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VARIABILITY OF THE WIND RESOURCE IN WYOMING

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WHY SHOULD I READ THIS?

Well, you're standing here. What else can you do? Anyway, while I've got your attention, I'd like to tell you about the promise and potential of wind energy. Wind is among the fastest growing industries across the entire economic spectrum. Within the last decade, installed US wind capacity has increased almost 18-fold-- and it's still increasing. At the moment, wind accounts for almost 3% of the nation's domestic electricity supply. In order to further the quest towards energy independence, substantial strides in alternative energy must be made. Add to this, the consequences of climate change, ever-increasing gas prices, surging global population, expanding proliferation of electric vehicles and the promise of high-tech "green" jobs, wind energy is in a position to capitalize on the kind of "perfect storm" of renewable energy initiatives taking place.

Several studies have concluded that generating upwards of 20% of the country's electricity just from wind is feasible. One of largest hurdles in accomplishing this task, though, lies in improving the accuracy of wind forecasts. Wyoming, in particular southeastern Wyoming, is one of the windiest places in the country and deserves much of the attention given to the practicality of wind energy. And if the wind in this region is to be harnessed, understanding the timescales on which the resource operates is critical for its successful implementation.

WHY AND HOW DO WE FORECAST THE WIND?

In a scenario in which wind accounts for a sizable portion of the domestic energy supply, the ability to accurately predict the resource is related to both the economics of using the resource and the efficiency with which it's delivered. In the electric grid, supply and demand must be equal at all times. As it stands, when demand for electricity goes up, grid operators just burn more fossil fuels to generate more electricity to meet demand-- the fuels are there, ready to be burned. No waiting. Pretty nice.

This theory doesn't work too well with a variable resource, like the wind. Wind can't be stored, so grid operators need to know when the wind is going to blow in order to effectively utilize the resource. Wind farm developers' profits are also related to the accuracy of wind forecasts. Numerical weather models are tools forecasters use to help predict the wind. Two models were used in this project:

North American Model (NAM)
Weather Research and Forecasting Model (WRF)

Both models are available in 12 kilometer (km) and 4 km spatial resolution flavors. The NAM is an operational weather model run four times a day by the National Centers for Environmental Prediction. The WRF is a model that anyone can download and run. Users can tweak and customize various settings within WRF to meet their needs, making it a powerful tool for forecasters and researchers alike. The data for this project spans the years 2008-2010.

WHAT IS WIND POWER?

There are two basic relationships that you need to know to understand wind power. The first is the "1/7 Power Law." Weather stations sprinkled across the country automatically record standard atmospheric variables, including the the wind at 10 meters (m) above the ground. Referred to as the hub height, modern wind turbines operate at 50 m. Widely used throughout the wind energy industry, the 1/7 Power Law provides a way of calculating the wind speeds at hub height based on the wind speeds recorded at 10 m.

$$u_{50} = u_{10}\left(\frac{50\text{ m}}{10\text{ m}}\right)^{1/7}$$

Here, u_{50} is the wind at 50 m and u_{10} is the wind at 10 m.

The second describes how to calculate wind power density from wind speed:

$$\text{Wind Power Density} \propto (\text{wind speed})^3$$

This says that wind power density (WPD) is proportional to the cube of the velocity. For example, if you double the wind speed, WPD increases by a factor of eight! ($2^3=2\cdot2\cdot2=8$). And at higher wind speeds, even a two meter per second (m s^{-1}) increase in the wind speed can increase the WPD by a factor of 2.5. This sensitivity of wind speed to WPD is both good and bad: it's good because just a small increase in wind speed can pay dividends in resulting WPD. And it's bad for the very same reason, at least in the context of trying to predict the wind. If the wind forecast is off by a few m s^{-1}, then the errors in the resulting WPD forecast can be significant.

WHY IS IT SO WINDY IN WYOMING?

The lowest region of the Continental Divide between Montana and New Mexico resides in the southeastern corner of Wyoming. This area is known as the Great Divide Basin and claims an elevation of roughly 2000 m. The surrounding terrain, in comparison, pierces the sky at heights above 3000 m with several peaks boasting elevations over 4000 m.

In the winter, pools of cold air develop in the Great Divide Basin as the jet stream moves southward from Canada. A ridge in the jet stream, centered over the eastern valleys of Utah, Nevada and Idaho, results in an area of high pressure. Conversely, the trough of the jet stream results in an area of low pressure, typically positioned over the Dakotas. These two systems create a pressure gradient across the state of Wyoming forcing the air eastward.

The mountain ranges in southeastern Wyoming act as a natural topographic funnel, as illustrated in Figure 1. The winds accelerate as they blow through the mountain ranges towards the Great Plains. Aptly named the "Wind Corridor," this area harbors some of the strongest winds in the country.

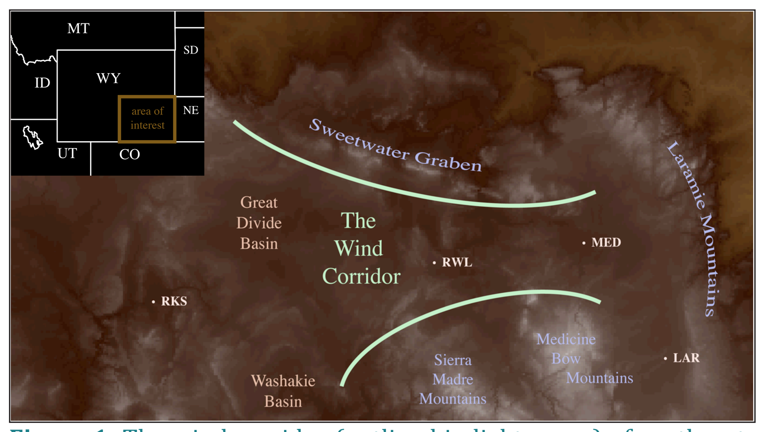

Figure 1: The wind corridor (outlined in light green) of southeastern Wyoming. Lighter white areas correspond to higher terrain.

HOW WELL DO THE MODELS WORK?

Figures 2 and 3 depict panel plots of the WPD in Wyoming for 2009. Figure 2 is a seasonal plot and Figure 3 is a diurnal plot. WPD is expressed in Watts per square meter (W m^{-2}): browns and dark greens signify areas of poor wind development and areas of reds and whites denote areas inclined for wind development. Like with the observational network, the 10 m wind is a standard model output variable. The 1/7 Power Law was used to calculate the wind at hub height and then the WPD was calculated.

Regarding Figure 2, a quick glance reveals several aspects of the annual cycle of WPD in Wyoming. During the summer, there is almost no wind potential, as

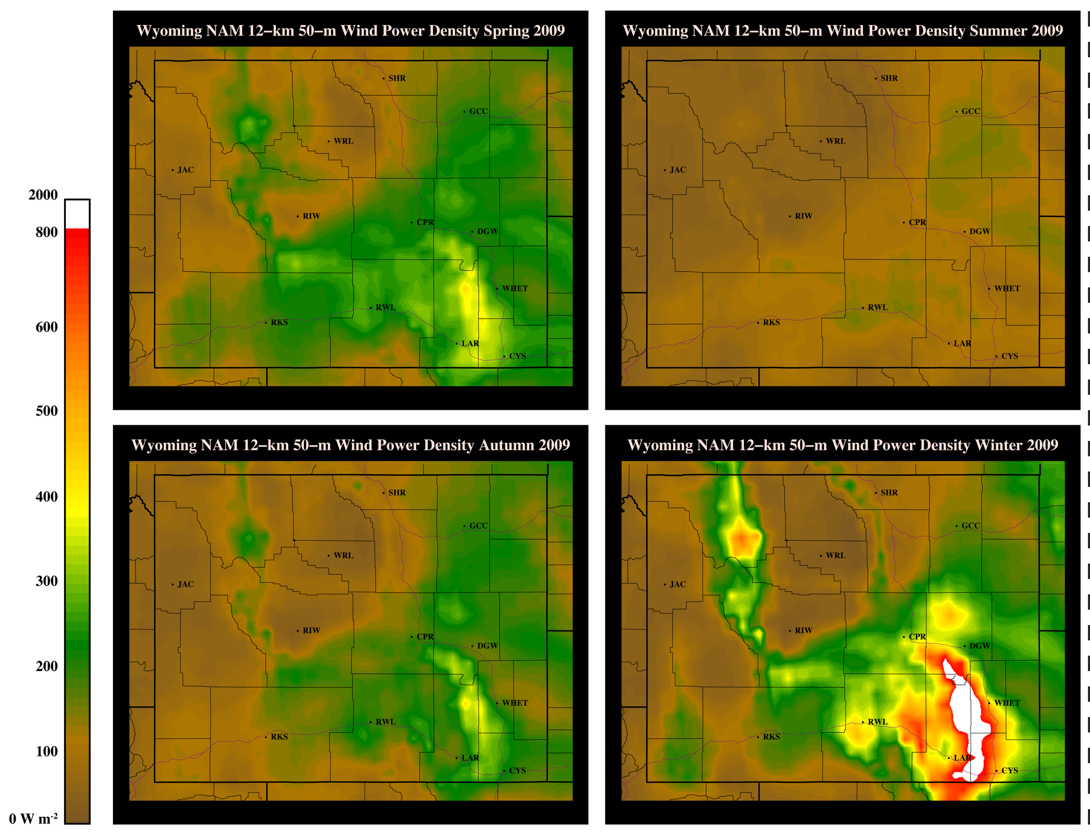

Figure 2: Annual cycle of wind power density (WPD) at 50 m using the NAM 12 km output.

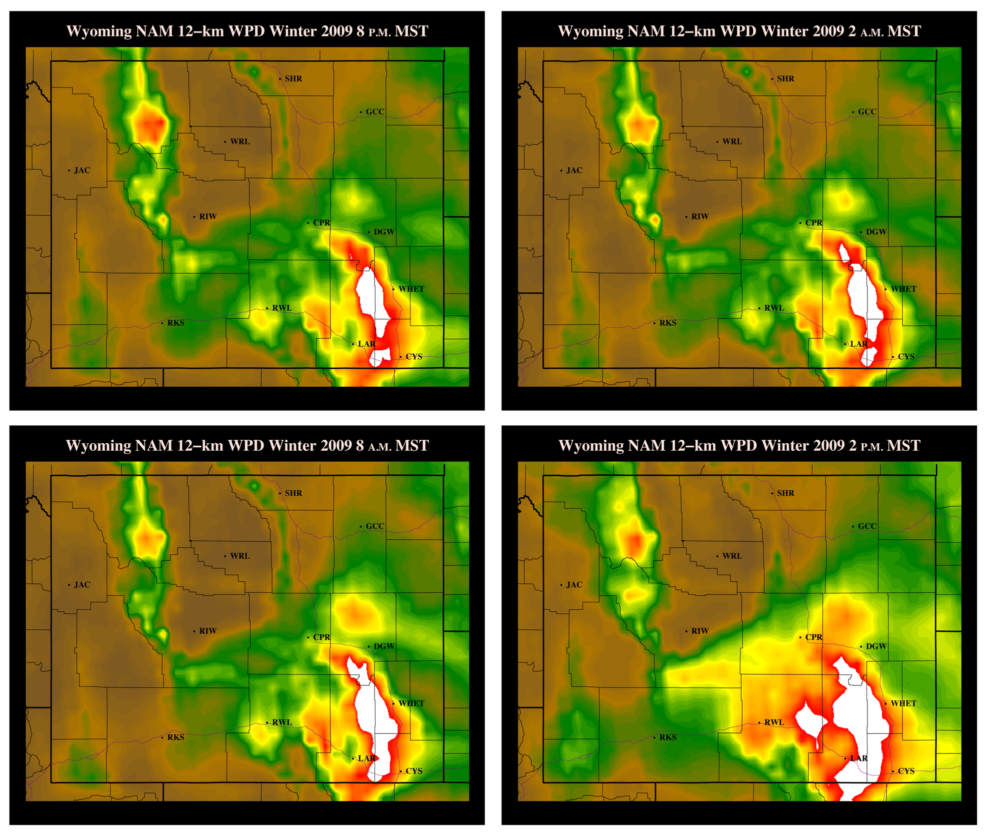

Figure 3: Diurnal cycle of wind power density (WPD) at 50 m using the NAM 12 km output.

evidenced by the fact that the map is mostly brown. Spring and Autumn afford about the same wind potential: mostly green, but there is a little bit of yellow in the southeastern corner of Wyoming. However, it's during the winter that provides the most wind potential. During the winter, the southeastern corner is flooded with white, indicating maximum WPD. Figure 3 illustrates how WPD varies over the course of a day during the winter: as the day progresses, WPD peaks in the afternoon, around 2 P.M. Figure 4 illustrates the diurnal cycle of WPD from the NAM 4 km, again at the same times as in Figure 3.

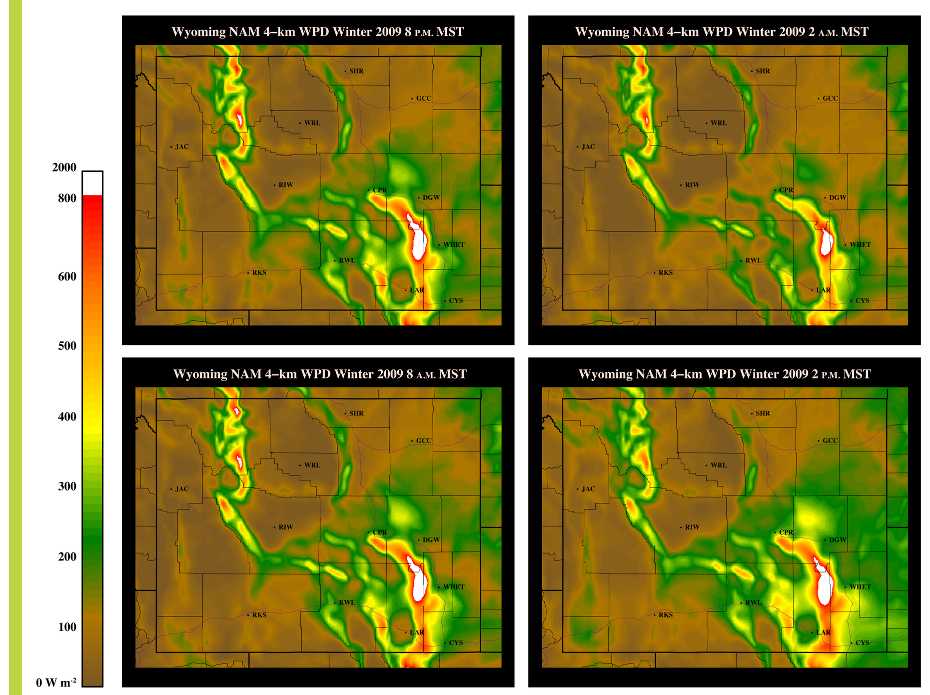

Figure 4: Diurnal cycle of wind power density (WPD) at 50 m using the NAM 4 km output.

It would not be unreasonable to assume that a higher resolution model would improve the forecast accuracy of WPD. But compared to Figure 3, Figure 4, a winter dirunal plot of WPD from the NAM 4 km, seems to simulate much less WPD over the course of the day. Though there is more spatial detail, especially in the southeastern corner of the state, there is much less white in Figure 4 than in Figure 3. This is especially true near the Laramie (LAR) valley. The NAM 12 km predicts WPDs on the order of 400-500 W m^{-2}. (Figure 3). The NAM 4 km, by contrast, simulates WPDs that never surpass 200 W m^{-2}.

Up to this point, we've focused just on the model output. But how do we know if it's right? Figure 5 shows four surface plots of WPD at two different locations: Cheyenne (CYS) and Laramie (LAR). Time is on the horizontal, both hour of the day (in universal or UTC time-- Wyoming is seven hours behind UTC) and month of the year. WPD is on the vertical. The color scheme is a tad different than the panel plots: purples and dark blues correspond to areas of poor wind resource and reds and maroons correspond to areas of rich wind resource. The observational data is on the top and the NAM 12 km output is on the bottom.

So what do we see? Well, the top plots show a lull of WPD in the summer months, as evidenced by the pool of blue. The surface plots peak in January and February and continue to rise towards the end of the day. These trends are what we saw in Figures 2-4: lots of WPD in the wintertime, peaking in the afternoon. And indeed, these trends are exhibited on the model surface plots. Unfortunately, the actual values of WPD are much lower on the model surface plots compared to the observational surface plots. In some instances, the difference approaches 1000 W m^{-2}!

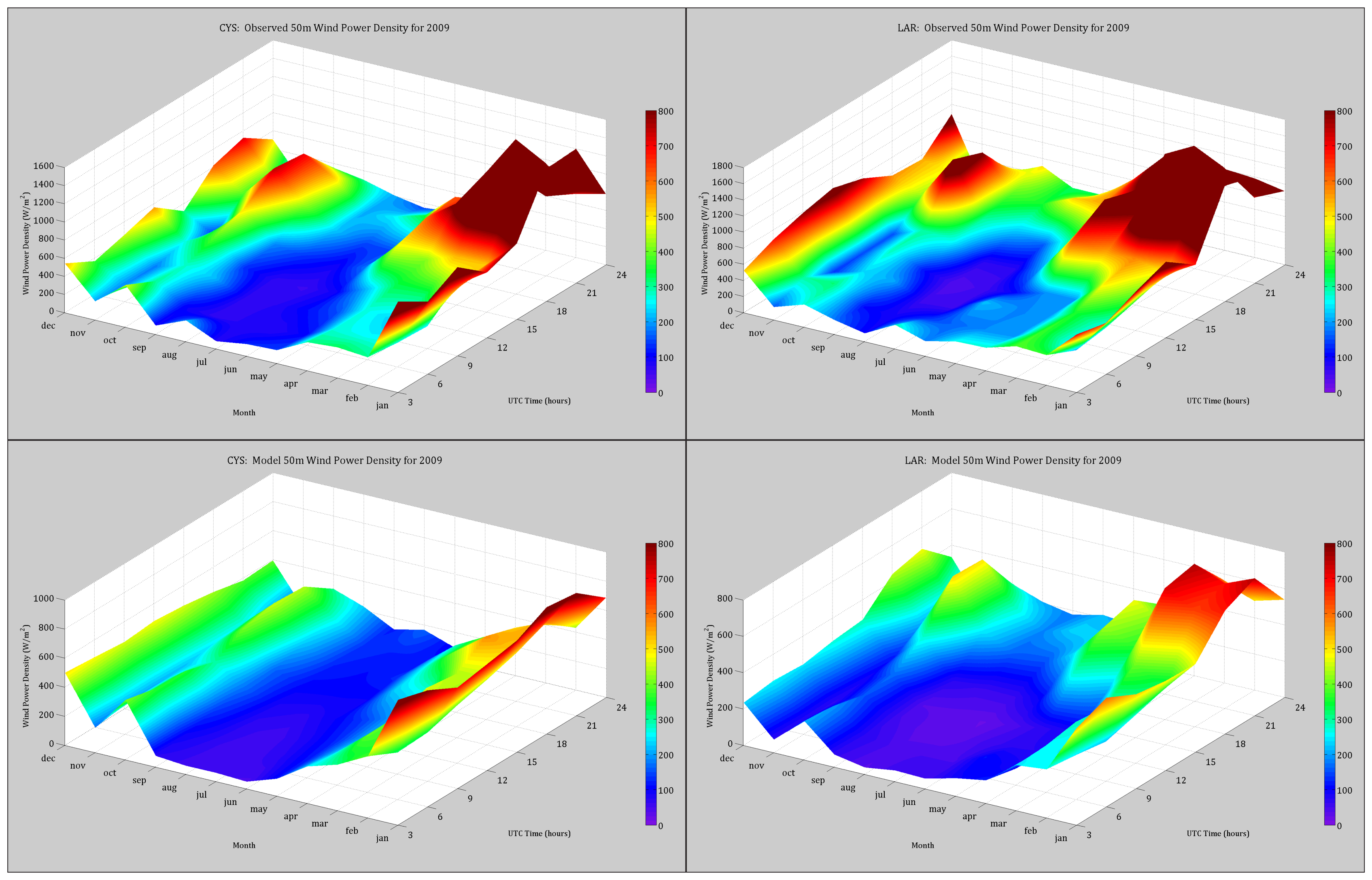

Figure 5: Surface plots of observational and model (NAM 12 km) WPD for Cheyenne (CYS) and Laramie (LAR) for 2009. Time of the day is in universal time (UTC)-- Wyoming is seven hours behind UTC. Blues correspond to times of poor wind resource and reds correspond to times of rich wind resource.

In efforts to improve model performance, custom WRF simulations were run for a windy day in January 2008. Figure 6 illustrates the domains of the WRF simulations: the resolutions of Domains 2 and 3 were 12 km and 4 km. Each WRF simulation utilized a different boundary layer (BL) parameterization. Recall, the BL is the lowest 1 km of the atmosphere-- the part of the atmosphere relevant to wind energy. Figures 7 and 8 illustrate the output from each simulation. 10 m wind speed (in m s^{-1}) is plotted on the vertical and time of day (in UTC). The grey line represents the observational data. The green and blue lines are the NAM output and the maroon and orange lines are the WRF output. A few things to note about these plots: at Laramie, the high resolution output is weaker for both the NAM and WRF. The blue line (NAM 4 km) is consistently below the green line (NAM 12 km) and the orange line (WRF Domain 3) is consistently below the maroon line (WRF Domain 2). The models all miss the ramp event towards the end of the day at both locations. At Cheyenne, the observational line peaks while all four model lines stay constant. At Laramie, the wind speeds near 22 m s^{-1} and all the runs fail to capture this event. Finally, the plots at each location look quite similar. In other words, there was no "miracle parameterization" that accurately simulated the observed wind speeds-- all four parameterizations performed equally poorly.

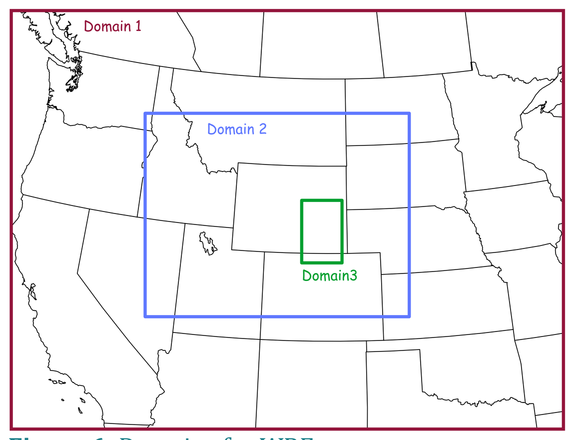

Figure 6: Domains for WRF runs.

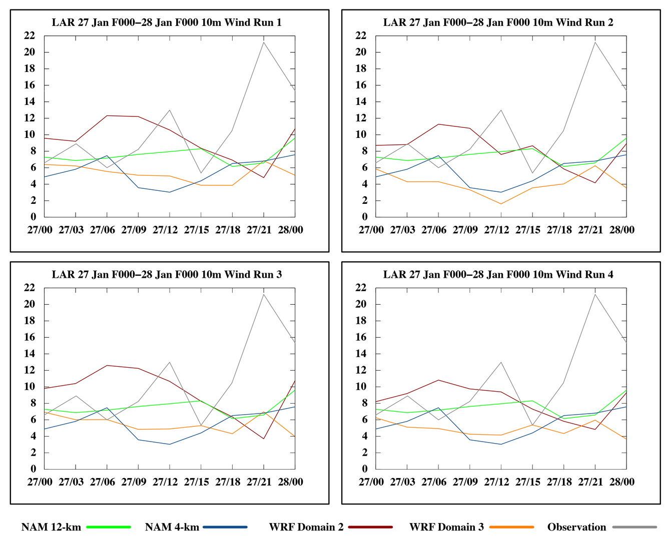

Figure 7: WRF output for Laramie.

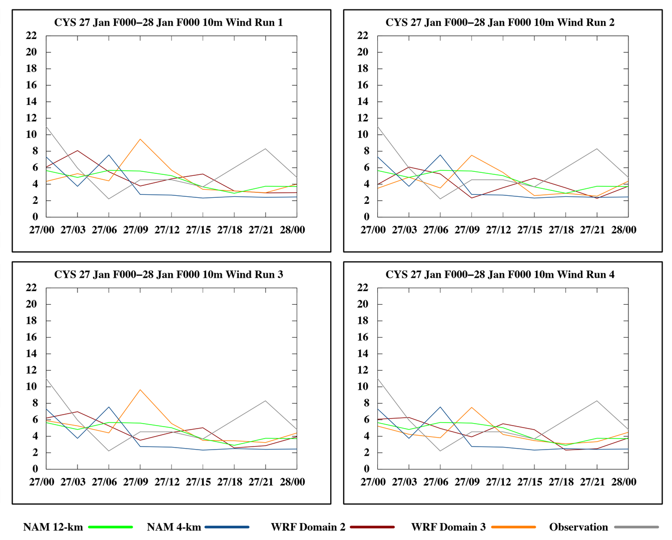

Figure 8: WRF output for Cheyenne.

WHAT DOES IT ALL MEAN?

The models capture the trends in the resource: WPD reaches a maximum in the wintertime and peaks in the afternoon. During the wintertime, as the jet stream moves southward, strong pressure gradients develop across Wyoming. In the summertime, the jet stream retreats northward, taking with it the ingredients required for these strong surface winds. The amount of solar radiation striking the surface peaks in the afternoon. This results in a well mixed BL in which turbulent kinetic energy from upper levels is transported down to the surface. But the model consistently under predicts the actual values of WPD. Figure 9 is a probability distribution (PDF) of the observational and model 10 m winds at Laramie and Cheyenne spanning winter 2008-2010. These four graphs help explain why the models under predict WPD. The observational PDFs are wider than their model counterparts. This speaks to the inherent variability, or randomness, of the resource: the wider the PDF, the more random. Due to the cubic relationship between WPD and wind speed, the presence of the higher wind speeds in the observational PDFs has a marked impact on WPD. Weather models currently used for forecasting the wind do a poor job of capturing these important high wind events. But to a certain degree this makes sense. These weather models were designed to predict the weather, not the wind. As the WRF runs showed, improvements to BL parameterizations need to be made, especially in areas near complex terrain, like the wind corridor. In short, alternative energy sources deserve alternative models.

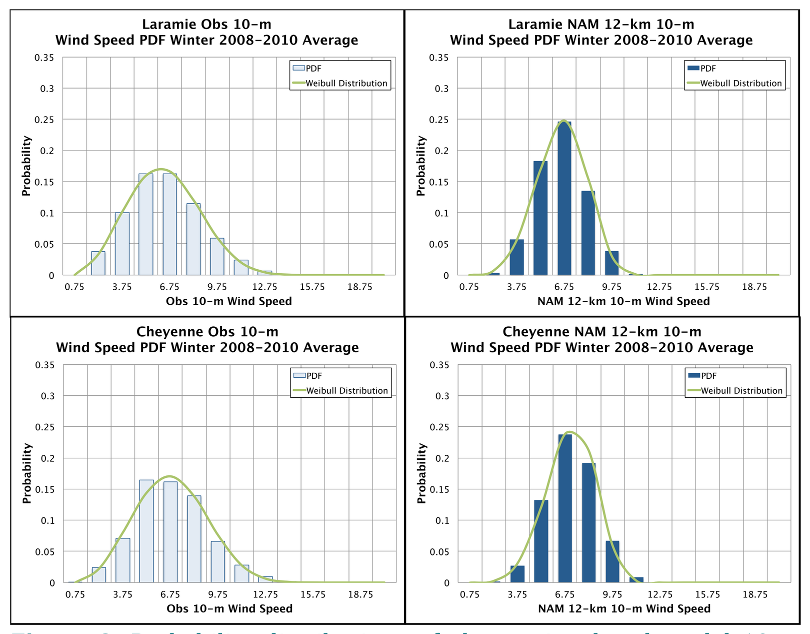

Figure 9: Probability distributions of observational and model 10 m winds for Laramie and Cheyenne.

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