Development of the Regional Climate-Weather Research and Forecasting Model (CWRF): Treatment of Subgrid Topography Effects

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1. Introduction

The CWRF is the climate extension of the Weather Research and Forecasting (WRF) model, incorporating inclusively all WRF functionalities for numerical weather prediction (NWP) while enhancing the capability for climate applications. The CWRF has built-in modules with realistic surface boundary conditions that are the most comprehensive among current weather and climate models and advanced physics parameterizations that improve surface-atmosphere and convection-cloud-radiation interactions (see Liang et al. 2005a,b,c,d for an introductory overview). In particular, Liang et al. (2005d) improved the treatment of the resolved (at the CWRF grid scale) topography effect by incorporating an analytic terrain-following reference model standard atmosphere (MSA). It was demonstrated that the MSA approach effectively solves the problem in spatial interpolation of initial and lateral boundary conditions due to terrain mismatch between the CWRF and the driving model and thus facilitates the CWRF to more realistically reproduce the 1993 summer record flooding in the Mississippi River basin, including the precipitation pattern, surface air temperature distribution and Great Plains low-level jet (LLJ).

This study continues the previous work (Liang et al. 2005d) but focuses on parameterizations of subgrid topography effects on momentum and radiation that are not explicitly resolved by at the CWRF. It is shown that the CWRF result is sensitive to these parameterizations. Here presented are the CWRF responses to various subgrid topographic representations and parameter selections, focusing on the downscaling skill of precipitation and surface temperature in the U.S.

2. Subgrid Topography Parameterizations

Given a grid spacing Δx, the effects due to topography variations smaller than that scale are currently not accounted at all in the CWRF. To avoid numerical instability, the terrain height is filtered to remove 4-grid waves. Thus the subgrid effects here denote for those relative to the mean terrain averaged over an area of $(4\Delta x)^2$ surrounding each grid center. Subgrid orography effects have been recognized as significant in coarse-resolution global models and generally incorporated via certain parameterizations. These effects, however, have usually been neglected in mesoscale models, except Rontu (2006b). As shown below, their impacts on mesoscale modeling are as important as for synoptic prediction. Here we focus on the following subgrid parameterizations, two for momentum and one for radiation:

Small-scale orography (SSO) turbulent form drag. Aerodynamic drag force by small-scale orographic features results from the non-separated sheltering mechanism of turbulent flow that creates an asymmetric pressure distribution across the obstacle (with the lowest pressure slightly downwind of the crest); it is a characteristic property of viscous, turbulent flow and forms favorably with stratification from neutral to moderately stable and orography scales below a few kilometers (Belcher and Wood 1996). Here only orography features at scales smaller than 3-4 km contribute to the SSO. Following Wood et al. (2001), the surface orographic stress is parameterized by

$$\vec{\tau}_{os} = C_{os} s_t^2 \vec{\tau}_{ts}$$

where C_{os} is the SSO tuning parameter depending on model resolution, set to 12.0 for the CWRF with 30-km grid spacing; $\vec{\tau}_{ts}$ is the surface turbulent stress, normally calculated in the land surface module; s_t is the tangent angle of mean maximum small-scale orography slope, derived as Rontu et al (2006a). Following Rontu (2006b), $\vec{\tau}_{os}$ is added to $\vec{\tau}_{ts}$ and the result is then transmitted to the boundary layer module for vertical diffusion depending on stability. This SSO parameterization is physically more reasonable than using an effective orographic roughness length in the land surface module. The latter treats every subgrid effect as turbulence irrespective of scale dependence and may affect not only the turbulent momentum but also heat and moisture fluxes (Rontu et al. 2002).

Mesoscale orography (MSO) buoyancy (gravity) waves drag. The need and complexity to parameterize the gravity waves generated by flow over subgrid orography are well recognized (see Kim et al. 2003 for a comprehensive review). Here the MSO scheme implemented into the CWRF is the advanced parameterization most recently developed by Geleyn et al. (2006) and evaluated by Catry et al. (2006). The surface orographic wave stress is parameterized by

$$\vec{\tau}_{ws} = C_{ws} \rho_s N_s \sigma_m \vec{v}_{fs}$$

where C_{ws} is the MSO tuning parameter depending on model type, set to 0.02 for the CWRF with 30-km grid spacing; ρ_s is surface air density; N_s is surface Brunt-Väisälä frequency; σ_m is standard deviation of mesoscale orography variability;

and $\vec{v}_{fs}$ is the fictive surface wind, depending on surface wind as modified by the anisotropy of subgrid mountains. For an elliptical mountain, the anisotropy is determined by the eccentricity of the ellipse (γ) and the angle of its minor axis with the model x-axis (ς). The surface stress $\vec{\tau}_{ws}$ is then propagated upward, with certain momentum deposition along the path depending on local wind and stability (*N*). In addition to the commonly used linear wave drag theory, the scheme incorporates several non-linear effects, such as reflected-wave resonance, wave trapping, moisture influence on stability, flow blocking and lift force, as well as numerical securities against linear and non-linear instabilities (see Geleyn et al. 2006 for details). The procedures for deriving the mesoscale orography parameters (σ_m , γ , ς) are given by Rontu et al. (2002, 2006a).

This MSO parameterization is more physically sound than the *envelope orography (ENV)* approach, where the grid-scale terrain height is artificially elevated in proportion to standard deviation of the subgrid orographic variability. As shown in Liang et al. (2005d), the ENV causes unrealistic representation of surface temperature that must be corrected by certain empirical lapse-rate adjustment. The posterior correction does not change the fact that this deficiency is already integrated into the whole model system through surface-atmosphere interactions. Thus, the more physically based MSO parameterization of gravity waves is preferred.

Orography effects on surface radiation (OSR). Complex topography affects surface radiation fluxes by its subgrid factors, including slope aspect, slope angle, sky view and shadowing. The CWRF incorporates the parameterization recently developed by Müller and Scherer (2005). The effects can be represented by modifying the surface radiation fluxes:

$$^{\downarrow}E^{*}_{s,dir} = {}^{\downarrow}E_{s,dir} f_{cor}$$
$$^{\downarrow}E^{*}_{s,dif} = {}^{\downarrow}E_{s,dif} f_{sky} + {}^{\uparrow}E_{s}(1 - f_{sky})$$
$$^{\downarrow}E^{*}_{l} = {}^{\downarrow}E_{l} f_{sky} + {}^{\uparrow}E_{l}(1 - f_{sky})$$

where superscript * denotes the flux including the orographic contribution and arrow indicates the flux direction; subscript *l, s, dir, dif* represents the longwave, shortwave and its direct and diffuse component, respectively. The sky view factor f_{sky} is a non-local but static property of topography only, which can be pre-calculated for each CWRF grid using the terrain distribution at the highest available resolution (1 km for this study). On the other hand, the correction factor f_{cor} changes with time, depending on the slope aspect and angle of topography, the elevation and azimuth angle of the sun, as well as the shadow masking by the surrounding mountains. The f_{cor} calculation is very time-consuming and unpractical for online. In a weather forecast model, Müller and Scherer (2005) proposed to calculate f_{cor} for individual grids at each hour and every 15° azimuth angle by a preprocessor; the tabulated values are later interpolated to the forecast time during the model execution. This approach, however, is not applicable for a regional climate model, where continuous long-term integrations are normal. To facilitate this, we have developed a parameterization for online calculation to capture the dominant topographic factors depending on the instant sun elevation and azimuth angles (to be presented in future).

3. CWRF climate responses

A series of CWRF climate simulations are conducted to study the model sensitivity to the three orography parameterizations outlined in section 2. The computational domain design is referred to Liang et al. (2004), with 30-km grid spacing over the continental U.S. and adjacent oceans (Fig. 1). Each integration covers May 2 to July 30, 1993, during which record flooding occurred in the Mississippi River basin. This extreme event has been identified with physical mechanisms at both the planetary and local scales and demonstrated to be an ideal case for developing, improving and evaluating regional climate models (Liang et al. 2001).

Table 1 lists all nine experiments, each identified with the orography representation in an optional combination of ENV, SSO, MSO and OSR outlined in section 2. To depict the sensitivity to the tuning parameters, we also include experiments where C_{os} and/or C_{ws} are decreased (1/2) and increased (3/2) from the reference values. The resolved topography at the model grid is constructed by using the WRF SI (Smart et al. 2005). Options TOPTWVL=4 and SILAVWT=0 produce a reference topography that conserves mass while removing 4-grid waves; SILAVWT=1 generates the ENV that maintains the effective mean barrier height. Except for ENV, all other experiments use the reference topography. The MSA approach is commonly adopted for mapping initial and lateral boundary conditions from the T62 (~1.875° or 210 km) R-2 reanalysis (Kanamitsu et al. 2002) to the CWRF grid mesh.

Table 1 also illustrates correlation coefficients, mean biases and root-mean-square errors (rms) of daily mean precipitation and surface air (2m) temperature during the entire integration period as compared with observations over the Midwest major flood area (MFA, outlined in Fig. 1) and whole USA. For MFA precipitation, CTL underestimates it by over 15% while ENV overestimates it by 13%; MSO best matches observations whereas the addition of SSO and/or OSR degrades the skill a little. All cases overestimate the total USA precipitation, with ENV being the worst, CTL the best, followed by MSO. For both MFA and USA, the correlation with the observed precipitation daily evolution is the highest by ORR and closely followed by MSO. Overall MSO improves the precipitation simulation, noticeably better than CTL and ENV, while SSO and OSR contribute small. For MFA temperature, CTL has a small warm bias while MSO has a stronger cold bias, which is somewhat worsen by addition of SSO but improved by OSR. A similar feature is identified with USA temperature except that CTL also has a cold bias. As expected, ENV has a severe cold temperature bias (-1.76 over the whole USA) because the model physical surface is artificially elevated. Although this temperature bias can be largely removed by applying a lapse-rate adjustment of the added terrain height (not shown), its interactions with other model components through coupling with land surface and boundary layer processes cannot be corrected in posterior. For all above statistics, the CWRF skill sensitivity to the SSO and MSO tuning parameters is generally small within the range of 0.5 to 1.5 factors of the reference values.

Figure 1 depicts geographic distributions of the differences between CWRF simulations using various orography representations and with observations for sea-level pressure, precipitation and surface air temperature averaged during the entire 90-day integration period. Here precipitation and temperature observations are from the dense station network with a resolution close to 30 km (see Liang et al. 2004 for the data description). Since the actual observation for sea-level pressure is not available, the R-2 field is used as a proxy; the credibility is thus discounted by deficiencies due to the incomplete model physics and coarse spatial resolution in the R-2 assimilation system.

Clearly, the CWRF using the reference topography without other subgrid orography treatment (CTL) produces 1-3 hPa higher sea-level pressure than the driving R-2 in most of the domain land, with maximum biases over the mountain peaks and their lee sides. The biases to the east (or lee sides) of the Rockies are largely eliminated by using the envelope orography (ENV), but those over the western mountains remain or further increase. The incorporation of the subgrid gravity wave parameterization (MSO) captures the main feature of the ENV effect, except that the bias reduction is relatively smaller to the east of the Rockies and improved over the western mountains. The result agrees with the original design of the MSO scheme that mimics the ENV impacts on momentum but using physically-sound principals.

The precipitation and temperature responses are more dramatic and different from those in sea-level pressure. For MFA, ENV substantially increases rainfall (from a 16% underestimation in CTL to a 13% overestimation) and decreases temperature (with a bias from +0.29 to -0.55°C). MSO well captures this signal, producing a more realistic precipitation (<+2% bias) but a colder temperature (-1.03°C). The MSO result is very encouraging since this record flooding event has been the long-standing challenge for the WRF and CWRF. Opposite responses are simulated along the Texas-Mexico border by both ENV and MSO, with the former being more intense in magnitude and latter broader in area coverage. A serious problem with ENV is that it substantially overestimates precipitation over most of the eastern and southern States while greatly underestimates temperature over most of the Rockies. MSO largely eliminates this problem, producing an overall more realistic precipitation and temperature distribution, and hence more advantageous than ENV.

The CWRF responses to the addition of the SSO parameterization are generally small in all fields. The model skill is actually degraded somewhat. The addition of the OSR also produces small responses, although a systematic warmer temperature is simulated over most of the domain land.

Note that there still exist substantial rainfall overestimation in the southern Great Plains and the northeast USA-Canada border as well as moderate precipitation overestimation and temperature underestimation along the southern and eastern USA coastal regions still exist, although the MSO parameterization improves these deficiencies somewhat. Reduction of these biases will be the focus of further model improvements.

4. Summary

The CWRF downscaling skill is demonstrated to be very sensitive to the treatment of topography, both at the resolved (Liang et al. 2005d) and subgrid (this study) scales. A long-standing problem with the WRF and CWRF in general is that the record flooding during 1993 summer over the Midwest is poorly simulated. As demonstrated here, this problem is effectively solved by using the MSO parameterization to incorporate the subgrid gravity wave drag on momentum. This approach is more advantageous, both in physics principals and skill enhancement, than the envelope orography method. The inclusion of the SSO and OSR parameterization has minor impacts. The result, however, may likely depend on model resolution. For example, when the spatial resolution increases, the OSR effect is expected to become more important for local surface temperature, while the MSO effect may partially be explicitly resolved by the model. There are also reasons to expect direct consequences of the SSO and MSO parameterizations more on near-surface wind than precipitation and surface air temperature shown here. A more rigorous evaluation including 10-m wind is warranted.

Given the improved representation of orography at both grid-resolvable and subgrid scales, we are optimizing (via inverse modeling) the cumulus parameterization and explicit cloud microphysics to reduce the remaining biases, especially over the southern Great Plains, northeast USA-Canada border, southern and eastern coastal States.

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Table 1. CWRF experiment description and result sensitivity. Shown are correlation coefficients (COR), mean biases and rms errors (RMS) of daily mean precipitation (mm/day) and surface air (2m) temperature (°C) as compared with observations over the Midwest major flood area (MFA) and whole USA. Each case is described by the orography representation in an optional combination of ENV, SSO, MSO and OSR, where a solid dot indicates the option is turned on. Subscript d and i denote for using a decreased (1/2) and increased (3/2) factor on the tuning parameters C_{os} and C_{ws}.

Case			CTL	ENV	MSO	ORO	ORR	MSO$_d$	MSO$_i$	ORO$_d$	ORO$_i$
Orography Scheme		ENV		●							
		SSO			●	●	●	●	●	●	●
		MSO				●	●			●	●
		OSR					●				
Precipitation	COR	MFA	0.48	0.51	0.56	0.56	0.57	0.54	0.57	0.53	0.57
		USA	0.50	0.40	0.60	0.58	0.61	0.61	0.59	0.60	0.61
	BIAS	MFA	-0.90	0.74	0.09	0.16	0.22	-0.20	0.24	-0.15	0.16
		USA	0.60	1.50	0.94	1.02	0.96	0.87	1.05	0.91	1.05
	RMS	MFA	4.30	4.84	4.44	4.30	4.30	4.23	4.43	4.35	4.49
		USA	1.33	2.01	1.44	1.50	1.44	1.41	1.51	1.44	1.52
Temperature	COR	MFA	0.89	0.91	0.87	0.86	0.86	0.88	0.86	0.87	0.86
		USA	0.97	0.98	0.96	0.96	0.96	0.96	0.96	0.96	0.96
	BIAS	MFA	0.29	-0.55	-1.03	-1.04	-0.97	-1.06	-1.10	-0.91	-1.13
		USA	-0.56	-1.76	-0.81	-0.84	-0.73	-0.90	-0.79	-0.87	-0.78
	RMS	MFA	2.32	1.74	2.24	2.26	2.25	2.18	2.31	2.19	2.38
		USA	1.24	1.84	1.26	1.25	1.20	1.34	1.23	1.30	1.23

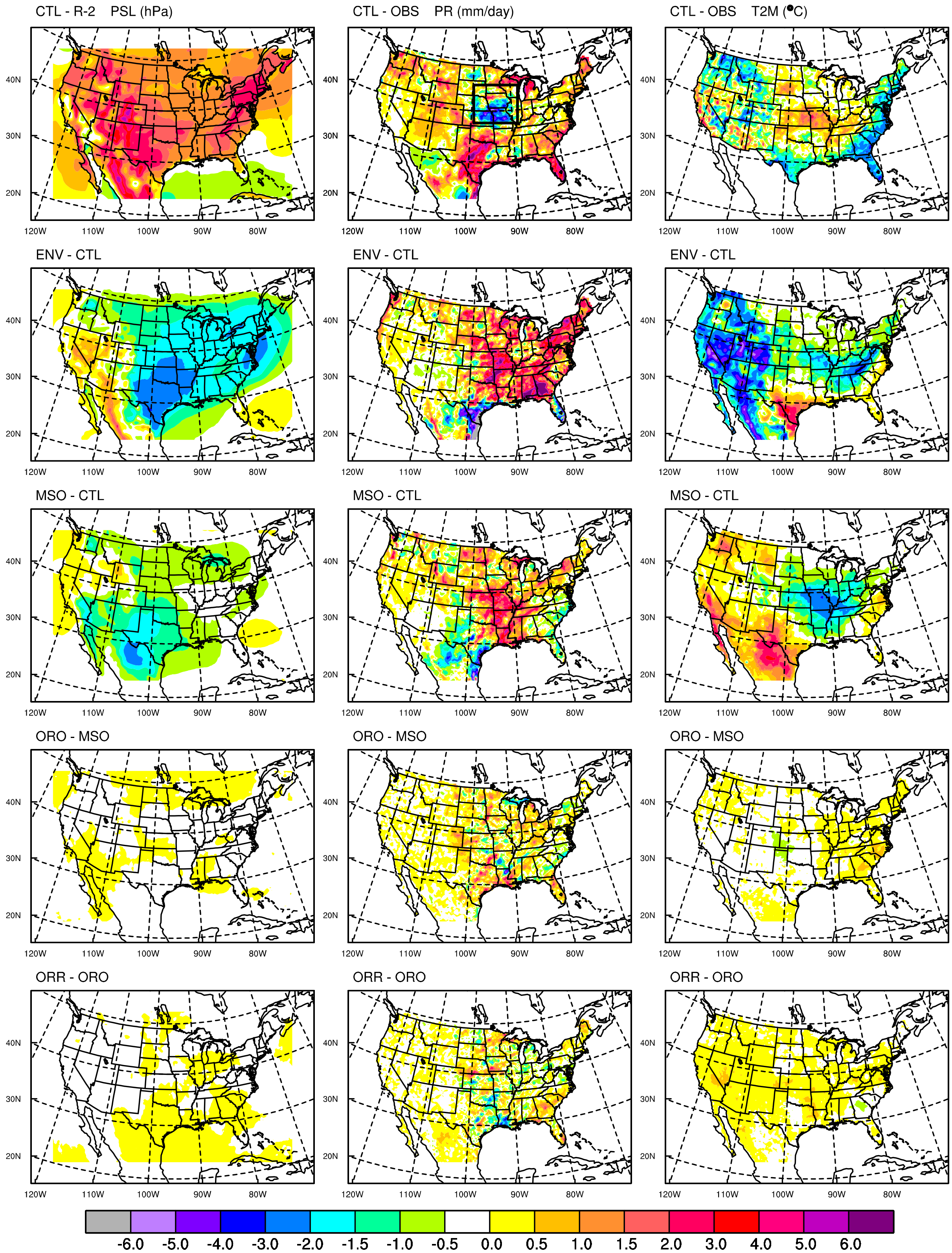

Figure 1. May 2–July 30 mean differences between CWRF simulations (see case description in Table 1) and observations (OBS) or reanalysis (R-2) for sea-level pressure (hPa, *left*), precipitation (mm/day, *middle*) and surface air temperature (°C, *right*). Outlined (*middle top*) is the major flood area (MFA) referred in the text.