# The Impacts of Wind Speed Trends and Long-term Variability in Relation to Hydroelectric Reservoir Inflows on Wind Power in the Pacific Northwest


**by**

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## Abstract

The use of wind power is growing rapidly in the Pacific Northwest (PNW) due to environmental concerns, decreasing costs, strong wind speeds, and the desire to minimize the impacts of streamflow variability on electricity prices and system flexibility through diversification. In hydroelectric dominated systems, like the PNW, the benefits of wind power can be maximized by accounting for the relationship between long term variability in wind speeds and reservoir inflows. Clean energy policies in British Columbia (BC) make the benefits of increased wind power generation during low streamflow periods particularly large by preventing the overbuilding of marginal hydroelectric projects to fulfill its legislated self-sufficiency requirements. The goal of this work was to help maximize the value of wind power by quantifying the long-term relationships between wind speed and streamflow behavior in BC. Wind speed data from the North American Regional Reanalysis (NARR) and cumulative usable inflows (CUI) from BC Hydro were used to analyze 10m wind speed and wind density (WD) trends, WD-CUI correlations, and WD anomalies during low and high inflow periods in the PNW (40°N to 65°N, 110°W to 135°W) from 1979-2010. Statistically significant positive wind speed and density trends were found for most of the PNW, with the largest increases along the Pacific Coast. WD-CUI correlations were weakly positive for most regions, with the highest values along the US coast (r ~0.55), generally weaker correlations to the north, and negative correlations (r ~ -0.25) along BC's North Coast. When considering seasonal relationships, the spring freshet was coincident with lower WD anomalies west of the Rocky Mountains and higher WDs to the east. A similar but opposite pattern was observed for low inflow winter months. When considering interannual variability, the lowest inflow years experienced positive WD anomalies (up to 40% increases) for the North Coast. In the highest inflow years, positive WD anomalies were widespread in the US and in smaller patches of central BC. By accounting for regional and temporal differences in the relationship between wind (WD) and streamflow (CUI) behaviour during wind farm site selection, the benefits of energy diversification can be maximized.

**Keywords**: Wind power; Hydroelectricity; Renewable energy; Climate variability; Pacific Northwest

## Dedication

*To everyone who supported, pushed, and put up with me. I could not have done it without you.*

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## List of Acronyms

| | |
|---|---|
| BC | British Columbia |
| CUI | Cumulative Usable Inflow |
| ENSO | El Nino Southern Oscillation |
| GWh | Gigawatt Hour |
| OLS | Ordinary Least Squares (Regression) |
| MW | Megawatt |
| NARR | North American Regional Reanalysis |
| NCAR | National Center for Atmospheric Research |
| NCEP | National Centers for Environmental Protection |
| PDO | Pacific Decadal Oscillation |
| PNW | Pacific Northwest |
| WD | Wind Density |

## Glossary

| | |
|---|---|
| Cumulative Usable Inflow (CUI) | CUI is a provincial summary of the electricity generating potential of all inflows into all major hydroelectric reservoirs in British Columbia that are weighted to account for each dam's particular energy conversion rate |
| Dispatchable Generation | Dispatchable energy sources are those which can be dispatched (i.e. turned on or off) on demand and can be relied on to provide a continuous energy supply (e.g. natural gas and coal) |
| Non-Dispatchable Generation | Non-dispatchable energy sources are those which cannot be relied on to provide a continuous energy supply or respond on demand (e.g., solar and wind) |
| Water Year | A 12-month period from October 1st through September 30th of the following year, identified here by the calendar year in which it starts. The water year differs from the calendar year to allow precipitation that falls as snow in the autumn and winter, and that melts the following year, to be counted together. |
| Wind Density (WD) | WD is an estimate of the electricity generating potential of winds at a given site, calculated by summing the cube of all wind speed observations over a given period |

# Chapter 1. Introduction

Understanding the changing nature of wind speeds in the Pacific Northwest (PNW) is important for many economic, scientific, and social reasons. Wind power is growing rapidly in the region, with total installed capacity in British Columbia (BC) set to increase from 246MW to 780MW in the near future (BC Hydro 2010). Washington State added 235.1MW in 2011 alone, surpassing 2800MW of total wind energy capacity (AWEA 2013). However, the availability and value of wind energy are susceptible to diurnal, seasonal, and interannual wind speed changes as well as market variability. Hydroelectric generation may also be affected by wind speed driven changes in reservoir levels due to changing evaporation rates (McVicar et al. 2012). Quantifying trends in wind speed behaviour is important for understanding potential changes in wind power availability, and also for predicting climate change related feedbacks between precipitation, temperature and vapour pressure (McVicar et al. 2008; Allan & Soden 2007; Held & Soden 2006; Wentz et al. 2013).

For areas with substantial hydroelectric resources, like the PNW, understanding wind behaviour in relation to streamflow variability can also be highly beneficial. Many studies have addressed the challenges of integrating wind and hydro power at the operational level, such as real-time voltage fluctuations and next-hour forecasting (Bélanger & Gagnon 2002; Karki et al. 2010; Kiviluoma & Holtinnen 2006; Matevosyan et al. 2009), and the benefits of matching diurnal electricity demand and wind speed profiles (Fripp & Wiser 2008; Joskow 2011; Lamont 2008; Neuhoff et al. 2008). However, the importance of poorly-correlated long-term variability in wind density (WD) and hydroelectric reservoir inflows has not been explored. For example, wind farms with above-average generation during low inflow periods would have greater value than otherwise similar sites where most generation occurred during periods of high inflows and reservoir levels when electricity prices are typically lower. Similarly, sites with below-normal generation during high inflow periods help to maintain system flexibility, thereby reducing the need to spill from overfilled reservoirs and pay wind farms to curtail production, as occurred in Washington State during the freshet of 2011 (Bonneville Power Administration 2011). Accounting for these inflow-related value fluctuations could lead to selecting wind farm sites with lower total generation, but that provide greater economic and social value due to more beneficial timing.

The benefits of wind and hydroelectric resources with poorly-correlated temporal behaviour are particularly strong in BC, where hydropower accounts for 95% of all electricity generation in the province (BC Hydro 2013a) and the BC *Clean Energy Act* (2010) requires that at least 93% of all generation come from clean or renewable sources. The *Clean Energy Act*'s self-sufficiency requirement also requires that in-province generation be able to meet all domestic demand by 2016, based on an average water year. Continuing to rely on hydropower in BC will likely result in rapidly rising costs as progressively lower quality sites are developed, and because the need to ensure self-sufficiency requires a much greater generation capacity than is needed in many years. This overdevelopment would also bring increasingly large environmental and social costs due to flooding, road and transmission line construction, and streamflow changes (Robinson 1997). Instead, the economic and environmental costs of constructing a reliable energy system can be minimized by selecting new sources with consistent or increased production in low water periods. With the lowest levelized cost of all sources in BC Hydro's 2008 Clean Energy Call, and making up nearly half of the resulting firm energy agreements, wind power is currently one of the strongest candidates to take on this role of diversifying BC's electricity mix.

Several wind speed studies have included or been conducted in the PNW, but the results have been inconsistent and their geographic extent in BC is very limited (Abeysirigunawardena et al. 2009; Enloe et al. 2004; Gower 2002; Klink 1999; Klink 2002; Pryor et al. 2009; Pryor & Ledolter 2010; Tuller 2004; Wan et al. 2010; Holt & Wang 2012). Griffin et al. (2010) reconciled some of these inconsistencies by studying a larger geographic area, finding small negative trends at inland sites, similar to the general stilling trends observed across much of the continental US (Pryor et al., 2009), and cyclic behaviour with no significant trends at coastal sites.

While these studies provide valuable information for certain locations, their applicability is severely limited by the exclusive use of meteorological station data and a focus on the coastal and southern portions of BC. Working with observational data presents many issues when analyzing long term climate trends and variability, such as data intermittency, changes in station location, technology, and post processing techniques, and varying time scales between stations. Station data in BC is also only available for a very small geographic area, with most stations located in the southwest corner of the province (Wan et al. 2010). For mountainous regions, where wind speed trends can vary greatly with elevation (McVicar et al. 2010), and remote coastal and northern areas that are most likely see wind power development, observational data is extremely sparse or only available for very short time periods, leaving a large gap in our understanding of the province's wind climate and its relationship with reservoir inflows.

The objectives of this study were three-fold. The first objective was to address limitations of wind speed data availability in the PNW by using North American Regional Reanalysis (NARR) data (Mesinger et al. 2006) to produce an analysis of long term wind speed behaviour with better spatial and temporal extent than is currently available. These results were then compared to previous observational studies to assess NARR's ability to capture site specific and regional variation in wind behavior in BC. Our second objective was to analyze the relationship between the variability in wind density and inflows into BC's hydroelectric reservoirs. Interannual correlations between local wind density and provincially-aggregated and weighted reservoir inflows were calculated and mapped. Wind density anomalies in the highest and lowest inflow years and seasons were also examined to determine where wind behaviour is significantly different when the hydropower system is most under stress. The locations of current and proposed wind farm projects were also examined to identify sites and regions that exhibit beneficial wind timing based on their performance during high and low inflow periods. Our third objective was to explain the potential climatic causes of regional variations in wind speed trends and wind density-inflow relationships, and to outline their consequences for future electricity generation and climatology in the PNW.

# Chapter 2. Data and Methods

## 2.1. Wind Speed Trends

Our study area extended from 40°N to 65°N and 110°W to 135°W, which encompasses a broad swath of western North America, the Pacific coast, and the eastern Pacific Ocean. This area includes the entirety of the provinces of British Columbia and Alberta, the states of Washington, Oregon, and Idaho, and portions of the surrounding states, the Yukon and Northwest Territories and the Alaskan Panhandle. This broad definition of the PNW allows us to more effectively investigate latitudinal and geographic patterns in wind behaviour. To help with the interpretation of results we separated the study area into 7 distinct regions based on both political boundaries and observed hydroclimatological behaviour (Table 2, Fig 1). Regional averages were calculated using the inverse variance weighting method to give greater priority to more robust trends and correlations.

All wind speed data were obtained from the North American Regional Reanalysis (NARR) dataset (Mesinger et al. 2006), produced by the National Center for Atmospheric Research (NCAR) and the National Centers for Environmental Prediction (NCEP). The NARR project is an extension of the NCEP-DOE Global Reanalysis (GR) that uses the high resolution NCEP Eta Model and its Data Assimilation System, the Noah land surface model, and several additional datasets to produce a higher resolution and more accurate reanalysis product for North and Central America. This process assimilates observations of many meteorological variables, including wind speed, temperature, precipitation, and pressure, onto a three-dimensional grid system with 45 vertical layers and a horizontal spacing of approximately 32km. Three-hourly and monthly mean 10m wind speeds were extracted from the NARR dataset from 1979 – 2010. The three-hourly data were then used to calculate monthly wind density totals by cubing each value and summing for each month. Wind densities were used to better represent changes in wind power potential, which are more closely related to the upper end of the wind speed distribution.

For each NARR grid location in the study area, linear trends were calculated for monthly mean winds and total wind density. While the assumptions of ordinary least squares regression (OLS) are not likely to be met for climate trend analysis, due to the cyclic, autocorrelated nature and non-normal distribution of wind speed and density data (Pryor & Ledolter 2010; McVicar et al. 2012), we used OLS to allow for better comparisons with previous wind trend studies, which used OLS almost exclusively (McVicar et al. 2012). Trends were also calculated taking into account temporal autocorrelation, producing results were very similar to those obtained using OLS, which is also consistent with the findings of previous studies (McVicar et al. 2012; Pryor & Ledolter 2010).

## 2.2. Reservoir Inflow Data and Correlations between Wind Density and Inflow

Reservoir inflow data for BC were obtained from BC Hydro in the form of monthly combined usable inflows (CUI, GWh) for 1979 to 2010, which were summed to produce seasonal and annual totals (Supplemental Table 1). CUI is a provincial summary of inflows into all major hydroelectric reservoirs that are weighted to account for each dam's particular energy conversion rate. CUI was chosen over other streamflow and precipitation measures because of its direct relationship to total potential hydroelectric generation and its ability to identify when the hydroelectric system is under stress. Unweighted or unaggregated precipitation and streamflow measurements would allow for greater climatological interpretation, but are not representative of provincial hydroelectricity generation and are therefore poor measures of variability in the value of wind power.

Annual CUI totals were based on the October through September water year, while seasonal analyses included the freshet period (May through July) when inflows are highest, and winter (December through March) when inflows are lowest in the PNW.

Pearson correlation coefficients were calculated between annual wind density and CUI totals for each NARR grid location. Although the assumption of a linear relationship is unlikely to be met, Pearson was chosen because other nonparametric tests, such as Spearman's rank correlation, reduce the sensitivity to extreme values, which were our primary interest.

## 2.3. Wind Density Anomalies in Low and High Inflow Periods

To determine whether wind densities during the lowest inflow periods were significantly different from those in other years, a non-parametric Mann-Whitney U (aka Rank Sum) test was used to compare WD totals for the lowest CUI years and WD totals in all remaining years. The two populations were considered distinct if the sum of the ranks of each population were statistically different ($p < 0.1$). This test was performed for the bottom three and five inflow years to test if the results were robust across low inflow years in general, or were rather a product of the particular years in question (Table 1). The same analysis was repeated for the highest three and five inflow years.

Similarly, to determine if wind density totals for the highest and lowest inflow seasons were statistically different from the rest of the year, the same analysis was performed for the winter (December-March) and freshet (May-July) seasons, testing the wind density totals in those months against all remaining months of the year.

**Table 1.** **Statistics for British Columbia's annual cumulative usable inflows (CUI). All annual totals are based on the water year of October through September, referenced by the starting calendar year.**

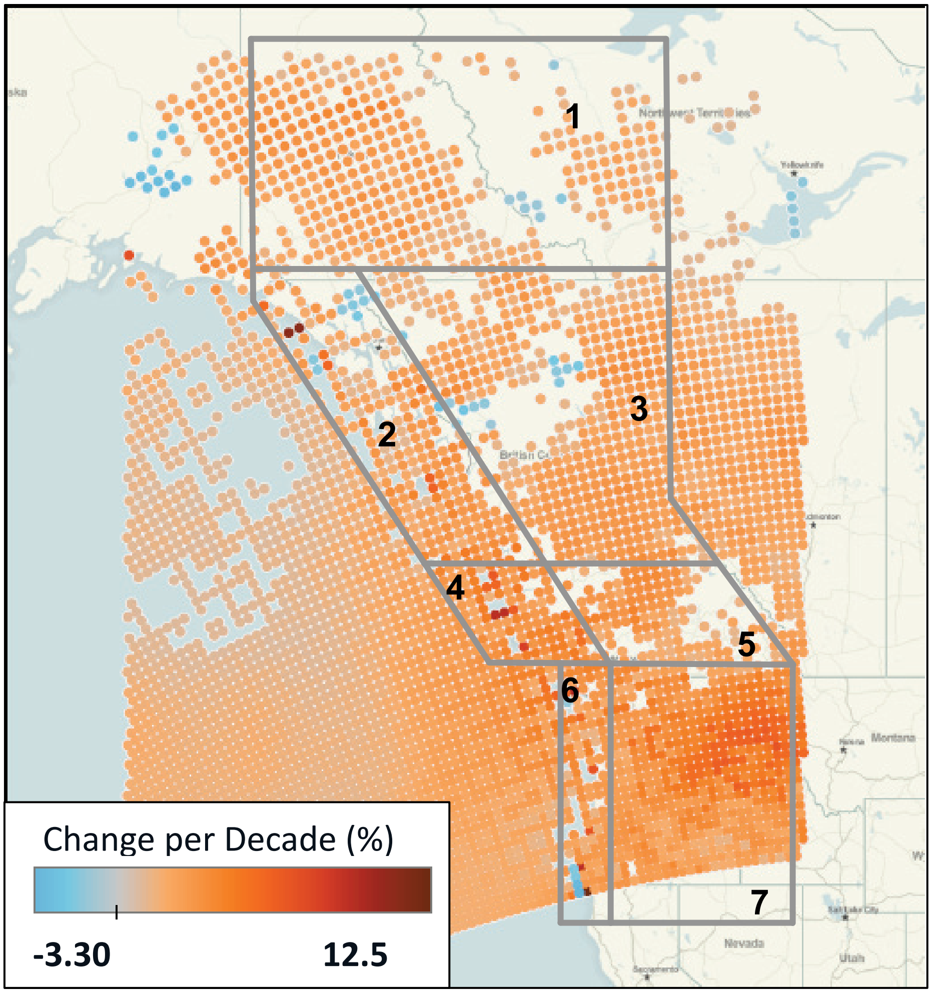
| Rank | Year | CUI Total (GWh) | Percent of Median Annual CUI Total (1979-2010) |
|---|---|---|---|
| **High Flow Years** | | | |
| 1 | 1996 | 51151.68 | 120.4% |
| 2 | 1995 | 50967.18 | 119.9% |
| 3 | 2006 | 47733.45 | 112.3% |
| 4 | 1998 | 47641.63 | 112.1% |
| 5 | 2010 | 47076.65 | 110.8% |
| **Low Flow Years** | | | |
| 28 | 1984 | 38160.43 | 89.8% |
| 29 | 1992 | 37990.44 | 89.4% |
| 30 | 2008 | 37104.53 | 87.3% |
| 31 | 1979 | 35914.5 | 84.5% |
| 32 | 2009 | 35713.58 | 84.0% |
| **Median** | | 42494.53 | |
| **Standard Deviation** | | 3983.72 | |

# Chapter 3. Results

## 3.1. Wind Speed and Wind Density Trends

The analysis of 10m NARR monthly average wind speeds showed significant positive trends for most of the PNW (Fig 1). However, the Far North, Northern Interior, and Southern Interior regions showed less consistent results, with more sites exhibiting non-significant trends.

The inverse variance weighted mean trends were similar in most regions (Table 2), however there was greater variation in the range of trends within each region. The North, South, and US Coasts contained locations with trends up to 0.480 to 0.561 m/s/decade (10.1 to 12.7%/decade). However, the US and North Coast regions also contained locations with some of the strongest negative trends, as low as -0.184 m/s/decade (-3.30 %/decade). In contrast, the Far North and the three Interior regions had relatively small differences between the maximum and minimum trends, ranging from 0.260 to 0.342 m/s/decade (6.05 to 7.42 %/decade), compared to the much larger trend range of 0.744 m/s/decade (16.0%/decade) for the US Coast.




1 – Far North
2 – North Coast
3 – Northern Interior
4 – South Coast
5 – Southern Interior
6 – US Coast
7 – US Interior

**Figure 1.** **Linear trends [m s$^{-1}$ (10 yr)$^{-1}$] in monthly average near-surface (10m) wind speeds from 1979 to 2010 for all NARR grid locations in the PNW and surrounding area. Only trends significant at the P < 0.1 level are shown.**

**Table 2. Summary of regional results for the Pacific Northwest, including inverse variance weighted averages of near-surface (10m) mean monthly wind speeds and wind density totals, and inverse variance weighted correlations between total annual wind density and CUI. See Figure 1 for region definitions.**

| Region | Wind Speed Trend ($m\ s^{-1}\ (10\ yr)^{-1}$) ($\%\ (10\ yr)^{-1}$) | WD Trend ($m^3\ s^3\ (10\ yr)^{-1}$) ($\%\ (10\ yr)^{-1}$) | WD-CUI Correlation |
|---|---|---|---|
| Far North | 0.0668 (1.79%) | $2.56 \times 10^3$ (5.47%) | 0.0326 |
| North Coast | 0.0598 (1.24%) | $1.14 \times 10^4$ (6.38%) | 0.107 |
| Northern Interior | 0.0698 (1.95%) | $4.05 \times 10^3$ (7.19%) | 0.185 |
| South Coast | 0.0620 (1.16%) | $2.95 \times 10^3$ (12.1%) | 0.151 |
| Southern Interior | 0.0629 (1.83%) | $2.97 \times 10^3$ (6.34%) | 0.202 |
| US Coast | 0.121 (1.86%) | $6.41 \times 10^3$ (10.5%) | 0.228 |
| US Interior | 0.0614 (1.84%) | $4.79 \times 10^3$ (9.57%) | 0.184 |

Wind density trends exhibited a similar pattern to the monthly mean wind speeds, with large increases for most of the PNW (Fig 2). The strongest trends were seen in the South Coast, US Coast, and the US Interior (Table 2), with many sites experiencing increases greater than 10%/decade, and some increases of up to 33%/decade. All of the northern regions, and the Southern Interior, generally exhibited smaller positive trends and contained more sites with non-significant trends (Fig 2). Only 14 NARR grid locations exhibited significant negative wind density trends ($P < 0.1$), mostly isolated to the northern Alaskan panhandle and the Great Slave Lake region of the Northwest Territories.

Mean wind speed and density trends at BC's existing and proposed wind farm sites were all positive and larger than their respective regional averages (Table 3). The largest WD increases, up to 10%/decade, were found in the North and South Coast, and in the Northern Interior where BC's three existing wind farms are located.

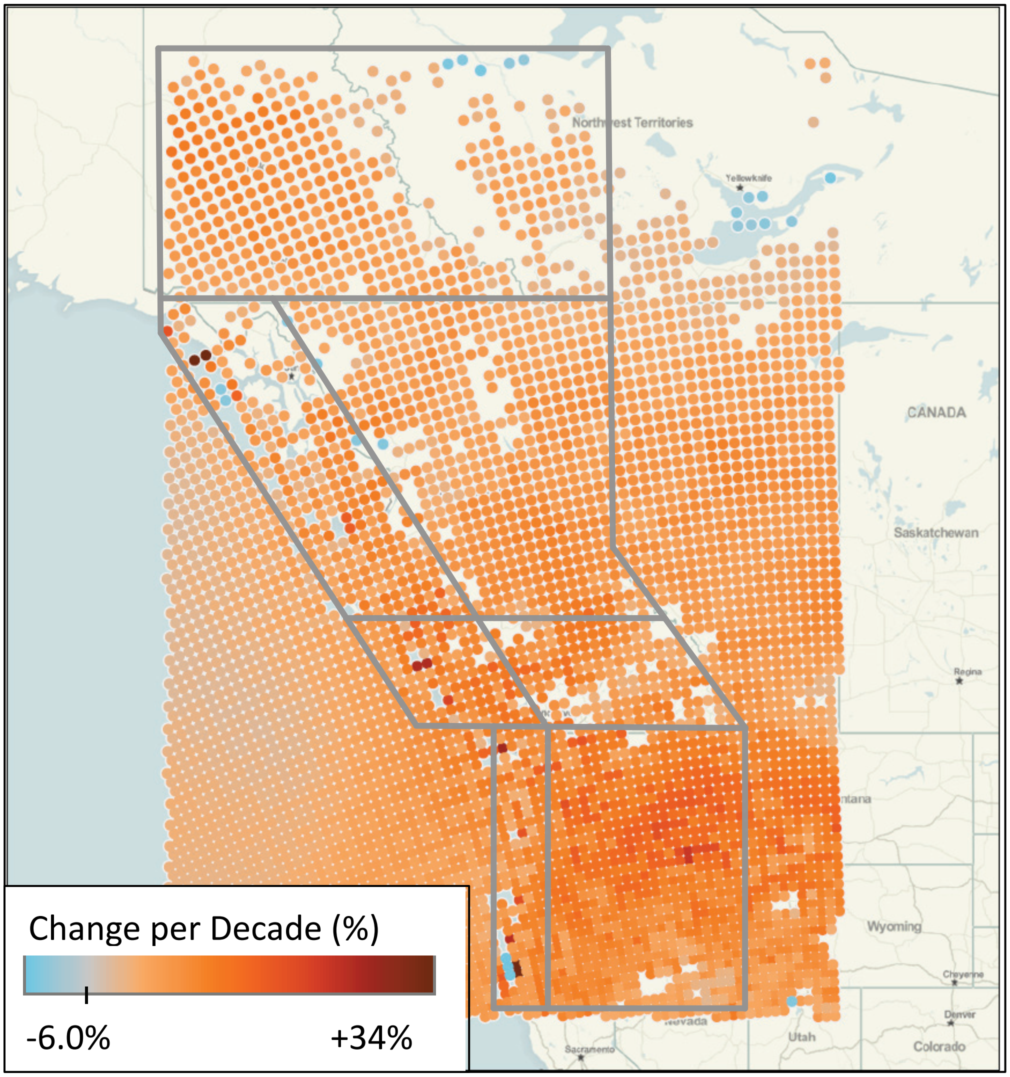



**Figure 2.** **Linear trends [% (10 yr)$^{-1}$] in total monthly surface (10m) wind density from 1979 to 2010 for all NARR grid locations in the PNW and surrounding area. Only trends significant at the P < 0.1 level are shown.**

**Table 3. Summary of regionally averaged results for all proposed and existing wind farm sites in British Columbia.**

| Proposed Wind Farm Locations by Region | Wind Speed Trend ($m\ s^{-1}$ $(10\ yr)^{-1}$) (% $(10\ yr)^{-1}$) | WD Trend ($m^{-3}\ s^{-3}$ $(10\ yr)^{-1}$) (% $(10\ yr)^{-1}$) | WD-CUI Correlation |
|---|---|---|---|
| Far North | 0.0629 (1.88%) | 91.7 (6.09%) | 0.0957 |
| North Coast | 0.163 (2.86%) | 100 (7.81%) | -0.0158 |
| Northern Interior | 0.0990 (2.51%) | 97.5 (8.17%) | 0.214 |
| South Coast | 0.177 (3.61%) | 100 (10.0%) | 0.185 |
| Southern Interior | 0.0756 (2.09%) | 89.7 (7.20%) | 0.246 |
| Existing (Northern Interior) | 0.0965 (2.52%) | 100 (8.48%) | 0.161 |

## 3.2. Interannual Wind Density-CUI Correlation

Most of the PNW exhibited weak, non-significant, positive correlations between annual CUI and WD totals (Figure 3). The highest average correlations were seen in the US Coast, and Southern Interior regions, ranging from 0.202 to 0.228, while the Far North and North Coast regions had the lowest, with values near or below 0.1 (Table 2). However, the sites with the strongest correlations were also found in the Far North, South Coast, and US Coast and Interior, with values of up to 0.498 to 0.556. The maximum correlations for the Far North and Southern Interior were the lowest at 0.309 and 0.381, respectively.

All regions, except for the Southern Interior and US Coast, had at least one location with a negative correlation between WD and CUI. However, even the strongest negative correlations, located in the North Coast and Far North regions, were not significant with minimum values as low as -0.281.

All of the proposed wind farm sites had similar WD-CUI correlations to their respective regional averages (Table 3). The North Coast sites were the most different from the regional average, with a mean WD-CUI correlation of -0.0158, compared to 0.107 for the entire region.

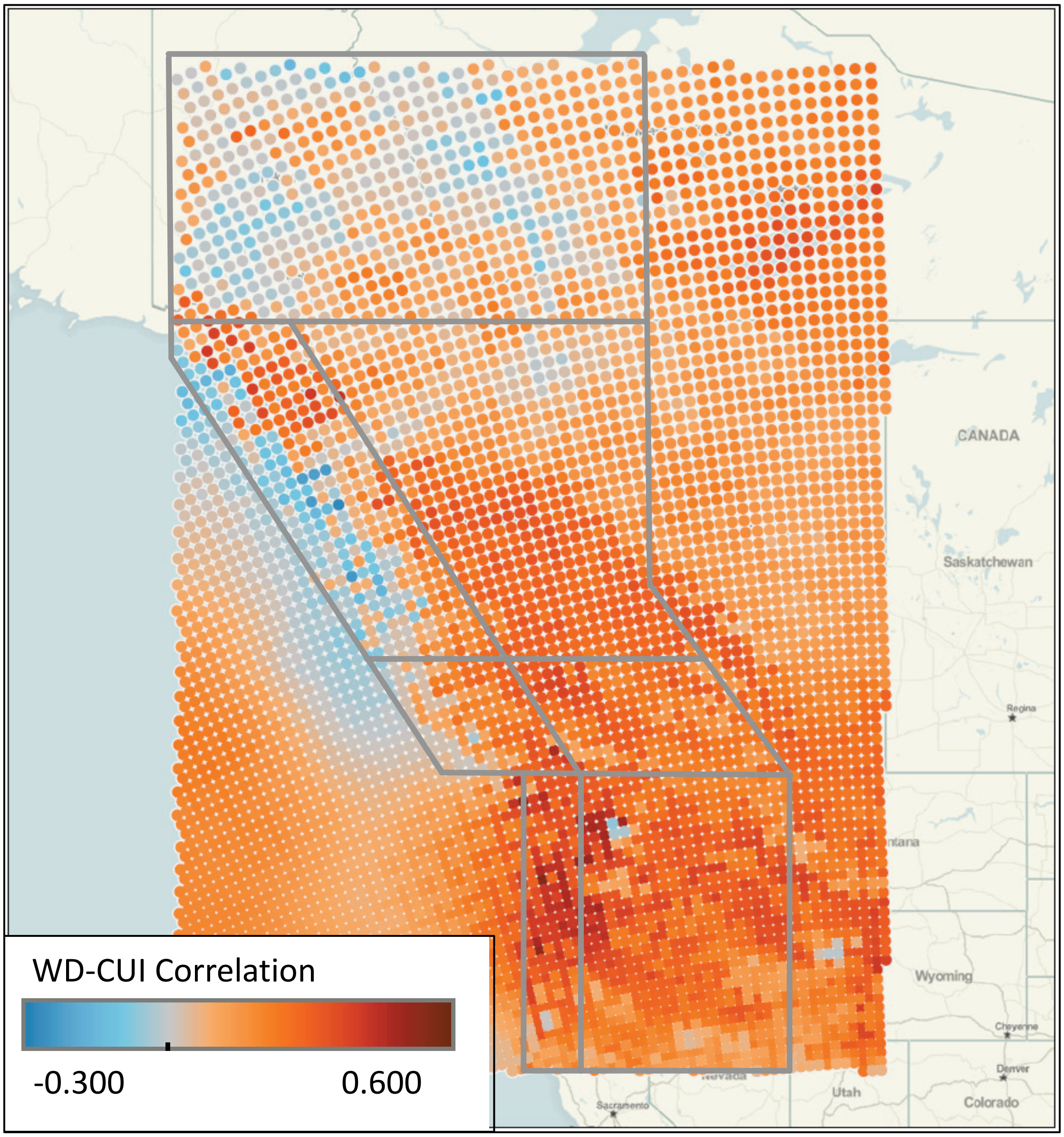



**Figure 3. Correlations between British Columbia's annual cumulative usable inflows (CUI) and surface (10 m) wind density totals for each NARR grid location in the PNW for 1979 to 2010. All annual totals are based on the water year of October through September, referenced by the starting calendar year.**

## 3.3. Wind Density Anomalies in Low Inflow Years

Wind density anomalies (the difference between WD totals for the period in question compared to an average year) varied substantially from region to region for the lowest inflow years (Figures 4 and 5). The North Coast had a large number of positive WD anomalies in both the three and five year cases, with annual wind densities increasing by an average of approximately 15% and 10%, respectively, compared to average years. The US Interior showed similar results to the North Coast, with many positive anomalies and average increases of up to 14.7% in the three driest years. In contrast, the US Coast was the only region to exhibit negative anomalies in both the three and five lowest inflow years, with average declines of 21.3% and 15.6%, respectively, during low inflow years.

The other regions (Far North, Northern Interior, and South Coast) contained sites with significant anomalies in the three lowest inflow years, but all exhibited substantially different behaviour when considering the five lowest inflow years. The Far North had many weak negative anomalies in the three lowest inflow years, but no sites exhibited significant anomalies in the five year case (Table 5). Like the Far North, the Northern Interior only exhibited significant anomalies in the three year case; however, these anomalies were all positive, with an average increase of 11.0%. The South Coast had few, but strongly positive anomalies in the three year case, resulting in the largest regional average increase of 25.9%. However, in the five year case the anomalies at these sites were no longer significant, causing the regional average to become weakly negative.

Anomaly magnitudes and geographic patterns of significance were similar for both the three and five year low inflow cases, indicating that the departures from normal were common to low flow years in general, and not merely particular to the years in question. The number of locations with significant anomalies was much higher for the three lowest CUI years compared to the five lowest years for most regions. However, the US Interior had more than double the number of significant anomalies for the five lowest inflow years compared to the three lowest inflow years (Table 4).

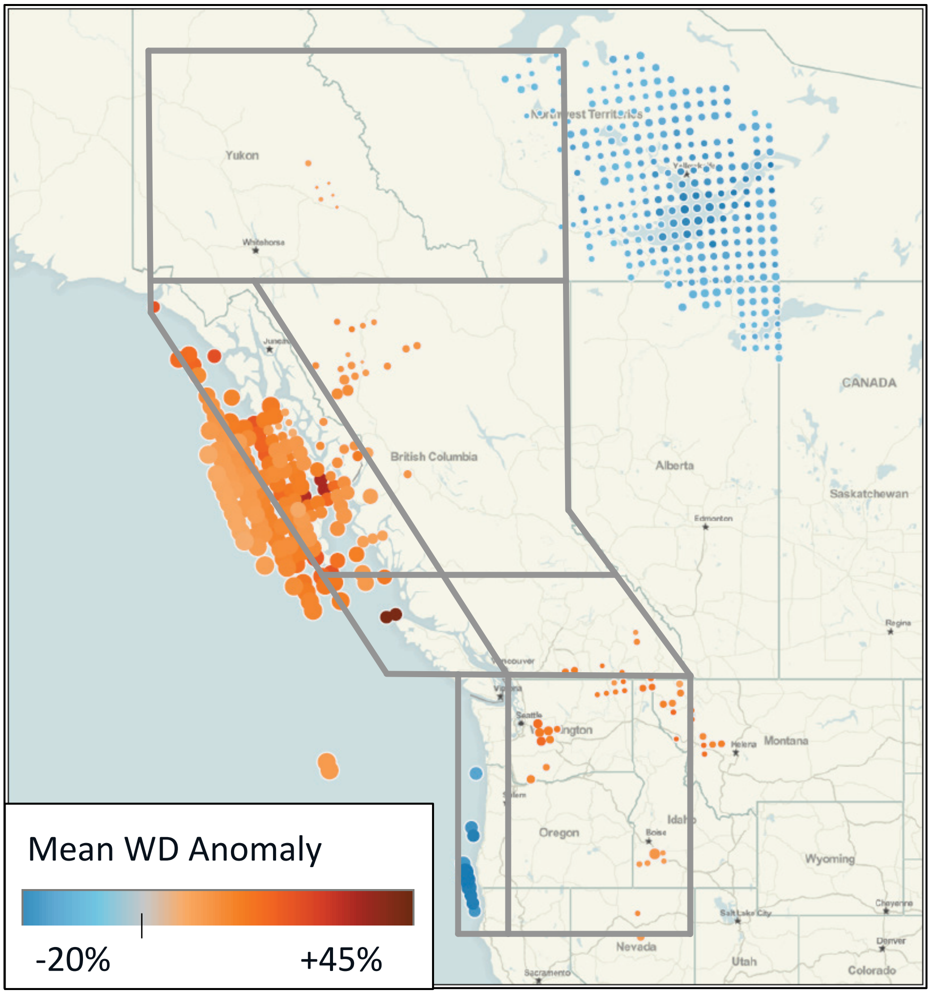



**Figure 4.** **Average anomalies in annual near-surface (10m) wind density totals in the three lowest CUI years (1979, 2008, 2009) that show statistically significant (P < 0.1) differences from annual wind density totals over the entire NARR data record (1979-2010). All annual totals are based on the water year of October through September, referenced by the starting calendar year. Colour indicates significant positive (orange) or negative (blue) correlations, and dot size indicates relative wind density totals over the entire NARR data record.**

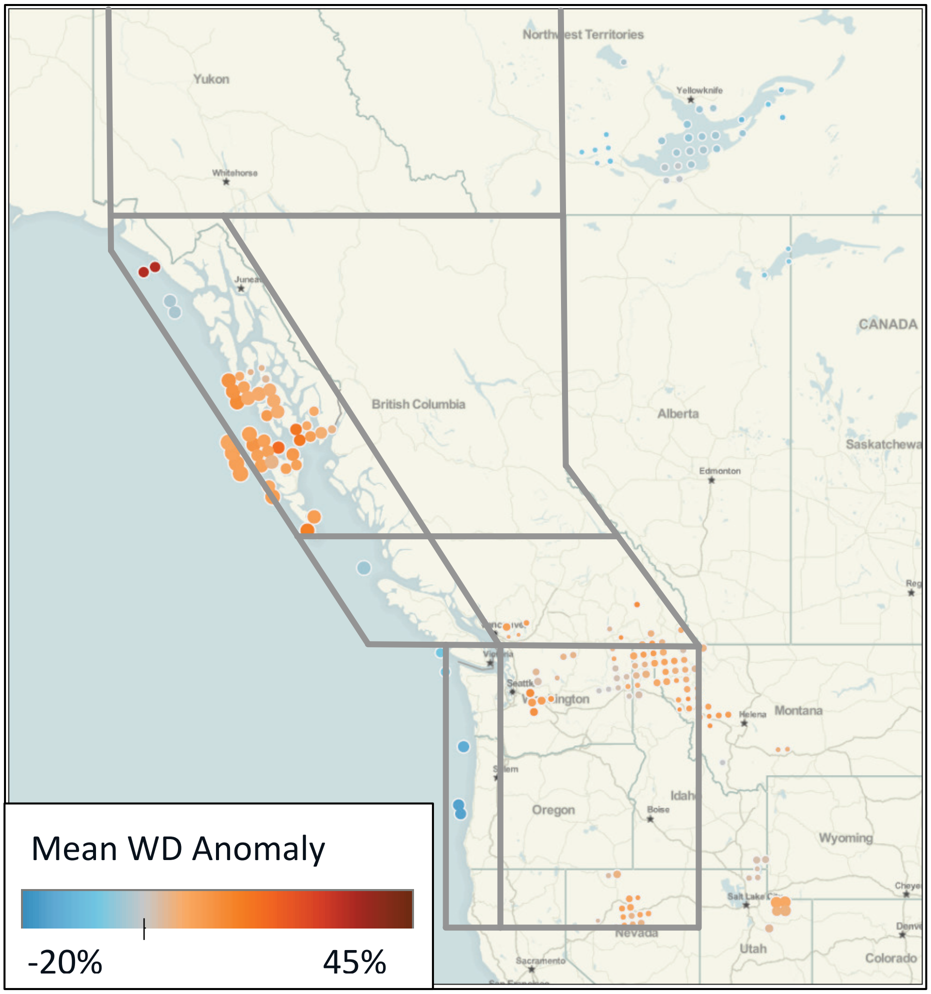



**Figure 5.** **Average anomalies in annual near-surface (10m) wind density totals in the five lowest CUI years (1979, 1984, 1992, 2008, 2009) that show statistically significant (P < 0.1) differences from annual wind density totals over the entire NARR data record (1979-2010). All annual totals are based on the water year of October through September, referenced by the starting calendar year. Colour indicates significant positive (orange) or negative (blue) correlations, and dot size indicates relative wind density totals over the entire NARR data record.**

**Table 4. Regionally averaged anomalies in annual near-surface (10m) wind density totals in the three and five lowest and highest CUI years. Anomalies are presented as the regional average percent change in wind density for NARR grid locations with significant anomalies compared with the average wind density for 1979-2010. Numbers in parentheses represent the number of NARR grid locations with statistically significant anomalies in each region. All annual totals are based on the water year of October through September, referenced by the starting calendar year.**

| | Low Inflow Years | | High Inflow Years | |
|---|---|---|---|---|
| **Region (Number of grid locations)** | **Mean 3-yr WD Anomaly (# Sites with Significant Anomalies)** | **Mean 5-yr WD Anomaly (# Sites with Significant Anomalies)** | **Mean 3-yr WD Anomaly (# Sites with Significant Anomalies)** | **Mean 5-yr WD Anomaly (# Sites with Significant Anomalies)** |
| Far North (767) | -0.966% (34) | 15.8% (2) | 69.2% (9) | 94.1% (3) |
| North Coast (220) | 14.7% (87) | 8.55% (37) | 39.6% (6) | 46.3% (1) |
| Northern Interior (415) | 11.2% (14) | NA (0) | 43.9% (73) | 48.6% (33) |
| South Coast (121) | 25.9% (5) | -3.69% (1) | 39.1% (3) | 48.2% (10) |
| Southern Interior (199) | 15.1% (7) | 7.19% (12) | 72.2% (4) | 62.5% (47) |
| US Coast (151) | -21.3% (8) | -15.6% (3) | 46.5% (56) | 39.6% (88) |
| US Interior (685) | 14.7% (31) | 5.95% (69) | 53.0% (277) | 53.5% (379) |

## 3.4. Wind Density Anomalies in High Inflow Years

Wind density anomalies for the highest inflow years were more homogeneous than for the lowest inflow years (Figures 6 and 7), with positive anomalies for all regions of the PNW (Table 4). The largest anomalies were found in the Far North, North Coast, and Southern Interior, where WD increased as much as 85.5% compared to average years during the three highest inflow years. However, the anomalies in these regions were relatively sparse compared to the US Interior, which had the most significant anomalies and many of the highest magnitudes, with an average WD increase of close to 53.0% (Table 4).

When comparing the three and five-year high inflow cases, the locations with significant wind density anomalies for the five highest years were shifted slightly southward when compared with those for the three highest years. The number of sites with significant anomalies in the five-year case declined for the North Coast and Northern Interior, but increased for all other regions (Table 4). Many of the anomalies located in central BC in the three-year highest inflow case (Figure 6) appear to shift to the south and became aligned with the Coastal and Rocky Mountain ranges when the five highest inflow years are considered (Figure 7). The US results are less varied between the two cases, with widespread positive anomalies for both the three and five year scenarios.

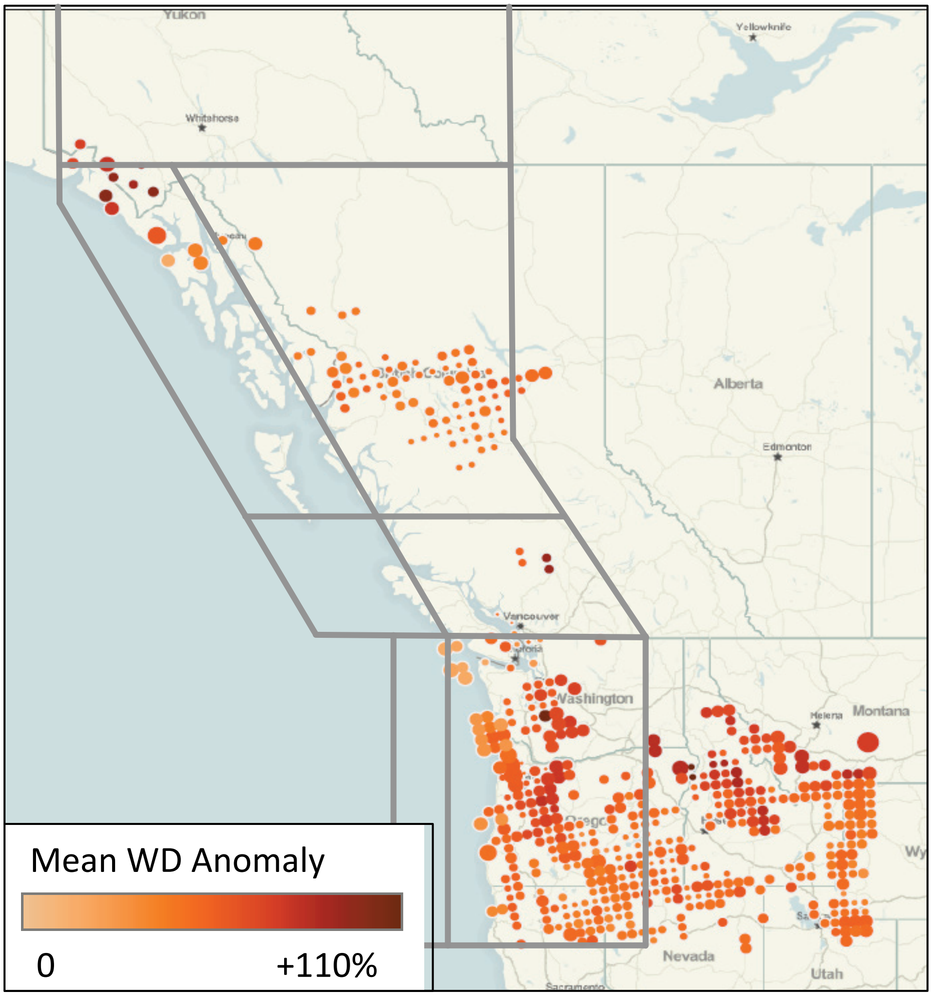



**Figure 6.** **Average anomalies in annual near-surface (10m) wind density totals in the three highest CUI years (1995, 1996, 2006) that show statistically significant (P < 0.1) differences from annual wind density totals over the entire NARR data record (1979-2010). All annual totals are based on the water year of October through September, referenced by the starting calendar year. Colour indicates significant negative correlations, and dot size indicates relative wind density totals over the entire NARR data record.**

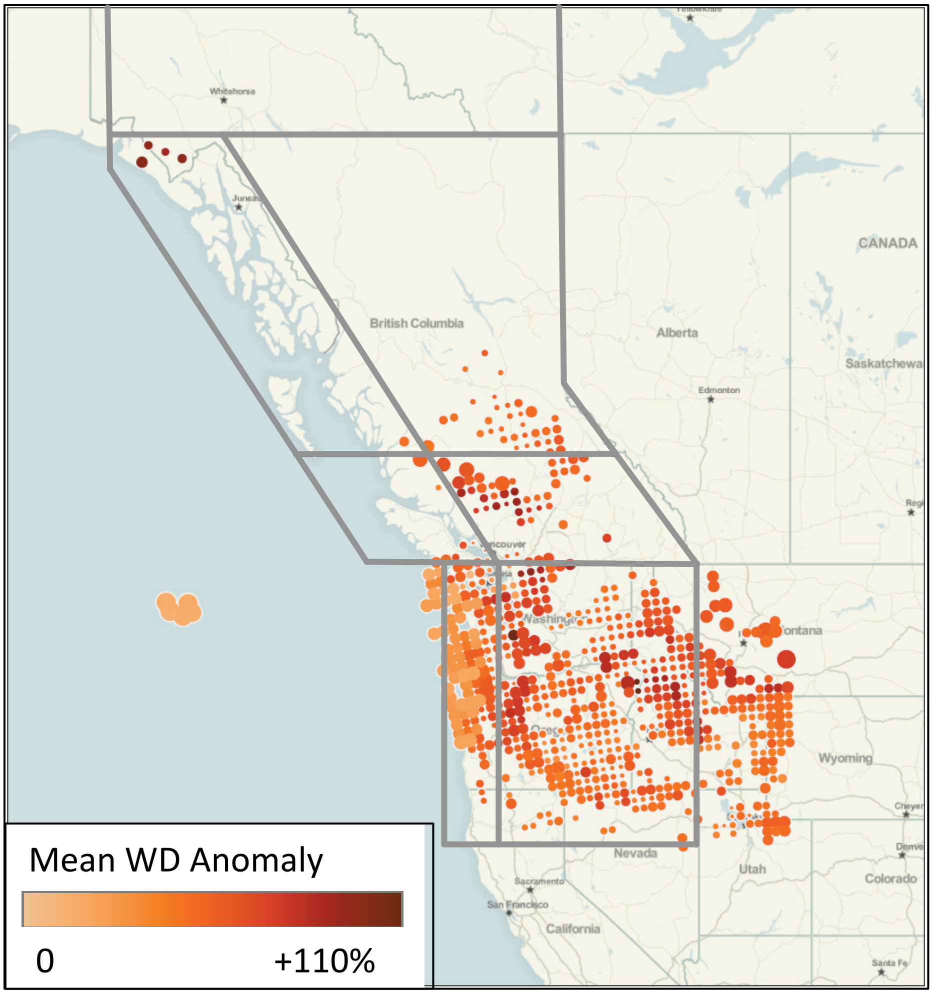



**Figure 7.** **Average anomalies in annual near-surface (10m) wind density totals in the five highest CUI years (1995, 1996, 1998, 2006, 2010) that show statistically significant (P < 0.1) differences from annual wind density totals over the entire NARR data record (1979-2010). All annual totals are based on the water year of October through September, referenced by the starting calendar year. Colour indicates significant negative correlations, and dot size indicates relative wind density totals over the entire NARR data record.**

## 3.5. Seasonal Variability

Almost all NARR grid locations exhibited significant changes in monthly WD totals in the winter and freshet seasons (Figs 8 and 9), compared to the rest of the year. The geographic patterns of winter and freshet anomalies were very similar but opposite in sign, with positive WD anomalies west of the Rocky Mountains in winter and negative WD anomalies during the freshet. The strongest positive winter anomalies and negative freshet anomalies were found in the three coastal regions (Table 5). Relative magnitudes of the winter and freshet WD anomalies were also very similar. The largest winter anomalies were found in the North Coast, up to 88.4%, with maximum values in the remaining regions between 59.3% and 67.6%. Similarly, the North Coast also had the strongest freshet anomalies, where WD decreased by as much as 85.3% compared to an average month. However, all other regions also had relatively large anomalies, ranging from -67.0% in the Southern Interior to -74.1% for the US Interior.

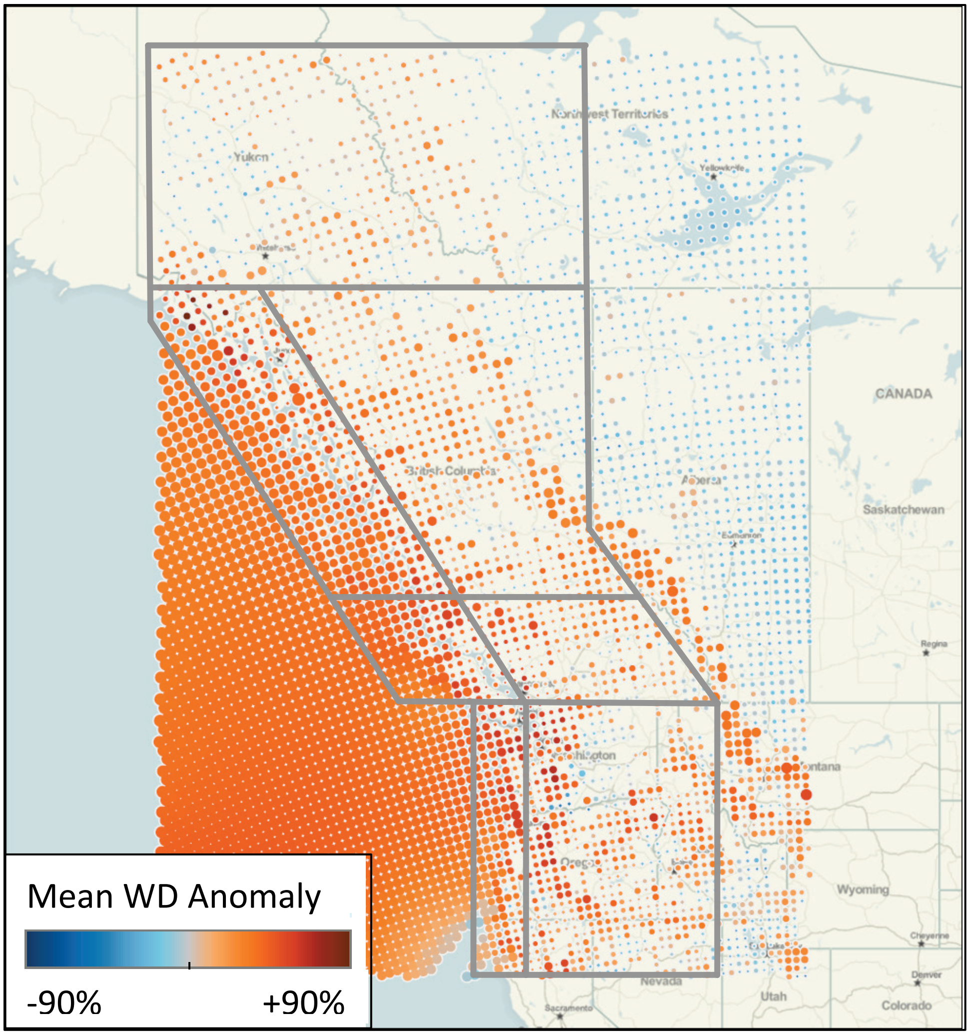



**Figure 8.** **Average anomalies in monthly near-surface (10m) wind density totals in the winter (Dec – March) that show statistically significant (P < 0.1) differences from monthly wind density totals over the entire NARR data record (1979-2010). Colour indicates significant negative correlations, and dot size indicates relative wind density totals over the entire NARR data record.**

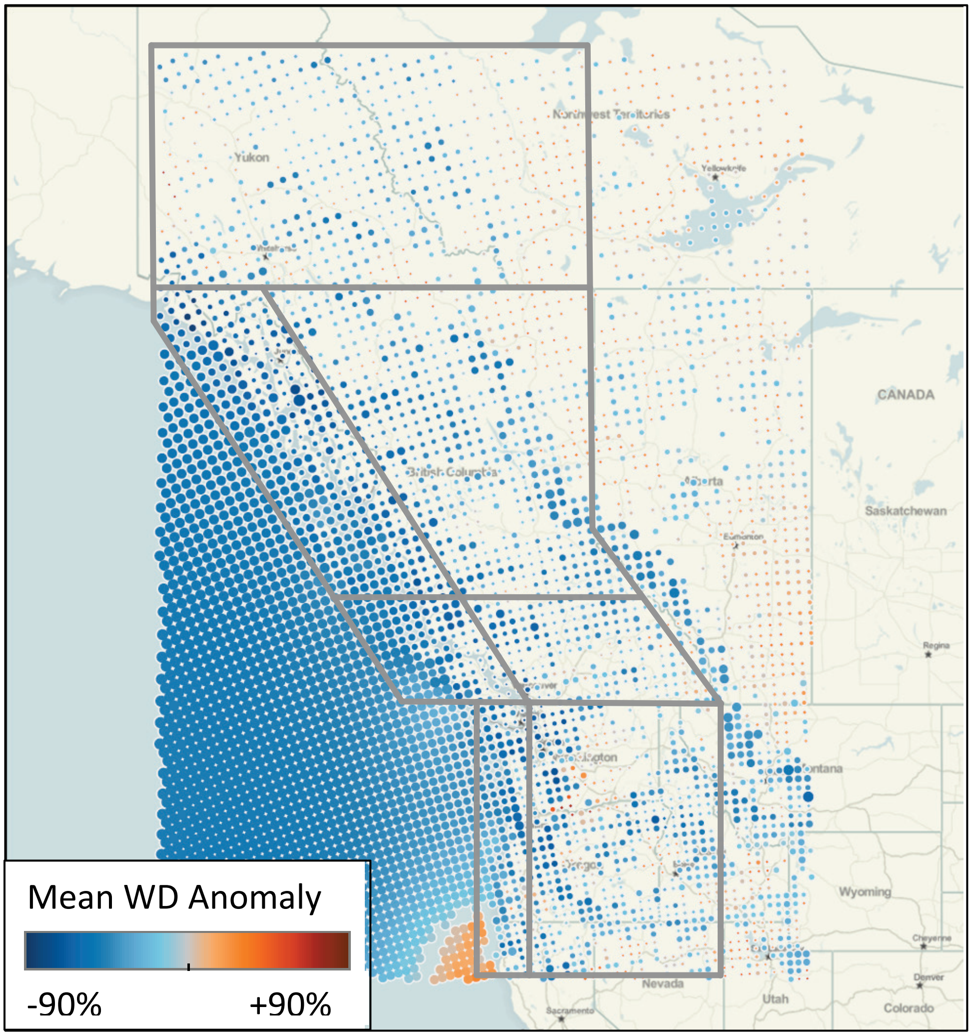



**Figure 9.** **Average anomalies in monthly near-surface (10m) wind density totals during the freshet (May – July) that show statistically significant (P < 0.1) differences from monthly wind density totals over the entire NARR data record (1979-2010). Colour indicates significant negative correlations, and dot size indicates relative wind density totals over the entire NARR data record.**

**Table 5. Regionally averaged anomalies in monthly near-surface (10m) wind density totals for the winter (Dec - March) and freshet (May - July) seasons. Anomalies are presented as the regional average percent change in wind density for NARR grid locations with significant anomalies compared to an average month. The number of NARR grid locations that exhibit significant anomalies in each case are shown in parentheses.**

| Region (Number of grid locations) | Regionally averaged Winter WD Anomaly (# NARR Sites with Significant Anomalies) | Regionally averaged Freshet WD Anomaly (# NARR Sites with Significant Anomalies) |
|---|---|---|
| Far North (767) | 3.69% (627) | -16.0% (661) |
| North Coast (220) | 39.6% (220) | -54.2% (220) |
| Northern Interior (415) | 19.0% (370) | -30.7% (380) |
| South Coast (121) | 42.5% (121) | -48.0% (121) |
| Southern Interior (199) | 23.4% (173) | -28.0% (173) |
| US Coast (151) | 36.1% (145) | -37.7% (138) |
| US Interior (685) | 18.7% (548) | -19.6% (526) |

# Chapter 4. Discussion

## 4.1. Wind Speed and Wind Density Trends

For most regions the NARR wind speed trends (Figure 1) were inconsistent with the declining or cyclic behaviour seen in recent studies of surface wind observations in southern BC (Abeysirigunawardena et al. 2009; Griffin et al. 2010; Tuller 2004; Wan et al. 2010), and the continental United States (McVicar et al. 2012; Pryor et al. 2009; Vautard et al. 2010). However, the positive trends do match well with other studies of reanalysis data in the American PNW (Holt & Wang 2012; Pryor et al. 2009), and with studies of surface observations at higher latitudes in Alaska, the Canadian Arctic, and the Antarctic (Lynch et al. 2004; Turner et al. 2005). Trends found in PNW station data have also typically been smaller and less geographically consistent than the widespread stilling seen for much of the rest of North America (McVicar et al. 2012; Pryor et al. 2009), and therefore the positive trends seen in the NARR data may not be entirely inconsistent with the observational data.

The increasing wind speeds at mid- and high-latitudes seen in the NARR data are consistent with many of the predicted effects of climate warming. Recent studies have suggested that the zone of tropical convection has been widening in recent decades (Seidel et al. 2008), which has been accompanied by poleward shifts in the zonal mean midlatitude westerlies, tropospheric jet (Lorenz & DeWeaver 2007; Lu et al. 2007), and Pacific storm tracks (McCabe et al. 2001; Yin 2005). Holt and Wang (2012) found that increasing wind speeds in Washington and Oregon were almost exclusively due to a strengthening of the zonal, westerly wind component. This demonstrates that the strengthening and poleward shift in the storm tracks and midlatitude cyclones could also be contributing to the positive wind trends found for most of the PNW.

The widespread positive wind density trends (Figure 2) bode well for the future of wind energy in the PNW, and BC in particular. Although no industrial scale wind power development currently exists along BC's Pacific coast, where the largest positive trends were observed, many potential sites have been proposed for this region because of historically high wind speeds. The large positive trends in wind speed and wind density for the coast will further strengthen the appeal of this area as the already strong resource will likely continue to increase.

While strengthening winds will increase power output at existing wind farms, and improve the viability of future projects, these same changes may lead to increased storm damage and risks to human health. This is a particular concern for coastal regions where the largest trends were observed, strong winds already exist, and a strengthening westerly component could greatly increase storm surge magnitude.

## 4.2. Wind Density–Inflow Interactions

The relationships between wind density and hydroelectric reservoir inflows have interesting implications for the development of wind power in BC. The dominance of hydroelectricity in the PNW results in large seasonal and interannual fluctuations in potential generation tied to natural variation in precipitation and streamflow, which can place the electricity system under stress during extreme high and low inflow periods. The value of energy, capacity, and system flexibility vary greatly between high and low inflow conditions (Woo et al. 2011; Voisin et al. 2006), and therefore the behaviour of wind power during these periods is extremely important in determining its economic and social benefits.

The widespread weakly positive correlations between annual CUI and wind density totals (Figure 3) suggest that the interannual variability in wind energy generation will roughly match that of reservoir inflows and water levels, while still moderating some of the climate related variability in provincial electricity supply. However, poorly or negatively correlated sites, such as those in the northern BC coast and the Alaskan panhandle, would provide an even greater moderating influence by having greater than average generation in low inflow years and reduced generation in wet years.

The ability of wind power to address energy deficiency in low water years may be of particular interest to BC. By increasing generation during these low inflow periods wind power may help to avoid overdevelopment and energy surplus in average and wet years. None of BC's existing or in-development wind farms exhibited significant wind density changes during low-flow years (Figures 4 and 5), indicating that BC's wind farms are not likely to have substantially reduced or elevated output during the driest years. Wind power from these sites will therefore do more to fulfill the self-sufficiency requirement than an equivalent hydroelectric project, which would likely have much lower production in these low inflow years. However, the more important finding for future wind farm development is that the North Coast region, including Haida Gwaii and smaller areas of southern and northwestern BC and northern Washington, all had significantly increased wind densities in the lowest inflow years (Figures 4 and 5). Wind density totals in these years were larger than the median by as much as 60%, making the value of wind farms in these areas potentially much greater than metrics based solely on annual averages would indicate. Of particular interest are the areas of northern Vancouver Island and the inshore channel off of Haida Gwaii where winds were strong and increasing, and where many wind farms have already been proposed.

Wind speed behaviour during high inflow periods should also be considered when selecting wind farm locations. Due to low or negative electricity prices and a reduced ability to manage reservoir levels because of the non-dispatchable nature of wind power, wind generation during high water periods can be of very little value or even detrimental to the operation of the electricity system (Bonneville Power Administration 2011; Joskow 2011). Wind farms that have reduced generation during high water years are therefore preferable to otherwise similar sites with consistent or increased production.

All significant wind density anomalies for the three and five highest inflow years were positive (Figures 6 and 7), but were less geographically consistent between the two cases than were the low inflow results. In BC, anomalies in the three-year case were seen in central BC and the Peace region, but in the five-year case anomalies were located mainly to the south, along the Coastal and Rocky Mountain ranges. While the three- and five-year anomaly patterns differed in BC, they were very similar for Washington and Oregon which exhibited widespread positive anomalies in the highest inflow years. Interestingly, the WD anomalies in the Peace region, where BC's existing wind farms are found, were larger than the percent increase in CUI for the three highest inflow years, when compared to average years. In contrast, the coastal regions, where the majority of the other proposed sites are located, showed no increase in wind density during high inflow years, indicating that wind farms at these locations would have less of an impact on system flexibility in the wettest years.

The different spatial patterns in the three- and five-year high flow anomalies may indicate that the relationships between inflows and WD are less consistent in the wettest years than the driest. This inconsistency, along with the greater importance of understanding wind density patterns in low water years to satisfy self-sufficiency requirements, means that high flow anomalies are unlikely to play a large role in wind farm site selection in BC. However, the WD anomalies for Washington State and Oregon were more consistent and are therefore likely common to high water years in general. The large positive anomalies found in the US PNW, and the rapid wind power development occurring in this region, could result in even larger energy surpluses in high water years, rather than the moderating effect that diversification is meant to bring. Because of the tightly integrated nature of the PNW energy system, such an increase in non-dispatchable generation, when reservoir capacity is already limited, could have consequences for the electricity market in both Canada and the US. The most likely effect would be declines in electricity prices, particularly during the freshet (Woo et al. 2013), and therefore a further reduction in the value of wind farms and other non-dispatchable sources, such as run-of-river, with increased generation in high inflow years.

**Seasonal Variability**

Along with interannual variability, PNW inflows undergo large seasonal variations. For example, the average monthly CUI during the spring freshet (May through July) is more than 7 times larger than during winter (December through March). Thus, wind behaviour during the low inflow winters and high inflow freshet periods can also be important in determining the value of potential wind farm sites. Increased wind power during the low inflow winter months can increase system flexibility, allowing water to be stored or released at each reservoir with fewer capacity and energy constraints, and can help to meet peak capacity demands caused by increased heating requirements (Kiani et al. 2013). Electricity prices are also typically highest during the summer and winter (Woo et al. 2011), making increased energy exports or decreased imports during these periods more profitable.

The significant positive wind density anomalies seen during winter for the majority of the PNW (Figure 8) again show that the timing of high wind speeds in BC can increase the economic and system benefits of wind power. The largest wind density anomalies were found along the Pacific coast, where strong winter storms bring high winds, with decreasing magnitudes in wind density anomalies found inland. There appears to be a strong orographic effect on winter anomalies, with large positive values for the western flanks of the Coastal and Rocky Mountains, much weaker positive anomalies in the lee of the Coastal Mountains, and negative values east of the Rockies. Wind density behaviour during the high inflow freshet period showed the same pattern as during winter but with opposite signs, dominated by negative anomalies rather than positive.

Similarly, the large decrease in wind speeds and wind densities during the spring freshet for both the Peace and coastal regions (Figure 9) is another major advantage for wind power over expanding hydroelectric generation. The majority of new generation in BC in recent decades has come in the form of ROR, which has no storage capacity and experiences a large increase in generation during the spring freshet. “Additional energy during the freshet (May through July) has limited value” because BC Hydro’s reservoirs are typically full due to high inflows, which reduces the ability to store excess energy, and because energy prices are typically lower or negative because of surplus hydroelectric generation throughout the PNW (BC Hydro 2013b).

## 4.3. Causes of Spatial Variability in Wind-Inflow Relationships

The spatial variability in the long-term CUI-WD relationship is likely due to different responses to regional climate variability and large-scale climate cycles such as the El-Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Although ENSO and PDO are defined by sea surface temperature anomalies (Trenberth 1997; Zhang et al. 1997), they have been correlated with changes in wind speed, precipitation, and streamflow in the PNW (Dettinger et al. 2001; Tuller 2004; Wang et al. 2006). ENSO typically varies year-to-year with a period of 5-7 years, while PDO tends to remain in one phase for two to three decades (Mantua et al. 1997).

CUI is a weighted aggregate of inflows into BC's hydroelectric reservoirs, and therefore its relationship to ENSO and PDO is dependent on the combined behaviour of all contributing watersheds. Approximately 81% of BC Hydro's annual hydroelectric generation comes from the Peace and Columbia basins, located in the Northern Interior and Southern Interior regions, with most of the remainder coming from the South Coast (BC Hydro, 2011). CUI variability is therefore largely determined by streamflow behaviour in the Northern and Southern Interior regions because of the geographic distribution of BC's hydroelectric dams and the heavy weighting of the dams in these regions.

Warm phases (positive indices) of both ENSO (El Niño) and the PDO are generally associated with reduced precipitation, streamflow, and storminess in the PNW, while cold phases (negative indices) are associated with colder, wetter, and stormier weather (Mantua et al. 1997; Rood et al. 2005; Wang et al. 2006). However, there is some regional variability in the streamflow response for both ENSO and PDO. ENSO is positively correlated with streamflow in the interior regions, but is negatively correlated on the coast (Wang et al. 2006), while PDO's effect on low streamflow events in BC is stronger on the coast than inland, and decreases moving from the south to north (Wang et al. 2006).

The climatic effects of PDO are also modulated by ENSO, enhancing the streamflow response when they are in phase, and reducing it when they are out of phase. PDO generally has a larger and more consistent influence that is modulated by the ENSO signal (Dettinger et al. 2001; Wang et al. 2006). However, Wang et al. (2006) also showed that the interaction between ENSO and PDO varies by region. Low streamflow periods were more frequent in the northern regions when ENSO and PDO were out of phase, whereas the southern regions experienced more low flow events when the two cycles aligned for both cold and warm phases (Wang et al. 2006). Future climate oscillations will therefore affect each region differently, with CUI variability dependent on the aggregate behaviour of all reservoir watersheds.

Wind speeds in the PNW are also influenced by ENSO and PDO (Tuller 2004; Abeysirigunawardena et al. 2009; Enloe et al. 2004), but location, rather than climatic oscillation, plays a much larger role in determining both average and extreme winds (Griffin et al. 2010). Positive PDO phases are associated with a high pressure system over western North America, lower air pressure gradients, and therefore less storm activity and lower mean wind speeds in the PNW. Likewise, negative PDO phases are associated with stronger pressure gradients and higher mean wind speeds (Tuller 2004). Similarly, peak winds were found to be higher during cold (La Nina) ENSO phases, with small decreases during warm (El Nino) phases (Abeysirigunawardena et al. 2009; Enloe et al. 2004). However, Griffin et al. (2010) showed that the strongest predictor of wind speed behaviour is site location. They found that coastal sites followed an eight to nine-year cyclic pattern, with no discernable long term trend, while interior sites had a small, linear downward trend.

The overriding effect of location on wind speed variability for coastal sites, compared to the more direct relationship between rainfall and large-scale climate oscillations, is likely the cause of the weaker WD-CUI relationships found in this region. While positive PDO and ENSO phases increase the likelihood of low inflow years, coastal winds continue to follow the eight to nine-year cycle identified by Griffin et al. (2010) in this region. The difference in cycle periods makes it less likely that low streamflow years will coincide with low wind speed years on the Pacific coast. In contrast, during positive (negative) PDO and ENSO phases interior wind sites will likely experience the same high (low) pressure systems as the hydroelectric reservoirs, resulting in similar impacts on both wind speeds and streamflow, and the strong CUI-WD relationships observed.

## 4.4. Limitations and Suitability of NARR Data for Climate Studies

Reanalysis data have been shown to be useful for climate trend analysis, as long as false trends introduced by changes in the observation and assimilation systems are corrected (Bengtsson et al. 2004). The introduction of the global satellite observation system between 1978 and 1979 resulted in a substantial positive shift in kinetic energy measurements that introduced a false positive trend in the long term wind speed record when years prior to 1978 were included (Bengtsson et al. 2004), which was the case with the previous generation NCEP/NCAR reanalysis. As NARR is limited to the period after 1979, the calculated wind speed trends are not affected by this particular change in the observation system. NARR wind speeds have also been shown to exhibit a negative bias of approximately 0.5m/s when compared with meterological station and radiosonde observations (Mesinger et al. 2006). However, this bias has not been shown to affect trend analysis (Pryor et al. 2009).

Previous studies using reanalysis data have calculated surface wind speed trends that are often inconsistent with those seen in observational data. McVicar et al. (2008) found that the negative wind speed trends seen in meteorological station data were poorly captured in three reanalysis products in Australia, even when using only reanalysis data after 1979. Similarly, Pryor et al. (2009) found that trends obtained using NARR data were often different or even opposite to those seen in observational data for the continental United States. In both of these cases stilling was seen in the observational data for most areas while the reanalysis data showed mainly negligible or positive trends.

In contrast, comparisons of observational and reanalysis wind speed trends farther above the surface have demonstrated greater agreement. Holt and Wang (2012) found positive wind speed trends using 80m NARR wind speeds for most of the United States, which were broadly consistent with studies of boundary layer winds (Li et al. 2010; Vautard et al. 2010).

Although 10m wind observations are assimilated into NARR (Mesinger et al. 2006), the station coverage in BC is very sparse, forcing a heavy reliance on extrapolating down from modeled higher elevation and boundary winds. This may explain why NARR exhibits similar positive wind speed trends at both the surface and higher elevations, as Holt and Wang (2012) and our results have shown, while opposite trends are seen in observational data (Pryor et al. 2009). Also, Vautard et al. (2010) suggested that increasing surface roughness could explain 25% to 60% of the continental stilling found in observational datasets. As the effects of surface roughness would primarily be present only in near-surface observations, it would not be captured by a reanalysis with little influence from station data.

Another limitation of the NARR dataset is that it does not capture the localized variability caused by the highly complex topography of the PNW. The results of this study can therefore only identify regions of interest for further study rather than specific ideal wind farm locations. Correlations between reanalysis wind fields and surface observations are likely to be stronger for coastal sites than for interior sites because of their closer proximity to the climatic conditions over the Pacific Ocean, which are the main drivers of interannual wind speed variation in BC (Curry et al. 2012).

Curry et al. (2012) also showed that downscaling wind speeds from regional predictors, such as the pressure gradient and relative vorticity, as occurs during the production of reanalysis datasets, is much better at capturing local characteristics of interannual variability than monthly, or seasonal variability. As the annual cycle is the dominant mode of variability for monthly and seasonal wind speeds and streamflow, analysis on this time scale simply relates their respective annual cycles, rather than specific local behaviour. This lack of local information in the monthly and seasonal data is demonstrated here by the highly uniform winter and freshet WD anomalies.

Despite these caveats and limitations, the wind-streamflow relationships calculated using NARR data should still be useful in the assessment of new wind power locations. The similar trends seen in the NARR data and observational boundary layer winds (Li et al. 2010; Vautard et al. 2010) suggest that NARR effectively captures wind behaviour at higher altitudes relevant for wind power development, even if disagreement exists in surface analyses. Similarly, NARR’s limited ability to represent detailed topographic variation in wind speeds at monthly and seasonal time scales should not diminish its usefulness in identifying potential wind farm sites. The CUI-WD relationship is most important on an interannual time scale, for which reanalysis has been shown to be able to distinguish local characteristics (Curry et al. 2012)

Regardless of the initial data source used to identify a potential wind farm location, extensive site specific observational studies will be required prior to final selection. Our analysis provides a means of identifying regions where more detailed analysis with observational data should be prioritized by focusing on sites with low or negative WD-CUI correlations, positive WD anomalies during winter and low inflow years, and negative WD anomalies during the freshet and high inflow years. These areas include northern Vancouver Island, Haida Gwaii, and the broader North Coast region.

# Chapter 5. Conclusions

Demand is increasing for wind power in the Pacific Northwest (PNW) as a component of the renewable energy portfolio, making it useful to quantify historical changes in wind speeds across the region. This study used wind speed data from the North American Regional Reanalysis (NARR) dataset to demonstrate that wind speeds appear to have increased across most of the PNW between 1979 and 2010. Wind densities (WD) were found to be increasing at an even faster rate and more consistently across the region, with positive trends for all of BC's current and proposed wind farm developments. The South Coast region experienced the largest increase in generating potential, at 12.1%/decade, while BC's existing wind farms in the Northern Interior region experienced an average WD increase of 8.48%/decade.

The province of British Columbia (BC) relies heavily on hydroelectric generation, which experiences large fluctuations in generation potential related to interannual and seasonal fluctuations in reservoir inflows. Electricity generation in low flow years is therefore particularly valuable by helping to meet BC's self-imposed self-sufficiency requirement. This analysis suggests that northern Vancouver Island, Haida Gwaii, and the broader North Coast region all contain sites with strong winds and negative correlations between annual wind density and cumulative usable inflows (CUI) estimated by BC Hydro. As such, wind farm sites in these regions could play a particularly useful role in meeting energy generation requirements in the lowest water years and help to moderate the variability in hydroelectric generation.

For most of the PNW wind densities are also significantly higher during the winter and significantly lower during the freshet, when compared to all other months of the year. The Pacific coast again has the most beneficial seasonal timing, with the largest wind density anomalies during both winter and freshet, along with the western portions of the Rocky Mountains. Although smaller trends were found for inland areas between the Coastal and Rocky Mountains, nearly every region still exhibited beneficial timing.

While these patterns were expected due to the strong storm seasonality in BC, they are still valuable for identifying regions of greater relative benefit. Widespread decreases in wind density during freshet when system flexibility is low, and increases during winter when capacity demands are highest, indicate that wind power located nearly anywhere in the province would have beneficial seasonal timing.

While this study has taken a first step in identifying potential wind farm sites with beneficial wind density timing relative to CUI, several additional steps are needed to verify these results. First, this study has identified several interesting candidate regions in BC that should be investigated further by comparing NARR and observational data. In addition to comparisons with existing observational data, the results of this study suggest the need for new meteorological stations that will allow for the testing of the accuracy of NARR’s wind fields and the heterogeneity of the WD-CUI relationships. The inclusion of both surface and turbine height anemometers at these sites would be particularly useful in assessing NARR’s ability to differentiate between surface and boundary layer winds, especially where station data is lacking. Also, wind farms are often located in topographically distinct areas, such as coastlines and ridges. Determining how the wind density behavior at these types of sites compares to the regional results could be important in identifying potential future wind farm sites.

A second step involves quantifying the economic value of beneficial wind timing prior to wind farm site selection. Many considerations are included when evaluating potential wind farm sites, such as construction, maintenance, and transmission costs, and the predicted energy output over the turbine's lifespan (Lee et al. 2009; AWEA 2013). For the wind density-inflow relationship to be included in this process the relative value of beneficial interannual and seasonal wind density timing compared to these other criteria must first be established. This will be a complex and ongoing process as it depends not only on the variability in electricity prices related to inflows and reservoir levels, but also on more difficult to quantify factors such as system flexibility and the role of wind power in meeting BC's self-imposed self-sufficiency requirement.

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# Appendix A.

# Supplemental Tables

**Supplemental Table 6. Annual and seasonal cumulative usable inflows (CUI) totals for British Columbia. Numbers in parentheses are the annual rankings. All totals are based on the water year of October through September, referenced by the starting calendar year. The freshet season is defined as May-July, and the winter season is defined as December-March.**

| Year | Annual CUI Total (GWh) (Rank) | Freshet CUI Total (GWh) (Rank) | Winter CUI Total (GWh) (Rank) |
|---|---|---|---|
| 1979 | 35914.5 (31) | 20402.13 (31) | 3723.48 (28) |
| 1980 | 46776.25 (7) | 26054.96 (11) | 6017.73 (2) |
| 1981 | 45054.37 (9) | 26790.15 (7) | 4145.18 (25) |
| 1982 | 42791.65 (15) | 23642.19 (18) | 4975.20 (7) |
| 1983 | 41806.62 (19) | 23061.93 (23) | 4480.56 (18) |
| 1984 | 38160.42 (28) | 22649.97 (25) | 3386.19 (32) |
| 1985 | 40391.40 (22) | 25062.61 (14) | 4265.37 (23) |
| 1986 | 43443.09 (14) | 26276.34 (10) | 4649.44 (15) |
| 1987 | 41994.64 (18) | 25101.71 (13) | 3995.18 (26) |
| 1988 | 38632.51 (26) | 21857.73 (28) | 3850.41 (27) |
| 1989 | 44729.41 (10) | 26724.76 (8) | 4706.35 (13) |
| 1990 | 46841.83 (6) | 26024.24 (12) | 4977.12 (6) |
| 1991 | 44072.44 (11) | 24728.37 (15) | 5583.34 (4) |
| 1992 | 37990.44 (29) | 20877.14 (30) | 3669.19 (29) |
| 1993 | 41077.62 (20) | 23568.13 (20) | 4633.11 (16) |
| 1994 | 40322.06 (23) | 23203.94 (21) | 4904.96 (8) |
| 1995 | 50967.18 (2) | 28820.92 (4) | 5691.82 (3) |
| 1996 | 51151.68 (1) | 30661.78 (2) | 4903.92 (9) |
| 1997 | 42730.70 (16) | 22945.87 (24) | 5094.74 (5) |
| 1998 | 47641.63 (4) | 27811.23 (6) | 4886.34 (10) |
| 1999 | 42258.36 (17) | 23721.81 (17) | 4375.65 (20) |
| 2000 | 38365.08 (27) | 22178.53 (26) | 3569.95 (31) |
| 2001 | 46563.82 (8) | 30001.12 (3) | 4331.94 (21) |

| Year | Annual CUI Total (GWh) (Rank) | Freshet CUI Total (GWh) (Rank) | Winter CUI Total (GWh) (Rank) |
|---|---|---|---|
| 2002 | 40104.24 (24) | 23170.24 (22) | 4689.19 (14) |
| 2003 | 41052.82 (21) | 20956.99 (29) | 4449.36 (19) |
| 2004 | 43972.59 (12) | 23885.14 (16) | 6100.92 (1) |
| 2005 | 39996.85 (25) | 23630.18 (19) | 4866.72 (11) |
| 2006 | 47733.44 (3) | 31027.16 (1) | 4834.47 (12) |
| 2007 | 43463.27 (13) | 26489.07 (9) | 4296.84 (22) |
| 2008 | 37104.52 (30) | 22048.35 (27) | 3576.41 (30) |
| 2009 | 35713.58 (32) | 19690.20 (32) | 4200.46 (24) |
| 2010 | 47076.65 (5) | 28725.35 (5) | 4563.99 (17) |