

Fetch-limited Wave Growth in Nootka Sound

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Abstract

Ocean waves are generated at every coast line in the world. Wave generation and growth depends on wind. One hypothesis explored by this study is fetch-limited wave growth. Fetch is how far wind travels over a body of water, and the hypothesis states that the farther wind travels, the bigger waves will be. Big waves have potential for destruction, which has led many scientists to create models in an attempt to predict where, when and how big waves will be. The other goal of this study was to test the accuracy of a well-known wave predicting model used by coastal engineers. Data was gathered in a fjord called Nootka Sound using microSWIFT buoys to measure and analyze wave spectrum. The data was analyzed and fit to the Coastal Engineering Manual's (CEM) model for wave growth. The results supported the hypothesis as larger fetch produced bigger waves. Comparing the observational data with the wave model suggested that the model was accurate for the wind conditions we were in, despite some disagreement.

Introduction

The height of wind waves is dependent on two main components; fetch, the distance wind travels over a body of water, and the time wind blows over a body of water (Kinsman, 1965). As these components increase, wave height and energy increases as well (Resio et al. 2012). The depth of the water column similarly affects waves, as shallower depths yield greater wave heights (Fracnis et al. 2011). With Pacific storms getting stronger, the potential for bigger

waves is a growing concern (Graham and Diaz 2001). Being able to predict waves is an essential tool for fishers, ports and other small boat users who need to know the intensity of waves to maintain their livelihoods. For example, small boats are not well equipped to face extremely rough conditions. Without accurate wave forecasts, ill-prepared vessels could depart for a journey on what seems like a calm day, only to find themselves caught in extreme wave conditions a few hours later.

In this study, analysis of fetch limitation will be studied in a fjord system called Nootka Sound located in western Canada. A previous study on fetch limitation done in the Arctic discovered that the energy and wave height can be significantly reduced by sea ice (Squire et al. 1995). Similarly, land masses in the water disperse wave energy so swell that comes from the open ocean rarely penetrate a fjord system such as Nootka Sound. (Thomson and Rogers 2014). With little to no swell entering into fjords, waves are primarily driven by wind within the fjord system itself; called wind waves (Uz et al 2003). Fjords have limited fetch relative to the open ocean, so wind waves in fjords tend to be fetch limited. Waves are considered fetch limited when they are not fully developed, meaning if they were to travel further their heights and energy would increase. Consequently, waves in fjords are usually much smaller than waves on the coast (Bogcuki et al. 2013). When wind begins to blow on the water, waves are relatively small with a short period (the time between each wave peak of a wave packet) as waves are “born” (Resio et al. 2002). As maturation of wave groups occur, and the waves propagate down a channel of water, (as long as there is fetch) wave heights grow and wave

periods increase (Resio et al. 2002). Although most of the time wind waves are small, winter storms in the North Pacific, especially during El Nino years, (Allan and Komar 2002) bring gale force winds that can create significant wind waves in these fjords. Big waves in Fjords can bring with them serious ramifications to structures, boats and even human lives.

Many different studies have empirically calculated and created model equations used to predict wave growth, each with varying levels of disagreement between them. One study done by Hasselmann (1973), also known as the Joint North Sea Wave Project (JONSWAP) produced a model in which the growth rates of waves were significantly smaller than other models. (Hasselmann et al. 1973). A study done by Kahma sits on the other side of the spectrum producing a model with relatively high growth rates (Kahma 1981). Young (1999) compares and contrasts various different wave growth models, including those done by Hasselmann and Kahma. Most models seem to agree fairly well though Kahma and Hasselmann's models are relative outliers. Young discredits the Hasselmann study because it used laboratory data to supplement their field data, and wave growth laboratory experiments are widely inconsistent with field observations (Young 1999). He also advises caution when using the Kahma model. The Kahma study was conducted under unstable atmospheric conditions with an unstable water column (Kahma 1981). Young states these conditions could alter wave growth and thus impact the accuracy of the model (Young 1999). Young's findings suggest that while some models are consistent, there is also varying levels of disagreement among them due to site specific variations and conditions. This emphasizes the complexity of measuring fetch limited

waves, making it a difficult ocean parameter to understand. The Coastal Engineering Manual (CEM) is a widely used tool to help understand the physics of waves, and how to protect shorelines from their destructive potential (Resio et. al 2002). To plan engineering tactics on the coast, accurate wave forecasts are necessary. Thus, the CEM produces a wave growth model as well. It is unclear how the model was produced, but because it is so widely used, it is imperative to empirically test the accuracy of the model. Hence, this study will be geared towards collecting wave data and fitting it to the CEM's wave growth model.

This study will assess the accuracy of the CEM's wave growth model. The experiment employs data collected at varying locations in Nootka Sound, providing varying fetch values. The abrupt topography of fjords isolates wind and wave energy enough to restart fetch. This is important in order to zero our measurements, meaning a location that "restarts fetch" has a fetch value of 0. With small fetch values in a fjord, it is likely that all of the waves we measured in this study will be fetch-limited. If the CEM model's accuracy is validated it is possible to use it as a method of predicting wave heights with given fetch and wind speed values in Nootka Sound.

Methods

To implement this experiment we set up deployments of drifters called microSWIFTS. MicroSWIFTS are drifters used to measure wave height and energy. Fetch measurements were

relative to a topographical structure that restarts fetch values by blocking off wind and wave energy up-wind of that location. At this topographical feature, fetch is assumed to be zero, with fetch values increasing downwind of the topographical feature. During each deployment, average wind speed was measured and recorded. Recorded wind speed and fetch measurements were then used to evaluate the model.

Data collection took place in Nootka Sound, British Columbia. Two inexpensive drifters created by Jim Thomson, called the MicroSWIFTs, were used to determine wave height. These drifters are made of large PVC pipe for the base, a cut yoga mat as a surface stabilizer, a water bottle and a cement weight used to counteract buoyant forces. Each drifter contains an accelerometer/GPS device that logs data internally at a frequency of 10 or 5 Hz. One drifter was equipped with a dog collar that would ping its location to a nearby device if the drifter got lost. The accelerometer is attached to the bottom of the cap of the water bottle, which sits securely in the water bottle when the cap is screwed on.

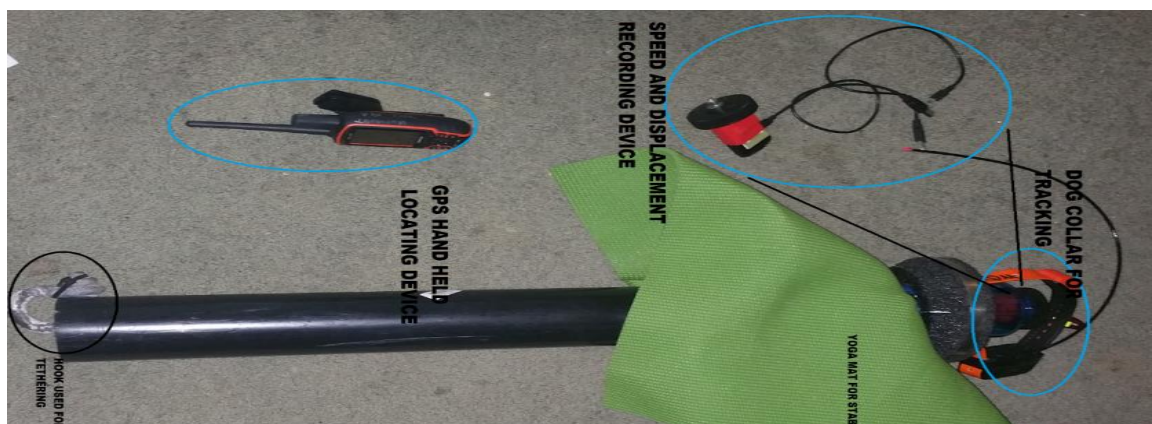


Figure 1: This is an example of one of two drifters used in this experiment, generously loaned by Jim Thomson. The device is meant to drift with the water, acting as a theoretical water particle that is tracked with a GPS device. The GPS also has a built in Accelerometer that was recording data at 10 Hz (10 times per second). The GPS logs data internally, so a dog collar was used to track the device if line-of-sight wasn't enough to locate it.

Two drifters were deployed on two different days, three times each. The drifters were dropped in the water at approximately the same time and location for each deployment and recorded data for 20-30 minutes. The site of the deployments was determined the day of deployment, due to variance in wind direction. The wind direction determines where fetch begins and ends. Wind direction was determined by an onboard anemometer. Once wind direction was determined, relative fetch deployment sites were planned out on a map. For both days, one of the deployments was set up at a location as close as possible to the topographical feature. This location would block off all wind and wave energy upwind of the deployment resulting in a very small fetch (distance from land mass to drop location). The last deployment would be downwind as far as possible, until another topographical feature was encountered, to get the longest possible fetch. If an imaginary line were drawn between the first and last deployment, that line would be parallel to the wind direction. During each deployment, the onboard anemometer was used to determine average wind speed for each deployment. The anemometer calculated average wind speed internally with a built in averaging function. The first day of deployments took place under weak winds from the northwest. The second day featured stronger winds from the west-southwest. Deployment

locations can be seen in Figure 2.

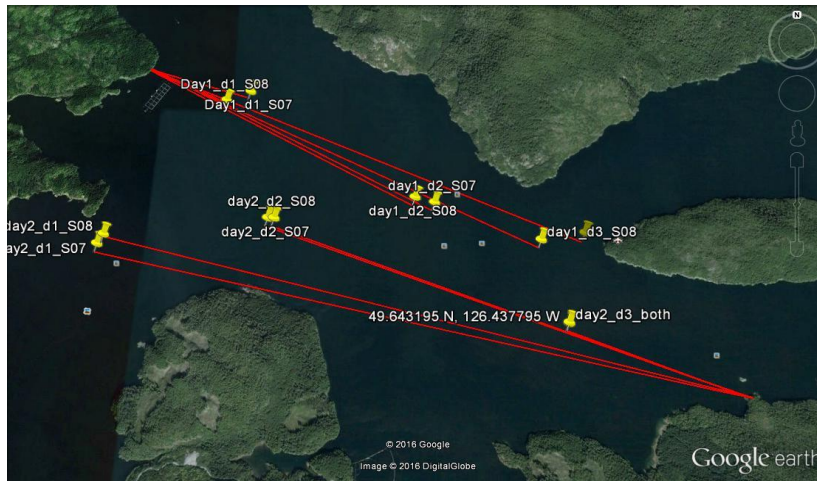


Figure 2: Average coordinates of the drifter during each particular drop. The red lines map out the path of the average coordinate to the nearest land mass relative to wind-direction at the time of the drop. The locations used are theoretically where fetch “begins” and the wind begins to act on the water. The land masses shown are big enough to block wind, thus assuming fetch begins at those locations is valid. Each tack represents a 20-30 minute time period of a drifter being in the water. Since both drifters were dropped in the water close together, they are usually coupled as two tacks relatively close together. S07 represents one drifter and S08 is the other.

Data from the drifters were transferred from the accelerometer to a program called QStarz Racing, which translated the raw data into an excel file containing 10 Hz time series of velocity components, drifter position, and measurement time. A MatLab code created by Jim Thomson was used to analyze the excel files. It utilizes the deep water orbital motion theory of waves to relate horizontal velocities to vertical velocities. The deep water orbital motion theory states that in deep water, waves have circular orbits. With circular orbits, the horizontal and vertical velocities are exactly equal. The code translates velocity components measured by the microSWIFTS into wave height, which is directly related to wave energy. Wave heights and energy are used to plot frequency vs. energy and to calculate significant as the average height of the highest 33% of waves recorded.

The code was modified for use on the small high-frequency wave encountered in the fjords. A frequency boundary had been set to ignore all waves with a period of 5 seconds or

less, appropriate for low frequency, open ocean swell. Since the fjord waves had periods of of 1-1.5 seconds, (based on observations) a new frequency boundary was set to ignore all data with a period larger than 2 seconds. The first and last two minutes of each deployment were discarded to avoid large spikes associated with deployment and retrieval of the drifters. On a few of the deployments, the device malfunctioned, yielding nonsensical data. Those deployments had no salvageable data and were thus neglected. The remaining data provided energy spectra, significant wave heights and average frequency for each drop.

The fetch of each deployment was measured using Google Earth. The average GPS location for each device on every deployment was calculated and then tagged on Google Earth. The line tool was used on Google Earth and traced a line from the marked location to the topographical feature that blocks fetch in a line directly parallel to wind direction. Fetch values were taken as the distance determined by these lines.

The code used to interpret the raw data produced energy spectra and significant wave height for each deployment. With these values and the calculated fetch, the observed data can be plotted alongside model results. The accuracy of the model equations can then be tested against our observational data.

Results:

Day 1 observations were recorded with an average wind speed of 3.4 meters per second, which produced small wind waves. The wind waves recorded ranged from heights of 3.19 to 6.14 centimeters, increasing with greater fetch. Day 2 observations were recorded with higher winds averaging approximately 8 meters per second. This produced larger waves with significant wave heights ranging from 5.03 to 9.53 centimeters, also increasing with greater fetch.

Two graphs were constructed to compare the observational data to the models. Fetch and wind data are the only empirical components needed to predict wave height and wave energy (Resio et al. 2002).

$$\frac{gH_{m0}}{u_*^2} = 4.13 * 10^{-2} * \left(\frac{gX}{u_*^2}\right)^{\frac{1}{2}} \text{ (Resio et al. 2002) – Wave Height Equation}$$

$$\text{Energy} = 0.0413 * \sqrt{\text{non – dimensional fetch}} \text{ Wave Energy Equation}$$

Where:

X = Fetch (m)

H_{m0} = Significant wave height (m)

g = Gravitational constant = $9.81 \frac{m}{s^2}$

u_{*} = friction velocity ($\frac{m}{s}$)

Non-dimensional fetch = $\frac{gX}{u_*^2}$

Frictional velocity (u_{*}) is calculated from the drag coefficient which is directly related to wind speed as: $C_D = 0.001 * (1.1 + 0.035 * \text{wind speed})$ (Resio et al. 2002). The frictional velocity is then calculated as: $u_* = \sqrt{C_D * \text{wind speed}}$. Model predictions of significant wave height

and wave energy as a function of winds speed and fetch can then be compared with observations.

The first graph compares the observed non-dimensional fetch and energy relationship against the CEM model of non-dimensional fetch and energy. (Figure 4). To make fetch non-dimensional, fetch is multiplied by g and divided by the square of u_* to account for wind speed within each variable. Calculated energy is initially non-dimensional when plugged into the Coastal Engineering Manual equation given above.

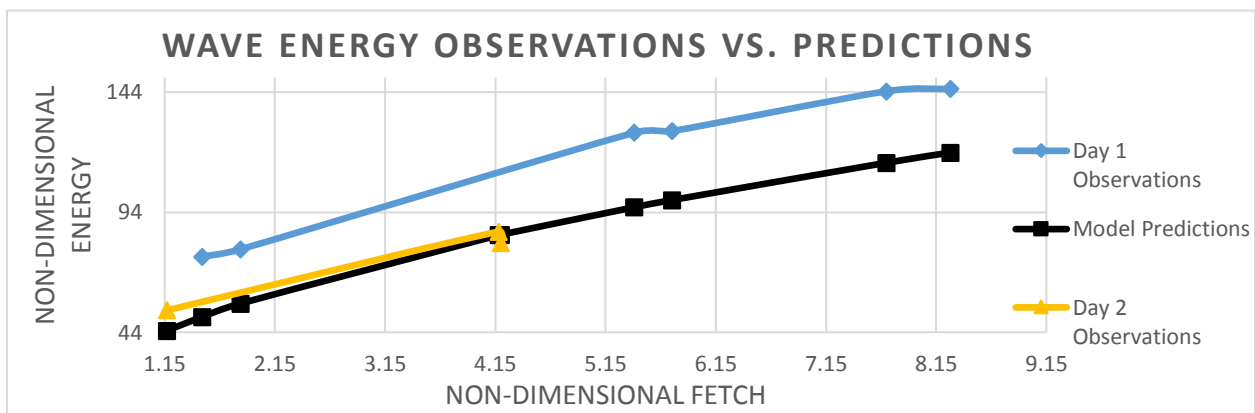


Figure 4: This graph attempts to validate wave energy observations to a model equation of fetch-limitation wave growth from the coast engineering manual. Each point represents a deployment of 20-30 minutes where an average significant wave height is taken and converted in to energy, and then plotted. The points come in sets of two because the two drifters were deployed close together, thus very similar fetch values. Day 2 has fewer observations due to technical difficulties with the accelerometer the second day.

The second graph compiled is a dimensional analysis of observed fetch vs. wave height relationships compared to fetch vs. modeled wave height (Figure 5). Significant wave height is related to energy, and thus a predicted wave height can be calculated from the non-dimensional predicted energy values. By multiplying non-dimensional energy by the square of u_* and then dividing by g we get values of predicted wave height.

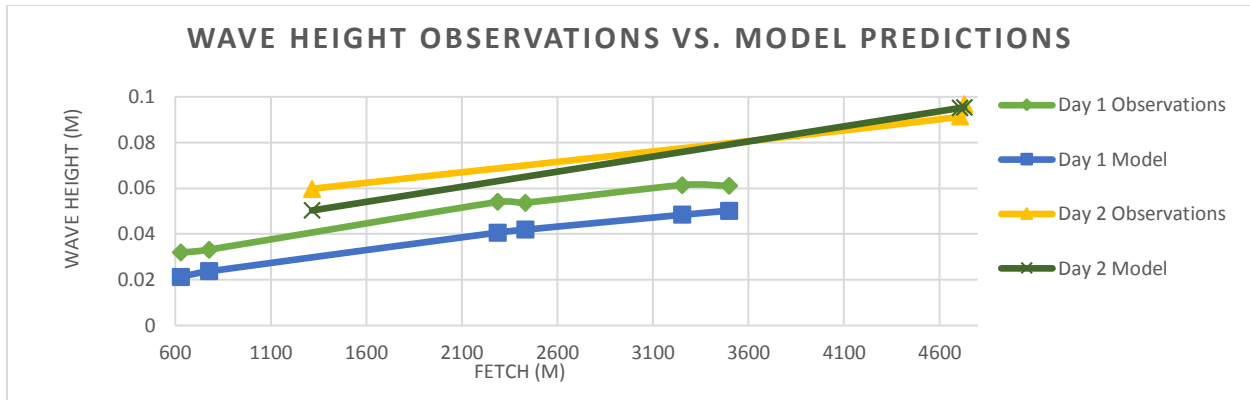


Figure 5: This graph is a simple comparison of physical values that are easier to grasp. Each point represents a specific deployment of 20-30 minutes. The wave height observations are significant wave heights gathered from the raw data. The fetch values vary from day to day due to wind direction changing the locations of deployments. The accelerometers malfunctioned for both of the most fetch limiting cases on day 2 which is why data starts at ~1200 m.

Discussion

The observational data is consistent with the model predictions, especially for the limited data of day 2. The day 2 line intersects the model predictions on both graphs, and the last portion of the line overlaps entirely. This suggests that the CEM model possesses predictive capability under the conditions present on day 2. Day 1 observations mimic the shape of the model in both graphs, but with an apparent bias. The causation of the bias is unclear, but further research is suggested in order to conclude why such bias exists in this model.

Error bars are left out of both graphs intentionally; not to deceive the reader, but due to the extent of the error bars extending beyond the scope of the graph. Wind speed error was most likely the greatest source of error. Winds are extremely variable and can shift direction and intensity on short time scales. On top of that, wind speed is squared when non-dimensionalizing our components which makes wind speed have a greater impact when

calculating error. Thus error for wind speed was the primary error calculated for this study. An uncertainty of 1 meter per second was used to calculate wind speed. Even with what is likely an under-estimated uncertainty, the error bars extended beyond the extent of the graphs' axis. Thus for clarity purposes, the error bars were omitted.

Wind speed was the largest source of error in this study, but there were many other contributors. When measuring fetch using Google Earth, the pinned locations are very accurate, but the lines drawn from them to a topographical, wind inhibiting feature, were prone to human error. The frequency boundary we revised also had error. Manipulating the frequency boundary by .1 Hz (approximately one third of a second) yielded a 15% change in significant wave height. There is also very likely to be noise from the device itself, which could explain the gap between day 1 observations and the model.

Conclusion

Our data in all cases show that wave height and energy grow with increasing fetch. This supports the hypothesis that waves in Nootka Sound are fetch limited, and thus mature as fetch increases. Although our results *technically* agree with the CEM model, to say the model can always be used as a reliable prediction tool for Nootka Sound under all conditions would be hasty. Our data *suggests* that the CEM model can predict fetch-limited wave heights for Nootka

Sound; but due to the limited amount of data and large room for error, further research under varying conditions is required. The microSWIFTs that were used in this project are based on a larger model of buoy called a SWIFT. These larger wave measuring devices are much more accurate and eliminate most of the error involved in the wave measuring process.

Consequently, these buoys are large and expensive. MicroSWIFTs were used due to their cost-efficiency and accessibility. Adding onto this study using the SWIFT buoys could lead to much more conclusive results for the CEM model's predictive capabilities.

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