FINAL REPORT FOR PROJECT FUNDING FROM USGS

1. ADMINISTRATIVE

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Project title:	Very High-Resolution Dynamic Downscaling of Regional Climate and Hydrology		
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2. PUBLIC SUMMARY

The south-central U.S. exists in a zone of dramatic transition in terms of eco-climate system diversity. Ecosystems across much of the region rely on warm-season convective precipitation. These convective precipitation is subject to large uncertainties under climate change scenario, possibly leading to gradual or sudden changes in habitats, and ecosystems. The convective precipitation in this region, occurring on a range of time and space scales, is extremely challenging to predict in future climate scenario.

In this project, we established a unique, cutting-edge, dynamic downscaling capability to address the challenge of predicting precipitation in the south-central U.S. in current and future climate scenarios. As the first step, a regional climate model (RCM) is developed by coupling a state-of-the-science land surface and hydrologic model, i.e., the Community Land Model (CLM), with the Weather Research and Forecast (WRF) model. Such a coupled system can better capture physical variability and extremes and be able to more accurately quantify the climate impacts on water availability and quality, and subsequent impacts on agriculture, wildlife, and cultural resources, etc. The RCM is run at unprecedented convection-resolving spatial resolutions (with grid cells smaller than typical convective storms) that are capable of explicitly and directly representing severe convective storms.

3. TECHNICAL SUMMARY

The convective precipitation in the south-central U.S., occurring on a range of time and space scales, is extremely challenging to predict in future climate scenario. To address this challenge, we seek to establish in this project a unique, cutting-edge, dynamic downscaling capability, by developing a regional climate model (RCM) at unprecedented convection-resolving spatial resolutions (with grid cells smaller than typical convective storms) that are capable of explicitly and directly representing severe convective storms.

As an initial step in this work, an RCM is developed and run at convection-resolving resolutions of 2-4 km, thereby eliminating cumulus parameterization that is known to be one of the largest sources of uncertainty for precipitation forecast. The atmospheric component model is based on a state-of-the-science non-hydrostatic mesoscale model, the Weather Research and Forecast model (WRF), that has been successfully applied to both weather prediction and regional climate simulations (the latter at coarser tens of km grid spacing so far), and allows for a seamless transition between weather and climate predictions. The Community Land Model (CLM) is linked to the WRF and provides the hydrological and land surface physics. For development, testing and evaluation, the RCM system is run out for ten years, forced using the 32-km North America Regional Reanalysis data set. Data from the Oklahoma Mesonet and DOE ARM sites will be used for evaluation of the RCM output.

Output of our convection-permitting (4 km) resolution simulation is analyzed and compared with NCEP, NARR, Stage IV-derived precipitation observations, corresponding 10-year cumulus parameterizing low-resolution (25 km) simulations, and one 50 km resolution NARCCAP simulation by WRF 2.0.1 with similar configurations. Results show significant advantages of convection-permitting RCM in simulating the extreme precipitation, diurnal cycle and associated atmospheric circulations, which are essential for the regional climate and hydrology in the Great Plains regions. Furthermore, the very high-resolution (especially convection-permitting resolution) dynamical downscaling is proven to have great potential in reproducing the observed precipitation and atmospheric circulation, and can be used for the future regional climate projections and for other regions beyond the Great Plains as well.

4. PURPOSE AND OBJECTIVES

The objective of this project, "Very High-Resolution Dynamic Downscaling of Regional Climate and Hydrology", is to develop a framework for dynamical downscaling of regional climate at high resolutions, forced using global climate model output. Specifically, this project aims to set up a convection-permitting (4 km) regional earth system model (RESM). The Weather Research and Forecast (WRF) model will be used to drive the RESM, coupled with the Community Land Model (CLM) to provide adequate surface and soil conditions. Lateral boundary conditions and initial conditions will be forced by the 32-km North America Regional Reanalysis (NARR). As an initial experiment to test and evaluate the system, a ten-year simulation (2000 – 2009) is run over a regional domain including much of the South-Central U.S. and northern Mexico. Model output is evaluated using regional observations.

The objectives outlined in original proposal have been completed as planned, and the results indicate that a convection-permitting (CP)/resolving resolution has greater potentials in more accurately simulating extreme precipitation events and in particular their temporal-spatial characteristics, given projections of general circulation models. At the same time, this WRF-based CP-resolution RCM also contains some significant biases, for example, wet biases around eastern boundary, probably due to the limited domain size and inconsistency of model solutions with the boundary forcing. While the modeling system should be further tuned and improved, the fact that the CP resolution simulations produced many of the mean climatological features better than coarser non-CP resolution runs is encouraging, and encourages greater exploitations of the benefits of higher resolutions, especially when precipitation is of a major concern. Whenever computational resources permit, even higher convection-resolving (CR) resolution, with roughly 1 km grid spacing should also be exploited. Ensemble simulations that account for model and model physics uncertainties can be run at CP resolutions to provide confidence information on the simulations. Properly simulating the amplitude, timing, and spatial distribution of convective precipitation in the historical record is critical to advancing future projections by regional climate

models. Decision makers across the U.S. Great Plains, including those who are partners with the South Central Climate Science Center, are demanding these products as well as guidance toward their use for planning purposes. This study has helped to take a step forward to serving the science needs of this larger community.

5. ORGANIZATION AND APPROACH

Scientists of the Center for Analysis and Prediction of Storms and the South Central Climate Science Center work together to develop and test the 4-km convection-permitting RCM, based WRF version 3.5.1, and applied it to downscaling of Great Plains climate in a hindcast mode. Three steps were taken: (i) establishment of the coupled convection-resolving RCM, (ii) completion of the reanalysis-driven simulations, and (iii) verification of the simulation results. The project timeline is run from 1 August 2013 to 31 July 2014. Establishment of a general operating RCM takes 4 months, with a working model available by 31 Dec 2013. Next, a decade of RCM simulations is run, with a completion date of 30 April 2014. Finally, results of the simulations are compared against observations, with a final report assessing the RCM impacts completed by 31 July 2014. Recently, a manuscript summarizing scientific findings of the project was submitted to the Journal of Geophysical Physics (Sun et al. 2015).

More specifically, the WRF-based RCM was run in a hindcast mode over the central U.S. covering the Great Plains and surrounding regions, at both 4 km and 25 km grid spacings, for a past 10 year period ending on December 31, 2009, forced at the boundary by the 32-km North America Regional Reanalyses (NARR) at 3 hourly intervals. Comparisons with the NARR and NCEP global reanalyses and with a 50-km WRF member of the Phase 1 North American Regional Climate Change Assessment Program are performed. Verification metrics and techniques from the climate community are applied to evaluate the accuracy and representativeness of the high-resolution model runs and improvement over larger-scale climate predictions.

6. PROJECT RESULTS

Across the U.S. Great Plains, heavy precipitation events (above 25 mm day^{-1}) account for over half of the total summer rainfall. Summer rainfall is closely tied to the evolution of the LLJ and has a distinct diurnal cycle, with convective initiation centered over the Rockies and propagating eastward over the Plains overnight. The nocturnal LLJ plays a critical role in this diurnal cycle by supplying ample moisture from the Gulf of Mexico northward into the U.S. Great Plains. It is important for RCMs to properly capture these processes.

The captured features by the 4-km WRF RCM include climatological and extreme heavy precipitation centers located over the Oklahoma-Kansas area (where the accumulated precipitation peaks between 10 and 15 mm day^{-1}). Daily precipitation initiates over the Rockies due to elevated heating in the late afternoon, then gradually propagates eastward, reaching the Central Plains in the early morning. Accordingly, the LLJ located roughly at 925 hPa and 100º W transports large amounts of moisture into Great Plains from Gulf of Mexico, and causes heavy precipitation over there. In addition, the nocturnal strengthened LLJ is essential for the early morning diurnal precipitation peak in the Central Plains.

The results show that the 4-km WRF RCM is capable of reproducing many of the major features of summer precipitation observed over the Great Plains, together with associated circulation features such as the boundary layer low-level jet and their diurnal variations. The 4-km WRF RCM performs in many aspects better than the similarly configured 25-km WRF RCM. The 4-km WRF RCM more accurately simulated the intensity, position, and diurnal cycle of the LLJ,

suggesting that the CP resolutions generated more realistic model physics and dynamics important for accurate precipitation simulations. The results indicate that a convection-permitting/resolving resolution has greater potentials in more accurately simulate extreme precipitation events and in particular their temporal-spatial characteristics, given projections of general circulation models (Figs. 1-7). Details on the following figures can be found in Sun et al. (2015).

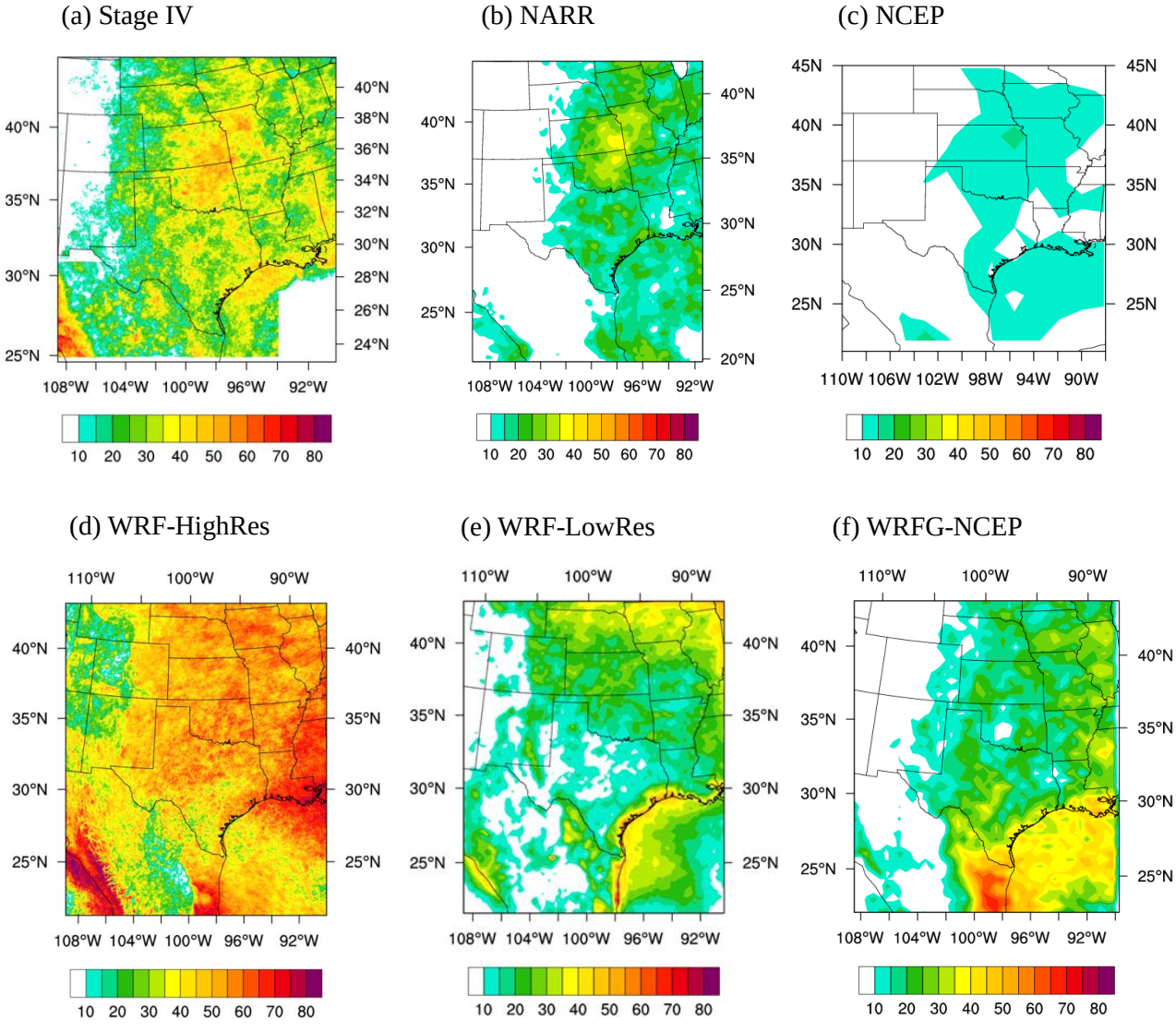

Fig. 1. Percentage of precipitation rate above 25 mm day^{-1} to the total amount of summer precipitation of (a) Stage IV, (b) NARR, (c) NCEP, (d) WRF-HighRes, (e) WRF-LowRes, and (f) WRFG-NCEP (unit is %). (a) is from 8-year 2002-2009 averaged data, (b-e) are calculated based on 10-year 2000-2009 averaged data, and (f) is from 10-year 1995-2004 averaged data.

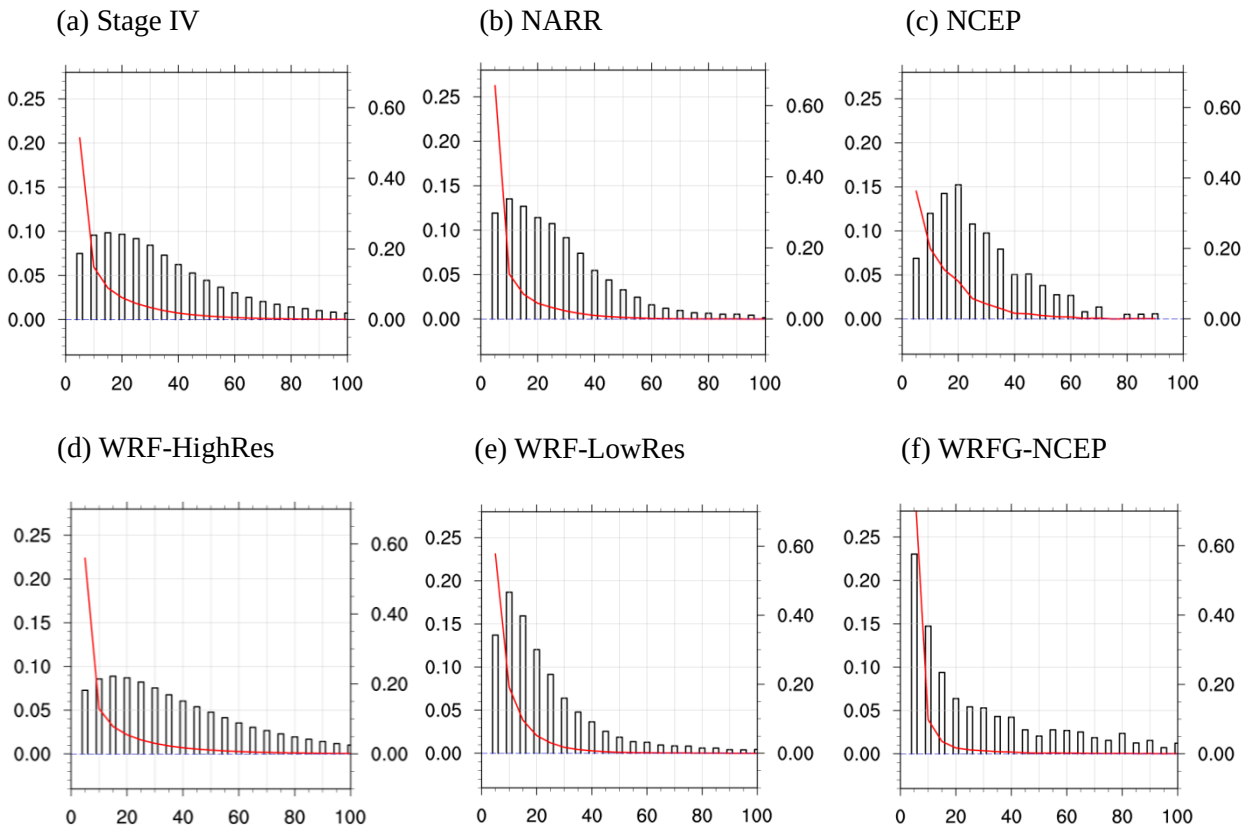

Fig. 2. Probability Distribution Function (PDF) (red solid line, right y-axis) and ratio of accumulated precipitation of every discrete interval 5 mm/day to the total summer precipitation amount based on summer daily precipitation (bar, left y-axis) over the OKKS region of (a) Stage IV, (b) NARR, (c) NCEP, (d) WRF-HighRes, (e) WRF-LowRes, and (f) WRFG-NCEP. (a) is from 8-year 2002-2009 data, (b-e) are calculated based on 10-year 2000-2009 data, and (f) is from 10-year 1995-2004 data.

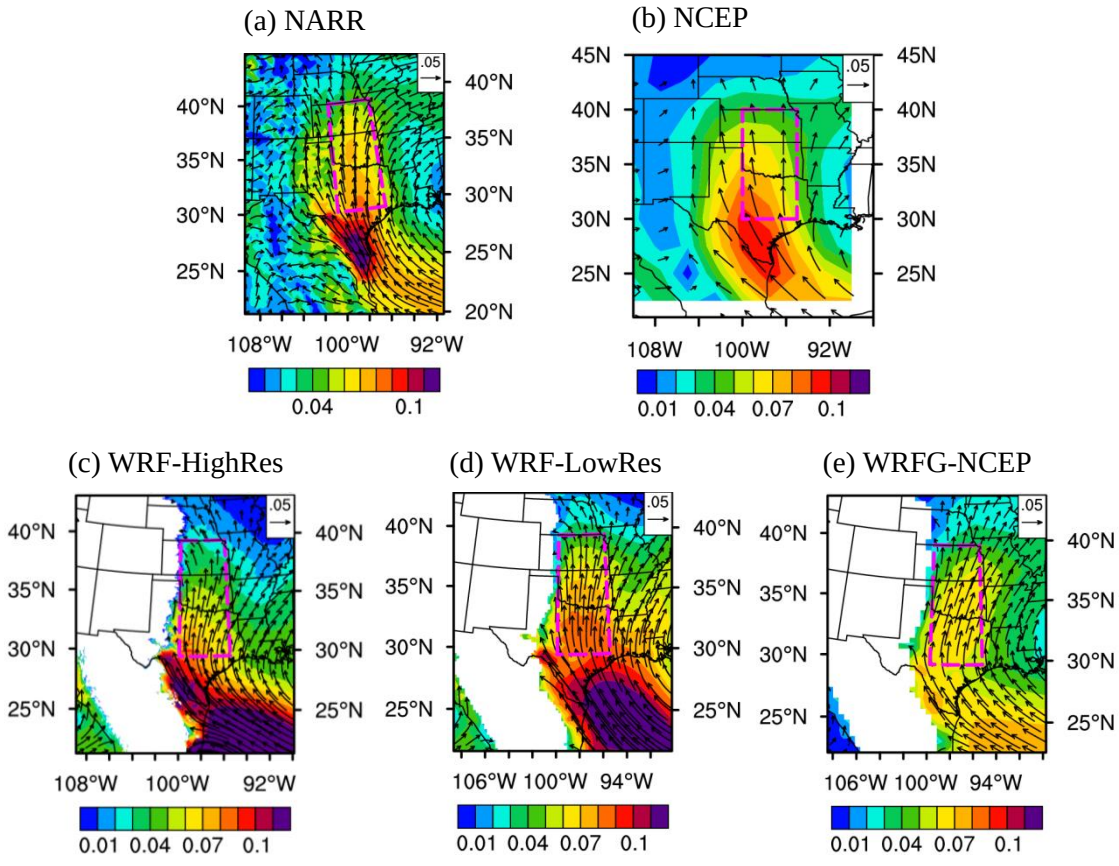

Fig. 3. Water vapor flux at 925hPa of (a) NARR, (b) NCEP, (c) WRF-HighRes, (d) WRF-LowRes, and (e) WRFG-NCEP, shaded is the amplitude, unit is m kg s^{-1} kg^{-1}. Rectangle box indicates the Great Plains LLJ region (100º W-95º W, 30ºN -40º N). (a-d) are the averages based on 10-year 2000-2009 data, and (e) is the average of 10-year 1995-2004 data.

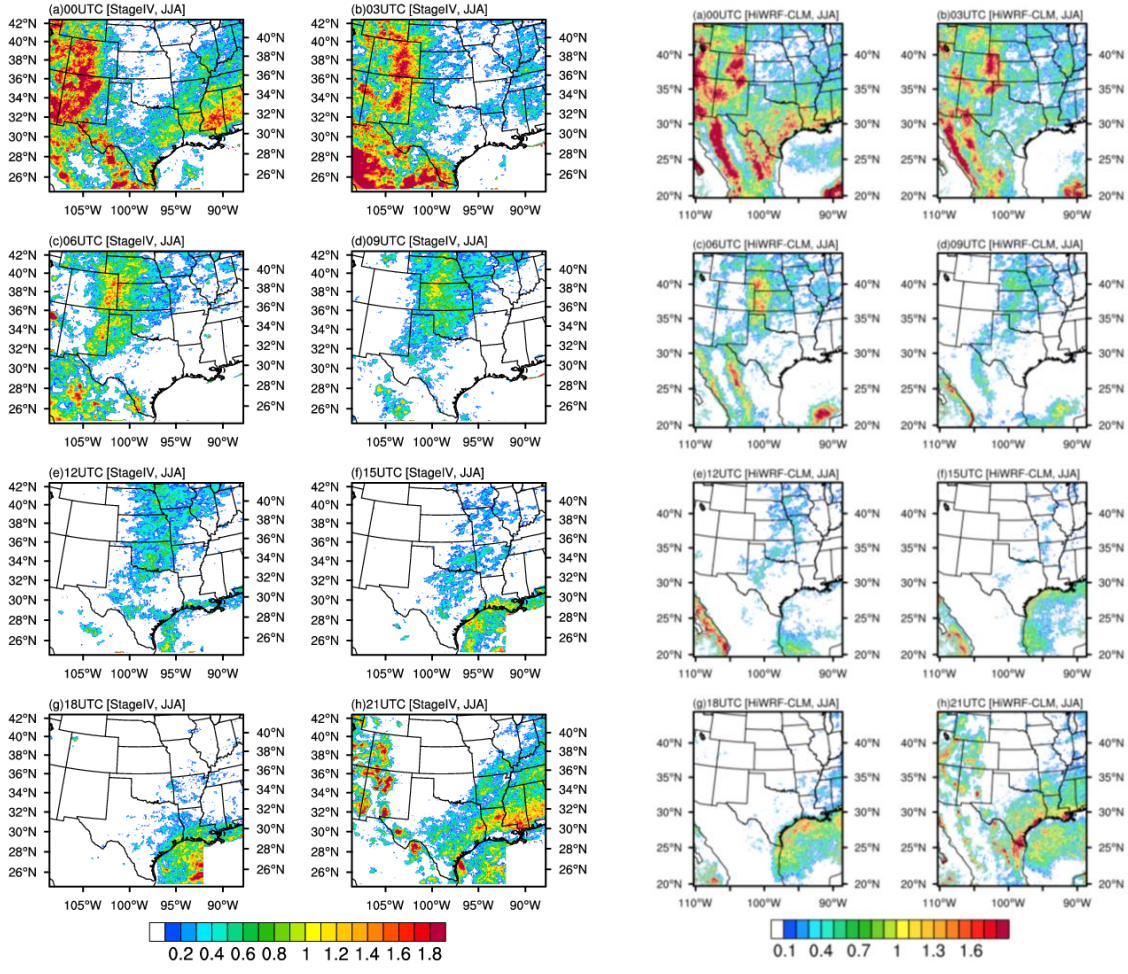

Fig. 4. Normalized diurnal precipitation deviations at (a) 00, (b) 03, (c) 06, (d) 09, (e) 12, (f) 15, (g) 18, and (h) 21 UTC of Stage IV (left) and WRF-HighRes (right) summer precipitation.

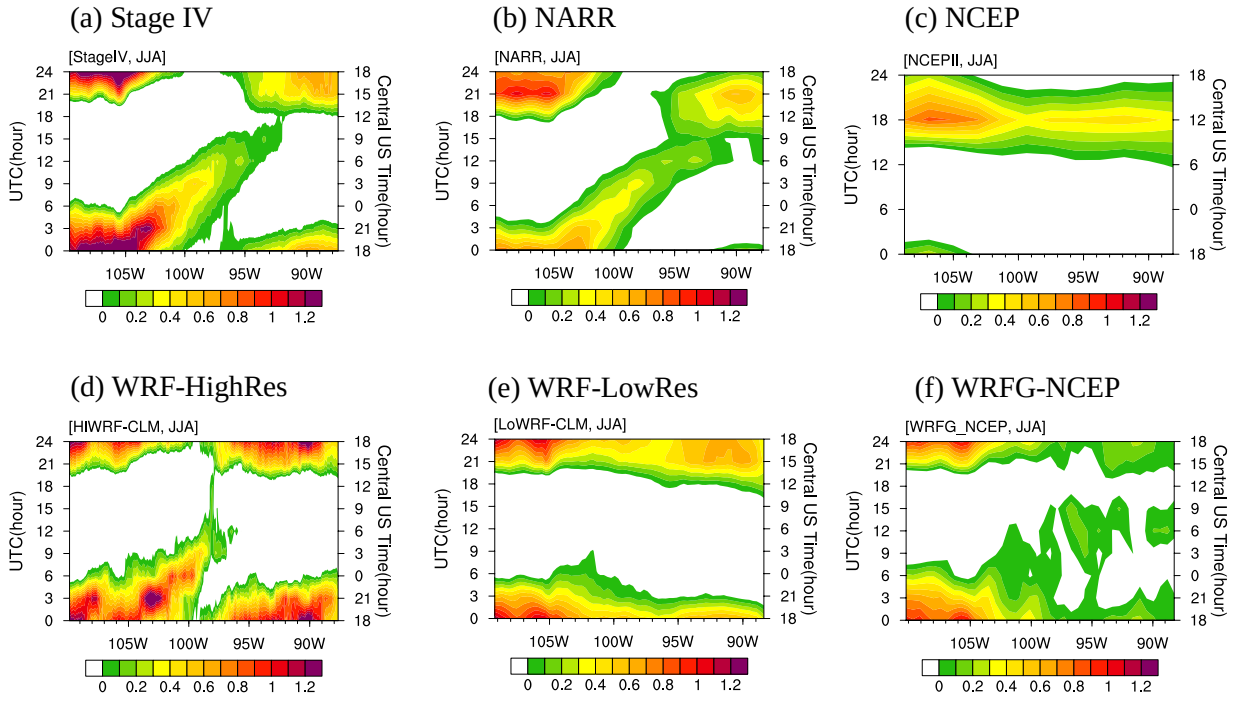

Fig. 5. Hovmöller diagram of normalized diurnal precipitation deviations averaged between 30º N and 40º N of (a) Stage IV, (b) NARR, (c) NCEP, (d) WRF-HighRes, (e) WRF-LowRes, and (f) WRFG-NCEP.

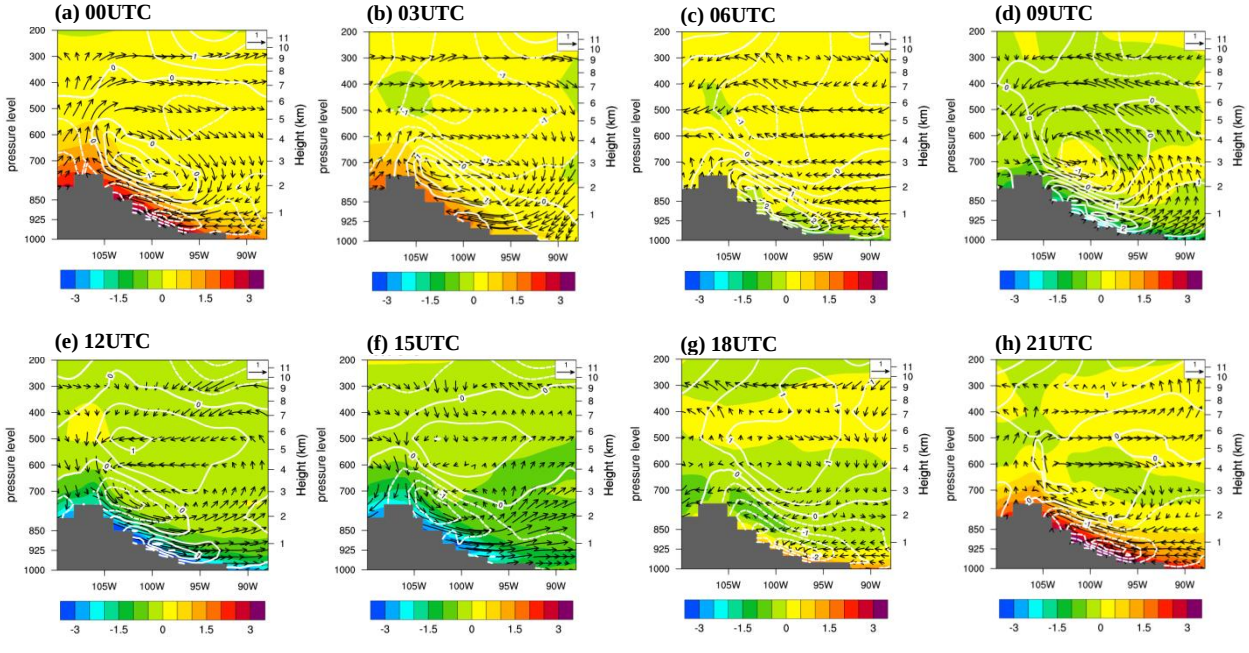

Fig. 6. East-west cross sections of diurnal deviations (from daily mean) of zonal vertical circulation (u unit: m s^{-1}, w unit: cm s^{-1}), temperature (colored), and meridional wind (contours) averaged between 30º N and 40º N at (a) 00, (b) 03, (c) 06, (d) 09, (e) 12, (f) 15, (g) 18, and (h) 21 UTC based on 10-year (2000-2009) averaged NARR data.

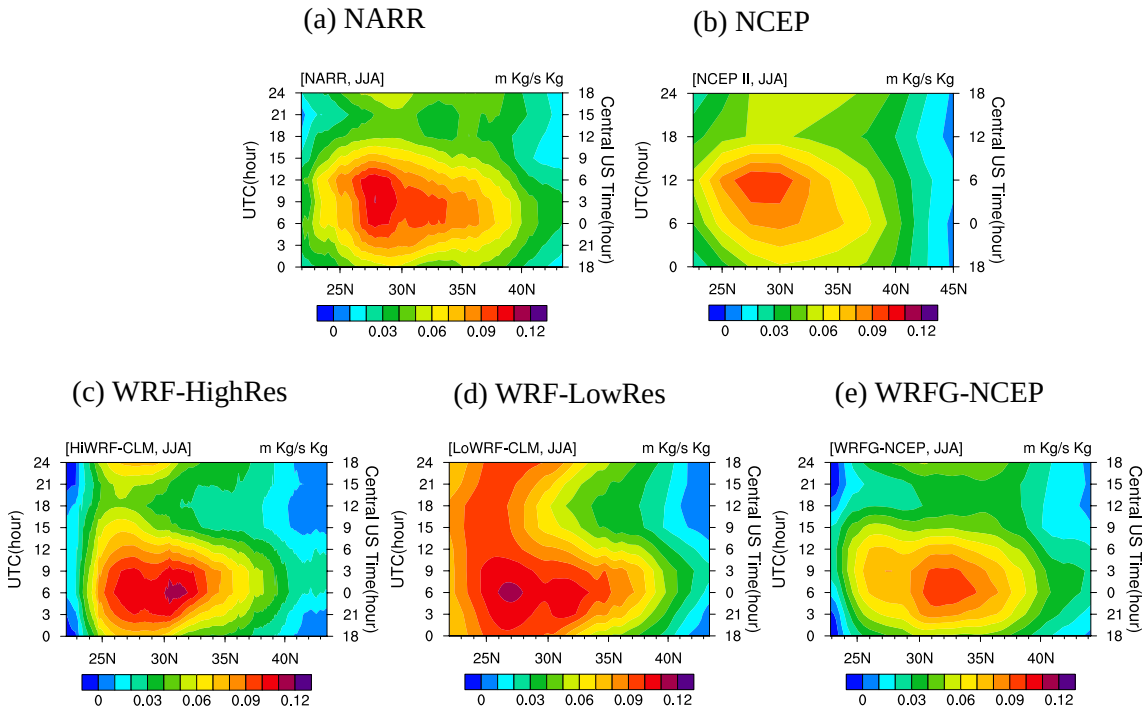

Fig. 7. Latitude-time diagram of meridional water vapor flux at 925 hPa averaged between 100 º W and 95 º W of (a) NARR, (b) NCEP, (c) WRF-HighRes, (d) WRF-LowRes, and (e) WRFG-NCEP.

7. ANALYSIS AND FINDINGS

(1) Finished 10-year central U.S. simulation at 4 and 25 km grid spacings.

(2) Demonstrated merits of the convection-permitting resolution in simulating heavy and extreme precipitation, precipitation diurnal cycle and associated atmospheric circulations.

(3) Finished a manuscript based on the convection-permitting resolution simulation (Sun et al. 2015).

Sun, X., M. Xue, J. Brotzge, R. McPherson, and K. Winton, 2015: Dynamic downscaling of central plains summer precipitation using a regional climate model based on the WRF: Merits of a convection-permitting resolution. *J. Geophy. Res.*, Submitted.

8. CONCLUSIONS AND RECOMMENDATIONS

A significant challenge in dynamical downscaling of global climate models is the ability to accurately represent convection. To assess the merits of a regional climate model (RCM) established based on the WRF and run at a convection-permitting (CP) resolution, hindcasts with the RCM are run at both 4-km and 25-km (non-CP) horizontal grid spacings for 10 years, forced by North American Regional Reanalysis (NARR) data. The model domain covers the U.S. Central Great Plains and the surrounding regions, with the Great Plains region is characterized by climate extremes and variabilities at sub-daily to decadal time scales. Climatologically, over

half of the total summer precipitation across much of the region falls within heavy convective events (above 25 mm day-1), and thus is ideal for testing RCM accuracy. In addition, the Great Plains have an unusual diurnal precipitation cycle with the daily peak in rainfall occurring overnight during the summer. This diurnal cycle results from the eastward propagation of convection that initiated over the Rocky Mountains late the previous afternoon. The Great Plains Low Level Jet (LLJ) also plays an essential role in summer mean precipitation and its diurnal cycle over the Central U.S.

The CP-model run successfully reproduced the major features of the Plains region summer precipitation. In particular, the extreme precipitation and diurnal cycle of precipitation over the central U.S. are well simulated. Furthermore, it more realistically simulated the LLJ and related atmosphere circulations that transport and redistribute moisture from Gulf of Mexico. On the contrary, the non-CP-model runs had relative large biases in atmosphere circulations, resulting in poorer precipitation simulations.

Despite the very high demand on supercomputing resources, we managed to complete the 10-year simulations (about 10 million CPU-hours were used), and obtained satisfying results. In the follow-on project, we would try different configurations and ensemble simulations at the CP-resolution to further optimize the configurations and to estimate uncertainties. Using the optimized configuration, we will then apply the CP-RCM to downscaling of future climate scenarios, nesting inside projects of global climate models.

9. OUTREACH

An article summarizing the results was submitted to Journal of Geophysical Physics, entitled "Dynamical Downscaling of Central Plains Summer Precipitation using a Regional Climate Model based on the WRF: Merits of a Convection-Permitting Resolution" by Xuguang Sun, Ming Xue, Jerald Brotzge, Renee A. McPherson, and Kim Winton. Some of the results were presented at the SC-CSC Stake Holder Meetings.