# Western Region Technical Attachment
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## Developing a Wind-Wave Relationship at Buoy 46088 In The Eastern Strait of Juan de Fuca

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### INTRODUCTION

The National Data Buoy Center first deployed Buoy 46088 (New Dungeness, WA), located at the east entrance to the Strait of Juan de Fuca, in July 2004. This relatively new buoy includes a full wave-array package, making it the first permanent wave-sensing buoy deployed in the inland waters of western Washington and used in operational forecasting. This new data source presents a unique opportunity for comparing actual wind and wave data with wind-wave assumptions that WFO Seattle marine forecasters have been using for many years.

With the newly available wave data from Buoy 46088, sometimes referred to simply as "Buoy 88", the purpose of this paper is to determine if the wind-wave relationship traditionally used by WFO Seattle marine forecasters applies at this buoy location. Furthermore, the observed wind-wave relationship will be broken down by wind direction. Finally, an Appendix will contain other information of interest to local forecasters that might now be directly related to the primary topic.

### PAST ASSUMPTIONS

Marine forecasters at WFO Seattle have traditionally used a one-to-one relationship to forecast wind waves when forecasting a particular wind speed. This one-to-one relationship is based on output of the Wave.exe program, which was developed by WFO Seattle lead forecaster Jay Albrecht using code provided in the *Handbook of Applied Meteorology* (Houghton, 1985, pp. 996-997). The program requires a user to input wind speed, fetch length, and duration. The program outputs wave height and period. (See Appendix for the equation contained within the program.)

Seattle forecasters, for the sake of simplicity, have been using the same assumption for fetch length and duration over *all* of its marine zones, both inland and coastal. The assumed input is a fetch length of 20 nautical miles and duration of 3 hours. These values ---which were developed more with fetch-limited Puget Sound in mind --- were assumed to be sufficiently representative of *all* of Seattle's marine zones. However, this assumption fails to consider the wider open waters of the Strait of Juan de Fuca and the Pacific coast. At Buoy 88, fetch lengths for the dominant westerly and southeasterly wind regimes are around 30 nautical miles and 25 nautical miles respectively.

Nonetheless, using the assumptions of a 20 nm fetch length and 3-hour duration, forecasters have long used the following one-to-one relationship to forecast wind waves:

| *Wind Speed (kts)* | | *Wind Waves (ft)* |
|---|---|---|
| 10 | ----------→ | 1 |
| 15 | ----------→ | 2 |
| 20 | ----------→ | 3 |
| 25 | ----------→ | 4 |
| 30 | ----------→ | 5 |
| 35 | ----------→ | 6 |
| 40 | ----------→ | 8 |

For example, a forecaster predicting a wind speed of 10 to 20 knots would automatically forecast wind waves of 1 to 3 feet. A forecast of 25 to 35 knots would automatically elicit a wind wave forecast of 4 to 6 feet. This methodology follows a linear 5:1 wind speed/wave height relationship from 10 to 35 knots, though many forecasters actually extrapolate the linear relationship to 40 knots and beyond.

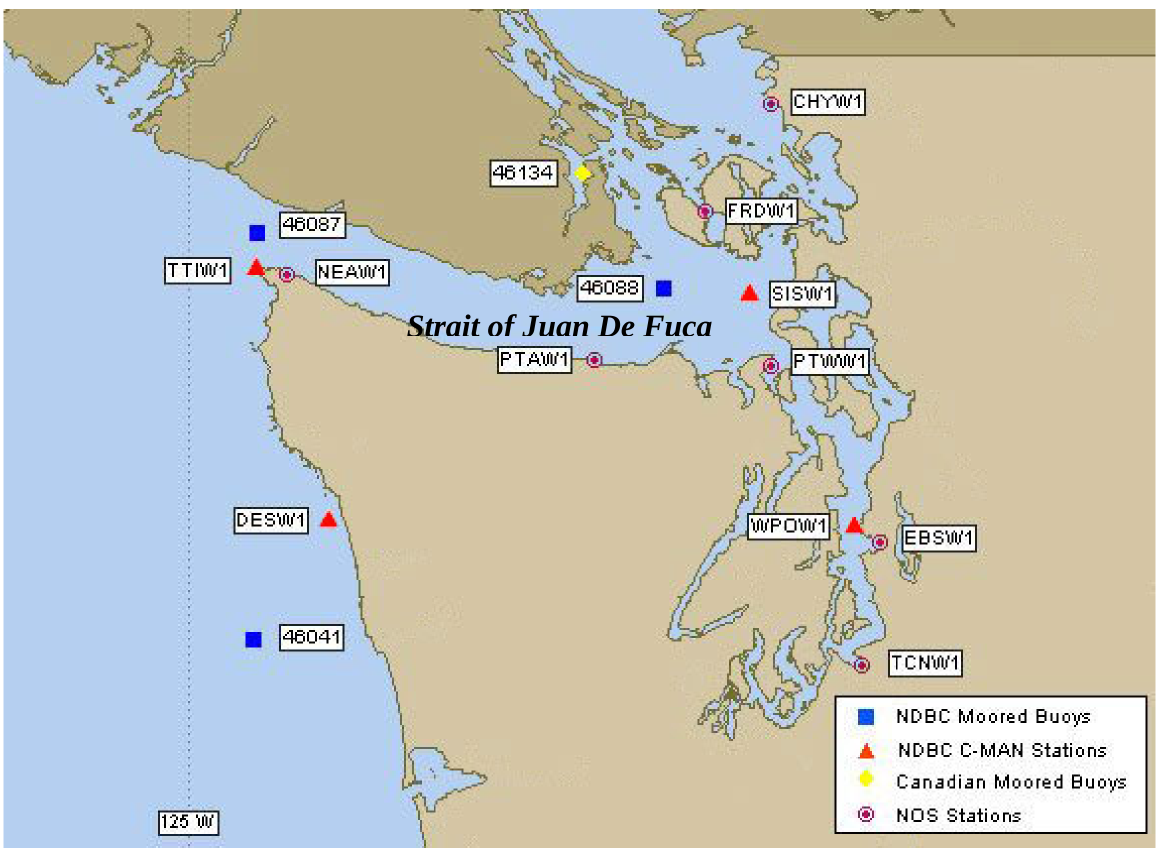


Figure 1. Map of western Washington NDBC Buoy/C-MAN sites. Buoy 46088 is located near the east entrance to the Strait of Juan de Fuca.

## METHODOLOGY OF DATA COLLECTION

To determine if past assumptions are true at the location of Buoy 46088 (see Figure 1), the authors obtained raw hourly data from the National Data Buoy Center website (www.ndbc.noaa.gov) for the period from January 1, 2005, through November 30, 2005. Just before this paper was submitted for final review, the author also added preliminary data for December 2006 in order to reflect the full 12-month calendar and to capture some stronger wind events than were previously included.

After the data was downloaded into a spreadsheet format, erroneous data needed to be eliminated. Such an example of erroneous data would be a dominant wave period of 99 seconds, mean wave direction of 999 degrees, and a wave height of 324.7 feet.

Once erroneous data was eliminated, a wind rose was developed to determine dominant wind regimes at this site (see Figure 2). This required a spreadsheet of wind speed and direction. Using these two parameters, the wind rose plotted all of the wind speeds with their corresponding directions, expressing wind speed categories as a percentage of the entire dataset. The two most dominant wind regimes were chosen for further analysis. The two regimes corresponded to westerly winds emanating from the Strait of Juan de Fuca and southeast winds emanating from Admiralty Inlet/Puget Sound. The plausible bounds for the two directions were then determined. The SE wind was defined to include directions from 100º to 170º, and the W wind from 225º to 315º. December 2006 data was not incorporated into the wind rose.

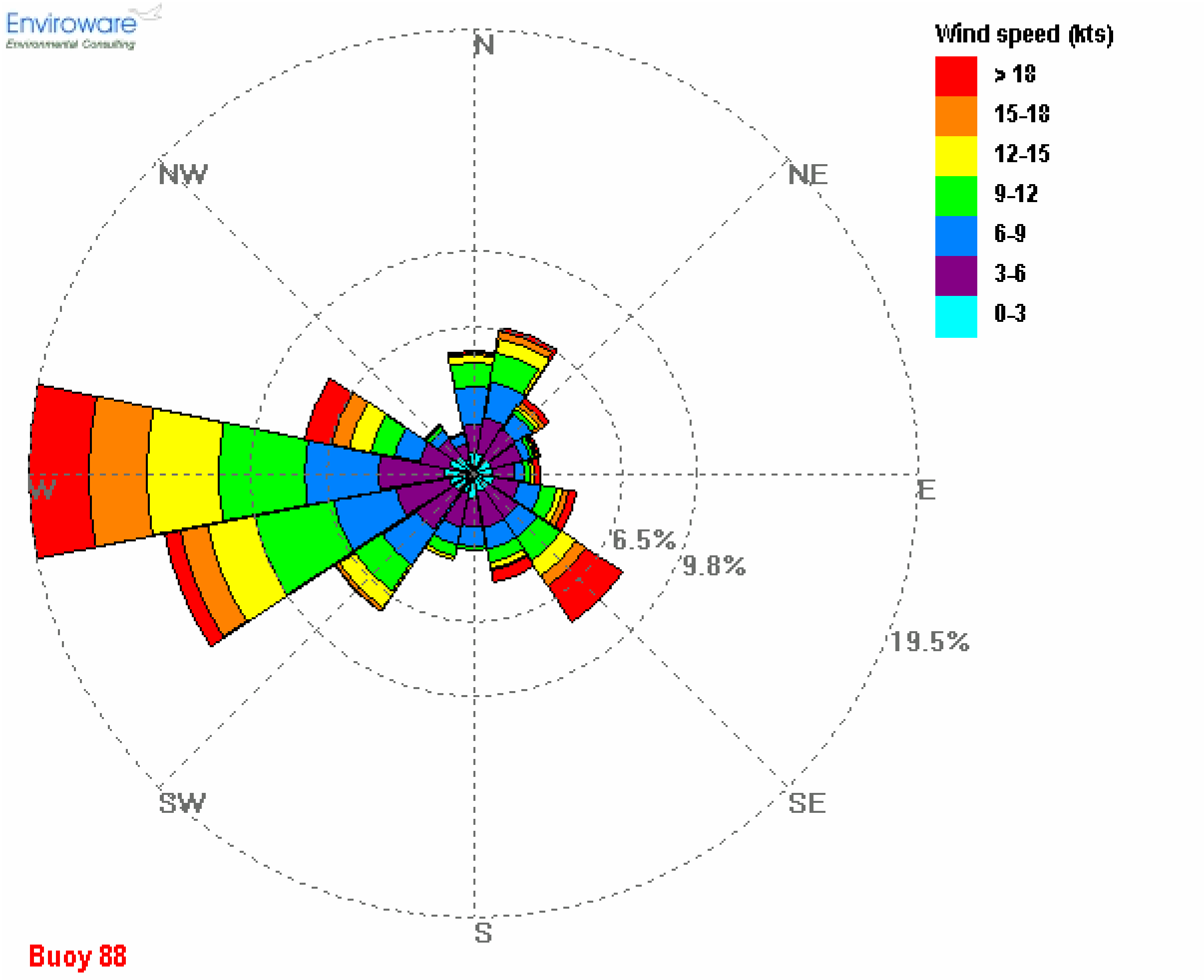


Figure 2. Wind rose for Buoy 46088. Period of record: January-November 2005.

The next step was to make a scatter-plot of the data. The first plot compared wind speed and wave height in order to obtain the upper limits of both (see Figure 3).

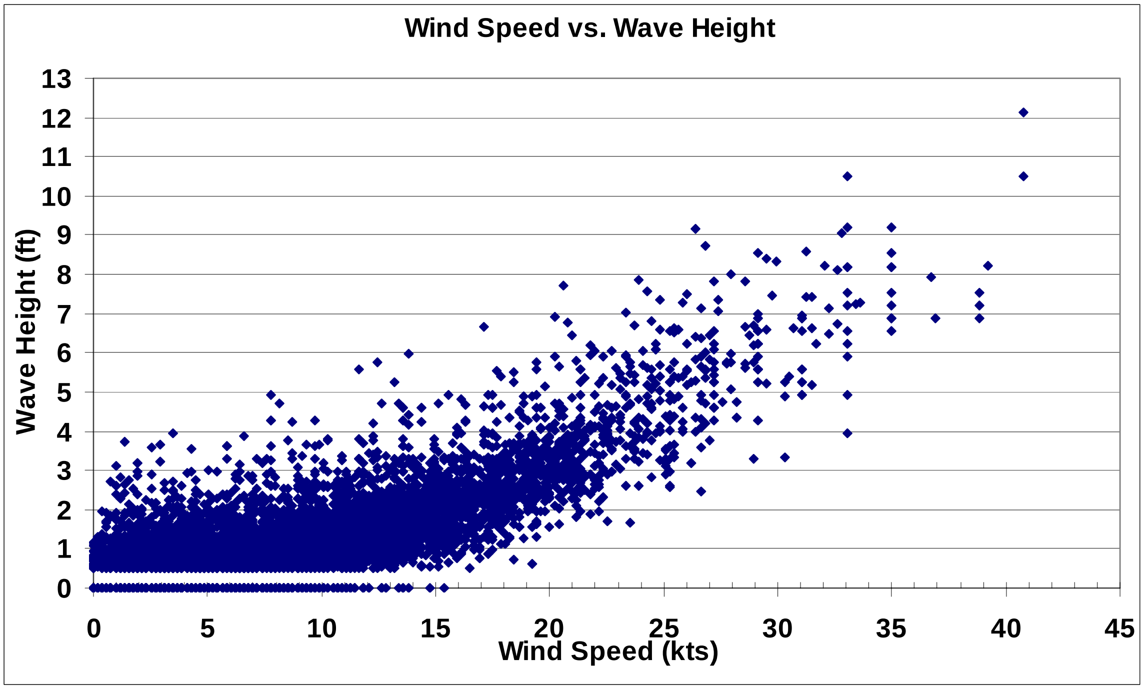


Figure 3. Scatter plot of all wind speed vs. wave height observations.

In order to analyze the wind/wave relationship for individual wind directions, data in the spreadsheet was then sorted by direction, and any data falling outside of the defined directional limits were set aside. Scatter plots of wind speed versus wave height were then plotted for the southeasterly and westerly wind regimes (Figures 4 and 6); a best fit line was determined for both regimes, noting differences among them (Figures 5 and 7).

A scatter plot was then created for the entire dataset, inclusive of all wind speeds and all directions (Figure 8). A separate scatter plot was created which accounted for a one-hour delay in the wind speed versus the wave height to better account for the response time of wave heights under changeable wind speeds (Figure 10). Best fit lines were determined using both the method with no time lag (Figure 9) and the method with a one-hour time lag (Figure 11). In each case, best fit lines are compared with the conventional wind-wave relationship currently used by forecasters.

## STATISTICAL ANALYSIS OF BUOY 46088 DATA

Cubic polynomial regressions were used to determine the best fit lines for each wind regime. This type of regression was chosen partly because of the cubic polynomial equation used in the Wave.exe program. In addition, cubic polynomial regressions yielded significantly better $R^2$ values compared to linear and squared polynomial regressions. (An $R^2$ value is an indicator of how well the "best fit line" fits the actual data. The higher the value $R^2$ is, the better the fit.) From a physical standpoint, cubic polynomial regressions also make sense since there is an upper limit to the development of wave heights, known as the fully arisen sea. A cubic polynomial line would be able to capture the upper limit, while a squared polynomial or linear regression would never reach an upper limit.

The strongest correlation between wind and waves was under the southeast wind regime, when the $R^2$ value was 0.76 (Figure 4). The westerly wind regime had a weaker $R^2$ value of 0.63 (Figure 6). Making use of the entire dataset --- without eliminating wind speeds below 10 knots or eliminating data based on wind direction --- produced a relatively strong $R^2$ value of 0.70 (Figure 8). Applying a one-hour time lag to wind speed (to account for wave response time) for the entire dataset boosted the $R^2$ value to 0.74 (Figure 10). Due to the relatively high $R^2$ value when using the one-hour delay, recommendations for wave height forecasting in the Conclusion section are based on results using the entire database with a one-hour wind speed time lag.

Despite the fact that this paper only considers the effect of wind speed on wave height, it should be noted that wind wave height is actually a function of fetch length, wind duration, and static stability of the atmospheric boundary layer **in addition to** wind speed, *not just wind speed alone*. This paper's consideration of wind speed alone and the omission of fetch length, wind duration, and static stability as considerations explains some of the wide scattering and lower $R^2$ values. Applying statistical analysis to just the consideration of wind speed understandably produces outliers and imperfections.

## SOUTHEAST WIND

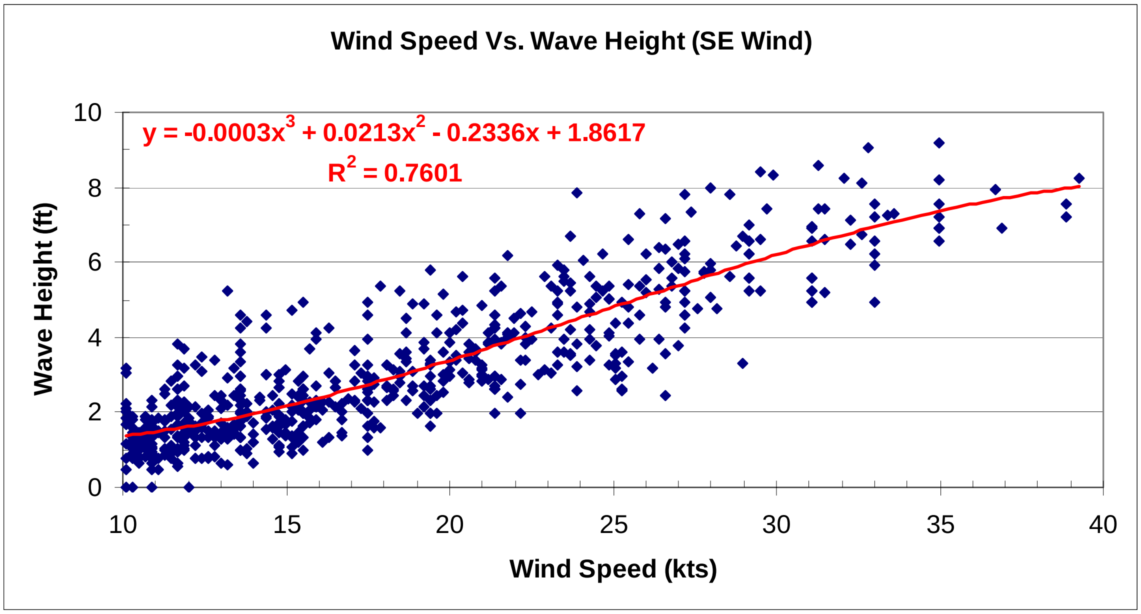


Figure 4. Scatter plot of observed Wind Speed versus Wave Height under the **SOUTHEAST** wind regime at Buoy 46088. Best fit line is in red.

| Southeast Wind Speed (knots) | Wind Wave Best Fit Line (feet) | Conventional one-to-one wave forecast (feet) |
|---|---|---|
| **10** | **1** | 1 |
| **15** | **2** | 2 |
| **20** | **3** | 3 |
| **25** | **5** | 4 |
| **30** | **6** | 5 |
| **35** | **7** | 6 |
| **40** | **8** | 8 |

Figure 5. The best fit line for **southeast** wind at Buoy 46088 shows a wind-wave relationship that exceeds the conventional one-to-one relationship with wind speeds of 25 to 35 knots.

## WEST WIND

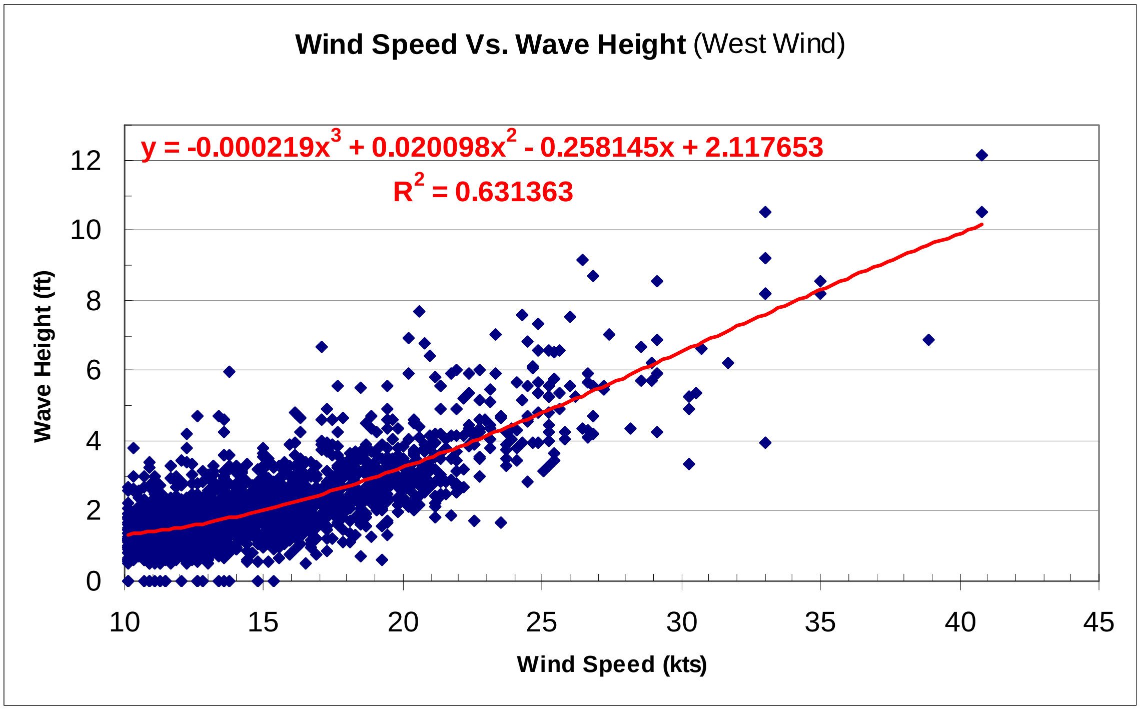


Figure 6. Scatter plot of observed Wind Speed versus Wave Height under the **WEST** wind regime at Buoy 46088. Best fit line is in red.

| West Wind Speed (kts) | Wind Wave Best Fit Line (feet) | Conventional one-to-one wave forecast (feet) |
|---|---|---|
| 10 | **1** | 1 |
| 15 | **2** | 2 |
| 20 | **3** | 3 |
| 25 | **5** | 4 |
| 30 | **7** | 5 |
| 35 | **8** | 6 |
| 40 | **10** | 8 |
| 45 | **11** | |

Figure 7. The best fit line for **west** wind at Buoy 46088 shows a wind-wave relationship that exceeds the conventional one-to-one relationship used by forecasters for wind speeds of 25 knots and higher.

## ALL SPEEDS AND ALL DIRECTIONS

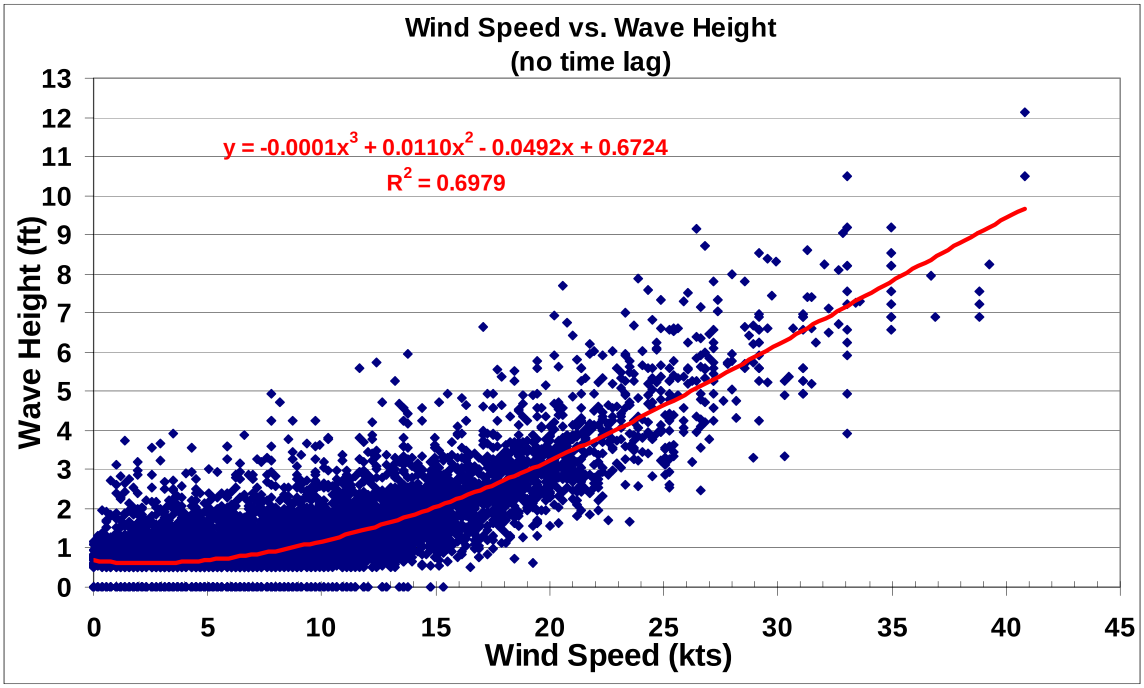


Figure 8. Scatter plot of observed Wind Speed versus Wave Height for all wind directions, inclusive of wind speeds under 10 knots. Best fit line is in red.

| Wind Speed (kts) | Wind Wave Best Fit Line (feet) | Conventional one-to-one wave forecast (feet) |
|---|---|---|
| 10 | **1** | 1 |
| 15 | **2** | 2 |
| 20 | **3** | 3 |
| 25 | **5** | 4 |
| 30 | **6** | 5 |
| 35 | **8** | 6 |
| 40 | **9** | 8 |
| 45 | **11** | |

Figure 9. The best fit line for **all directions and all wind speeds** at Buoy 46088 shows a wind-wave relationship that exceeds the conventional one-to-one relationship with wind speeds of 25 knots and greater.

## ALL SPEEDS AND ALL DIRECTIONS WITH ONE-HOUR WIND SPEED TIME DELAY

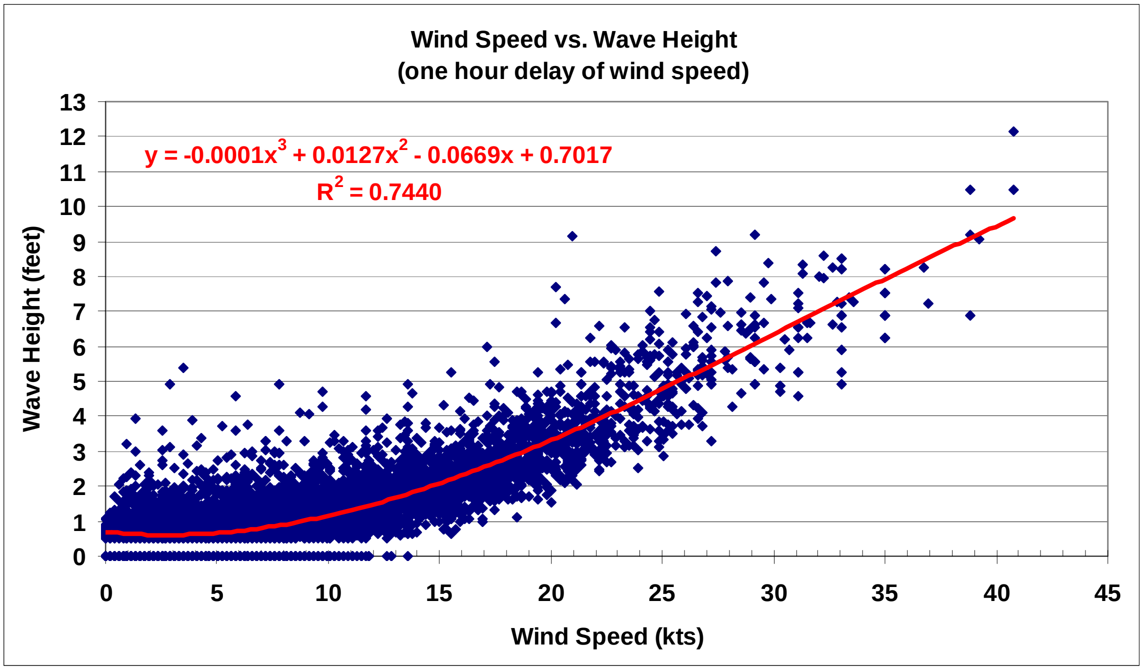


Figure 10. Scatter plot of sustained Wind Speed vs. Wave Height for the entire dataset. In this analysis, **wind speed was delayed by one hour compared to wave height** to better account for the response time of resulting wave heights, i.e. the duration term. Best fit line is in red. **$R^2$ value for this fit is noticeably stronger than for the version with no time lag.**

| Wind Speed (kts) | Wave Height Best Fit Line (in feet with **one-hour response time**) | Conventional wave forecast (feet) |
|---|---|---|
| 10 | **1** | 1 |
| 15 | **2** | 2 |
| 20 | **3** | 3 |
| 25 | **5** | 4 |
| 30 | **6** | 5 |
| 35 | **8** | 6 |
| 40 | **9** | 8 |
| 45 | **11** | |

Figure 11. Accounting for a one-hour time delay to allow wave height to respond to changes in wind speed, the best fit line for **all directions and all wind speeds** at Buoy 46088 shows a wind-wave relationship that exceeds the conventional one-to-one relationship with wind speeds of 25 knots and greater.

## CONCLUSIONS

The two most common wind directions observed at Buoy 46088 are westerly and southeasterly winds. Westerly winds coming from the Strait of Juan de Fuca are most predominant in terms of frequency. Southeasterly winds occur less frequently but can equal the strength potential shown of the westerlies.

Analysis of the wind-wave relationship at Buoy 46088 yielded foreseen results when lower wind speeds were observed. More importantly, it also revealed flaws in WFO Seattle's wind-wave forecasting assumptions with sustained wind speeds of 25 knots or higher. Based on data from Buoy 46088, WFO Seattle marine forecasts have been using values for wave height that are one or two feet too low with wind speeds in the 25 to 45 knot range.

The strongest statistical correlation occurred when using the entire dataset with a one-hour wind speed delay applied to help account for the time needed for waves to respond to changing wind speeds (Figure 10). Using this relationship, the authors conclude that the Best Fit values in Figure 11 represent optimal forecast values of wave height based on prescribed values of wind speed. Therefore, **the authors recommend using the following new wind-wave relationship when forecasting for the Strait of Juan De Fuca and along the Pacific coastal marine zones:**

| *Wind Speed (kts)* | *Wind Waves (ft)* |
|---|---|
| 10 | 1 |
| 15 | 2 |
| 20 | 3 |
| 25 | 5 |
| 30 | 6 |
| 35 | 8 |
| 40 | 9 |
| 45 | 11 |

However, a difference in wave height of one or two feet when the wind is already in stronger ranges may not have much operational impact on mariners. Most small craft operators will not venture out of port when the wind speed is 25 knots, and a one- or two-foot difference in short-period wind waves will have little impact on operators of large ocean-going ships; large ships are more heavily impacted by long-period ocean-born swell. Still, this study does identify a systematic forecasting error that the authors recommend incorporating into WFO Seattle marine forecasts.

# APPENDIX

This appendix contains data that might be deemed inconclusive and other data gleaned from this study which may be of interest to local forecasters but that do not support the main purpose of this paper.

| Wind Speed (kts) | Wave Height Best Fit Line (in feet with **one-hour response time**) | Wave Height Best Fit Line (in feet with **no response time**) | Average Best Fit Line | Conventional wave forecast (feet) |
|---|---|---|---|---|
| 10 | 1 | 1 | **1** | 1 |
| 15 | 2 | 2 | **2** | 2 |
| 20 | 3 | 3 | **3** | 3 |
| 25 | 5 | 5 | **5** | 4 |
| 30 | 6 | 6 | **6** | 5 |
| 35 | 8 | 8 | **8** | 6 |
| 40 | 9 | 9 | **9** | 8 |
| 45 | 11 | 11 | **11** | |
| 50 | 12 | 12 | **12** | |
| 55 | 12 | 13 | **13** | |
| 60 | 12 | 14 | **13** | |
| 65 | 12 | 14 | **13** | |

Figure 13. Data in this study produces best-fit lines that are conclusive only up through 45 knots. This table applies the regression equations in Figures 8 and 10 for speeds up to 65 knots. While inconclusive, the equations suggest 12 to 14 feet may be the upper limit of wave heights that could potentially occur at Buoy 88.

# APPENDIX

## LONG-PERIOD SWELL

WFO Seattle forecasters have never officially forecast long-period ocean-born swell in the Strait of Juan de Fuca, but there has been curiosity and speculation among forecasters about how much swell travels from the Pacific through the Strait and what impact it might have. Some forecasters have given first- and second-hand accounts of witnessing 1 and 2-foot ocean-type swell reaching the west coast of Whidbey Island.

Data collected in the course of this study suggests that long-period swell (defined here as dominant wave period greater than or equal to 10 seconds), presumably from the Pacific Ocean, was the dominant wave most frequently during the spring and autumn months. Dominant long-period waves started the year at a secondary minimum in January, increasing until March. The frequency bottomed out from June through August. Long-period wave frequency began to climb again in September, peaking in October, finally starting a winter decline in November (see Figure 12).

Of the hours when the dominant wave period was 10 seconds or more, wave height exceeded 1.0 feet about 32% of the time; it exceeded a height of 2.0 feet only about 5% of the time. Dominant long-period waves higher than 3.0 feet occurred less than 0.1% of the time when long-period waves were observed. Since the height of long-period waves rarely exceeds 2.0 feet, long-period swell should be considered a low-impact occurrence and serves as an endorsement of the office protocol of not forecasting swell in the Strait.

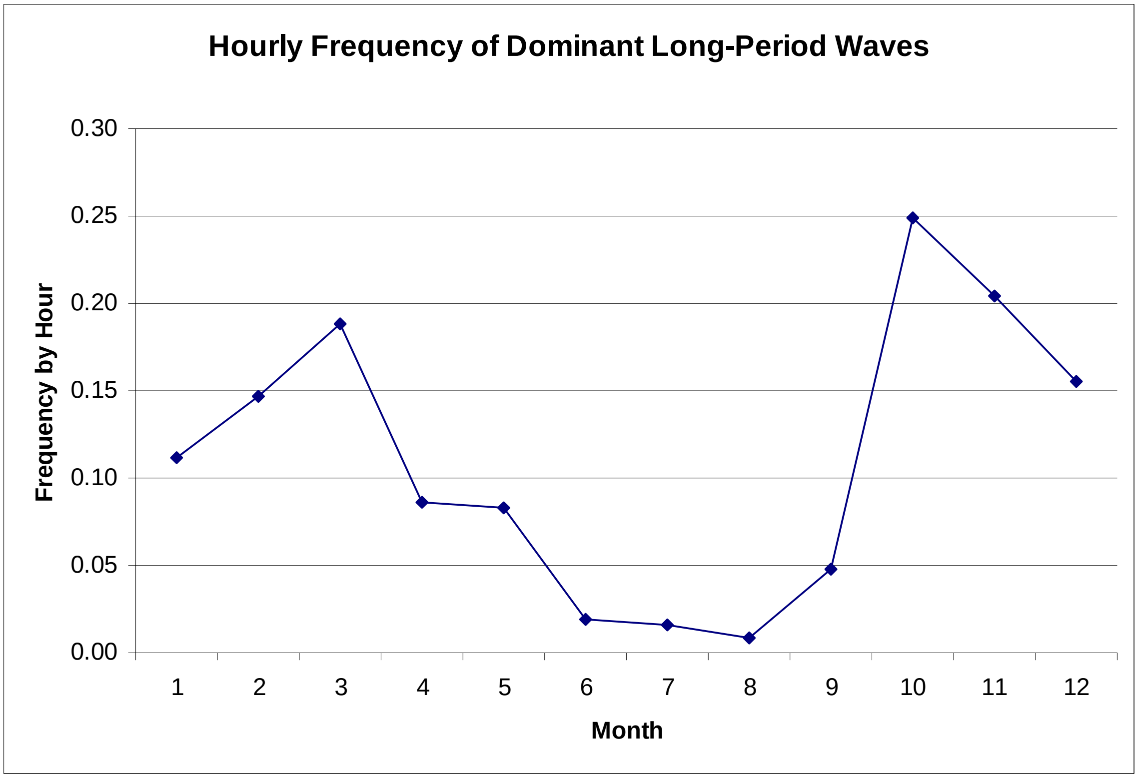


Figure 12. Hourly frequency of dominant wave periods greater than or equal to 10 seconds, broken down by month.

EQUATION USED IN “WAVE.EXE” PROGRAM FOR WAVE HEIGHT

**Wave Height =** $10 * ((A1*x^3 + A2*x^2*y + A3*x*y + A4*y^3 + A5*x^2 + A6*x*y + A7*y^2 + A8*x + A9*y + A0) - (B1*z^3 + B2*z^2*y + B3*z*y + B4*y^3 + B5*z^2 + B6*z*y + B7*y^2 + B8*z + B9*y + B0))$

Where, $x$ = input fetch $y$ = input wind speed $z$ = input duration

| | |
|---|---|
| A1 = 7.13504522296 x $10^{-3}$ | B1= 0.085192797993 |
| A2 = 3.55212535953 x $10^{-2}$ | B2 = -0.230343294892 |
| A3 = -0.478068285659 | B3 = -1.33470083822 |
| A4 = 0.801345961748 | B4 = -3.05781095613 |
| A5 = -0.139573547731 | B5 = 4.72578055894 x $10^{-2}$ |
| A6 = 2.44962663843 | B6 = 4.60259986981 |
| A7 = -2.44693762039 | B7 = 14.4363405171 |
| A8 = -1.29318213255 | B8 = -3.14235754616 |
| A9 = 2.8327157926 | B9 = -21.3452077512 |
| A0 = -1.29530377986 | B0 = 10.3581898104 |

# APPENDIX

## GUST POTENTIAL

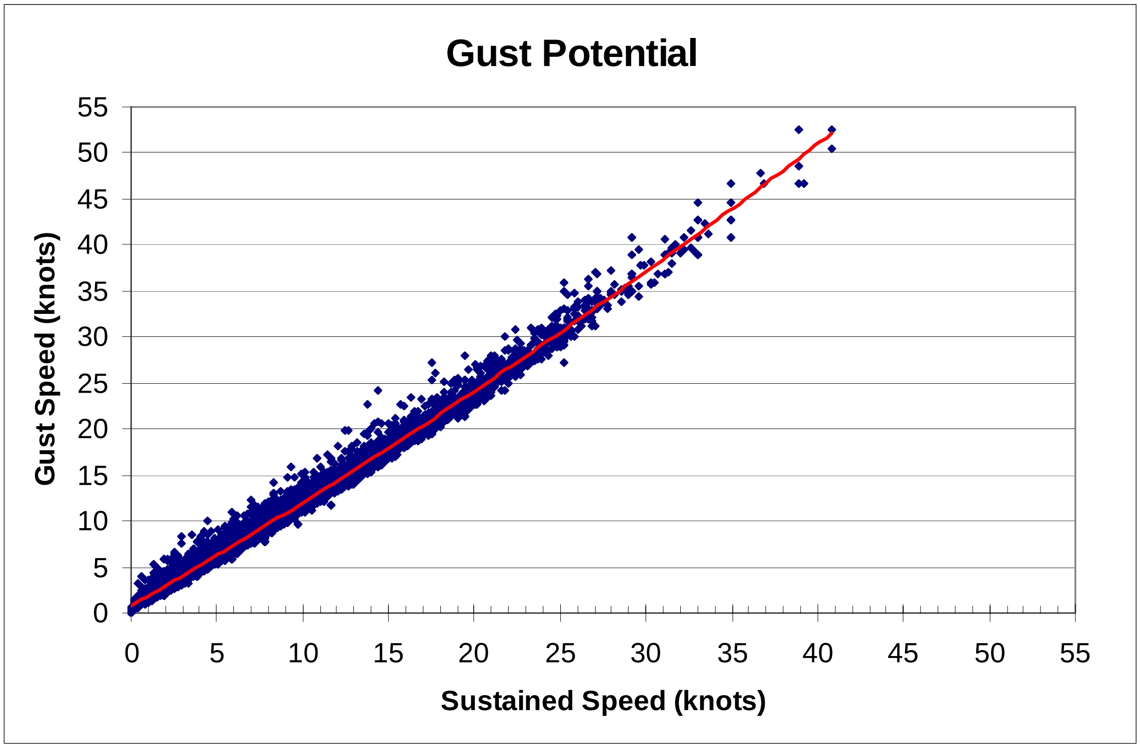


Figure 13. Scatter plot of sustained wind speeds and corresponding gust speeds.
Average Sustained Speed: 9.0 knots
Average Gust Speed: 11.0 knots
Average Gust/Sustained Ratio: 1.22

Median Sustained Speed: 7.8 knots
Median Gust Speed: 9.5 knots
Median Gust/Sustained Ratio: 1.23


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# BIBLIOGRAPHY

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