986820**	0.0009928	0.9552
Spring and Summer (Apr2011-Sept2011)	0.777691	0.028094	**1.161248**	0.001295	0.9575
Fall and Winter (Oct 2011-Feb 2012)	1.433123	0.044088	**1.201601**	0.001495	0.9518
Route 1-Annual	1.3037561	0.0175171	**1.0896831**	0.0008613	0.9746
Route 2-Annual	3.791515	0.097436	**1.153736**	0.003646	0.9235
Route 3-Annual	2.81958	0.06967	**1.20032**	0.00201	0.951

1. The Annual Mean Wind and Gust Relationship

The annual wind and gust relationship included the complete wind and gust data collected from April 2011 to February 2012 for all of the three ferry routes. As shown in Table 2, the intercept and the slope of the linear regression were 0.7696146 and 1.1986820. The mean wind speed for the total collection period ranged from 0.01 to 127.87 km/hr, and the gust speed ranged from 1.61 to 174.20 km/hr. From the annual wind and gust relationship graph in Figure 3, it could be observed that the data exhibited a clear linear trend, but in the section where wind speed was less than 90 km/hr, there existed a wide spread of the data above and below the regression line, which could indicate that there were other factors influencing the gust speed associated with a particular mean wind speed. For example, Weber's study on surface wind gust statistics suggested that as height increases the slope of the linear regression of gust and wind decreases. (Weber et al., 2001)

The annual linear regression described the wind and gust relationship for the general areas of Georgia Strait and Hecate Strait. The slope of the annual relationship was larger than the spring and summer relationship, and smaller than the fall and winter relationship. This was expected since the annual relationship included all of the data from the four seasons.

2. Seasonal Variation of the Mean Wind and Gust Relationship

The annual wind and gust data were divided at October 2011, with calm spring and summer conditions represented by April 1st to September 30th 2011 data and fall and stormy winter conditions represented by October 1st 2011 to February 29th 2012 data.

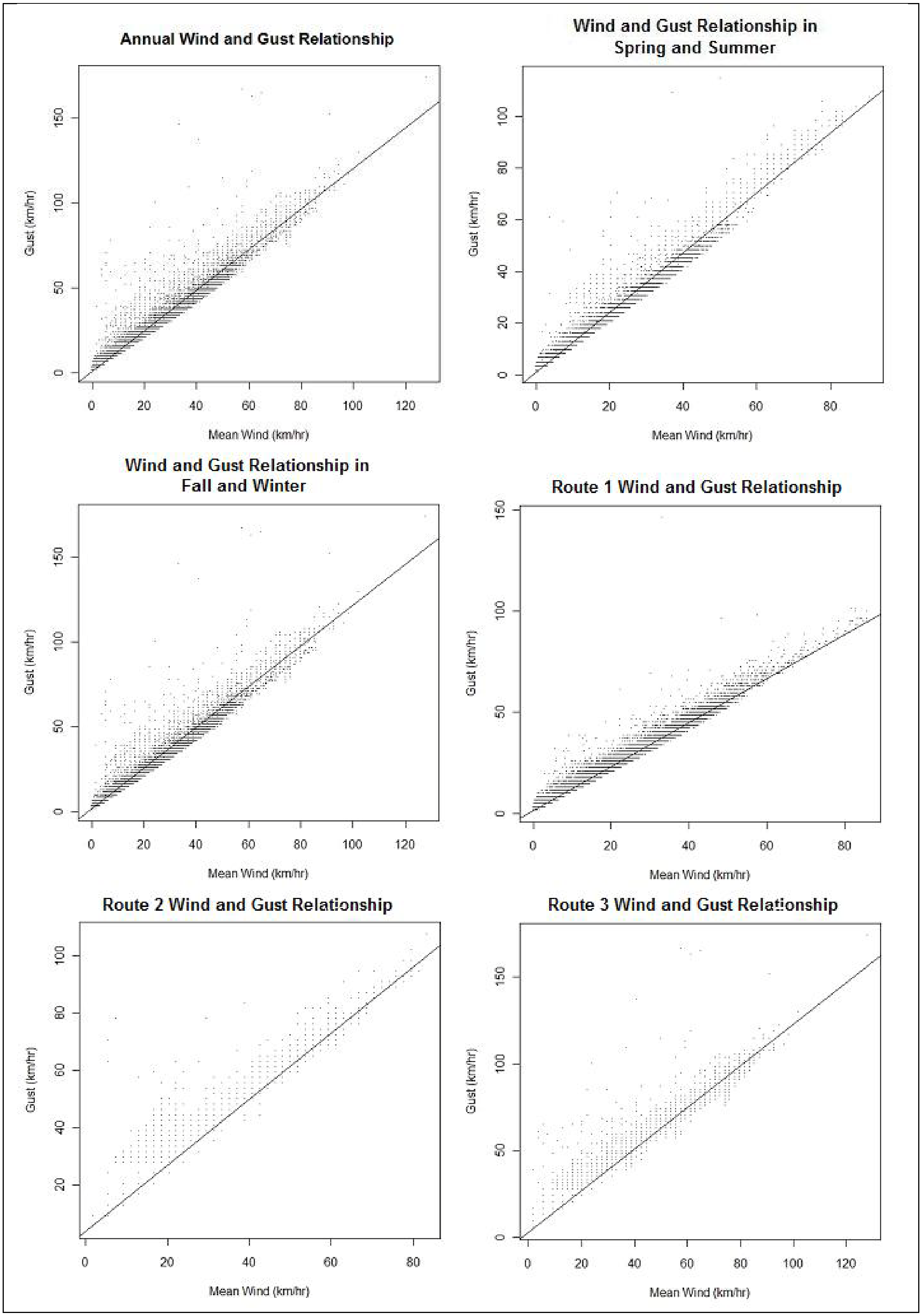

Figure 3. Graphs of Gust speed vs. Mean Wind speed for different subsets of data.

The slope for spring and summer conditions was 1.161248, which was less than the slope for fall and winter conditions, 1.201601. The standard deviations of both slopes were relatively small and the adjusted R-square values were both above the significant level of 0.95. The difference between the two slopes confirmed with the study conducted by Hewston and Dorling which described the winter season as having more extreme gust occurrences. (Hewston & Dorling, 2011)

For the spring and summer dataset, the wind speed ranged from 0.01 to 90.81 km/hr with an average of 16.68 km/hr, and the gust speed ranged from 18.25 to 114.90 km/hr with a mean gust of 21.97 km/hr; for the fall and winter dataset, the wind speed ranged from 0.01 to 127.87 km/hr with an average of 24.88 km/hr, and the gust speed ranged from 1.61 to 174.20 km/hr with a mean gust of 31.32 km/hr. The average values of the wind and gust of the fall and winter dataset were approximately 1.5 times the corresponding average values in the spring and summer dataset, and the maximum wind and gust speeds were also much higher in fall and winter. Moreover, comparison of the two graphs associated with seasonality analysis on Figure 2 showed that there were faster wind and gust in the winter and fall graph, so it was expected that the slope of the linear regression of wind and gust in fall and winter to be larger than in spring and summer.

3. Mean Wind and Gust Relationship for Each of the Three Ferry Routes

Linear regressions for the three ferry routes were obtained using the data from weather stations adjacent to each route. The resultant linear wind and gust relationship represented the annual conditions specific to route1, 2 and 3. Weather stations used for each ferry route were listed in Table 1, and the regression coefficients were shown in Table 2. The adjusted R-squared values ranged from approximately 0.92 to 0.97, and p-values indicated statistical significance for the three linear relationships for route 1, 2 and 3. The slope for route 1, 1.0896831, was the smallest compared to the slopes of route 2 and 3, which were 1.153736 and 1.20032 respectively.

The variations between the slopes for the three ferry route could be explained by the data used for each route. Table 3 listed the quartiles, means and maximum values of the wind and gust dataset used for route 1, 2 and 3. From the table, it could be observed that the wind and gust speeds at route 1 were much lower than at route 2 and 3, and values of 1st and 3rd quartile wind and gust at route 3 were approximately doubling the values at route 1.

Table 3. Summary table of wind and gust dataset used for each ferry route

	Wind speed (km/hr)				Gust speed (km/hr)			
Ferry Route	1st Quartile	**Mean**	3rd Quartile	**Max.**	1st Quartile	**Mean**	3rd Quartile	**Max.**
route 1	8.95	17.03	22.78	85.87	11.27	19.86	25.75	146.45
route 2	12.97	22.88	27.80	83.39	16.68	30.19	38.92	107.49
route 3	20.39	30.75	40.77	127.87	24.09	39.73	53.74	174.20

Both of routes 1 and 2 were ferry routes crossing the Strait of Georgia, so the linear regression coefficients for these two routes should be similar, but the variation presented in the results could be explained by the fact that for route 1, there was only one weather station located at Tsawwassen Terminal reported gust speed. All adjacent weather stations did not report gust speed. Therefore, the relatively smaller slope and lower wind and gust speeds shown in Table 3 only represented the conditions at the Tsawwassen Terminal. The linear regression relationship obtained for route 1 did not capture the conditions across the Georgia Strait.

Conversely, for route 2 and route 3, there were sufficient weather stations reporting gust speed, and Figure 2 also showed that the locations of the utilized weather stations efficiently covered both sides and the middle waterway of the strait, so the linear regression relationships for route 2 and route 3 should characterize the conditions at the Strait of Georgia and Hecate Strait. Close comparison between the wind and gust magnitude of route 2 and 3 summarized in Table 3 indicated that the wind and gust were much stronger at Hecate Strait than at the Strait of Georgia. Hence, the slope of the linear regression for route 3 was larger than for route 2 as shown in Table 2.

Potential explanation for the different wind and gust magnitudes experienced at the two straits included the following: Haida Gwaii was smaller and at a much further distance from the coast than Vancouver Island. For the weather systems approaching the coast, a wider waterway at Hecate Strait would cause less surface drag, and the relatively smaller Haida Gwaii provide less terrain roughness comparing to Vancouver Island, which served as a more prominent obstruction for blocking faster wind coming from the west Pacific. Therefore, the wind and gust speed were higher in Hecate Strait than in Georgia Strait. In addition, gap wind, which existed in mountainous regions, could bring arctic cold air from the Northern interior through the mountain valleys to the coastal regions, and the channeling of wind by valleys and straits created fast cold winds with gusts reaching 40 m/s (144 km/hr). (Stull, 2009) Hecate Strait was located more northward than Strait of Georgia and could be impacted more by gap winds which lead to the faster wind and gust.

4. Influence of Wind Speed on the Mean Wind and Gust Relationship

The linear regressions were computed for the three wind classes described in the Method section, and the slope and intercept for each wind class were listed in Table 4. The slope for the medium to strong wind class was the largest comparing to the other two wind classes, and the slope for the storm to violent storm wind class was the smallest. This result confirmed with the study conducted by Davis and Newstein, which concluded that gust factors decreased with increasing wind speed. (Davis & Newstein, 1968)

Table 4.Linear Regression coefficients for 3 wind classes
(The complete summary statistics could be found in the "R script output" PDF document)

Wind Classes	Intercept	**Slope**
Medium to Strong Wind (30~50 km/hr)	-1.092956	**1.223697**
Very Strong Wind to Gale (51~75 km/hr)	-0.2961004	**1.1721814**
Storm to Violent Storm (76~102 km/hr)	-24.913514	**1.122466**

However, the adjusted R-squared values ranged from 0.5 to 0.7 for the linear regressions, and the p-values for all of the intercepts showed small significance, which indicated that a linear relationship probably could not capture the wide spread of the data. Nevertheless, the p-values for all of the slopes indicated statistical significance, so if only considering the slope of the linear regressions, the comparison between three wind classes demonstrated that as wind speed increased, the slope of the linear regression decreased.

Conclusion

The study computed linear regressions of mean wind and gust speeds for three ferry routes with data collected at twelve weather stations from April 1st 2011 to February 29th 2012. Ferry route 1 and 2 connected across the Georgia Strait, and route 3 connected across the Hecate Strait. The relatively high adjusted R-squared values listed in Table 2 indicated that the linear regression relationships were statistically significant, and the graphs in Figure 3 showed that the wind and gust data followed a linear trend.

An annual relationship was established for the region covering the Strait of Georgia and Hecate Strait:

Gust(km/hr)**=1.1986820***Mean Wind Speed(km/hr)**+0.7696146**

The linear relationship could be used to forecast gust speeds from mean wind speeds for the West Coast region. The seasonal variation of the wind and gust relationship was also investigated. The slope of the linear regression for fall and winter was larger than the slope for spring and summer, which indicated that stronger gust and wind were experienced in fall and winter seasons. The influence of wind speed on the mean wind and gust relationship was determined by comparing the slopes of linear regressions for three wind classes. The result showed that as wind speed increased, the slope of the linear regression decreased, which confirmed with other research studies.

To examine the specific condition at each ferry route, linear regressions of wind and gust at each route was computed: For route 1 connecting across Georgia Strait South, since there was only one weather station reporting gust speed, the wind and gust relationship obtained did not represent the general conditions at Georgia Strait. However, for route 2 and route3, there were sufficient weather stations providing gust data, so the linear regressions computed for route 2 and route 3 represented the wind and gust relationships at Georgia Strait and Hecate Strait respectively. The slope of the linear regression for route 3 being larger than the slope for route 2 showed that wind and gust were much stronger at route 3 (Hecate Strait) than at route 2 (Georgia Strait).

On the other hand, there existed a vertical spread of the data that could not be captured by the linear regression relationship, so further research could be aimed to investigate the reason for the spread. Moreover, it would also be beneficial for future research studies to focus on analyzing wind direction at each weather station in the West Coast region, since the wind and gust relationship could also be related to local wind patterns as demonstrated by the difference in linear regressions between route 2 and route 3. Lastly, if more weather stations provided gust speed record, there would be more data available for more comprehensive analysis of the wind and gust relationship in the West Coast region.

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