Downscaling in WRF from Regional Climate to Storm Scale for Different Vegetation and Boundary Condition Sources

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1. INTRODUCTION

One of the main goals of downscaling is to examine regional weather events that are influenced by small-scale phenomena such as topography, land-sea interactions, or convection (Feser and von Storch, 2008). For the most part, large global scale simulations or reanalyses are downscaled to long-term regional climate scale so that the large scale forcings can be maintained. Overall, regional climate models (RCMs) have had some deal of accuracy in predicting meteorological features, but have struggled in timing and placement of some features, including precipitation maxima, 850 hPa geopotential height, and wind vectors. Researchers have looked to different methods of downscaling from global to regional climate scales in order to maximize accuracy (Alexandrau et al. 2007; Feser and von Storch 2008; Li et al. 2008; Qian et al. 2003). None of this research focused on storm scale properties in their dynamical downscaling efforts.

One of the main parameters used to examine the performance of an RCM is precipitation. While precipitation is poorly represented in RCMs (Kunkel et al. 2002) and numerical weather prediction in general, it is a physical parameter that is observed fairly routinely in the United States for easy comparison. This study will examine some of the synoptic and mesoscale differences that affect precipitation amount and location by downscaling an RCM simulation to a storm scale simulation in the Advanced Research Weather and Research Forecasting (WRF-ARW) model (Skamarock et al. 2008). Because RCMs are largely driven by lateral boundary conditions (LBCs) at their boundaries, another set of WRF simulations will be initialized by downscaling North America Regional Reanalysis (NARR) data to the storm scale for comparisons sake.

Another factor that is being considered in these simulations is vegetation cover. Stauffer (2010) ran RCM simulations for the entire growing season (Mar 1-Nov 1) of 2007, one using default WRF green vegetation fraction, the other using green vegetation fraction derived from the Moderate Resolution Imaging Spectroradiometer (MODIS), providing near real-time estimations of vegetation cover. This study will examine a five-day period from 1200 UTC 27 June through 1200 UTC 1 July 2007 that exhibited high precipitation over the Southern Great Plains. Two simulations will involve the downscaling of the MODIS and default RCMs, respectively, and are the two main simulations of interest. An additional two simulations will be downscaling NARR data using both MODIS and default vegetation cover.

2. MODEL SETUP

Four separate simulations are run using WRF Version 3.2.1 with differing initial boundary conditions and vegetation covers. All four domains are 151x151 with a grid spacing of 15 km. All simulations begin at 1200 UTC on 27 June 2007 and continue uninterrupted through 1200 UTC 1 July 2007. This event was chosen because it was a weak convective event that produced well over 250 mm of rain over eastern Kansas and western Missouri during the simulation period and caused major flooding in southeastern Kansas.

Two of the domains are initialized from a larger WRF RCM which are described in detail in Stauffer et al. (2010) and Stauffer (2010). The default RCM simulation initializes one domain with default vegetation cover, while the MODIS RCM initializes a domain using MODIS vegetation cover. The domains that are initialized from the NARR only differ in their vegetation covers, one default and one MODIS. The time of the simulation used in the present study is about four months into the RCM simulations.

WRF is run using WRF Single-Moment 6-class (WSM6) for microphysics (Hong and Lim 2006), the CAM radiation scheme (Collins et al. 2004), the NOAH land surface scheme (Chen and Dudhia 2001a, b), the YSU planetary boundary layer scheme (Hong et al. 2006), and the Kain-Fritsch updated cumulus parameterization (Kain 2004). All simulations are run with the same physics schemes so that the differences among domains are limited to initial conditions and the vegetation cover.

3. RESULTS

The two different sets of initial conditions generated vastly different atmospheres among the simulations. The precipitation patterns from the NARR simulations matched each other fairly well, but under-predicted the amount in the central Great Plains. The RCM simulations were markedly different from the NARR and observations. The amount of precipitation is shown in Fig. 1 among the four different simulations. This section will discuss the synoptic differences and vegetative forcings.

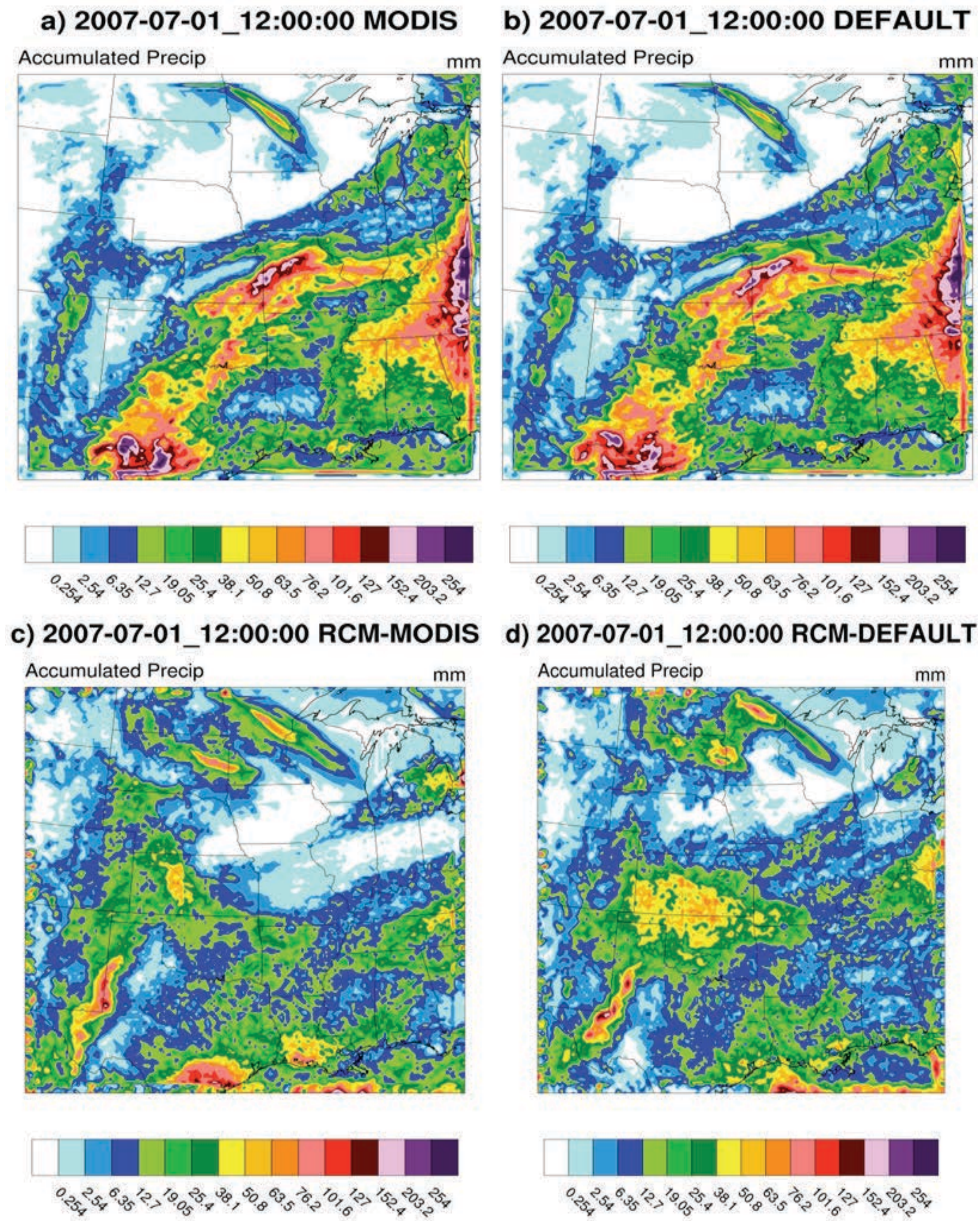

Figure 1: Total simulated precipitation for a) NARR MODIS, b) NARR Default, c) RCM MODIS, and d) RCM Default.

a. Synoptic setup

The simulation period begins with a weak trough at 300 hPa situated north of the Great Lakes and a slight ridge located over the Canadian Rockies. By 0600 UTC 28 June, a small shortwave can be seen ejecting off of the upper ridge east of the Colorado Rockies. This feature remained fairly consistent through the period, deepening near the end of the simulation. The wave's progression was quite slow, not reaching the Missouri River until the end of the simulation, suggesting an omega block type pattern. At the 500-hPa level, a persistent trough of low pressure is present through the simulation around the Missouri River Valley. In the low levels, onshore flow from the Gulf of Mexico into the Mississippi Valley is persistent, bringing rich moisture north into the Ozarks and Missouri Valley. At the surface, a nearly stationary front completes the setup, slowly moving south toward a surface cyclone located around the Red River through the period. For observed precipitation amounts from this storm, refer to Table 1.

As discussed above, the four simulations produced very different results, and all simulations under-predicted the amount of precipitation in the central Great Plains. The synoptic setup varied greatly among the two differing sets of initial conditions (NARR, RCM), creating different atmospheres that are not heavy precipitation producers.

b. NARR Simulations

The NARR initializations performed much better than the downscaled RCM simulations in reproducing this event. For both NARR simulations, the locations of the 300-hPa and 500-hPa troughs are fairly close to the observed location for the majority of the simulation. The middle levels begin to differ from observations around 1200 UTC 29 June. At 700 hPa, a closed low is present in both observations and the simulations, but the NARR simulations begin to retrograde the low to the south and west toward the Big Bend in Texas, while it remains fairly stationary in the observations. A fairly similar anomaly can be seen at the 850-hPa level. An 850-hPa anticyclone begins to form in both the observations and in the simulations over the Eastern Dakotas, but the ridge shows a little more tenacity and is located farther south in the simulations around the Nebraska-Iowa border.

At the surface, features are initially represented fairly well in the simulations. The surface low around the Red River is slightly weaker in the simulations, but in general, its timing and location are very close in the earlier times of the simulation. By 1500 UTC 29 June, a simulated cyclone around the Big Bend begins to intensify, but in the observations, there is no signal of this cyclone whatsoever. The location of the stationary boundary stays similar to observations through most of the simulation, but due to the differences in the upper levels and the anomalous surface cyclone, the precipitation generally falls only to the south of the boundary in the simulations and in west Texas, where almost no precipitation was observed.

The retrograding of the upper level low pressure system and formation of the surface cyclone in the NARR simulations greatly affects the distribution of moisture across the region of interest. In the simulations, the troughs' associated moisture ridge begins to retreat south, away from Northern Missouri, as dry continental air begins to wrap the anticyclone. The bulk of the moisture is transported towards the center of the deepening cyclone near the Big Bend, much farther south than in the observations. The simulated system in Texas does produce a surplus of precipitation, some of which should have been in Oklahoma, Kansas, and Missouri. For simulated rain amounts in specific locations, refer to Table 2.

Table 1: Observed precipitation amounts for selected cities from 1200 UTC 27 June through 1200 UTC 2 July.

Date	Kansas City, MO	Springfield, MO	Butler, MO	Fredonia, KS	Del Rio, TX
2007	(MCI) (mm)	(SGF) (mm)	(BUM) (mm)	(1K7) (mm)	(DRT) (mm)
27-Jun	27.94	13.72	0.00	6.35	42.67
28-Jun	6.10	1.02	51.05	33.78	0.00
29-Jun	2.29	10.67	41.15	132.08	0.00
30-Jun	6.60	14.73	13.72	298.70	0.00
1-Jul	0.00	31.50	92.46	M	0.00
Total	42.93	71.63	198.37	470.92	42.67

Table 2: Simulated total event precipitation for selected cities for each simulation.

Simulation	Kansas City, MO	Springfield, MO	Butler, MO	Fredonia, KS	Del Rio, TX
Total Precip (mm)	(MCO)	(SGF)	(BUM)	(1K7)	(DRT)
NARR MODIS	8.71	93.96	190.69	92.64	136.38
NARR Default	9.41	59.72	189.49	69.53	99.09
RCM MODIS	2.41	8.86	1.62	7.80	7.30
RCM Default	2.23	5.44	1.62	7.76	7.51
Obs (Table 1)	42.93	71.63	198.37	470.92	42.67

c. RCM Simulations

The RCM downscaled simulations produced a significantly different atmosphere than observations and the NARR downscaled simulations. At the 300-hPa and 500-hPa levels, the general patterns in the observations and simulations are quite similar. The simulations begin with a weak trough over the Great Lakes and a weak ridge west of the Dakotas. The trough in these simulations is slightly weaker in addition to being less defined. Due to the constraints of the domain, it is difficult to determine the extent of the ridge and trough development, but one feature that is somewhat striking is that the ridge axis is slightly farther downstream of the observed location. The axis of the ridge at 500 hPa is located around the Dakota-Montana borders, while the observed ridge axis is located around central Montana. The flow regimes also vary greatly, especially in the southern half of the domains. Areas simulated in Texas have winds orthogonal to the observed winds at certain points of the simulation. The general trends in the upper levels for the simulated winds are to be easterly in the southeast gradually shifting to more northerly in west Texas. Observed winds show light southerly flow in the southeast shifting quickly to northerly in west Texas. In the northern half of the domain, the flow is better handled, with a stronger westerly core of winds present across the northern Great Plains, with the polar jet stream being well north of the area of interest for this case.

In the lower levels, the flow is significantly different in a portion of the country very important to precipitation formation in the Missouri Valley. At both the 700- and 850-hPa levels, the simulated flow north of the Gulf of Mexico is offshore or parallel to the coast. Clearly, this will lead to a different moisture distribution and precipitation pattern. It appears that the moisture for the RCM simulations originated from the Pacific rather than the Gulf of Mexico, as noted in observations. At 0000 UTC, the differences in patterns become more apparent at 700 hPa. In observations, a trough is dropping through the center of the country with a closed low forming along the Red River. The RCM simulations are building a ridge over the central Plains with only a small closed cyclone around the Big Bend. A ridge does begin to build in observations a few hours later, but by 1800 UTC 29 June, the simulated ridge has intensified to a controlling level, inhibiting any precipitation formation in the area of interest. The non-favorable flow around the Gulf in the simulations persists through the end of the simulations at the 700-hPa level. At the end of the simulation, a sharp trough is noted over the northern Great Plains that is not present in observations. At the 850-hPa level, a similar trend is noted. Offshore flow into the Gulf is simulated through much of the simulations around the Mississippi River delta. The placement of the southern cyclone in the observations is almost unidentifiable in the simulations, which may be partially due to the higher elevations on the western edge of the domains, but the lack of a true cyclone around the Red River persists through the simulation.

The surface features for the RCM simulations also vary from the observations. The simulations produce a different flow regime again early in the simulation, and the surface pressures are higher than those observed. The location of the surface boundary is close to start with, but the pressure analyses are noticeably different. As the simulation progresses, the fields do begin to move closer to reality, but the upper level moisture and flow differences are too great to bring precipitation amounts closer to reality.

All of the above factors contributed to the more extreme lack of precipitation in the RCM simulations referenced in Fig. 1. The main concerns of this research are the causes of the different atmospheric evolution in the RCM downscaled simulations. Pan et al. (1999) noted that precipitation maxima tended to drift downstream in long term regional climate simulations, because winds aloft are too robust. Judging by the location of the upper level ridge axis, this solution seems feasible, but the feature was not so far downstream as to change precipitation patterns significantly. Due to the constraints of the domain, it is difficult to determine whether a strong precipitation signature is farther downstream. Alexandrau et al. (2007) noted that RCM simulations contain a certain amount of internal variability. Despite RCMs being driven largely by LBCs, some simulations have shown different solutions with the same initial conditions. This factor is difficult to judge for this study due to computing constraints not allowing for ensemble type simulations. The timing of the simulations could have had an additional impact. The simulation began almost four months into the original RCM simulations, giving features some time to drift from reality, possibly downstream as discussed earlier, in addition to giving errors time to accumulate. The length of the simulations is also somewhat unfavorable when considering spin-up effects of the model, but due to the computing constraints, a longer simulation would have tapped much more available computing resource, particularly for a single processor. A final possible explanation for error could stem from the choice of physics parameterizations, particularly the cumulus scheme. Physics are quite important to RCMs due to their regional scales. Selection of different parameterizations may have hurt or hindered the RCM simulations, but it is something that must always be considered for future downscaling studies. Refer to Figs. 2 and 3 for synoptic comparisons among NARR and RCM simulations.

d. Vegetative forcing

Vegetation cover has an influence on planetary boundary layer (PBL) features in numerical weather prediction. Vegetation affects the distribution of latent and sensible heat fluxes across the domain, which will in turn have an impact on the temperature and moisture in the low levels of the model. Near real-time representation of vegetation in the model environment has been shown to improve RCM simulations' prediction of temperature and precipitation for growing season length simulations (Stauffer 2010). For this study, as mentioned above, the default and MODIS derived vegetation covers are tested for each set of LBCs (see Fig. 4). For both sets of LBCs, the comparisons between the MODIS and default have not been as extreme as the synoptic differences. This storm simulation was clearly driven by synoptic scale features rather than mesoscale or vegetative forcings.

Comparisons of sensible and latent heat fluxes show that the vegetation had a larger impact in the RCM simulations compared to the NARR simulations (see Figs. 5 and 6). The "streaked" differences can be attributed to the slight differences in the cloud cover and precipitation patterns. 2-m air temperature differences among the MODIS and default simulations can be seen in Fig. 7. Again the differences in temperature among the two vegetation schemes are increased for the RCMs compared to the NARR simulations. The NARR pattern of temperature difference remains in a similar arrangement through the simulations, following the stationary boundary south towards the anomalous cyclone over the Big Bend. The RCM pattern is more disorganized through the simulation. Model derived PBL heights showed a similar result, with the RCM having more extreme differences compared to the NARR (see Fig. 8).

Soil moisture and vegetation cover are secondary, long-term forcings in RCMs that tend to have less of an impact on the simulations compared to large scale external forcing, LBCs, and synoptic patterns. This was also the case in downscaling to storm scale from a continental scale source such as the NARR. While there were impacts on the surface fluxes, the sensible weather was not deeply influenced by the difference in vegetation cover.

4. CONCLUSIONS AND FUTURE ERROR EVASION

This study examined downscaling to storm scale for a high precipitation event over the central Great Plains in late June 2007. Fredonia, KS received 470.92 mm of rain through the days of the simulations where data were available. Dynamical downscaling from an RCM and the NARR in WRF to the storm scale produced exceptionally different results. Both RCM simulations under estimated the amount of precipitation, while the two NARR simulations were slightly better in the central Plains. The synoptic features are the catalyst of change for all simulations, as anomalies began to form in the simulations. The RCM anomalies started earlier in the simulation, limiting the moisture over the central Great Plains. The NARR simulations ran fairly well until about midday local time 29 June, when a cyclone started to become apparent in Texas around the Big Bend, siphoning moisture away from the central Plains.

Near real-time vegetation cover (MODIS) did not vastly improve the simulations for this study compared to default vegetation, because the synoptic features were dominant. While some mesoscale differences are expected, dominant synoptic forcing will overshadow any small scale surface features.

When downscaling in WRF to storm scales, large scale RCM simulations have been shown to be inferior for examining storm scale features. This study, unfortunately, cannot be considered an overarching conclusion for this field of research. Too many variables have not been examined due to time and computing constraints. Further study is needed in order to determine whether RCMs can handle being downscaled. Changing physics schemes, adjusting conditions at the outer boundaries of the inner nest, and additional simulations may improve some of the results from this study. Additional research can be done with shorter storm events and deep convection, rather than this fairly long lasting stratiform rain event driven by synoptic features. While this study did not produce favorable results, it does not mean that this work should be abandoned. The future of RCM downscaling generally lies in the transition from global circulation models into smaller regions, but taking RCM domains down to the storm scale may be a necessity for the future in the realm of climate change.

5. ACKNOWLEDGEMENTS

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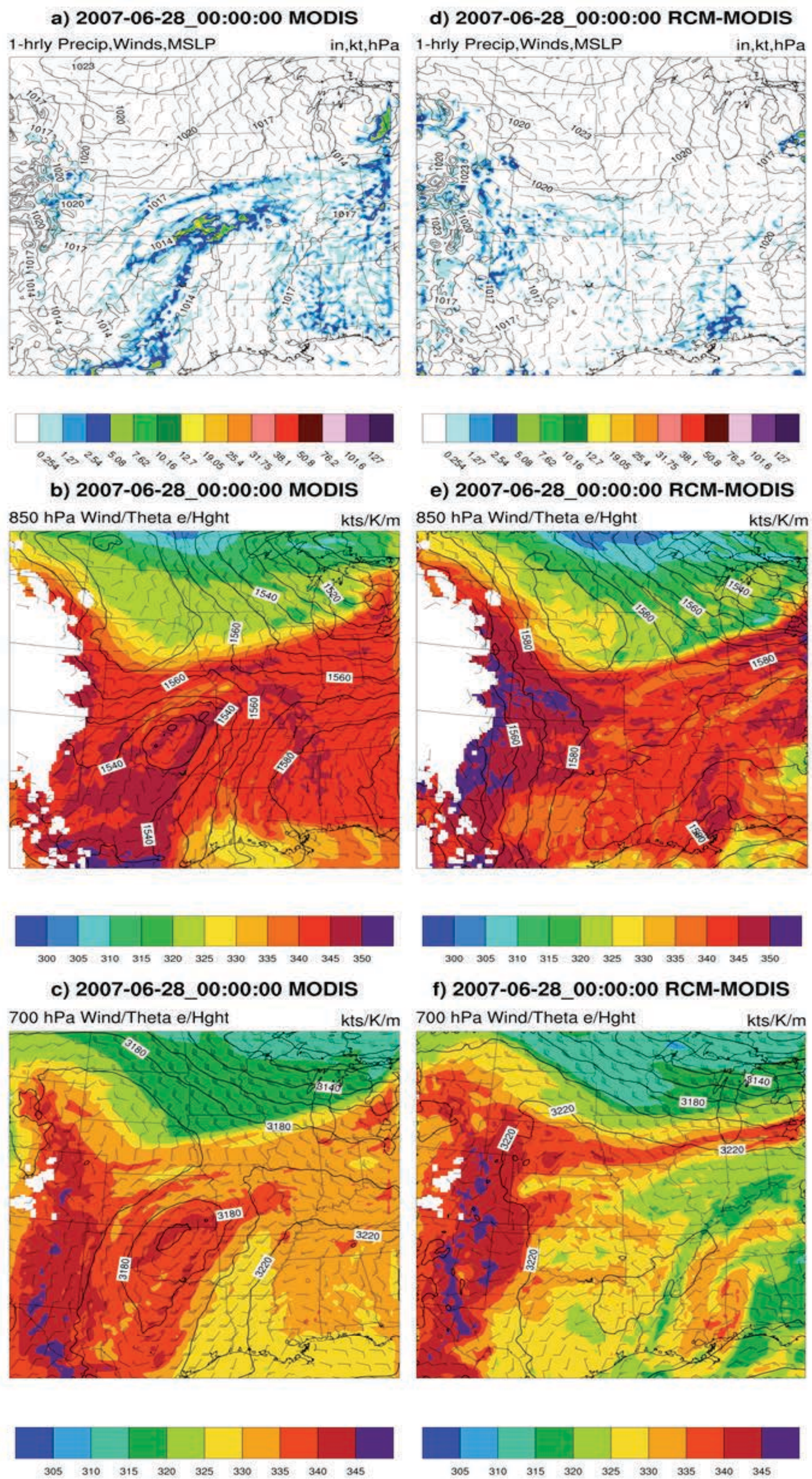

Figure 2: Synoptic setup for 0000 UTC 28 June for a) NARR MODIS surface, b) NARR MODIS 850 hPa, c) NARR MODIS 700 hPa, d) RCM MODIS surface, e) RCM MODIS 850 hPa, and f) RCM MODIS 700 hPa. The NARR simulations for this time step are fairly representative of observations, while the RCM simulations exhibit a clear difference.

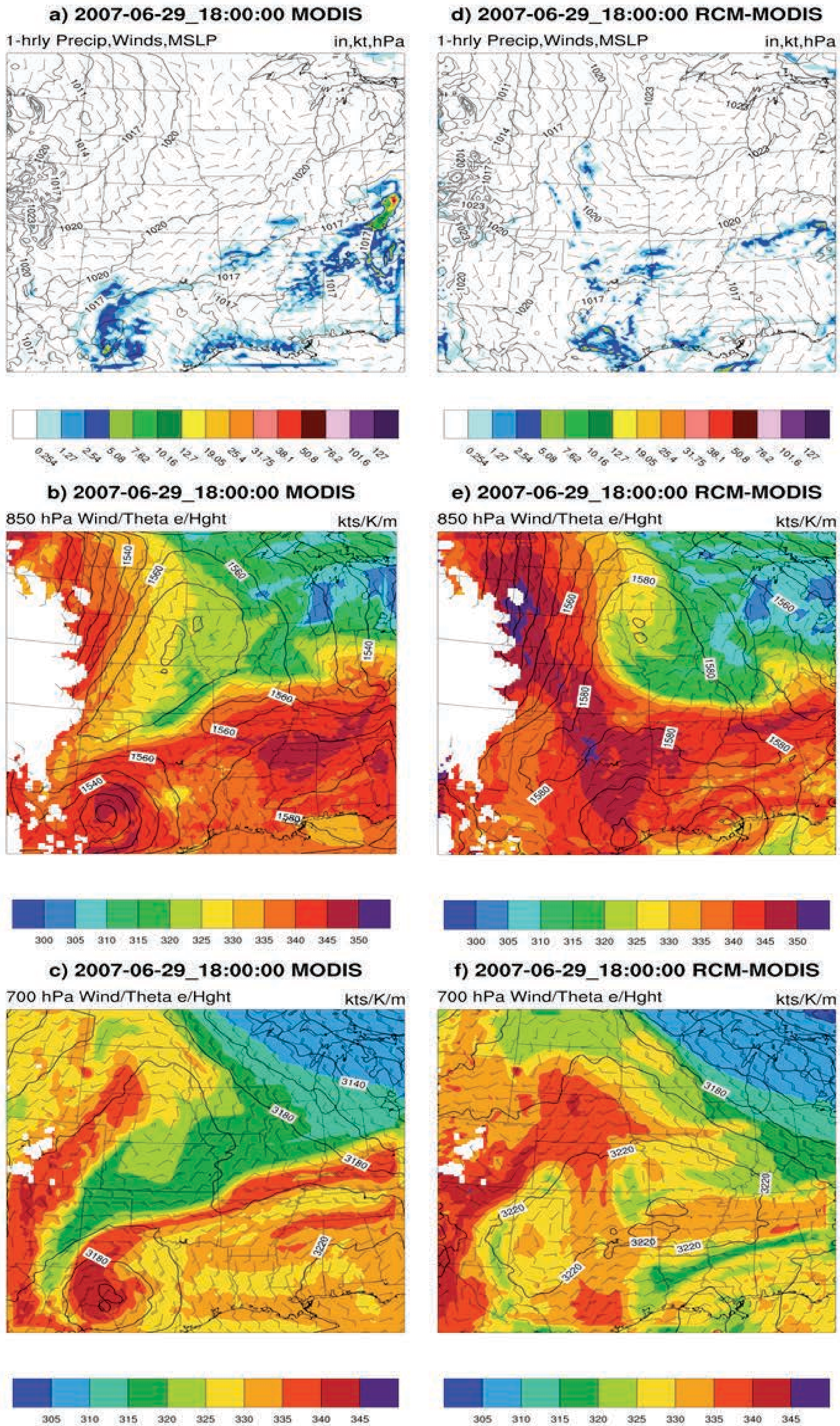

Figure 3: As in Fig. 2 but for 1800 UTC 29 June. Here, the NARR simulations began to diverge from observations, as the cyclone around the Big Bend deepens at 700 and 850 hPa. The RCM simulations are still in disagreement with both NARR and observations.

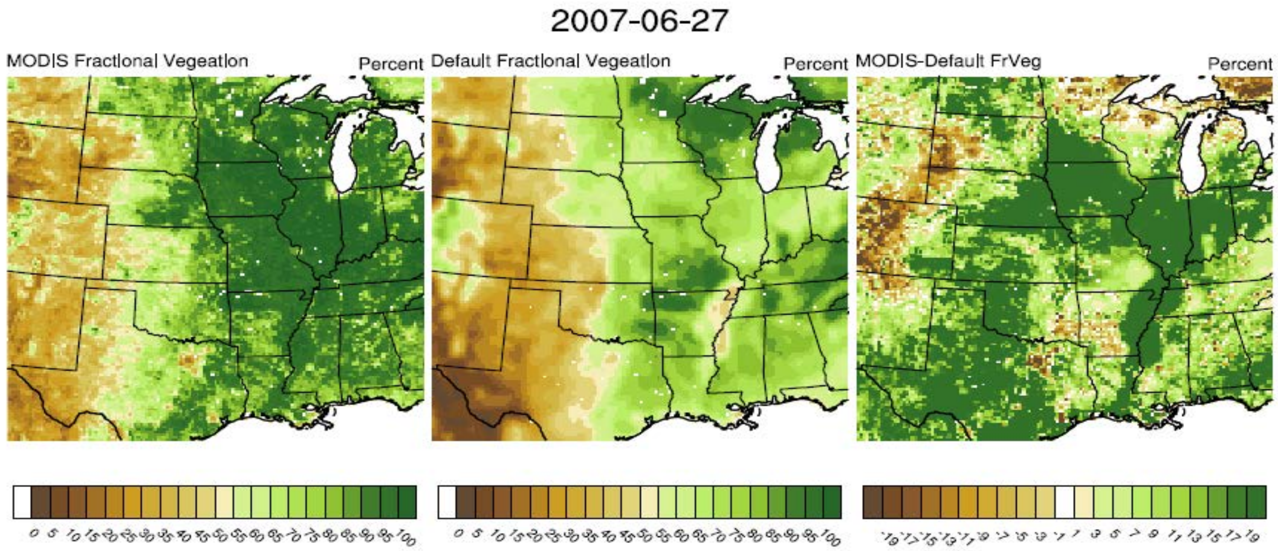

Figure 4: Plot comparing vegetation fraction for the MODIS and Default, and the difference between the two on 27 June.

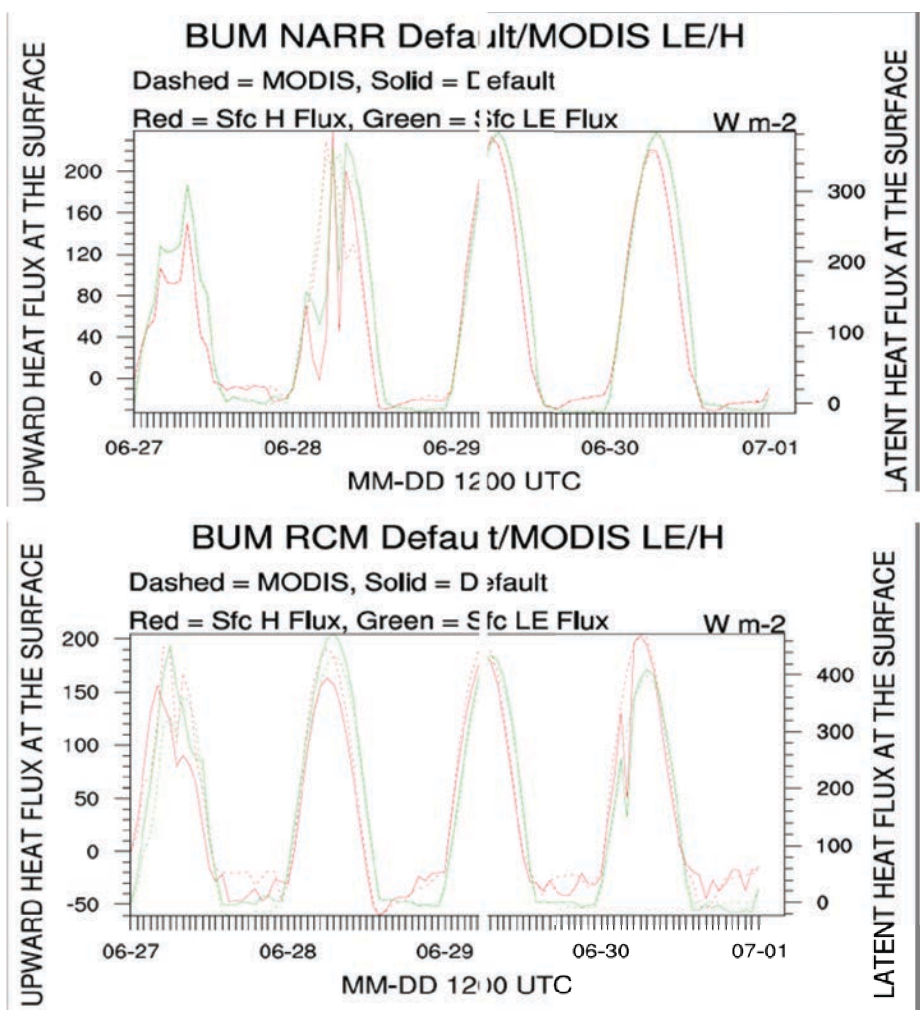

Figure 5: Time series for Butler, MO (BUM) comparing latent and sensible heat flux through the simulation period using NARR and RCM with both MODIS and Default vegetation cover.

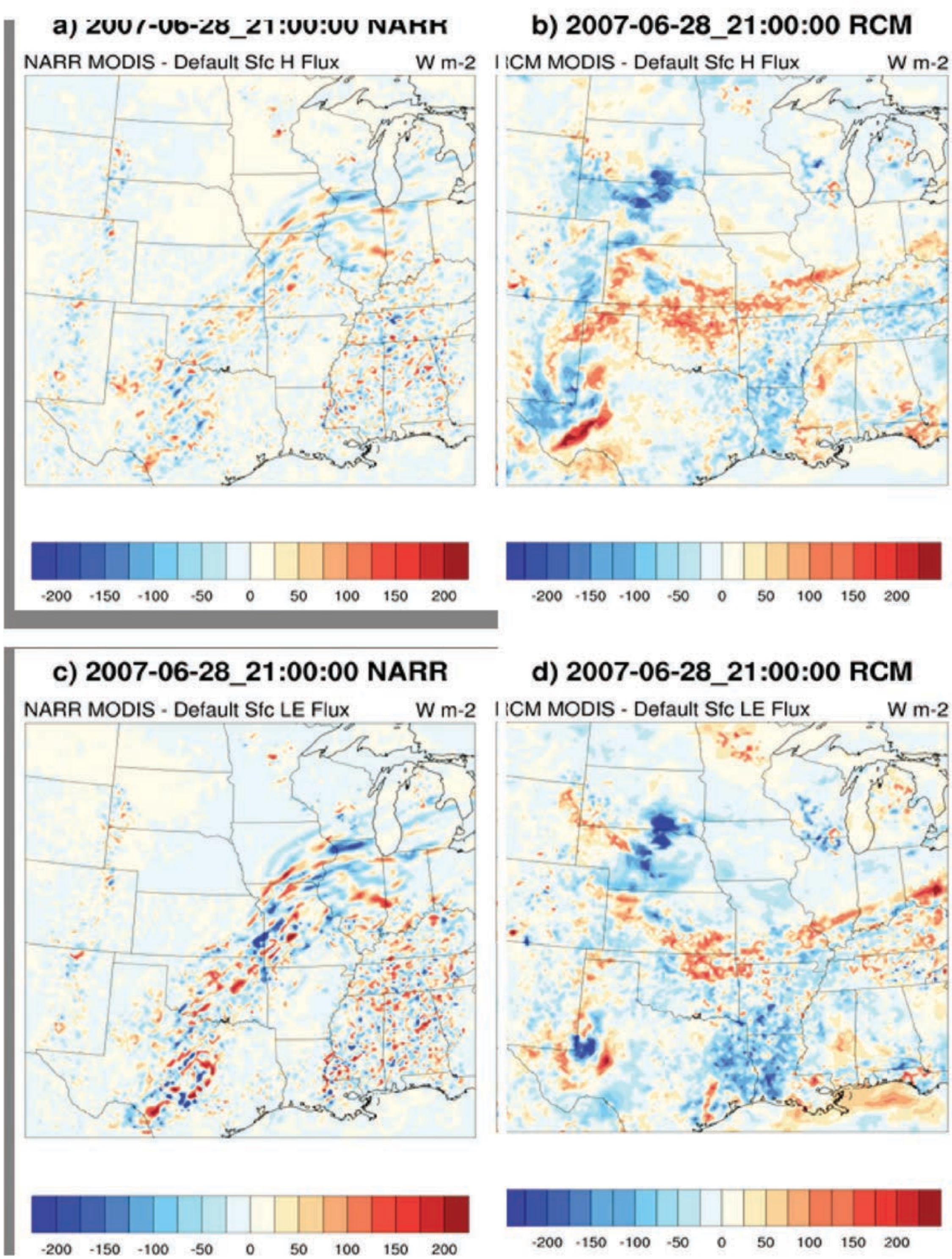

Figure 6: Plot comparing differences in heat fluxes (MODIS – Default simulations) for a) NARR Sensible, b) RCM Sensible, c) NARR Latent, and d) RCM Latent.

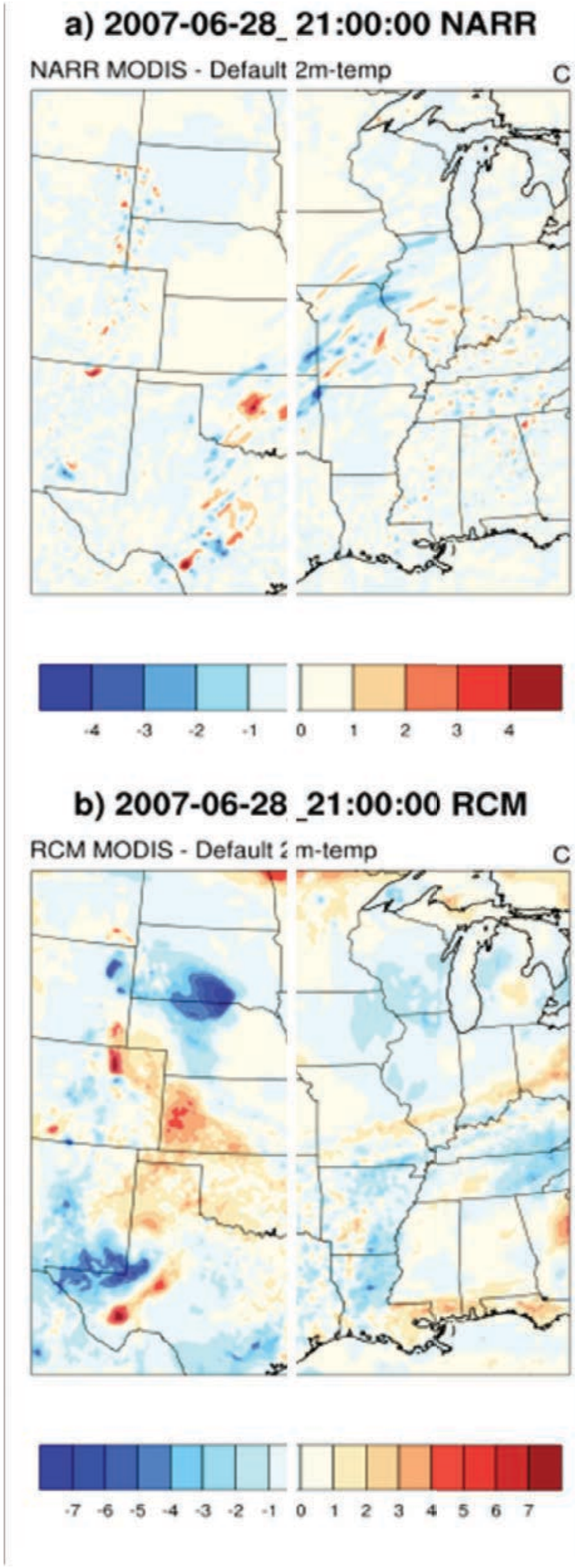

Figure 7: Plot showing differences in simulated 2m air temperature for a) NARR and b) RCM at 2100 UTC 28 June. This time was chosen to represent peak heating.

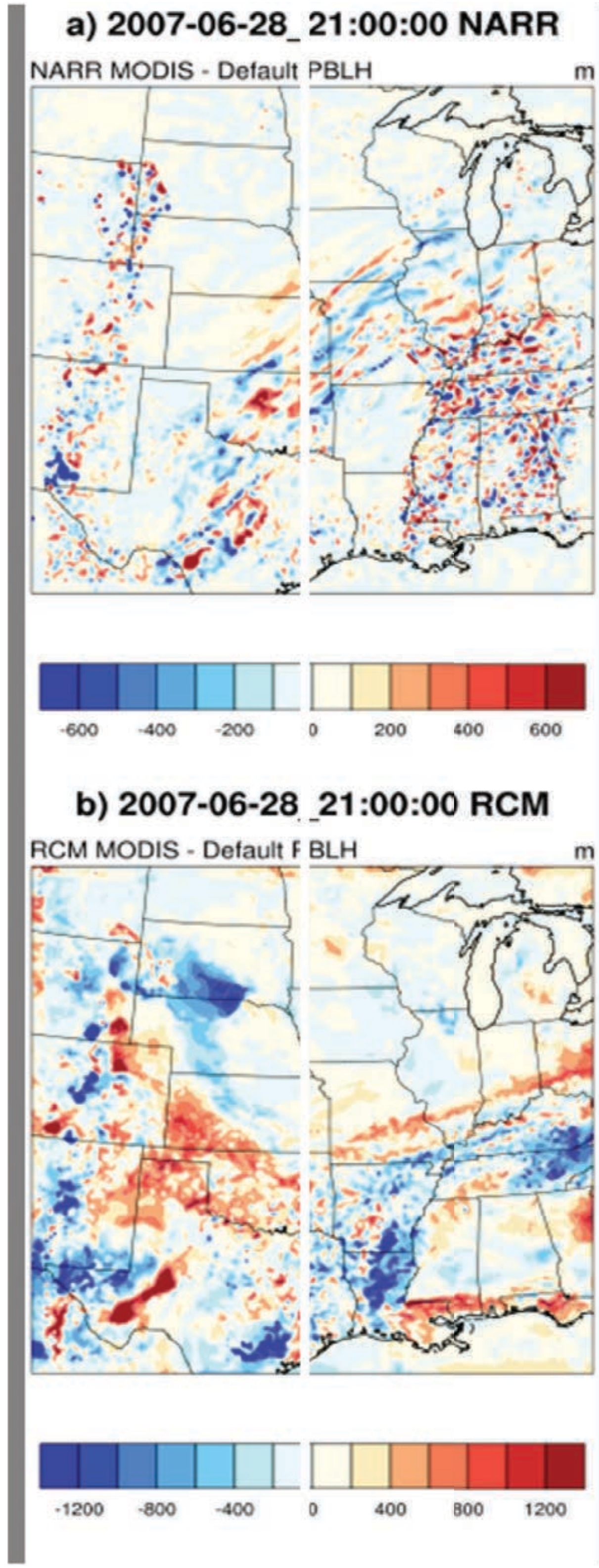

Figure 8: As in Fig. 7 but for differences in simulated planetary boundary layer height.