Impact of WRF Physics and Grid Resolution on Low-level Wind Prediction: Towards the Assessment of Climate Change Impact on Future Wind Power

H. S. Chin, L. Glascoe, J. Lundquist, S. Wharton

March 4, 2010

Fifth International Symposium on Computational Wind Engineering
Chapel Hill, NC, United States
May 23, 2010 through May 27, 2010

The Fifth International Symposium on Computational Wind Engineering (CWE2010)
Chapel Hill, North Carolina, USA May 23-27, 2010

Impact of WRF Physics and Grid Resolution on Low-level Wind Prediction: Towards the Assessment of Climate Change Impact on Future Wind Power

H.-N. S. Chin[a], L. Glascoe[a], J. Lundquist[b], and S. Wharton[a]

[a]Lawrence Livermore National Laboratory
[b]University of Colorado at Boulder

ABSTRACT: The Weather Research and Forecast (WRF) model is used in short-range simulations to explore the sensitivity of model physics and horizontal grid resolution. We choose five events with the clear-sky conditions to study the impact of different planetary boundary layer (PBL), surface and soil-layer physics on low-level wind forecast for two wind farms; one in California (CA) and the other in Texas (TX). Short-range simulations are validated with field measurements. Results indicate that the forecast error of the CA case decreases with increasing grid resolution due to the improved representation of valley winds. Besides, the model physics configuration has a significant impact on the forecast error at this location. In contrast, the forecast error of the TX case exhibits little dependence on grid resolution and is relatively independent of physics configuration. Therefore, the occurrence frequency of lowest root mean square errors (RMSEs) at this location is used to determine an optimal model configuration for subsequent decade-scale regional climate model (RCM) simulations. In this study, we perform two sets of 20-year RCM simulations using the data from the NCAR Global Climate Model (GCM) simulations; one set models the present climate and the other simulates the future climate. These RCM simulations will be used to assess the impact of climate change on future wind energy.

1 INTRODUCTION

One of the key elements to meet the challenge of DOE's 20% wind energy by 2030 is the assessment of climate change impacts on future wind resources in the United States. As all wind parks in the United States are currently on-shore, any forecasting system must have ability to accurately represent the interactions between the PBL and the surrounding topography. Depending on the complexity of the local topography of inland wind farms, terrain can play an important role in determining the amount of wind power. Therefore, the model grid resolution, in addition to model physics, may be a crucial factor that decides the accuracy of wind predictions.

The ultimate goal of this study is to perform long-range simulations for assessing the impact of climate change on future wind energy in the United States; the main focus is on the wind changes over the state of Texas. Currently, there are two popular approaches used in numerical weather prediction: (1) ensemble forecasting and (2) deterministic forecasting. Due to computational constraints, the ensemble approach is impractical for decade-scale RCM simulations. On the other hand, the forecast errors of deterministic simulations are highly sensitive to the quality of initial/boundary conditions, model physics, and numerical methods. To minimize the drawback of the deterministic approach, we use short-range weather forecasts to explore the sensitivity of model physics and grid resolution and to determine an optimal model configuration for decade-scale RCM simulations in order to quantify climate change impacts on future wind resources.

In this study, the model setup and the experimental design for both short-range and long-range simulations are presented in Section 2. Section 3 shows the results for short-range simulations. A summary and future work follows in section 4.

2 MODEL SETUP AND EXPERIMENT DESIGN

The Advanced Research WRF (ARW) modeling system version 3.1 is used in this study. The ARW is a non-hydrostatic and fully compressible code. It uses the sigma-pressure coordinate in the vertical direction to better simulate airflow over complex terrain. The model solves the governing equations in flux-form, which enables conservation of mass and scalar quantities. The model physics contains cumulus convection, microphysics of cloud processes and precipitation, long- and short-wave (LW and SW) radiation transfer, turbulence and diffusion, PBL, surface layer, and soil layer modules. There are a variety of choices for each of the physical processes. However, the WRF model physics does not predict sea surface temperature (SST), but it does provide an alternative to read in this field. In this study, the SST field is taken from a large-scale dataset, and updated by the forcing model every 6 hours throughout simulations. The reader is referred to Skamarock et al. (2008) for further details.

2.1 MODEL SETUP

The main interest of this study is the impact of local terrain on low-level wind prediction. Towards determining optimal physics parameterizations, the sensitivity of model physics to the PBL, surface and soil-layer schemes is assessed in the context of short-range low-level wind forecasts. Additionally, the impact of terrain representation with varied horizontal grid resolution is also evaluated. The vertical axis contains 41 levels with a constant grid spacing of 20 m below the lowest 200 m, and then gradually stretched aloft. The top of the model domain resides at a height of 50 hPa. Static fields (e.g., land-use, terrain, and soil-type) with a resolution of 30 arc second (~ 1 km) are used to initialize the simulations. Positive-definite advection is activated for moisture variables. A third-order Runge-Kutta time splitting scheme is adopted, and sound waves are treated explicitly in the horizontal and implicitly in the vertical on shorter sub-steps. Fifth and third order numerical schemes are used for the horizontal and vertical advection, respectively.

2.2 EXPERIMENTAL DESIGN

2.2.1 SHORT-RANGE SIMULATIONS

Short-range simulations are performed in five horizontally nested domains with resolutions of 36, 12, 4, 1.333, and 0.444 km to gauge the impact of model grid resolution on wind speed and wind energy forecast over complex terrain. Due to the sensitive nature of wind farm data, detailed information of wind farm measurements is not disclosed. The location of the wind farms is used to define the center of the model domains. RMSEs, which are used to assess WRF performance, are computed from tower measurements of wind farms or meso-net stations. All short-range WRF simulations last for 54 hours to cover a spin-up period (~ 6 hours) and two full diurnal cycles under synoptic conditions for well defined diurnal cycles of valley winds.

We choose 5 events with the clear-sky conditions in short-range simulations to focus on the impact of model physics from PBL, surface layer, and soil layer processes on low-level wind prediction; 4 options of PBL physics (YSU, MYJ, MYNN, and ACM2), 3 options of surface physics (Monin-Obukhov; M-O, MYNN, and Pleim-Xu), and 2 options of soil physics (RUC and Pleim-Xu). The well-known Noah soil-layer scheme is not used in this study due to the existence of a floating point error for simulations with a grid size less than 12-km. Due to compatibility constraints of model physics, only seven physics combinations are used in this study. The rest of the model physics setup such as microphysics (two-moment Morrison scheme), cumulus (Grell-Devenyi), and radiation transfer (CAM) is based on our prior experience on a CA precipitation study (Chin et al., 2010).

The event occurring on 1 July 2004 is selected for the CA case. A series of WRF simulations with 5 grid resolutions and 7 physics combinations are validated against tower measurements at heights ranging from 18 to 30 m from 11 stations. These WRF simulations are also used to compare with our prior COAMPS simulation of the same case. This COAMPS simulation was performed without soil-layer physics. The soil temperature used to compute energy exchange between surface and the soil layer in COAMPS is based on the climatology values. The reader is referred to Chin et al. (2005) for the details of this model. The simulation of this case is initialized using Eta model data with a horizontal resolution of 40 km from the National Centers for Environmental Prediction, and the lateral boundary conditions are computed every 6 hours.

Four additional events are chosen for the TX case: 12 April 2008 (Event -1), 20 June 2008 (Event -2), 29 August 2008 (Event -3), and 14 September 2008 (Event -4). The same set of WRF simulations are performed for the TX case whereas these simulations are driven by North American Regional Re-analysis (NARR) data at a horizontal grid resolution of 32 km. Reanalysis data provide us the best proxies of observations, which can minimize large-scale forcing error. The tower measurements from 4 mesonet stations are used to validate the WRF simulations of the TX case.

2.2.2 LONG-RANGE SIMULATIONS

In this study, we conduct two sets of 20-year RCM simulations driven by GCM data; one set studies the present climate (1985-2004), and the other examines the future climate (2015-2034). The duration of the future climate simulations is based on project sponsor’s requirements. This choice also fits the need for DOE’s wind energy goals by 2030. To enable WRF for the RCM simulations, we need additional modifications: (1) disable WRF’s leap-year calendar since GCM data do not account for leap years, (2) develop an interface to inject the GCM data into the WRF grid structure, and (3) output the GCM SST as a separate file to allow proper air-sea interaction in the RCM simulations.

To avoid the problem of climate drift in the GCM-RCM coupling, a popular approach is to reinitialize the RCM simulations from large-scale forcings on a monthly basis (Pan et al., 1999). This method has an additional benefit that it allows us to run simulations for multiple months simultaneously, significantly increasing our throughput. It also circumvents the problem that WRF – like most RCMs – wasn’t designed for long runs and therefore doesn’t conserve mass through boundary conditions. However, our recent study (Caldwell et al., 2009) detects a serious drawback of monthly RCM runs due to the reset of initial conditions. This problem arises from the significant underprediction of winter snow-depth in the GCM data, which results in a drier soil layer in the subsequent warmer months (Chin, 2008); this defect can influence surface latent and sensitive heat fluxes, and thus affect the PBL development. As a result, the RCM simulations in this study are performed on a yearly basis, starting from 1 September of each selected year before the snow season begins.

Since the primary interest of this study is in the Texas area, the model setup of the RCM simulations is based on the results of short-range simulations for the TX case. RCM simulations are performed in three horizontally nested domains with resolutions of 27, 9, and 3 km to assess the impact of climate change on future wind energy. The outer domain of the RCM simulations covers the whole United States, and the second and third nested domains enclose the entire Texas and NW Texas, respectively. So far, the RCM simulations are not completed yet for detailed analysis. However, we will present these results in the conference.

3 RESULTS: SHORT-RANGE SIMULATIONS

3.1 CA CASE

The use of WRF for low-level wind prediction was motivated by our earlier modeling effort with Naval Research Laboratory's model (COAMPS) for the simulation with dominant summer-time drainage flow at a CA wind farm. Although the forecast error of wind speed in COAMPS is clearly reduced with increasing horizontal grid resolution, substantial discrepancies appear near the day/night transition period (Fig. 1). These discrepancies are attributed to the lack of soil-layer physics in COAMPS, where the soil-layer temperature is prescribed by the climatology values so that the diurnal cycle of surface properties cannot be realistically represented. In contrast, the forecast error of wind speed in WRF is significantly improved, particularly during the day/night transition time with higher grid resolution as soil-layer physics is included. Due to the nonlinear relationship of wind power with wind speed, 20% error of wind speed in COAMPS can lead to nearly 100% error in the wind power, as shown in the second diurnal cycle of Fig.1. This wind power forecast is also greatly improved in WRF.

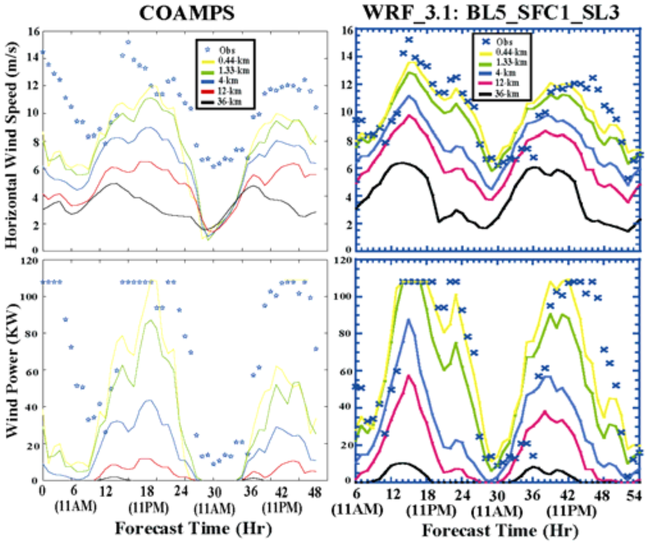

Fig. 1. Time series of 18-m hourly forecast wind speed and wind power at station 9 of the CA case. Colored lines represent results from different grid resolutions, and blue crosses are the observations. Left panels are for COAMPS and right panels for WRF.

In addition to the grid resolution, the sensitivity of model physics is also studied in the WRF simulations using the composite results from 11 stations at the CA wind farm. The results of RMSEs indicate that the grid resolution plays a very important role in the prediction of low-level wind at this wind farm, and that this forecast error converges at a grid resolution near 1 km (Fig. 2). Additional WRF simulations with a 10-m terrain dataset are also performed in this study (not shown), and they exhibit very little difference from their counterparts with the 1-km terrain data. Our WRF simulations further indicate that the physics configuration also has substantial influence on the forecast error. For this application, a particular setting of model physics, such as number 3 and 6 of physics configuration in Fig. 2 exhibits its superiority to the other options.

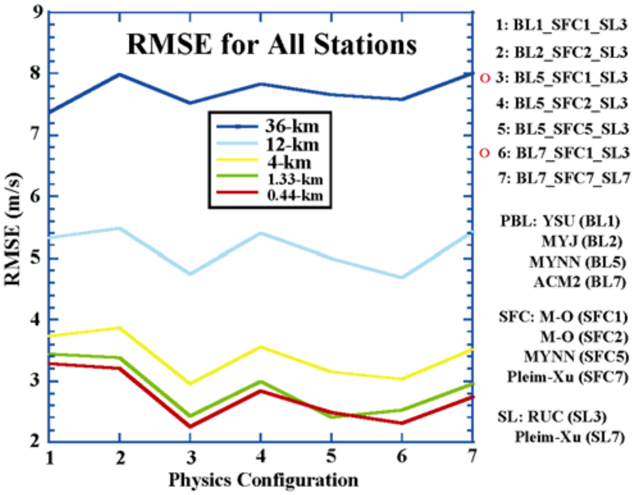

Fig. 2. Root mean squared errors of WRF forecast wind speed composited from 11 stations at the CA wind farm. Colored lines represent results from various grid resolutions. The horizontal axis indicates the physics configurations as shown above.

3.2 TX CASE

The topography distribution of this TX wind farm is smoother than its counterpart in the CA case. The elevation change of the CA case is 600 m while this change is only about 100 m in the TX case. As a result, the magnitude of valley winds at this TX wind farm is weakened by reduced surface radiative daytime heating or nighttime cooling. Thus, the local wind is mainly governed by large-scale forcing, and exhibits little influence by the grid resolution.

At this geographic location, some well-known meso-scale phenomena, such as nocturnal low-level jet (LLJ) and dryline are replicated in our WRF simulations. The intensity of the LLJ in Event -4 of the TX case is more sensitive to the model PBL scheme (Fig. 3), but less sensitive to the grid resolution (not shown). Meanwhile, the NW-SE oriented mountain ridges in TX provide geographic preference of a drier zone across the area near this TX wind farm. The intrusion of warm and moist air from the Gulf Stream in Event -1 favors the formation of a well-organized dry zone (typically called dryline), which can develop its own meso-scale convergent (northerly) flow to suppress the prevailing southerly zone (Fig. 4). The timing of the predicted wind shift is highly sensitive to the choice of PBL physics.

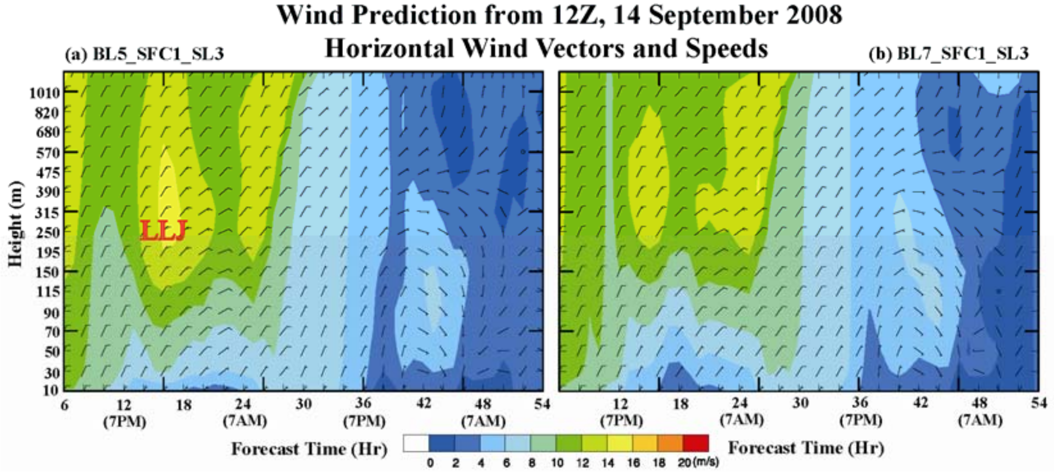

Fig. 3. Vertical profiles of horizontal wind prediction with the grid resolution of 0.444-km at the TX wind farm for Event -4 using varied PBL schemes. LLJ marks the location of a simulated nocturnal low-level jet. (a) MYNN PBL scheme, and (b) ACM2 PBL scheme.

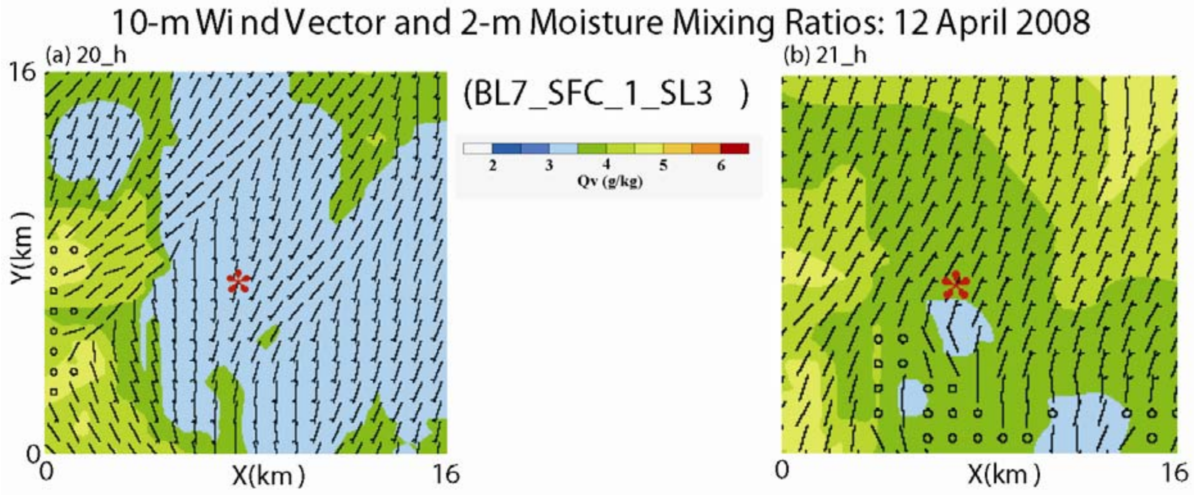

Fig. 4. Horizontal cross-sections of predicted 10-m wind vector and 2-m mixing ratio of water vapor from the simulation with grid resolution of 0.444-km for Event -1 using the physics configuration of BL7-SFC1-SL3. Red point marks the location of the TX wind farm. (a) Hour 20, and (b) Hour 21.

Unlike the CA case, the impact of grid resolution on the forecast errors of low-level winds is not clearly indentified at the TX wind farm for all selected events (Figs. 5 and 6). Part of the reasons may be attributed to smaller elevation changes in this area. Therefore, terrain induced valley winds are much weaker than prevailing large-scale airflow. In addition, there is no prominent preference of physics configuration for the lowest RMSEs. Every option of physics configurations can have a chance for the lowest forecast error of selected events. Due to project sponsor's primary interest in TX, this outcome makes it difficult to determine the optimal physics configuration for RCM simulations. To this end, the occurrence frequency of lowest RMSEs for all events and measurement stations provides an alternative measure to determine our optimal physics configuration (namely, number 2) for the RCM simulations (Fig. 7). This optimal physics configuration consists of MYJ PBL, Monin-Obukhov surface, and RUC soil-layer schemes.

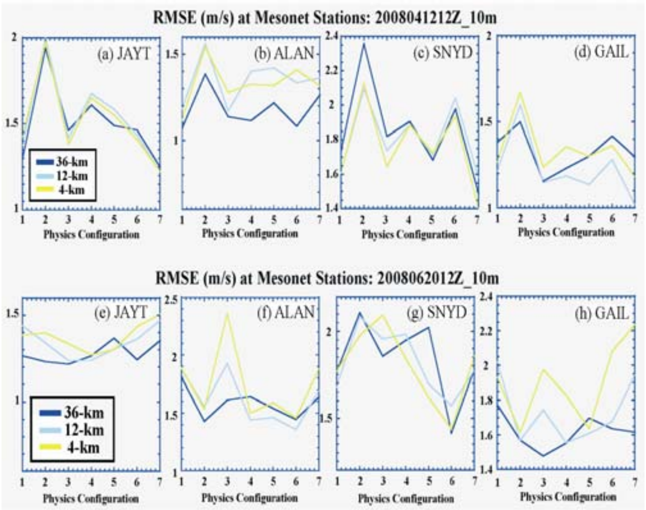

Fig. 5. As in Fig. 2, except for the TX case from four meso-net stations (JAYT, ALAN, SNYD, and GAIL) at 10-m. (a) – (d) for Event -1, and (e) – (h) for Event -2.

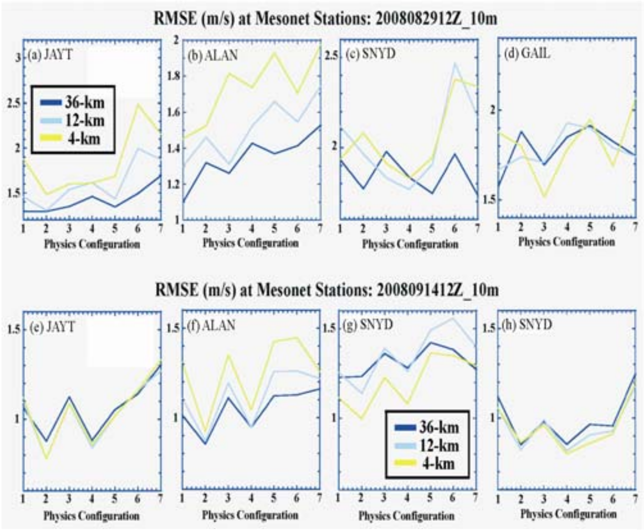

Fig. 6. As in Fig. 5, except for Event -3 (a-d) and Event -4 (e-h).

4 SUMMARY AND FUTURE WORK

Due to complete physics and multiple options of each physical process, the WRF model is selected for this study to assess the impact of climate change on future wind energy in the United States with a concentration on the state of Texas. The main focus of this study is on the inland wind farms over complex terrain. Therefore, we select 5 events at two wind farms (one in CA and the other in TX) with clear sky conditions for our short-range simulations to explore the sensitivity of model physics and horizontal grid resolution on low-level wind forecast with an emphasis on the interaction among PBL, surface and soil-layer processes.

Results indicate that the forecast error of the CA case is persistently reduced with increasing grid resolution due to the improved representation of valley winds. Further, there exists a preference of model physics configuration with lowered forecast error at this location. In contrast, the forecast errors of the TX case at 4 mesonet stations exhibits little grid resolution impact and no favorable physics configuration. Due to project sponsor’s interest in TX, the occurrence frequency of RMSEs in this area is used to determine an optimal physics configuration for decade-scale RCM simulations. This optimal physics configuration consists of MYJ PBL, Monin-Obukhov surface, and RUC soil-layer schemes.

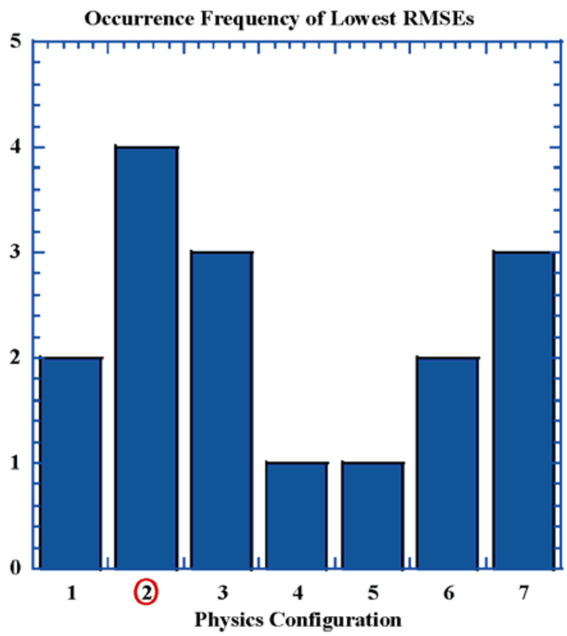

Fig. 7. The occurrence frequency of lowest RMSEs based on simulations with all nested domains for 4 mesonet stations and 4 events of the TX case.

So far, we have completed 90% of the proposed RCM simulations. We will finish the remaining simulations, and then analyze the results. We will use these RCM simulations to compute the tendency change of future wind energy and to estimate forecast bias of the present-climate simulations using NARR data. Based on the derived forecast bias from the present-climate simulations, we can project more reliable future wind energy, assuming the uncertainty of the GCM data remains the same for both present and future climates.

5 ACKNOWLEDGEMENTS

The authors wish to thank Drs. Chuck McGowin and D. Yen-Nakafuji for providing measurement data of the CA case to validate our model results, NOAA's National Climatic Data Center, Lawrence Berkeley National Laboratory’s Earth System Grid system, and West Texas Mesonet for making their datasets available online. This work is supported by Siemens Energy, Inc., and performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

6 REFERENCES

Caldwell, P. M., H-N S. Chin, D C. Bader, and G. Bala, 2009: Evaluation of a WRF Dynamical Downscaling Simulation over California. *Climatic Change*. **95**, DOI 10.1007/s10584-009-9583-5. (UCRL-JRNL-360731)

Chin, H.-N. S., M. J. Leach, G. A. Sugiyama, J. M. Leone Jr., H. Walker, J. S. Nasstrom, and M. J. Brown, 2005: Evaluation of an urban canopy parameterization in a mesoscale model using VTMX and URBAN 2000 data. *Mon. Wea.* , **133**, *2043-2068.* (UCRL-JRNL-203360)

Chin, H-N S., 2008: Dynamical Downscaling of GCM Simulations: Toward the Improvement of Forecast Bias over California. (LLNL-TR-407576)

Chin, H-N S., P. M. Caldwell, and D C. Bader, 2010: Exploration of California Wintertime Model Wet Bias. *Mon. Wea. Rev.(in revision) (*UCRL-JRNL-360731)

Pan, Z., E. Takle, W. Gutowski, and R. Turner: 1999, `Long simulation of regional climate as a sequence of short segments'. Mon. Weath. Rev. **127**, 308-321.

Skamarock W.C., and Coauthors, 2008: A Description of the Advanced Research WRF Version 3. NCAR TECHNICAL NOTE, NCAR/TN–475+STR.