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Dynamical Downscaling of GCM Simulations: Toward the Improvement of Forecast Bias over California

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1. INTRODUCTION

The effects of climate change will mostly be felt on local to regional scales. However, global climate models (GCMs) are unable to produce reliable climate information on the scale needed to assess regional climate-change impacts and variability as a result of coarse grid resolution and inadequate model physics though their capability is improving. Therefore, dynamical and statistical downscaling (SD) methods have become popular methods for filling the gap between global and local-to-regional climate applications. Recent inter-comparison studies of these downscaling techniques show that both downscaling methods have similar skill in simulating the mean and variability of present climate conditions while they show significant differences for future climate conditions (Leung et al., 2003). One difficulty with the SD method is that it relies on predictor-predictand relationships, which may not hold in future climate conditions. In addition, it is now commonly accepted that the dynamical downscaling with the regional climate model (RCM) is more skillful at the resolving orographic climate effect than the driving coarser-grid GCM simulations.

To assess the possible societal impacts of climate changes, many RCMs have been developed and used to provide a better projection of future regional-scale climates for guiding policies in economy, ecosystem, water supply, agriculture, human health, and air quality (Giorgi et al., 1994; Leung and Ghan, 1999; Leung et al., 2003; Liang et al., 2004; Kim, 2004; Duffy et al., 2006). Although many regional climate features, such as seasonal mean and extreme precipitation have been successfully captured in these RCMs, obvious biases of simulated precipitation remain, particularly the winter wet bias commonly seen in mountain regions of the Western United States.

The importance of regional climate research over California is not only because California has the largest population in the nation, but California has one of the most sophisticated water collection and distribution systems in the world. Therefore, adapting California's water management system to climate change presents significant challenges. Besides, the strong scale interaction between atmospheric circulation and topography in this region provides a challenging testbed for RCMs. Thus, the success of California winter precipitation forecast over mountains would greatly help develop a reliable water management system to adapt to climate change.

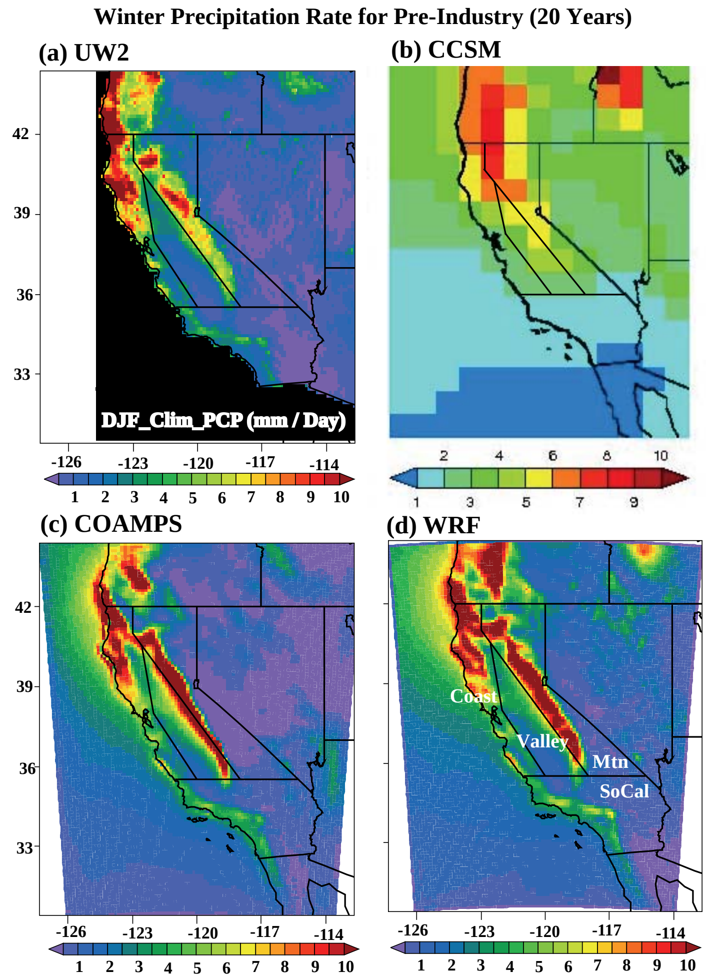

Fig. 1. Winter observed and simulated surface precipitation rate (mm day^{-1}). COAMPS and WRF are driven by 20-year CCSM data for the pre-industry climate (1870). (a) Observation (1915-2003). (b) CCSM. (c) COAMPS. (d) WRF.

LLNL's first 20-year RCM simulations started with Naval Research Laboratory's COAMPS model for the pre-industry case over the California region. Due to the lack of sea surface temperature (SST) update in the model, these simulations are composed of 240 monthly runs with temporally-invariant SST in each simulation. Results indicated that COAMPS significantly improves the spatial distribution of simulated winter surface precipitation as compared to its CCSM counterpart (Fig. 1). However, there exist two noticeable drawbacks; (1) the wet bias over mountains, (2) westward shift of the mountain rainband. The absence of interannual variability of surface air temperature appearing in COAMPS simulations is attributed to the lack of soil-layer physics (Fig. 2a); as a result, the soil temperature is given from climatology data. These COAMPS deficiencies were improved in the WRF (the Weather Research Forecast model, Version 2.2) simulation with the use of soil-layer physics (Figs. 1d and 2b). However, the winter wet bias remains, though the magnitude is slightly reduced.

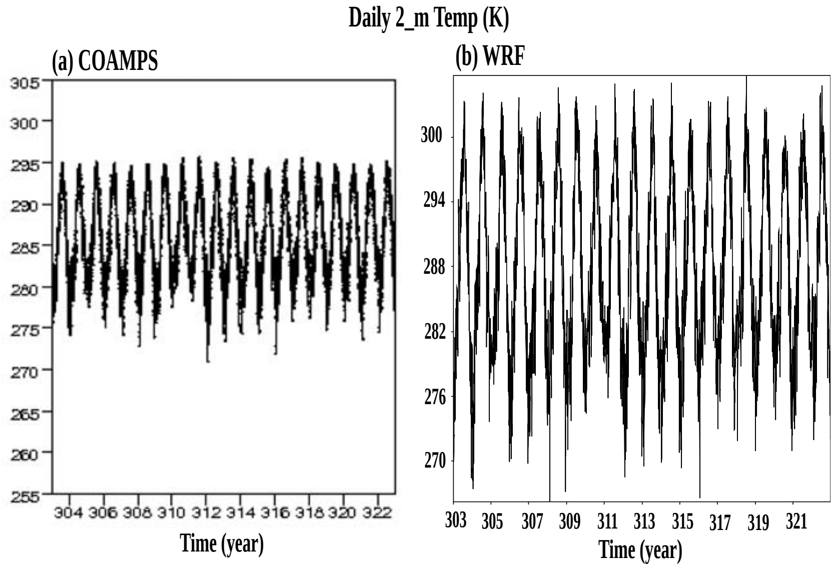

Fig. 2. Time series of simulated 2_m temperature averaged over the land. (a) COAMPS. (b) WRF.

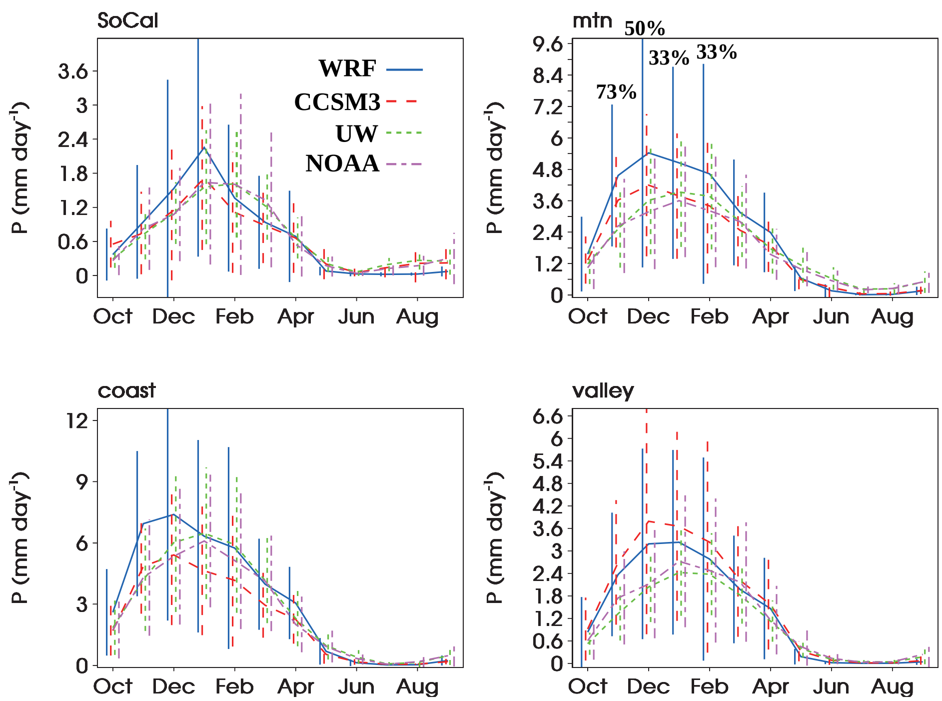

Fig. 3. Seasonal cycle of climatological-average precipitation for each of the region labeled in Fig. 1d. Error bars represent one standard deviation. The percentages shown in the mountain region are the errors with respect to UW measurements.

Further details of 40-year WRF (Version 2.2) simulation for the present climate case are discussed by Caldwell et al. (2008). Results still exhibit large winter wet bias over the whole California as compared to UW and NOAA observations (Fig. 3). The winter wet bias of these 40-year simulations with respect to UW measurements over the mountain region ranges from

70% (early winter) to 30% (late winter). Another striking deficiency of these simulations is the snow pack forecast (Fig. 4). The poor CCSM snow depth forecast leads to unrealistic reset of this field in the monthly WRF simulation, which relies on CCSM for boundary conditions. As a whole, LLNL's recent RCM simulations clearly demonstrate the need for further improvement.

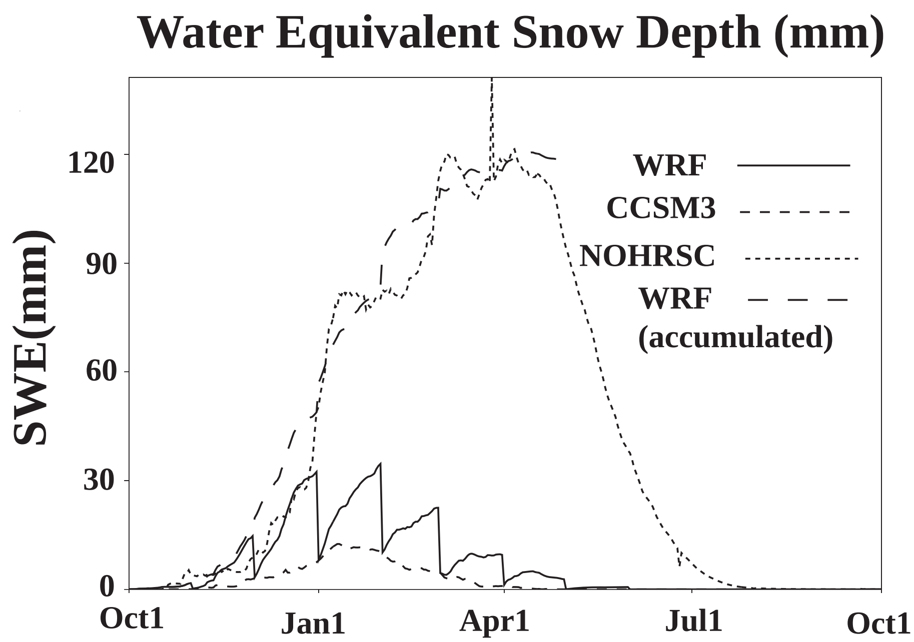

Fig. 4. Annual climatology of mountain-region water equivalent snow depth. NOHRSC represents the measured values.

The objective of this study is to incorporate new model development in WRF to further improve regional climate simulations, particularly the winter wet bias and snowpack-reset over California mountains, and to assess their impacts on hydrology. The ultimate goal of this work is to develop an integrated, multi-scale modeling capability (i.e., a GCM-RCM pairing) to understand and prepare for the impacts of climate change on the temporal and spatial scales that are critical to California's and nation's future environmental quality and economical prosperity.

2. MODEL DESCRIPTION

The model used in this study is the Advanced Research WRF (ARW) modeling system, a community model maintained by the National Center for Atmospheric Research (NCAR). The ARW is non-hydrostatic and fully compressible, and uses the sigma-pressure coordinate in the vertical axis to better simulate air flow over complex terrain. The model has a flux-form set of governing equations for better numerical conservation of mass and scalars. The ARW contains very complete model physics, and multiple options for each physical process, such as cumulus convection, microphysics of cloud and precipitation, long- and shortwave (LW and

SW) radiation, turbulence and diffusion, planetary boundary layer (PBL), surface layer, and soil layer representations. The reader is referred to Skamarock et al. (2007) for further details on the ARW.

The physical processes used in this study include Kain-Fritsch (Kain and Fritsch, 1990) Grell-Devenyi (Grell and Devenyi, 2002) cumulus schemes, Goddard (Tao et al., 2003a) and Thompson (Thompson et al., 2004) microphysics parameterizations, Rapid Radiative Transfer Model (RRTM) longwave radiation (Mlawer et al., 1997), Dudhia (1989) shortwave radiation, Yonsei University (YSU) boundary layer scheme (Hong et al., 2006), and Rapid Update Cycle (RUC) surface parameterization (Smirnova et al., 2000).

All simulations shown in this study are performed with two levels of nested grids, which are in two-way coupling. The outer coarser-grid domain has a grid spacing of 36 km with a grid-size ratio of 3 to define the inner fine-grid domain. The inner grid (Δx = 12 km) is chosen to better resolve the local topography of the coastal ranges. Five grid points are specified in each relaxation zone of the outer lateral boundaries. Additional sensitivity experiment of this nudging zone size is tested with 12 grid points. A total of 100 (90) and 130 (120) grid points are selected to define the east-west and north-south axis of the finer (coarser) grid domain, respectively. Only the results from the 12-km resolution of the inner grid domain are shown in this study. The impact of the outer grid domain size is also examined by enlarging the grid dimension to 150% in both horizontal directions. The vertical axis contains 31 levels with 15 m resolution near the ground and gradually coarser resolution aloft. The domain top resides at the altitude of 50 mb (~ 20 km). The 30-second resolution static field data (land-use, terrain, and soil-type) are used to initialize simulations. The third order Runge-Kutta scheme is used in the time-splitting integration with sound waves treated explicitly in the horizontally and implicitly in the vertical on shorter sub-steps, and 5th and 3rd order scheme for the horizontal and vertical advection, respectively. A time step of 120 seconds is used in the coarser grid domain.

3. TASKS TO BE ADDRESSED

a. Modifications to WRF

LLNL's prior WRF (Version 2.2) simulations were restricted to shorter-range (monthly) forecast for regional climate applications due to the absence of SST update. This missing feature, along with CCSM's poor snow depth forecast, results in unrealistic snowpack reset, which might substantially affect simulated surface and sub-surface properties. NCAR has implemented a SST update capability in the later versions of WRF, and enables us to better represent air-sea interaction for longer-range regional climate simulations. To avoid the simulated climate drift from long-range simulations, we perform yearly simulations to account for the problems in both snow-reset of shorter-range simulation and model error growth of longer-range integration. For the longer-range simulation, the leap-year calendar of WRF needs to be modified to work with CCSM's non-leap-year simulation. In addition, the CCSM interface to WRF grids needs additional changes to broaden its compatibility with grid structures from different sources of CCSM data (e.g., latitude-longitude and Gaussian grids). The coastline mismatch problem between CCSM and WRF grids, mainly affecting warmer months in our prior WRF simulations is fixed using PNL's CCSM offline interface to interpolate CCSM SST into WRF grids. Additionally, NCAR has implemented a modified Thompson microphysics scheme and a new NASA Goddard microphysics scheme in the latest version of WRF (Version 3.0.1).

b. Yearly Simulation

With the incorporation of these new developments in WRF, we present a benchmark yearly simulation with continuous SST update along with monthly simulations (no SST update) using WRF 3.0.1 with CCSM data from October 1 to the following September 31 of a given year (0299). These simulations are driven by one-year CCSM data from the present climate case and are used to gauge the impact of the surface snowpack reset and the effectiveness of the yearly simulation in this study.

c. Short-Range Simulations

Additional simulations are performed to test the impact of physics options and numerical aspects on the winter California wet bias. The short-range (36-h) forecast driven by NCEP ETA 40-km data is first presented to assess the impact of microphysics and cumulus schemes on winter surface precipitation prediction over mountains.

d. Monthly Simulations

Sensitivity tests of model cloud/precipitation physics options, numerical impact of nudging (relaxation) zone size for lateral boundary conditions (5 points vs. 12 points), and the size of the outer coarse-grid domain (control size vs. 50% more in both horizontal directions) are conducted using a single and additional 10 consecutive January CCSM data of the present climate case (See Table I). These additional simulations are used to explore the possible causes of the winter California mountain wet bias.

Table I. Configuration Outline of monthly simulations.

Version / Physics & Numerics	V_2.2	V_3.0.1	
Microphysics	Thompson (MP8)	Modified Thompson (MP8)	Goddard (MP7)
Sub-grid Cumulus	Kain-Fritsch (CU1)	Kain-Fritsch (CU1)	Grell-Devenyi (CU3)
Relaxation Zone	5 Points	5 Points	12 Points (12R)
Outer Domain Dimension	Control (100 x 130)	Control (100 x 130)	1.5 * Control (Ln1)

4. RESULTS

a. Yearly Simulation

The benchmark yearly simulation is first used to assess the impact of SST update and its resulting snowpack reset on surface and sub-surface properties (Fig. 5a). Results indicate that the snowpack reset over mountains seen in monthly simulations has little impact on surface precipitation and ground temperature (Figs. 5b and 5c). In contrast, its primary impact is found in surface and sub-surface runoff, and soil-layer moisture, particularly after the late spring (Figs. 5d-e). This effect has more important implication to hydrology and water management. This impact also explains why CCSM suffers a summer-time dry bias in the soil layer since the lower snow depth of monthly WRF runs can dry up the soil layer even after the late spring.

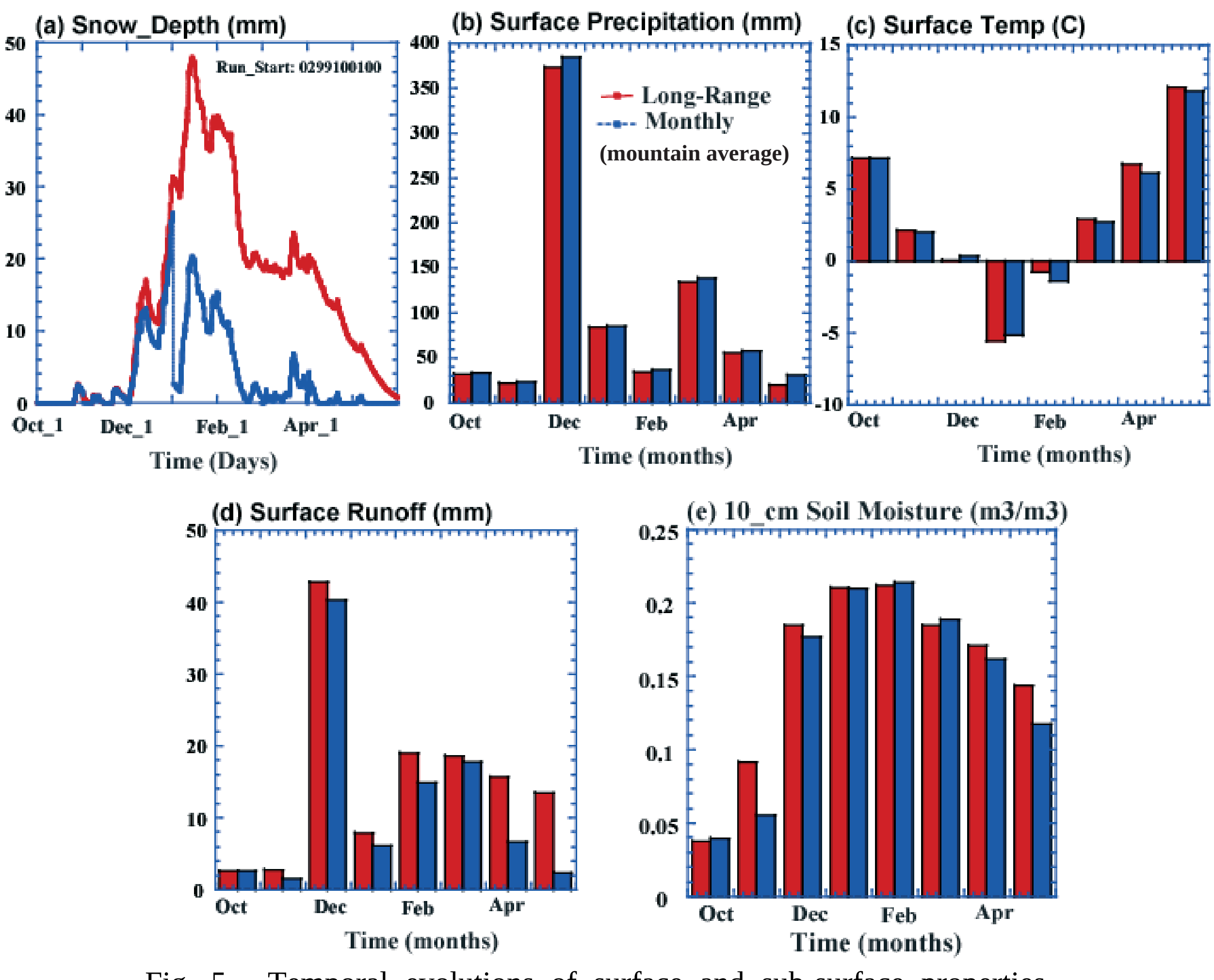

Fig. 5. Temporal evolutions of surface and sub-surface properties averaged over mountains. (a) Snow depth. (b) Total precipitation. (c) Temperature. (d) Runoff. (e) 10-cm soil moisture.

Due to the high elevation of California terrain, the geo-potential heights at 250-mb and 500-mb are used to examine the effectiveness of yearly simulation at upper levels. CCSM data act as the ground true forcing to drive the WRF simulation in this benchmark test. Results indicate that WRF exhibits reasonably good forecast skill in the upper-level field of the yearly simulation although noticeable differences from their CCSM counterparts appear after 6 months (Figs. 6 and 7). This outcome suggests that the error associated with the yearly simulation remains fairly small. Therefore, the simulated climate drift may not occur in this range of simulation.

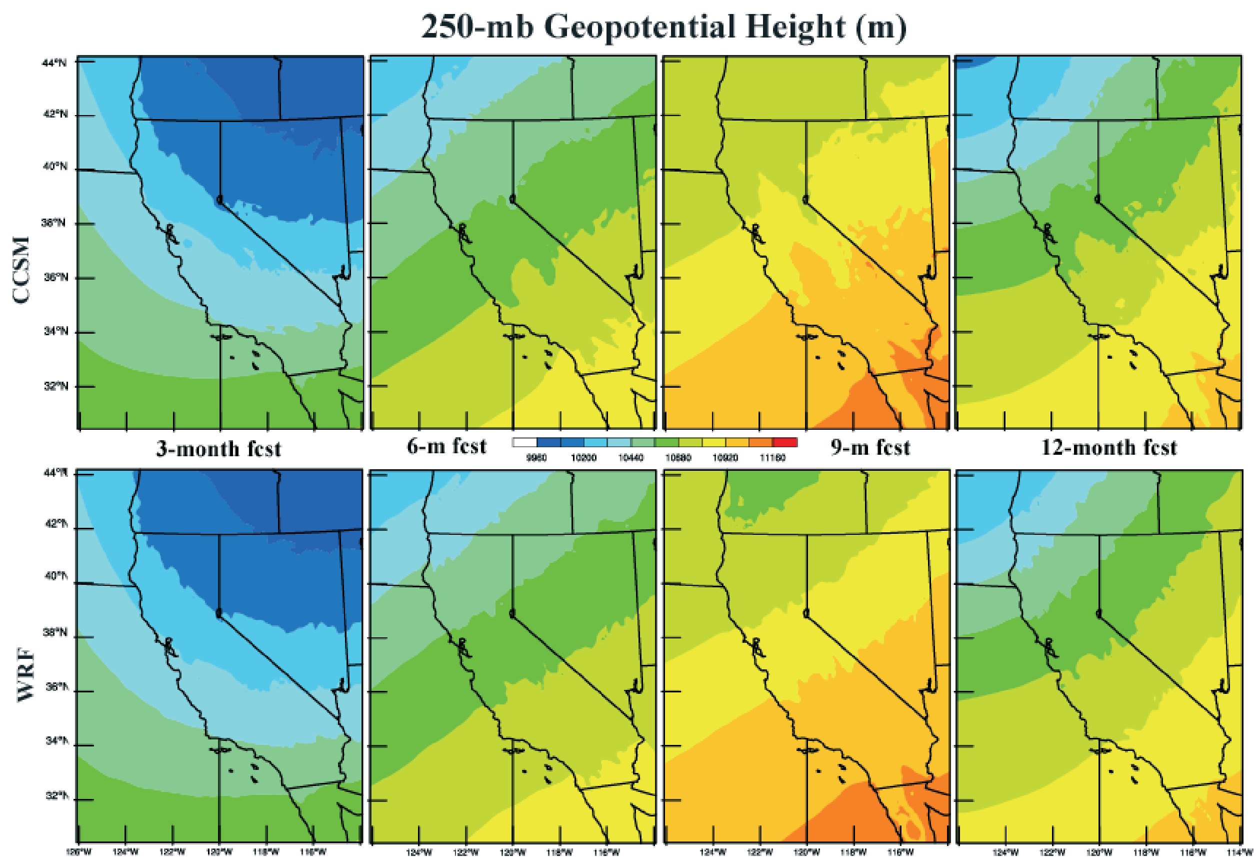

Fig. 6. Horizontal cross-sections of WRF 250-mb geopotential height forecasts at 3, 6, 9, and 12 months of simulation time, respectively (bottom), and their corresponding counterparts in CCSM data (top).

b. Short-Range Simulations

To explore possible causes of the winter California wet bias over mountains, both short-range (36-hour) and long-range (monthly) simulations are presented in this study. Results of the short-range simulation indicated that both modified Thompson (MP8) and new Goddard microphysics (MP7) schemes in Version 3.0.1 result in substantial reduction of surface precipitation over mountains (Figs. 8a, 8b, and 8c). Particularly, the new Goddard microphysics parameterization along with Grell-Devenyi cumulus scheme (CU3) in WRF V3.0.1 greatly improves the mountain wet bias (Fig. 8e). The local maximum of mountain precipitation at (121°W, 40 °N) from the improved WRF simulation (Fig. 8e; 120 ~ 140 mm) is in close agreement with the rain gauge measurement (131 mm), but is slightly higher than the radar estimation (100 ~ 120 mm). This improved WRF simulation is considered more skillful since the radar-based measurement tends to under-estimate mountain precipitation by 15% or so (Dinku et al., 2002).

The impact of larger relaxation zone size (12 points) is barely seen in this short-range simulation while this impact is discernible in the long-range simulation. Part of the reasons is that the propagation of this impact into the model domain takes longer than 36 hours. Therefore, this impact is hard to detect in the short-range simulation. In addition, the domain coverage of our simulation resides near the western boundary of ETA 40-km data so that the impact of the outer domain size is unable to be examined in this short-range forecast.

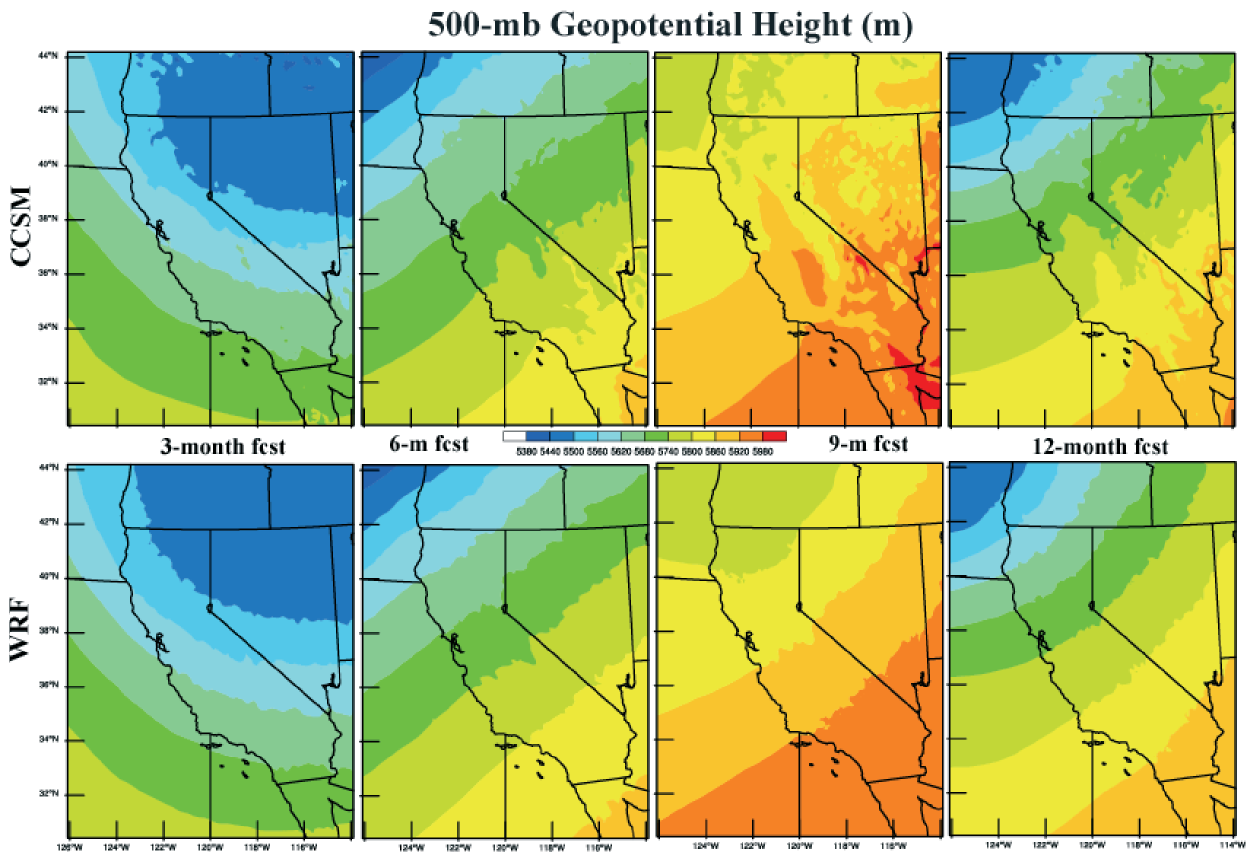

Fig. 7. As in Fig. 6, xecept for 500-mb.

c. Monthly Simulations

Figure 9 displays surface accumulated precipitation of sensitivity experiments from monthly simulations of a single January from CCSM present-climate data. The numbers at the bottom left corners of Fig. 9 indicates the area average of surface monthly accumulated precipitation over mountains. This figure contains the simulations from two different versions of WRF (2.2 and 3.0.1). The modified Thompson microphysics scheme in Version 3.0.1 has substantial changes from its earlier scheme in Version 2.2. Both Thompson (MP8) and Goddard (MP7) microphysics schemes in Version 3.0.1 along the use of Kain-Fritsch cumulus parameterization (CU1) leads to noticeable reduction of surface precipitation over mountains (16.0% and 13.4%, respectively) as compared to the prior result using Version 2.2 (Figs. 9a, 9b, and 9c). Further reduction of surface mountain precipitation (with respect to the amount from Version 2.2) occurs with another cumulus scheme (Grell-Devenyi: CU3 for additional 9.6%, see Fig. 9d) and the use of larger relaxation zone for smoother nudging of large-scale conditions (12 points vs. 5 points; for additional 10.6%, see Fig. 9e) while this reduction caused by the impact of larger outer domain size is negligibly small (1.3%, see Fig. 9f).

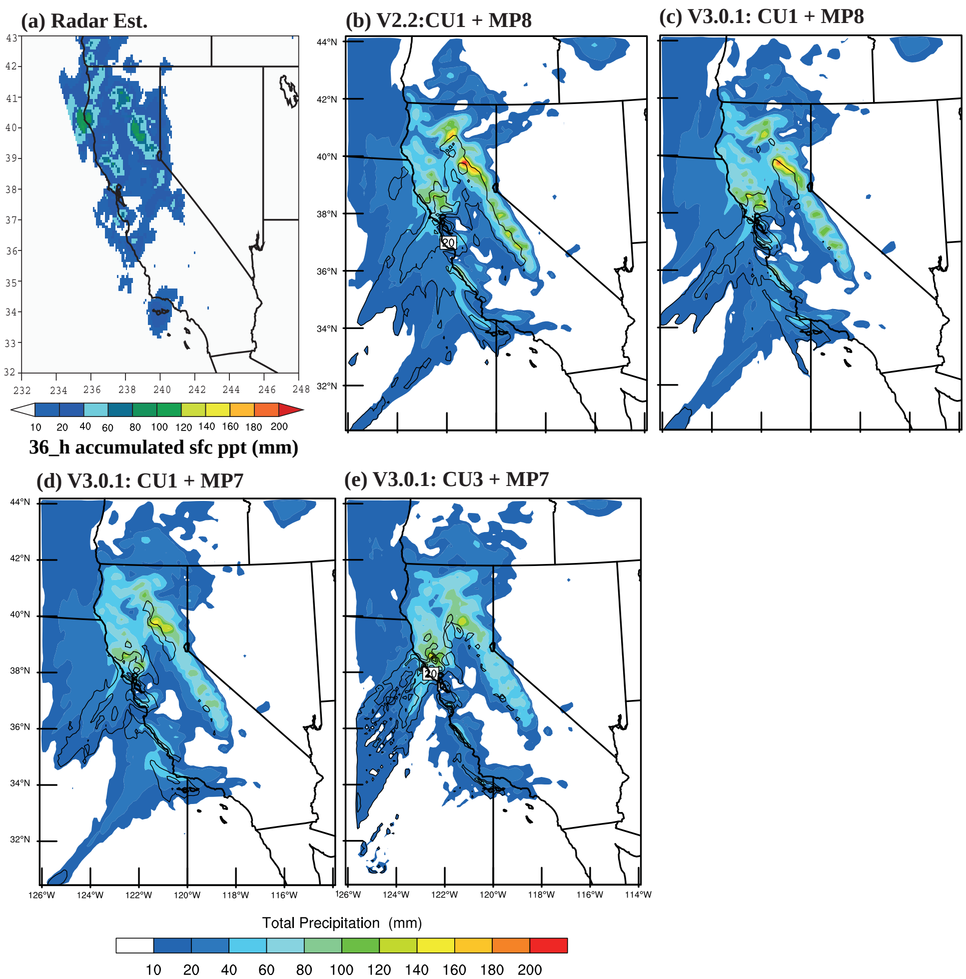

Fig. 8. Horizontal cross-sections of surface short-range (36-hour) accumulated precipitation. (a) Radar-estimated rainfall. (b) WRF V2.2 with Kain-Fritsch cumulus (CU1) and Thompson microphysics (MP8) schemes. (c) WRF 3.0.1 with Kain-Fritsch cumulus (CU1) and Thompson microphysics (MP8) schemes. (d) WRF 3.0.1 with Kain-Fritsch cumulus (CU1) and NASA Goddard microphysics (MP7) schemes. (e) Grell-Devenyi cumulus (CU3) and NASA Goddard microphysics (MP7) schemes.

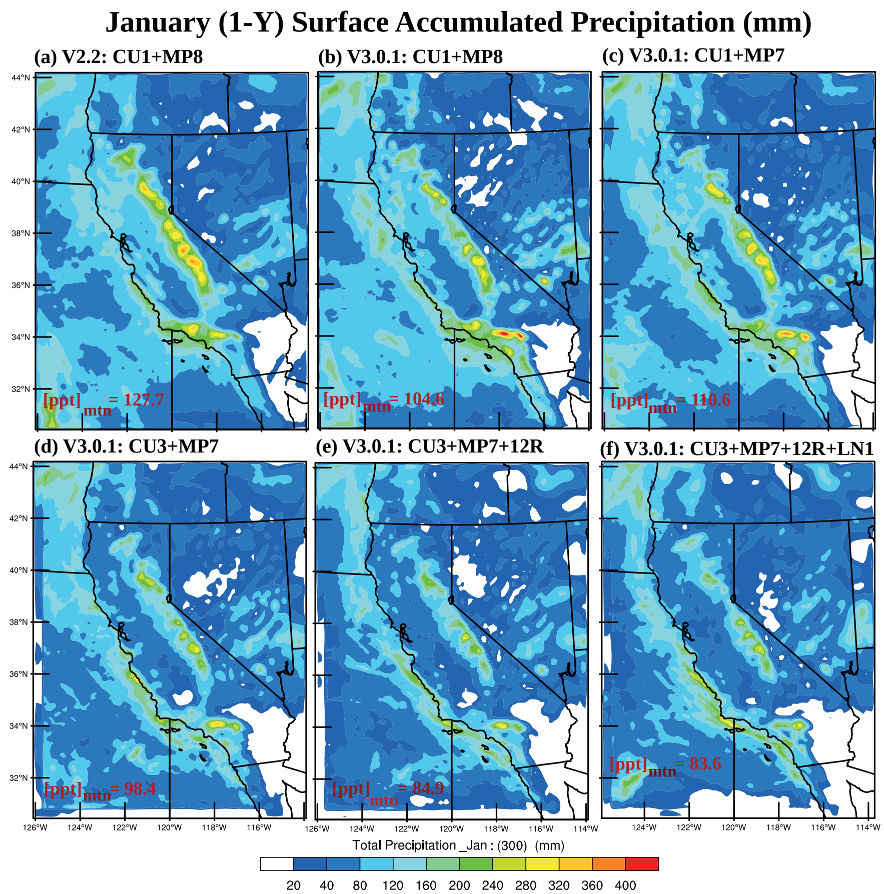

Fig. 9. As in Fig. 8, except for monthly simulations from a CCSM January (Y-300). All experiments in this figure have the relaxation zone size of 5 points, except for (e) and (f), which have 12 points. LN1 in (e) stands for the larger outer domain size. The area average over mountains is shown at the lower left corner of each simulation.

The same sensitivity experiments as in Fig. 9 are also assessed using additional 10 consecutive CCSM January data. However, the modified Thompson microphysics scheme in Version 3.0.1 barely shows reduction of mountain surface precipitation, and produces even stronger surface precipitation near the coastline (Figs. 10a and 10b). Similar result is also seen in the simulation with the Goddard microphysics scheme, except for weaker local maximum of mountain precipitation (Fig. 10c). These results indicate that the impact of microphysics schemes on surface precipitation has evident year-to-year variation so that longer samples may be needed for more reliable conclusion. In contrast, the influence of Grell-Devenyi cumulus scheme and larger relaxation zone remains clearly indentified in 10-year January simulations (Figs. 10d and 10e; 6.2% and 6.0%, respectively). Unlike the single January case, 10-year January simulations with larger outer domain size exhibit the enhancement of surface precipitation over mountains (Fig. 10f). The larger outer domain size used in this study should be used with caution. The control outer domain coverage ranges from 20 °N to 50 °N. The larger outer domain is further extended from 10 °N to 60 °N; the applicability of Lambert conformal map projection becomes more questionable in the tropics. Therefore, the generalized map projection using latitude and longitude grids in WRF Version 3.0.1 may be more appropriate for testing this domain size impact.

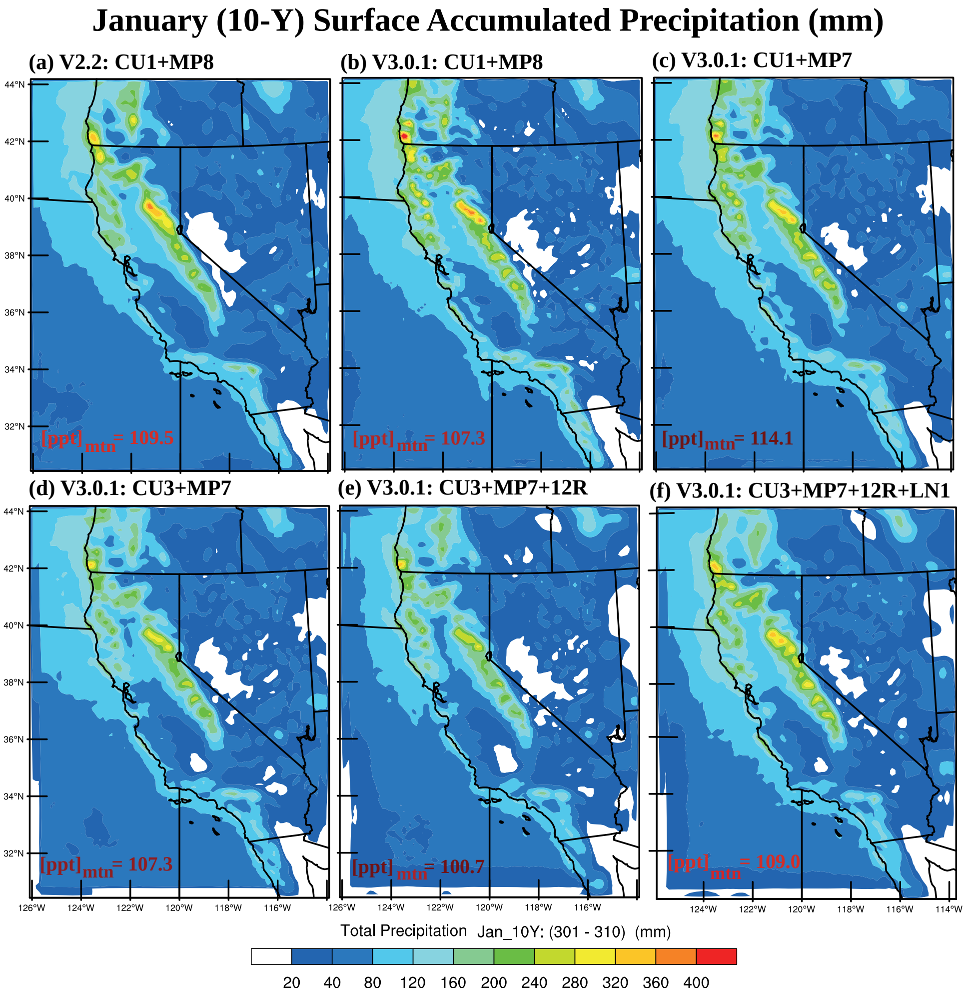

Fig. 10. As in Fig. 9, except for monthly simulations from 10 consecutive CCSM January (Y301-Y310).

5. SUMMARY AND DISCUSSION

A new version of WRF is available to run long-range simulations with sea surface temperature update for proper air-sea interaction, and to accommodate CCSM data with different grid structure. Results of yearly and monthly simulations indicate that the monthly snowpack reset over mountains has little impact on surface precipitation and ground temperature while its primary impact is found in the surface and sub-surface runoff, and soil-layer moisture, particularly after the late spring. The yearly WRF simulation seems to have fairly good forecast skill in upper-level fields although minor discrepancies may appears after 6 months. The yearly simulation suggests that the simulated climate drift may not occur in this range of simulation.

The impact of microphysics schemes on surface precipitation exhibits large year-to-year variation so that longer than 10 years of simulations are needed to assess this impact completely. In contrast, the Grell-Devenyi cumulus scheme and the larger relaxation zone size persistently show their impact on reducing the winter California wet bias over mountains. Due to the improper applicability of Lambert conformal map projection to the tropics, an alternate map projection for latitude-longitude grids in WRF Version 3.0.1 is recommended to further evaluate the impact of outer grid domain size on the winter California mountain wet bias.

In addition, the sensitivity of WRF precipitation forecast to the choice of cumulus parameterization suggests a need to run a higher grid resolution (say, 9 km) to avoid the use of any cumulus scheme in the regional-scale simulation since the minimum grid size to run the cumulus scheme is set to 10 km by default in most of RCMs. This alternative can balance the computational cost and model physics sensitivity. Additionally, LLNL's GCM-RCM approach for regional climate simulation does not consider the uncertainty of GCM large-scale conditions to the simulated bias as compared to the observations. Therefore, a parallel set of WRF simulations using large-scale analysis data (best available proxies for observations) is recommended to limit the forecast bias caused by WRF alone. As a result, we can estimate the magnitude of forecast bias by GCM data, and use it as a base to adjust our RCM simulations for future climate change.

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References

Caldwell, P. M., H-N S. Chin, D C. Bader, and G. Bala, 2008: Evaluation of a WRF Dynamical Downscaling Simulation over California. *Climatic Change* (Accepted with revision)

Dinku T., E. N. Anagnostou, and M. Borga, 2002: Improving Radar-Based Estimation of Rainfall over Complex Terrain. *J. Appl. Meteor.*, **41**, 1163-1178.

Dudhia, J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a Mesoscale Two-Dimensional Model. *J. Atmos. Sci.*, **46**, 3077-3107.

Duffy, P. B., and Coauthors, 2006: Simulations of Present and Future Climates in the Western United States with Four Nested Regional Climate Models. *J. Climate*, **19**, 873- 895.

Giorgi, F., C. S. Brodeur, and G. T. Bates, 1994: Regional Climate Change Scenarios over the United States Produced with a Nested Regional Climate Model. *J. Climate*, **7**, 357- 399.

Grell, G.A. and D. Devenyi, 2002: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques, *Geoph. Res. Let*., **29**, NO 14., 10.1029/2002GL015311, 2002.

Hong, S.-Y., Y. Noh, and J. Dudhia, 2006: A new vertical diffusion package with an explicit treatment of entrainment. *Mon. Wea. Rev*., **134**, 2318-2341.

Kim, J., 2004: A Projection of the Effects of the Climate Change Induced by Increased CO_2 on Extreme Hydrologic Events in the Western U.S. *Climatic Change*, **68**, 153- 168.

Leung, L. R., and S. J. Ghan, 1999: Pacific Northwest Climate Sensitivity Simulated by a Regional Climate Model Driven by a GCM. Part I: Control Simulations. *J. Climate*, **12**, 2010- 2030.

Leung, L. R., Y. Qian, X. Bian, and A. Hunt, 2003: Hydroclimate of the Western United States Based on Observations and Regional Climate Simulations of 1981-2000. Part I: Seasonal Statistics. *J. Climate*, **16**, 1892- 1911.

Liang, X.-Z., L. Li, and K. Kunkel, 2004: Regional Climate Model Simulation of U. S. Precipitation during 1982-2002. *J. Climate*, **12**, 2010- 2030.

Mlawer, E., S. Taubman, P. Brown, M. Iacono, and S. Clough, 1997: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res.*, **102**, 16663-16682.

Skamarock W.C., and Coauthors, 2007: A Description of the Advanced Research WRF Version 2. NCAR TECHNICAL NOTE, NCAR/TN–468+STR.

Smirnova, T., J. Brown, S. Benjamin, and D. Kim, 2000: Parameterization of cold-season processes in the MAPS land-surface scheme, *J. Geophys Res*., **105**, 4077-4086.

Tao, W.-K., J. Simpson, D. Baker, S. Braun, M.-D. Chou, B. Ferrier, D. Johnson, A. Khain, S. Lang, B. Lynn, C.-L. Shie, D. Starr, C.-H. Sui, Y. Wang and P. Wetzel, 2003a: Microphysics, radiation and surface processes in the Goddard Cumulus Ensemble (GCE) model, *A Special Issue on Non-hydrostatic Mesoscale Modeling, Meteorology and Atmospheric Physics,* **82**, 97-137.