Investigation of model parameters for high-resolution wind energy forecasting: case studies over simple and complex terrain

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Abstract

Wind power forecasting, turbine micro-siting, and turbine design require high-resolution simulations of atmospheric flow. Case studies at two West Coast North American wind farms, one with simple and one with complex terrain, are explored using the Weather Research and Forecasting (WRF) model. Both synoptically and locally-driven events that include some ramping are considered. The performance of the model with different grid nesting configurations, turbulence closures, and grid resolutions is investigated through comparisons to observation data. For the simple terrain site, no significant improvement in the simulation results is found when using higher resolution. In contrast, for the complex terrain site, there is significant improvement when using higher resolution, but only during the locally-driven event. This suggests the possibility that computational resources could be spared under

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certain conditions, for example when the topography is adequately resolved at coarser resolutions. Physical parameters such as soil moisture have a very large effect, but mostly for the locally-forced events for both simple and complex terrain. The effect of the PBL scheme choice varies significantly depending on the meteorological forcing and terrain. On average, prognostic TKE equation schemes perform better than non-local eddy viscosity schemes. *Keywords:* high-resolution simulations, terrain complexity, ramping event, wind energy forecasts

1. Introduction

Wind power forecasting benefits greatly from accurate predictions of atmospheric conditions at the heights spanned by wind turbines (~40-120m). Better simulation of the relevant physics could enable operational practices such as integration of larger fractions of wind power into power grids, scheduling maintenance on wind energy facilities, and defining design criteria for next-generation turbines and siting. Increases in available computational power have made high-resolution simulations of the atmospheric boundary layer more practical. The model operator, however, is required to make proper choices regarding model grid spacing, turbulence parameterization, land-surface representations and the configuration of initial and lateral boundary conditions for accurate simulations. The “proper” choice of these parameters is highly dependent on the situation under consideration.

As renewable energy sources begin to represent a larger fraction of the energy portfolio, additional strain is placed on the energy industry as these sources have to date been less predictable than traditional energy sources

17 (Mahoney et al., 2012). Precise spatial analysis of weather events and im-
18 proved weather prediction are crucial to both long and short-term energy
19 management. Accurate short-term (minutes to days) forecasting increases
20 the amount of wind power which can be integrated into electrical grid opera-
21 tions at a lower cost as it allows operators to make better real-time and day-
22 ahead operations decisions. These decisions lead to a more efficient energy
23 market by reducing the amount of polluting energy reserves (e.g., natural
24 gas, coal) needed to maintain system security (Marquis et al., 2011).

25 This paper analyzes and investigates some of the available parameters
26 for atmospheric modeling for wind energy applications and their effects on
27 predictions of wind speed at turbine hub heights for two case studies. We
28 investigate several time periods which include ramping events at two wind
29 farm locations on the West Coast of the United States, one over simple and
30 the other over more complex terrain. “Ramping” refers to a rapid change
31 in wind speed over a short time period and is of great interest to wind farm
32 operators for preventing turbine fatigue and predicting power output. The
33 exact definition of a ramping event varies in practice; examples include a 20%
34 capacity change in production over a thirty-minute period (Freedman et al.,
35 2008), or a pre-specified change in the magnitude of system-wide production.
36 In this paper, a ramping event is defined as an increase or decrease in wind
37 speed of at least 7 m/s in less than 3 hours.

38 Atmospheric conditions have a large effect on the predictability of wind
39 speed and ramping events. Meteorologically-driven wind and ramping events
40 may be due to atmospheric motions at several scales. For example, thermally-
41 driven winds such as sea breezes, mountain-valley circulations, or low-level

42 jets occur at local scales, whereas the passage of a cold front is a synoptically-
43 driven phenomenon. In all these cases, associated wind transitions may sim-
44 ply appear as large ramps in the wind speed time series to wind farm sys-
45 tems operators, though the cause for the wind changes can be quite different
46 (Freedman et al., 2008). Larger, synoptically-driven features have longer
47 time scales and are expected in theory to be more straightforward to fore-
48 cast than local-scale phenomena, which usually require fine scale information
49 about land-surface conditions and turbulent mixing in the atmosphere.

50 In addition to the synoptic conditions, local topography can significantly
51 affect a model’s prediction abilities. Many studies over complex terrain point
52 to increasing grid resolution as a means to achieving better agreement of sim-
53 ulations with observations (see e.g. Gronas and Sandvik (1999); Grell et al.
54 (2000); Mass et al. (2003); Chen et al. (2004); Carvalho et al. (2012)), and this
55 should be more important for locally-driven transitions. In contrast, low res-
56 olution mesoscale models may be adequate for many situations if the major
57 features of the terrain are simple and adequately captured. The representa-
58 tion of subgrid turbulent motions and sub-grid features in the topography
59 and land use can also play a role in a model’s ability to accurately capture
60 wind flow (Hanna and Yang, 2001).

61 There is uncertainty about the appropriate grid nesting strategy, includ-
62 ing selecting adequate turbulence parameterizations and initialization data
63 when moving to high resolution (Wyngaard, 2004). Another major challenge
64 is conserving computational resources, especially when making ultra-high
65 resolution forecasts, for example for predicting ramping events in the next
66 few hours or days. Current models used by wind farm operators use a range

67 of resolutions, often coarser than 1 km horizontally. This begs the question
68 of whether this resolution is fine enough to capture the required flow fea-
69 tures or whether computational resources could be saved by using coarser
70 resolution. Accuracy is extremely important to wind power operators as im-
71 provements of just 1 m/s in wind speed forecasts can mean millions of dollars
72 in savings because of financial penalties for both overestimating and under-
73 estimating power production. Suitable model configurations, however, may
74 vary drastically depending on the terrain and other site conditions.

75 Here we perform simulations at two different sites for which terrain com-
76 plexity varies greatly to develop insight into the ability to capture shifts in
77 wind speed that are important to wind farm operators. The two sites are
78 chosen to represent opposite ends of the spectrum in terms of terrain com-
79 plexity, and two extreme types of forcings (locally weak and synoptically
80 strong) are investigated at each site for the results to serve as a possible
81 guide for a broad range of wind farms and forcing conditions. This study is
82 relevant to wind energy forecasting in terms of day ahead forecasting. Short
83 time periods are selected due to the computational cost of simulations at high
84 resolutions. These time periods are chosen to be of interest to the wind indus-
85 try by including ramping events with synoptic and local forcing to determine
86 the importance of model parameters in each case. After exploring the model
87 parameter space for these cases, a week-long simulation is performed for one
88 group of settings to investigate longer time periods.

89 We use the Weather Research and Forecasting (WRF) model as our sim-
90 ulation tool (Skamarock and Klemp, 2008). WRF is intended mainly for
91 mesoscale atmospheric simulations and includes large-eddy simulation (LES)

92 capabilities. WRF has a fully compressible, Eulerian and non-hydrostatic
93 equation set. Although we focus our study on only two wind farms, the
94 farms are located in regions of high density, high MW wind power instal-
95 lation, making the results from this study meaningful to a large sector of
96 the U.S. wind community. Our complex terrain wind farms are located in a
97 region with at least 5,000 MW of installed capacity, while our simple terrain
98 farm is in an area of at least 700 MW of installed capacity (American Wind
99 Energy Association, 2012).

100 The simple terrain wind farm, with a 150 MW capacity, covers an area
101 of about 10 km by 10 km with a fairly flat topography which includes a few
102 hills with elevation variations of less than 150 m (see figure 1a). The complex
103 terrain site spans a series of wind farms with over 500 MW installed spread
104 across 37 km (north-south) by 53 km (west-east) and features much larger
105 elevation differences of 1500 m (see figure 1b). Observation data are available
106 from SODARs, meteorological towers, and cup anemometers on the turbine
107 nacelles that can be used for comparison to numerical simulations. Wind
108 speed accuracy is ± 0.5 m/s for SODAR and ± 0.3 m/s for cup anemometers.
109 The turbine hub height for both wind farms is 80 m.

110 [Figure 1 about here.]

111 The effects of horizontal and vertical grid resolution (section 3.2), 1-way
112 vs. 2-way nesting (section 3.4), and turbulence closure models (section 3.5)
113 are examined here. Results are presented below, along with discussion of the
114 numerical setup and grid nesting approaches.

115 2. Numerical Simulation Setup

116 2.1. Grid nesting and topography

117 Four nested grids are used to simulate flow conditions for the wind farms
118 at horizontal resolutions of 8.1 km, 2.7 km, 900 m, and 300 m. The main
119 features of the topography become visible at 2.7 km for the simple terrain
120 case and 900 m for the complex terrain, but fine structures become much
121 better resolved at 100 m resolution for both cases (figure 1). Topography
122 was extracted from a 10 m resolution data set available from the USGS.
123 The terrain is smoothed near the boundary for each nested sub-domain to
124 match the elevations for the surrounding coarser grid. WRF uses a terrain-
125 following, hydrostatic-pressure vertical coordinate system with the top of the
126 model being a constant pressure surface. The vertical grid spacing is normally
127 assigned by default by WRF, or it can be specified by the user to decrease
128 spacing near the bottom of the model and stretch it near the top. The
129 minimum vertical grid spacing (Δz_{min}) at the surface, as well as the average
130 spacing (Δz_{avg}), are listed in table 1 for the grid configurations used. The
131 domain height is approximately 13 km for the simple terrain case and 18 km
132 for the complex terrain case to allow a larger damping region at the top of the
133 domain (thus also requiring more vertical levels). The grids for the complex
134 terrain site are larger so as to include more surrounding topographic features;
135 the simple terrain site is not near any significant topographic features which
136 would warrant a larger domain. Larger domains have been tested but have
137 not shown any significant differences (not shown). This model setup is fairly
138 standard for a nested WRF simulation. All the nested domains are the same
139 size and centered within each other.

[Table 1 about here.]

Several challenges are encountered with WRF over complex terrain. The terrain-following coordinates are considerably distorted near the surface over steep terrain which leads to numerical instability in the model. Reducing the time step, smoothing the terrain, and decreasing the vertical resolution near the ground were all attempted but resulted in significant distortion or excessive run time. The most effective option in our case is to adjust the time off-centering in WRF that weights (forward in time) the vertically-implicit acoustic-time-step terms in the model to damp instabilities associated with sound waves and sloping model levels (Durran and Klemp, 1983; Dudhia, 1995). The off-centering is accomplished by using a non-zero, positive coefficient in the acoustic time-step vertical momentum equation and geopotential equation.

2.2. Computational time

The computational time for these simulations is reasonable for short-term forecasting applications. The smaller simple terrain site needed about 9 hours of wall time for a 48 hour simulation, while the complex terrain site needed about 43 hours of wall time for a 48 hour simulation. Simulations for both sites used 144 processors for the 4 concurrently simulated domains (1:3 nesting ratio used for horizontal and temporal resolutions).

2.3. Initialization and lateral boundary conditions

Initial and boundary conditions were obtained from the National Center for Atmospheric Research (NCAR) North American Regional Reanalysis

(NARR) data. NARR is available at 32 km horizontally at 29 vertical levels (1000-100hPa; excluding surface) to force the WRF simulations at the coarsest grid. Lateral boundary condition forcing was applied at three-hour intervals and linearly interpolated in between. Relaxation towards the lateral boundary values was applied around the edge of the domain. Simulations were performed for 48 hours for the short term events and for an extra 120 hours for the week-long statistical analysis. Output was stored at ten-minute intervals and used to generate initial and boundary conditions for the nested grids. Simulations using NAM for initialization were also performed, but the overall conclusions were similar (not shown).

2.4. *Surface characteristics*

WRF uses 33 land use categories (including ice and water) from USGS. The simulations use National Land Cover Database (NLCD) data at 30 m resolution which is mapped from the native 19 land use categories to the USGS 33 land use categories. The Noah Land Surface Model was used with initial moisture and soil temperature in four layers interpolated from NARR. Land-atmosphere coupling effects on the boundary layer, such as soil moisture initialization, can have a significant effect on simulation results, and at finer resolutions it may be necessary to use finer-scale soil initialization fields (Woodward et al., 2009; Williams et al., 2009; Chow et al., 2006). Section 3.3 examines the role of soil moisture on the model results.

2.5. *Turbulence*

WRF provides several turbulence closure options for the Reynolds-Averaged Navier Stokes (RANS) equations of motion. These closures are referred to

187 as Planetary Boundary Layer (PBL) schemes and they parameterize verti-
 188 cal turbulence diffusion (or vertical mixing) in physical space. All the PBL
 189 schemes make use of second order horizontal diffusion on the model levels,
 190 where gradients are simply taken along coordinate surfaces. The horizontal
 191 eddy viscosity is determined from horizontal deformation using a Smagorin-
 192 sky first-order closure approach.

193 Several of the PBL schemes use a prognostic turbulence kinetic energy
 194 (TKE) closure that predicts the sub-grid TKE using a TKE equation to
 195 obtain the vertical eddy viscosity. These include the base case Mellor-
 196 Yamada-Janjic (MYJ) scheme (Janjic, 1994), the Quasi-Normal Scale Elim-
 197 ination (QNSE) PBL (Sukoriansky et al., 2005), the Mellor-Yamada Nakan-
 198 ishi and Niino Level 2.5 (MYNN2) and 3 (MYNN3) PBLs (Nakanishi and
 199 Niino, 2006), the Bougeault-Lacarrere (BouLac) PBL (Bougeault and Lacar-
 200 rere, 1989), the University of Washington (UW) scheme (Park and Brether-
 201 ton, 2009), and the Grenier-Bretherton-McCaa (GBM) scheme (Grenier and
 202 Bretherton, 2001). Unlike the prognostic TKE PBLs, the Yonsei University
 203 (YSU) scheme (Hong et al., 2006) and its predecessor, the Medium-Range
 204 Forecast (MRF) model (Hong and Pan, 1996), are both non-local vertical
 205 eddy viscosity schemes. The Asymmetric Convective Model (ACM2) (Pleim,
 206 2007) uses a hybrid approach with non-local upward mixing and local down-
 207 ward mixing. The Total Energy Mass Flux (TEMF) scheme (Angevine et al.,
 208 2010), which uses a sub-grid total energy prognostic variable with mass-flux
 209 type shallow convection, is also tested, but is numerically unstable for the
 210 synoptically-forced complex terrain case and is not compared in this work.
 211 All the PBL schemes compared in this work (see section 3.5) make use of the

212 Noah land surface model and use the recommended surface-layer physics op-
 213 tion in WRF (which is particular to each PBL scheme). ACM2 makes use of
 214 the MM5 Monin-Obukhov surface-layer scheme instead of its recommended
 215 surface-layer scheme, because the recommended scheme is designed for the
 216 Pleim-Xiu land surface model (which is not used in this study).

217 **3. COMPARISON WITH OBSERVATION DATA**

218 Results comparing simulations with observation data for the two-day
 219 events are given in this section. Four main cases will be described: a locally-
 220 forced and a synoptically-forced case for both the simple and complex terrain.
 221 These events occur during four different selected time periods. The naming
 222 convention for each case is explained in table 2, along with a brief descrip-
 223 tion of the ramping. Case CTL does show rapid changes in wind speed, but
 224 the magnitude of the wind speed is too low to consider any of these changes
 225 ramping events by our definition of a 7 m/s wind speed change.

226 [Table 2 about here.]

227 For each simulation period, a number of different model configurations is
 228 tested, using different resolutions, grid nesting, vertical levels, and turbulence
 229 closure models. The naming convention for these runs is “(finest horizontal
 230 resolution)_(number of points in vertical)”, as shown in table 3. Note that
 231 the base case simulation for the simple terrain (ST) site uses 49 vertical
 232 levels, while the base case simulation for the complex terrain (CT) site uses
 233 54 vertical levels due to the different domain heights. All the results are
 234 from 1-way nesting and the Mellor-Yamada-Janjic turbulence model unless

otherwise noted. The week-long simulations (section 3.6) are an extension of their respective short-term cases for 5 additional days.

[Table 3 about here.]

3.1. Comparison strategy

A Doppler mini SODAR (Model4000, Atmospheric Systems Corporation, Santa Clarita, CA) collected high vertical resolution, three-axis wind velocity data at a 1 Hz per beam sampling resolution. SODAR data were averaged over 10-minute intervals to calculate mean horizontal and vertical wind speed, direction, latitudinal, longitudinal and vertical turbulence intensities, and turbulence kinetic energy at 10 meter intervals at heights 20-200 m above ground level (AGL). The data was quality controlled according to accepted SODAR standards (e.g. Antoniou et al. (2003)) (see Wharton and Lundquist (2012)). SODAR 10-minute intervals are compared with instantaneous model output at 10 minutes.

The time series and profile figures in the next few sections are located at the SODAR site, at the center of each domain, and are representative of other locations in the domain. SODAR data are available at 10 meter intervals from 20-200 m AGL, however at elevations above 100 m the data are sparse. To quantify the comparisons, error tables (such as table 4) show the root-mean-square errors (RSME) and mean absolute errors (MAE) between the SODAR data and the simulations over 20-200 m above the ground, averaged over 48 hours. They are defined as:

$$MAE = \frac{1}{M} \sum_{j=1}^M \frac{1}{N} \sum_{i=1}^N |A_{i,j} - B_{i,j}|$$

$$RMSE = \sqrt{\frac{1}{M} \sum_{j=1}^M \frac{1}{N} \sum_{i=1}^N (A_{i,j} - B_{i,j})^2}$$

where M is the number of time steps; N the number of vertical grid points; A observation data; and B simulation data. RMSE and MAE may be insufficient for evaluating model performance during ramp events, although industry practice still heavily relies on these metrics. Newer techniques, including the critical success index, need to be further developed and studied to evaluate ramp forecasts (Marquis et al., 2011). The evolution of wind speed and wind direction during these events is presented in figures (such as figure 3) comparing different cases at 80 m AGL. The observations are, in most sections, compared to 1-way nested run resolutions: 300m (4 grid nests), 900m (3 grid nests), 2700m (2 grid nests), and 8100m (1 grid).

3.2. *Effects of resolution*

3.2.1. *Topography resolution*

The required grid resolution depends greatly on the nature of the local topography. The chosen horizontal resolutions (see table 1) seem to easily capture the topography of the simple terrain site. Figure 2a shows how all the resolutions, fine and coarse (except for the 8100 m case), capture the hill and general topography of the wind farm quite well. Conversely, it is not as easy to capture the terrain of the complex topography site (figure 1b). Figure 2b indicates that the coarser horizontal resolutions (8100m and 2700m) do not capture the complexity of the terrain, but the finer resolutions do.

[Figure 2 about here.]

278 3.2.2. *Effects of horizontal resolution during locally-forced events*

279 We first examine locally-forced events over simple (Case STL) and com-
280 plex terrain (Case CTL) and compare output from 1-way nested runs to
281 evaluate the impact of grid resolution. Case STL shows an increase in wind
282 speed on the first day at 16 UTC that is slightly more gradual and starts ear-
283 lier than what is shown by the SODAR and does not capture the minimum
284 wind speeds observed by the SODAR (see errors in table 4 and figure 3a).
285 The down-ramping event on day 2 from 13 UTC to 16 UTC, where the wind
286 speed decreases from 10.5 m/s to 3 m/s, is well captured by the simulations
287 when compared to the observations, however, the minimum of the ramp is
288 not. Case CTL corresponds well with the SODAR for most of the first day
289 including the increase in wind speed from 17 UTC to the end of the day, but
290 fails to capture the lower wind speeds the observations show for the second
291 day and instead shows a large increase in wind speed.

292 The difference in performance for the various grid resolutions for Case
293 STL is small, as seen in the error metrics listed in table 4. The results are
294 very similar across all resolutions with the finest producing a slightly smaller
295 error than the coarser ones preceding it. This is somewhat surprising as we
296 expected to see more distinct differences between the resolutions. The verti-
297 cal profiles in figures 4a and 4b show time slices at the SODAR location from
298 two different times, with varying levels of agreement with the SODAR. Un-
299 der these conditions relatively coarse horizontal resolution (2.7 km) appears
300 to be adequate for capturing the shift in wind speed at the wind turbine
301 hub heights (~ 80 -100 m) for Case STL as there is little improvement for the
302 finer resolutions. These results agree with other simulations such as those

303 from Yver et al. (2013), which showed improvement from 12 km horizontal
304 resolution to 4 km but not from 4 km to 0.8 km for a California coastal
305 area. Deppe et al. (2012) did not register any improvement from 10 km to 4
306 km horizontal resolution for their simple terrain site in Iowa. The terrain is
307 adequately resolved on all grids in the simple terrain case and the mean flow
308 patterns are very similar.

309 The dependence on grid resolution for Case CTL is much more significant
310 as the error metrics show in table 4. In this case the two finer resolutions (900
311 and 300 m) compare better to the SODAR observations than the two coarser
312 resolutions, as shown in figures 3c and 3d. The improvement from 8100 m to
313 2700 m resolution is most noticeable, while improvement from 2700 m to 900
314 m is less and 900 m to 300 m even less. The vertical profiles in figures 4c and
315 4d show two different time slices at the SODAR location; Case CTL shows a
316 clear advantage to using high resolution simulations during certain times of
317 the day, particularly resolution finer than 8100 m. It is worth noting in the
318 vertical profiles (figure 4) that WRF may not always accurately capture the
319 magnitude, but does somewhat more accurately represent the vertical wind
320 shear profile. More accurate comparisons to the SODAR are observed with
321 finer resolution in complex terrain because the details of the topography are
322 better resolved, which can dramatically influence winds.

323 Case STL seems to predict wind speeds close to those of the SODAR but
324 the timing is slightly off for the increased wind speed event that starts at
325 16 UTC on the first day and wind speeds are over-predicted just before the
326 increase when comparing to observations. While there is clear improvement
327 with higher resolution in the first hours, Case CTL over-predicts wind speeds

after the first 25 hours of the simulation and skews MAE and RMSE calculations so that the finest resolution does not give the lowest value. Errors calculated separately for just the first day show much smaller values (table 4). These inaccuracies are later found to be at least partially attributed to misrepresentation of soil moisture in WRF (see section 3.3).

[Figure 3 about here.]

[Figure 4 about here.]

[Table 4 about here.]

3.2.3. *Effects of vertical resolution during locally-forced events*

Vertical spacing may have a significant effect on the accuracy of wind speed and direction predictions, particularly when wind shear is strong, e.g. in the case of nocturnal low level jets which can also be responsible for ramping events (see e.g. Storm et al. (2009)). To examine the need for high vertical resolution in high-shear regions, 4 sets of grids (with 1-way nesting) are examined. The grids were generated as follows: 300m_49 (and 300m_54) uses a *tanh* function to stretch the vertical grid spacing so that there is minimum spacing near the ground of ~30 meters which is stretched higher up into the atmosphere; 300m_70 uses specified grid levels that provide spacing of about 10 m in the lowest 200 m of the atmosphere and then stretched above (for Case STL) or start at 10 m and are stretched above (for Case CTL); 300m_40 is created by specifying 40 levels in WRF and using the default spacing (the minimum spacing is ~55 m and average spacing is ~309 m). Figure 5 shows the evolution of wind speed. Table 5 shows

the RMSE and MAE between simulations and observations along with the average vertical spacing in the range where observation data exists (20-200m). Surprisingly, the grids all give very similar results for the Case STL ramping event, with the lower resolution 300m_40 providing slightly worse results. The less computationally intense option in this case appears adequate for predicting ramping. This agrees with other studies such as Floors et al. (2013), which compared 41 vertical levels against 63 vertical levels within lidar range over the simple terrain coast of Denmark and found almost no improvement with vertical resolution.

Case CTL shows quite a bit more variation with vertical resolution. Table 5 appears to show that the WRF chosen 40-level setup gives the most accurate results followed by the 70 vertical levels stretched case, and finally the 54-level *tanh* stretched case. However, if the second day (during which the simulations over-predict the wind speed due to land-surface conditions mismatch between WRF and observations [discussed in section 3.3]) is excluded, the different resolutions seem to perform similarly, with the two finest vertical resolutions outperforming the coarser resolution. This suggests that for locally-forced complex terrain cases the results benefit slightly from an increase in the number of vertical levels used. The differences from changing the vertical resolution appear less significant than the horizontal resolution effects described above. Zhang et al. (2013) and Talbot et al. (2012) made similar conclusions from their simulations over complex terrain, where increased vertical resolution improved comparisons to observations to some degree, but not as significantly as horizontal resolution.

[Figure 5 about here.]

[Table 5 about here.]

3.2.4. *Effects of horizontal resolution during synoptically-forced events*

In this section we compare the effects of horizontal resolution in simulating the two synoptically-forced events. Once again output is compared from 1-way nested runs to evaluate the impact of grid resolution for both simple and complex terrain. The SODAR observations of the evolution of wind speed 80 m above the surface are presented for Case STS (figure 6a) and Case CTS (figure 6b). Simulations for Case STS compare rather well with the SODAR observations at all resolutions as the errors in table 6 show. All resolutions accurately capture the major ramping event at 18 UTC to 21 UTC on the second day, where wind speed increases from 4 m/s to 16 m/s, and match the observations quite well over the rest of the simulation. A cold frontal passage results in the increase in wind speeds for Case CTS at about 12 UTC on the first day and passes the next day at about 12 UTC as the ramping indicates. The simulation for Case CTS corresponds with SODAR observations with almost all grid resolutions as the error comparison in table 6 indicates. The simulations are slightly off in capturing the large ramping event on the first day from 10 UTC to 12 UTC, where wind speed increases from 10 m/s to 20 m/s. The largest differences between the resolutions are observed at 2 UTC on the second day, but there is no observation data for that time period. The MAE error for Case CTS of around 3.5 m/s is likely due to a forcing problem (initial/boundary conditions) because the different resolutions give very similar results for quite complex terrain. Most of the errors occur at the ramp up or after the cold front. Zhang et al. (2013) also found that the magnitude of errors is generally greater in the strong forc-

401 ing than weak forcing cases as the errors appear more closely related to the
402 influence of the weather systems.

403 It is of note that noticeable differences are observed with grid resolution
404 for the complex terrain case during local forcing (section 3.2.2) but not during
405 synoptic forcing. It may be that lateral boundary condition errors dominate
406 under strong synoptic forcing. It is not surprising that Case STS does not
407 show any improvement with increased resolution when Case STL did not
408 show any either due to the ease with which the various resolutions capture
409 the simple terrain. Furthermore, the simulations for the synoptically-forced
410 cases do not deviate as much from the observations as the locally-forced cases
411 discussed previously. The strong synoptic forcing likely dominates over any
412 other local forcing parameters that might have a significant effect on the
413 wind fields such as soil moisture variation.

414 [Figure 6 about here.]

415 [Table 6 about here.]

416 3.3. *Effects of land-surface conditions during locally-forced events*

417 Overall, there appear to be relatively small differences between results
418 from different grid configurations except for the locally-forced complex ter-
419 rain (CTL) case, as described above. Both locally-forced events, however,
420 showed large errors when compared to SODAR observations. This is espe-
421 cially true in capturing the lower wind speeds at hub height (~ 80 m), so there
422 is certainly room for improvement in the simulations. Here we examine the
423 effect of land-surface forcing for Cases STL and CTL. These simulations are
424 designed to test the role of soil moisture in the locally-forced cases, which

425 are anticipated to be more sensitive to land-surface forcing (Chow et al.,
 426 2006). Two soil moisture extremes are compared to the base case for both
 427 locally-driven terrain cases. In one extreme, the initial soil moisture value is
 428 set to 90 percent or almost fully saturated for the whole domain and left to
 429 adjust in time according to soil type. In the other extreme, the soil moisture
 430 value is initialized at 0.02 percent or almost completely dry for the whole do-
 431 main. Figure 7a shows that when the soil for Case STL is initialized as dry,
 432 it over-estimates the wind speeds slightly more than the base case. When
 433 Case STL is initialized as saturated, however, it is much better able to match
 434 the full extent of the down-ramping at 16 UTC on the second day, while not
 435 capturing the later peaks as well. For the complex terrain domain, figure 7b
 436 shows that saturated initial conditions for Case CTL yield results similar to
 437 the base case. The dry soil initialization, 300m_54_dry, however, captures the
 438 minima of the SODAR much better for the second day. The dry case shows
 439 reduced error when compared to the base and saturated cases as shown in
 440 table 7. The surface energy fluxes can be drastically affected by the soil
 441 moisture and strongly influence wind speeds at hub-height. This suggests
 442 that hub-height winds are sensitive to soil moisture and that accurate rep-
 443 resentation of land-surface conditions may be just as important for accurate
 444 simulations in this case, rather than just looking at differences in resolution
 445 or other model configuration parameters.

446 [Figure 7 about here.]

447 [Table 7 about here.]

448 3.4. *Difference between 1-way and 2-way nesting*

449 In 1-way nesting, the finer domains do not influence the parent domains.
450 With 2-way nesting, the finer grid feeds information back to the coarser
451 parent domain. The coarser grid is then updated with higher resolution
452 fields which theoretically leads to a more accurate simulation result. 2-way
453 nesting is thought to be important when fine-scale features that are resolvable
454 on the finer domain affect meteorological conditions on a larger scale. Harris
455 and Durran (2010) found that 2-way nesting is in general superior to 1-way
456 nesting in an idealized comparison of the linear 1-D shallow-water model.
457 1-way nesting performs better only when very poorly resolved waves strike
458 the nest boundary. Liu et al. (2011) tested WRF-LES for wind energy with
459 data assimilation over real terrain and compared 1-way and 2-way nesting.
460 They found that, in general, 2-way nesting agrees best with the observations.

461 Figure 8 shows time series of wind speed for the 1-way nested base case
462 and the 2-way nested case each with the same four nesting levels. Under
463 strong synoptic-scale forcing, it is likely that 1-way nesting will be adequate
464 for feeding information from the larger scales to the finer scales. Case STL
465 (simple terrain locally-driven forcing) in figure 8a shows an insignificant dif-
466 ference between 1-way and 2-way nesting even with local forcing. The simi-
467 larity is most likely due to the negligible benefit of finer horizontal resolution
468 (see section 3.2.2) for this case that results from the simplicity of the to-
469 pography. Case CTL (complex terrain locally-driven forcing), in figure 8b,
470 shows a noticeable improvement with 2-way nesting when compared to the
471 1-way nested base case. Table 8 quantifies these differences and indicates
472 that the terrain at finer resolutions affects the coarser domain results be-

473 cause improvement with higher resolution is observed in this case due to the
 474 complexity of the terrain. There is little difference between 1-way and 2-way
 475 nesting for both synoptically-forced simulations, Cases STS and CTS, where
 476 the strong synoptic forcing overwhelms any local influences on winds due to
 477 terrain complexity.

478 [Figure 8 about here.]

479 [Table 8 about here.]

480 3.5. Comparing WRF Planetary Boundary Layer (PBL) schemes

481 Other works have examined the effects of Planetary Boundary Layer
 482 (PBL) schemes in WRF (see section 2.5 above for descriptions) and most
 483 have found that no single PBL scheme can be recommended for all circum-
 484 stances as each scheme has its own strengths and weaknesses (Zhang et al.,
 485 2013; Yver et al., 2013). Xie et al. (2013) compared two nonlocal mixing
 486 schemes, YSU and ACM2, with two local mixing PBL schemes, MYJ and
 487 MYNN2, at 3 km horizontal resolution over Southeast England for numerous
 488 stability conditions. They found that local PBL schemes considerably under-
 489 estimate the entrainment heat fluxes for convective cases, while the nonlocal
 490 schemes exhibit stronger mixing and agree better with large-eddy simulation
 491 studies. However, the 10 m wind speed RMSE values for the four schemes for
 492 the months of June and November vary by less than 0.1 m/s and were quite
 493 similar for all the cases. Yver et al. (2013) compared 4km horizontal resolu-
 494 tions of the YSU, MYJ, QNSE, MYNN2, ACM2, BouLac, UW, and TEMF
 495 schemes over a one month period along the California Coast and found that

all the schemes present similar results and generally agree with the observations. Xie et al. (2012) compared the YSU, ACM2, MYJ, and BouLac PBL schemes over Hong Kong for June and November at 1 km resolution. The 10 m wind speed RMSE showed that ACM2 and YSU perform slightly better than MYJ and BouLac by about 0.25 m/s. Most other works looked at wind speed comparisons near the surface at 10 m elevation, where surface friction effects are strong, because of the availability of data, but Deppe et al. (2012) compared the YSU, MYJ, QNSE, MYNN, and ACM2 PBL schemes with ensemble simulations at turbine hub height (80 m) in Iowa at 10 km horizontal resolution. They found that nonlocal schemes (YSU and ACM2) overall performed better than local PBL schemes (MYJ, QNSE, MYNN) by MAE differences of about 0.15 m/s on average for month long simulations. Here we compare almost all the PBL schemes available in WRF at turbine hub height at fine horizontal and vertical resolution and at the simple and complex terrain sites.

Figure 9 shows how the different PBL schemes in WRF perform in each of the four cases tested at 300 m horizontal resolution. The RMSE for each case (STL, STS, CTS, and CTL) along with the average of all the cases (Total AVG) is shown for each PBL scheme. The average of all the cases (Total AVG) is calculated based on the time duration of each case (Case CTL has half the weight of the other cases because we only consider the first 24 hour period for which the results are reasonable and not the full 48 hours). The PBL schemes are ordered along the x-axis from lowest case average RMSE to highest case average RMSE (left to right) with the average RMSE indicated below the PBL scheme name in units of meters per second.

521 The GBM PBL scheme performs the best with the lowest averaged RMSE
 522 of 2.54 m/s compared to the base case MYJ PBL scheme, which is third
 523 best with an average RMSE of 2.74 m/s. The PBL schemes all seem to
 524 perform rather similarly with less than 0.14 m/s RMSE separation between
 525 each scheme, except for the poor performance from the MRF PBL which is
 526 0.28 m/s worse than the second to worst performer (YSU). MRF is a legacy
 527 PBL scheme in WRF and is improved on by YSU. Neglecting MRF, the
 528 different PBL schemes differ less than an average RMSE of 0.5 m/s for the
 529 tested cases, though this difference could be significant from a forecasting
 530 perspective. The TKE based PBL schemes seem to cluster together and
 531 overall outperform the non-local vertical eddy viscosity schemes (YSU and
 532 MRF), which perform the worst. The ACM2 scheme, which uses a hybrid
 533 approach, places fourth overall with an average RMSE of 2.78 m/s.

534 Certain PBL schemes perform better for specific cases. GBM does partic-
 535 ularly well for Case CTS, however, all the schemes have their highest RMSE
 536 error for this case. MYJ has the lowest RMSE for Case CTL, and all the
 537 PBL schemes have their lowest RMSE error for this case except MRF. ACM2
 538 does best for Case STL along with the MYNN schemes, and UW outperforms
 539 the others for Case STS. The PBL schemes, for the most part, do not show
 540 any significant improvement from 2700 m to 300 m horizontal resolution for
 541 all the cases except Case CTL. The average RMSE improvement, if any, for
 542 Cases STL, STS, and CTS does not exceed 0.025 m/s with the largest single
 543 improvement for a scheme not exceeding 0.18 m/s (QNSE for Case STL, with
 544 MYJ's 0.08 m/s improvement coming in second). MRF is the only exception
 545 with a 0.6 m/s improvement for Case CTS, but this scheme performs much

worse than any other scheme in this case (QNSE's 0.11 m/s improvement is second highest). The PBL schemes show more significant improvement with resolution for Case CTL with an average RMSE improvement of 0.39 m/s. The largest improvement is 0.66 m/s for GBM and YSU, while the smallest improvement is 0.16 m/s for UW.

It is difficult to recommend one PBL scheme for every situation, but general guidelines can be extracted from this comparison. The TKE based PBL schemes clearly outperform the non-local vertical eddy viscosity schemes. MRF has a significantly higher average RMSE than the rest of the schemes and this is mostly a result of its particularly poor performance for the complex terrain cases. While its RMSE is closer to average for the simple terrain cases, it is never in the top four PBL schemes. It is not recommended to use the MRF PBL scheme for wind energy applications. YSU's average RMSE error is closer to the other PBL schemes than MRF's, but it too never rates better than fifth place for any of the cases. However, it does not show the large errors associated with MRF for the complex terrain cases and might be an acceptable alternative for cases in which computational resources are limited, because it does not calculate the TKE equation. It is still not recommended for periods dominated by stable conditions, because the use of a non-local eddy viscosity scheme is not best suited to cases where the turbulent eddies are of a smaller scale than the vertical grid spacings of the model (Pleim, 2007). ACM2 is a top performer in this study, especially for Case STL. It is able to switch between stable conditions (local eddy diffusion as in MYJ) and unstable conditions (local and nonlocal transport). MYJ, the base case, performs respectably by coming in third overall with an average

571 RMSE of 2.74 m/s and does particularly well for Case CTL. It is a good
572 base case choice because it makes use of the TKE equation and is the second
573 oldest scheme implemented into WRF after MRF.

574 [Figure 9 about here.]

575 3.6. *Effects of grid resolution on week-long simulations*

576 In addition to short-term forecasts, there is interest in longer-term perfor-
577 mance of simulations to assist with forecasting and wind resource character-
578 ization. A week-long simulation is performed using the locally-driven simple
579 and complex terrain test cases to further examine grid resolution effects on
580 predicted disturbances of wind speed and turbulence intensity distributions
581 for a specific site. The simulation is for 7 days after the start of Case STL and
582 Case CTL respectively. Changes in long-term distributions could be useful
583 for more detailed site evaluations for turbine placement.

584 3.6.1. *Week-long results for wind speed*

585 The results obtained from week-long simulations for horizontal wind speeds
586 fall in line with the shorter term 48 hour simulations. The finer resolution
587 runs for Case STL show little variation in wind speed distributions from the
588 coarser resolutions as shown in the probability density function (PDF) in
589 figure 10a though there is an advantage to using 2700 m or finer grid spac-
590 ing for representation of faster, less frequent winds as suggested in the error
591 metrics (table 9). The PDFs are created at hub height above ground and
592 binned into 18 equally spaced bins that span the minimum and maximum
593 range for each category at the SODAR location during a week of summer.

594 They all show, along with the SODAR, that during this summer week, wind
 595 speeds are rather high and favorable for producing wind energy.

596 The week-long simulations for Case CTL also show similar results com-
 597 pared to the shorter term 48 hour simulations. Figure 10b and table 9 show
 598 improvement with higher resolution, though the improvement beyond 900
 599 m is small. Zhang et al. (2013) looked at errors in 10 m surface wind from
 600 WRF simulations in complex terrain for both 3 day and month long simula-
 601 tions for horizontal resolutions ranging from 27 to 1.11 km. They found that
 602 higher resolution simulations do not outperform coarser simulations in many
 603 cases most likely because of the inability of the numerical model to depict
 604 near-surface structures even with better terrain representation. Yver et al.
 605 (2013) also found that there is improvement in month-long simulations from
 606 12 km to 4 km horizontal resolution, but not from 4 km to 0.8 km.

607 [Figure 10 about here.]

608 [Table 9 about here.]

609 3.6.2. Week-long results for turbulence intensity

610 Turbulence intensity is also vital to consider in determining potential
 611 wind farm locations, because a value that is too high (roughly greater than
 612 20% of the mean wind speed) will result in feathered wind turbines to avoid
 613 damage (and hence a loss in power production). The definition of turbulence
 614 intensity is:

$$TI = \frac{\sqrt{\sigma_u^2 + \sigma_v^2 + \sigma_w^2}}{U_{mean}} \quad (1)$$

615 where U_{mean} is the average horizontal wind speed over a time period,
 616 $\sigma_u; \sigma_v; \sigma_w$ are the standard deviations of wind speed over that same time
 617 period in the East-West, North-South, and vertical directions respectively.
 618 The turbulence intensity for the SODAR is calculated by averaging the wind
 619 speed at every recorded second over a 10 minute period and calculating the
 620 standard deviation of each component of wind speed. The turbulence inten-
 621 sity for the simulations is obtained using WRF's output of TKE from MYJ,
 622 $\frac{\sqrt{TKE}}{U}$.

623 As figure 11a shows, there is little difference in the distribution of TKE
 624 among the various resolutions (except the coarsest 8100 m case) for Case
 625 STL. They all show similar results and estimate probability areas close to
 626 the SODAR. The peaks for the turbulence intensity are slightly off, with the
 627 simulations predicting slightly lower turbulence intensity when compared to
 628 the SODAR. However, as the number of bins increases the peaks come closer
 629 together. This site seems to be almost ideal during this particular time of
 630 year for wind turbines, as turbulence intensity only exceeds 20% less than
 631 4% of the week.

632 The week-long simulations for Case CTL, shown in figure 11b, appear to
 633 greatly under-predict turbulence intensity for the time period. The finer res-
 634 olutions are slightly better compared to the SODAR observations and predict
 635 a greater occurrence of higher turbulence intensity for the week. Overall, the
 636 simulations seem to under-predict higher instances of turbulence intensity.
 637 This could be a problem when evaluating potential turbine siting locations,
 638 as Case CTL shows the simulations predict turbulence intensity exceeding
 639 20% only about 20% of the week while observations show this threshold ex-

640 ceeded about 75% of the week. It is important to note that the SODAR
 641 turbulence measurements have a degree of uncertainty. These uncertainties
 642 generally bias the turbulence intensity magnitudes towards higher values (see
 643 Wharton and Lundquist (2012) for full discussion). The observations show
 644 more instances of low wind speed than the simulations (figure 10b); this
 645 may be why turbulence intensity for the observations is much higher than
 646 for the simulations, because for the same standard deviations of the wind
 647 speed components, lower wind speed (see denominator of equation 1 above)
 648 results in higher turbulence intensity even when there may not be more tur-
 649 bulence. However, even when wind speeds are higher for both (as in Case
 650 STL), the simulations still seem to under-predict turbulence intensity. The
 651 results for both cases show a higher frequency of low turbulence intensity
 652 than the observations indicate. Most of these values appear to correspond
 653 to the minimum turbulent kinetic energy (TKE) ($0.1 \text{ m}^2/\text{s}^2$) set in the MYJ
 654 model. This agrees with Xie et al. (2013), who found that MYJ appears
 655 to under predict TKE when compared to observations and MYNN. These
 656 results suggest that there is room for improved turbulence closures for wind
 657 turbine siting purposes.

658 [Figure 11 about here.]

659 4. Conclusion

660 There is increasing demand to provide higher resolution, high precision,
 661 forecasts of winds for wind energy applications. Little guidance exists to
 662 aid numerical modelers as they push numerical weather prediction models
 663 to their limits. This paper illustrates the sensitivity, or lack thereof, of the

664 numerical results to various model configuration parameters. Case study
665 simulation results were presented using WRF to capture both synoptically
666 and locally-driven events at two different sites where terrain complexity varies
667 greatly to develop preliminary insight into the ability to capture shifts in wind
668 speed that are important to wind farm operators.

669 The effects of grid resolution, 1-way vs. 2-way nesting, turbulence clo-
670 sure models, and week-long simulation results were examined in this paper.
671 Large changes in wind speed were reasonably represented with all grid resolu-
672 tions and grid nesting configurations tested for the simple terrain simulations
673 (Cases STL and STS). These results are counter-intuitive when considering
674 general recommendations to use higher resolution. Given the simple terrain
675 of this wind farm it may be concluded that resolution does not necessar-
676 ily bestow the benefit of increased accuracy. There was improvement with
677 higher resolution and 2-way nesting when simulating a locally-forced event
678 over complex terrain. Terrain as complex as at the complex terrain site dis-
679 cussed in this paper warrants higher resolution simulations to predict winds,
680 especially during weak forcing. During strong synoptic forcing, the complex
681 terrain site showed minimal sensitivity to grid resolution, indicating that the
682 forcing greatly dominates over local topographic influences. This suggests
683 that computational resources may be spared by wind farm operators and
684 forecasters if the site consists of simple terrain or even in certain cases with
685 synoptic forcing over complex terrain. Simulations at high resolution could
686 be most important in complex terrain and under local forcing.

687 It is of interest to note that the synoptically-driven events were better
688 simulated (compared to observation data) than the locally-driven events for

689 both wind farms; this is expected because the strong synoptic forcing in most
 690 cases overshadows other parameters. Land-surface parameters had more of
 691 an effect on the simulation results than resolution or the options used for
 692 turbulence closure during the locally-forced events, as demonstrated here
 693 by varying soil moisture conditions. Initialization conditions could be re-
 694 sponsible for errors in the simulation results in some cases. It is difficult to
 695 recommend one PBL scheme that works best for every situation. The choice
 696 of a PBL scheme for a certain case may vary significantly depending on the
 697 meteorological forcing and terrain. On average, the prognostic TKE equation
 698 schemes gave more accurate results when compared to observations (partic-
 699 ularly GBM, UW, and MYJ). The non-local vertical eddy viscosity schemes
 700 (YSU and MRF) performed worse on average, most likely due to their weak-
 701 ness during strongly stable situations, but YSU might be acceptable in some
 702 cases in which computational resources are limited. Week-long simulations
 703 showed similar results to the short-term simulations. The MYJ turbulence
 704 closure seemed to consistently under-predict turbulent kinetic energy in both
 705 cases.

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Figure 1: Wind farm topography for the 300 m horizontal resolution WRF domain comparing (a) the simple terrain site to (b) the complex terrain site.

(a) Simple terrain (ST) site

(b) Complex terrain (CT) site

Figure 2: West-East cross-section of topography through the center of the 300 m resolution domain for simulations at different horizontal resolutions (see table 3).

(a) Case STL

(b) Case STL

(c) Case CTL

(d) Case CTL

Figure 3: Horizontal wind speed and direction 48 hour time series for locally-forced simple and complex terrain simulations at different horizontal resolutions at 80 m hub height compared to SODAR.

Figure 4: Vertical profiles of horizontal wind speed for locally-forced simple and complex terrain simulations at different horizontal resolutions compared to SODAR at single time slices.

(a) Case STL

(b) Case CTL

Figure 5: Horizontal wind speed 48 hour time series for different vertical resolutions for the locally-driven complex and simple terrain cases at 80 m hub height compared to SODAR.

(a) Case STS

(b) Case CTS

Figure 6: Horizontal wind speed over a 48 hour time series for synoptically-forced simulations over simple and complex terrain (STS and CTS) at different horizontal resolutions compared to SODAR at 80 m hub height.

(a) Case STL

(b) Case CTL

Figure 7: Horizontal wind speed for saturated and dry soil moisture initializations compared to the base case and SODAR for a 48 hour locally-driven time period over both simple and complex terrain (STL and CTL) at 80 m above ground.

(a) Case STL

(b) Case CTL

Figure 8: Horizontal wind speed 48 hour time series comparing SODAR observations to 1-way (base case) and 2-way nesting for the locally-driven simple and complex terrain sites (STL and CTL) at 80 m hub height.

Figure 9: Horizontal wind speed RMSE (m/s) comparing 300 m horizontal resolution simulation results for different WRF PBL schemes against SODAR observations for each individual case (STL, STS, CTS, CTL) and a time based average for all the cases (Total AVG). PBL schemes are arranged from lowest average RMSE on the left to highest average RMSE on the right.

(a) Case STL

(b) Case CTL

Figure 10: Horizontal wind speed PDF for locally-forced week-long simulations comparing different horizontal resolutions over simple and complex terrain (STL and CTL) to SODAR at hub height.

(a) Case STL

(b) Case CTL

Figure 11: Turbulence intensity PDF for locally-forced week-long simulations comparing different horizontal resolutions over simple and complex terrain (STL and CTL) to SODAR at hub height.

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	Simple Terrain				Complex Terrain			
Δh (m)	(nx,ny,nz)	Δz_{min} (m)	Δz_{avg} (m)	Δt (s)	(nx,ny,nz)	Δz_{min} (m)	Δz_{avg} (m)	Δt (s)
8100	(96,96,49)	35	246	30	(348,252,54)	32	232	30
2700	(96,96,49)	35	246	10	(348,252,54)	32	232	10
900	(96,96,49)	35	246	3.33	(348,252,54)	32	232	3.33
300	(96,96,49)	35	246	1.11	(348,252,54)	32	232	1.11
300	(96,96,40)	60	309	1.11	(348,252,40)	63	402	1.11
300	(96,96,70)	10	177	0.74	(348,252,70)	12	228	1.11

Table 1: Simulation parameters for each grid resolution for both the simple and complex terrain sites.

Abbreviation	Description of Event	Actual Ramping Time	Actual Ramping Magnitude
STS	S imple T errain case, S ynoptically-forced	Frontal passage 24 hours into simulation (3 hrs after sunrise)	4 to 16 m/s in 3 hrs
STL	S imple T errain case, L ocally-forced	Appears 37 hours into simulation (10 min after sunrise)	10 to 3 m/s in 3 hrs
CTS	C omplex T errain case, S ynoptically-forced	Cold front 10 hours into simulation (4 hrs before sunrise)	10 to 20 m/s in 2 hrs
CTL	C omplex T errain case, L ocally-forced	no ramping	no ramping

Table 2: Abbreviations and event descriptions for the different cases investigated.

Run name	Configuration
300m_49	simple terrain (ST) base case simulation, 4 1-way nested grids, 49 vertical levels, 300 m horizontal resolution
300m_54	complex terrain (CT) base case simulation, 54 vertical levels
300m_70	70 vertical levels
300m_40	40 vertical levels (chosen by WRF)
300m_49_2way, 300m_54_2way	4 2-way nested grids
900m_49, 900m_54	900 m horizontal resolution, 3 1-way nested grids
2700m_49, 2700m_54	2700 m horizontal resolution, 2 1-way nested grids
8100m_49, 8100m_54	8100 m horizontal resolution, 1 grid
300m_49_sat, 300m_54_sat	all grids initialized with saturated soil
300m_49_dry, 300m_54_dry	all grids initialized with dry soil

Table 3: Simulation configurations and naming (everything is the same as base case unless otherwise noted).

	Simple Terrain Case (STL)		Complex Terrain Case (CTL)			
Resolution	MAE	RMSE	MAE	RMSE	MAE	RMSE
					1 st day	
300m	2.14	2.57	2.19	3.06	0.83	1.05
900m	2.16	2.57	2.10	2.93	0.95	1.19
2700m	2.17	2.62	2.31	3.17	1.12	1.43
8100m	2.27	2.74	3.24	3.88	2.04	2.28

Table 4: MAE and RMSE (m/s) for horizontal wind speed compared to SODAR over 48 hours for locally-forced simple and complex terrain cases (STL and CTL) at different horizontal resolutions.

Resolution	Simple Terrain Case (STL)			Complex Terrain Case (CTL)				Avg. Vertical Spacing in 0-200m range (m)
	MAE	RMSE	Avg. Vertical Spacing in 0-200m range (m)	MAE	RMSE	MAE 1 st day	RMSE	
300m	2.14	2.57	38.05 (5 points)	2.19	3.06	0.83	1.05	42.95 (5 points)
300m_40	2.19	2.65	73.50 (3 points)	1.90	2.72	1.03	1.28	75.65 (3 points)
300m_70	2.15	2.57	9.90 (20 points)	2.06	2.89	0.80	1.00	19.53 (11 points)

Table 5: MAE and RMSE (m/s) of horizontal wind speed for different vertical resolutions of the locally-forced simple and complex terrain cases (STL and CTL) compared to SODAR over 48 hours.

	Simple Terrain Case (STS)		Complex Terrain Case (CTS)	
Resolution	MAE	RMSE	MAE	RMSE
300m	1.65	2.28	3.50	4.26
900m	1.60	2.21	3.55	4.29
2700m	1.60	2.12	3.39	4.15
8100m	1.73	2.25	3.54	4.36

Table 6: Horizontal wind speed MAE and RMSE (m/s) over a 48 hour period for a synoptically-forced event over simple and complex terrain (STS and CTS) comparing different horizontal resolutions to SODAR.

	Simple Terrain Case (STL)		Complex Terrain Case (CTL)	
Resolution	MAE	RMSE	MAE	RMSE
300m	2.14	2.57	2.19	3.06
300m_sat	1.54	1.95	2.22	3.10
300m_dry	2.67	3.27	1.37	1.87

Table 7: Horizontal wind speed MAE and RMSE (m/s) for locally-driven simple and complex terrain (STL and CTL) cases comparing different soil moisture initializations to SODAR over a 48 hour period.

	Simple Terrain Case (STL)		Complex Terrain Case (CTL)	
Resolution	MAE	RMSE	MAE	RMSE
300m (1-way base case)	2.14	2.57	2.19	3.06
300m_2way	2.17	2.60	1.71	2.38

Table 8: MAE and RMSE (m/s) for wind speed comparing SODAR to 1-way vs. 2-way nesting for the locally-driven simple and complex terrain cases (STL and CTL) over a 48 hour period.

	Simple Terrain Case (STL)		Complex Terrain Case (CTL)	
Resolution	MAE	RMSE	MAE	RMSE
300m	2.24	2.74	1.85	2.64
900m	2.29	2.8	1.97	2.76
2700m	2.23	2.67	2.12	2.94
8100m	2.45	2.86	2.62	3.40

Table 9: Horizontal wind speed MAE and RMSE (m/s) for locally-driven events over simple and complex terrain (STL and CTL) compared to SODAR for a week-long period at hub height.