

Chapter 2

An Evaluation of the Community Land Model (Version 3.5) and Noah Land Surface Models for Temperature and Precipitation Over Nebraska (Central Great Plains): Implications for Agriculture in Simulations of Future Climate Change and Adaptation

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Abstract With increasing evidence of climate change, future decision-making among crop modelers and agronomists will require the inclusion of high-resolution climate predictions from regional climate models as input into agricultural system simulation models to assess the impacts of projected ambient CO₂ increases, temperature and general climatic change on crop production. Before they can be implemented in climate adaption studies and decision-support systems, weather variables must be reliable and accurate. This study evaluated weather variables generated from computer simulations using two land surface models, (LSMs) coupled to a regional climate model, namely, Weather Research Forecasting (WRF 3.2). The land surface models tested are the Community Land Surface Model CLM 3.5 and the Noah Land surface model. Ground truth observations

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from 7 stations in Nebraska from a dry year, a normal year and a wet year (2002, 2005 and 2008 respectively) were used to evaluate the model results. Model results were also compared for their spatial ability to mimic distance-standard error weather variables. Both LSMs performed well in predicting the maximum and minimum temperatures in 2002, 2005 and 2008. Rainfall predictions by both models were not as reliable, based on evaluation for individual stations as well as spatially (state-wide).

Keywords Climate change • Land surface models • Regional climate models

Introduction

With ever increasing evidence of climate change, future decision-making among crop modelers and agronomists will require the inclusion of climate predictions in agricultural system simulation models to assess the impacts of projected ambient CO₂ increments and attendant climatic changes on crop production. These agricultural simulation models rely on predictions from Global Circulation Models (GCMs) to provide useful climatic and weather data to simulate crop responses. Water resource planners require accurate runoff estimates to develop safe and secure structural designs that incorporate the effects of climate change and variability. They also need to make informed decisions on energy production levels, instream flows, water supplies and water quality.

Several researchers (e.g., Brown et al. 2000; Mearns et al. 2001; Easterling et al. 2001; Niu et al. 2009; Ko et al. 2010; among many others) have used agricultural system simulation models to assess the impacts of projected ambient CO₂ increases and resultant climatic change on crop production. These crop models require weather data as inputs, and the sources of future weather data are predicted weather patterns from General Circulation Models. However, there are concerns about the “input-data-induced uncertainties” (Niu et al. 2009, p. 268) that reduce the confidence in results and thus, threaten the usefulness of the output generated from crop simulation models.

Concerns about the reliability of the output data from GCMs, especially at the 100 km spatial scale typically used in them. Of particular interest, GCMs rely on Land Surface Models (LSMs) to estimate surface gas exchange fluxes. LSMs utilize algorithms to estimate energy fluxes such as Latent Heat (LE), Sensible Heat (SH) and Soil Heat Flux (G). Clearly both agriculture and water resources will benefit from improved predictions of future climate. Land Surface Models are used to compute the hydrological, biogeophysical and biogeochemical processes involved in latent, sensible and soil heat land surface-atmospheric fluxes (Wei et al. 2009). A wide range of LSMs are currently in use today, each varying in their temporal and spatial scales and especially in their degree and type of physical parameterization. Unfortunately, even with the same forcings from the atmosphere; latent, sensible and ground surface fluxes can vary considerably from one LSM to another because they differ in their varied levels of complexity and their description

of relevant processes; thereby introducing differences in simulated weather variables (e.g., PILPS, Pitman et al. 1999; Wei et al. 2009; Evans et al. 2005).

This purpose of the study was to evaluate weather variables generated from computer simulations using two land surface models, (LSMs) coupled to a regional climate model, namely, Weather Research Forecasting (WRF 3.2). The land surface models tested are the Community Land Surface Model CLM 3.5 and the Noah Land surface model. Ground truth observations from 7 stations in Nebraska from a dry year, a normal year and a wet year (2002, 2005 and 2008 respectively) were used to evaluate the model results. Additionally, spatial and temporal precipitation predictions were evaluated using the Precipitation-elevation Regressions on Independent Slopes Model (PRISM) daily estimates (Daly et al. 1994). The better LSM would be recommended for future weather variable predictions.

Expected Climate Trends for Nebraska

Throughout history the Earth's climate has seen changes at various scales; local, regional and global. It is expected to continue changing and this changes are being exacerbated by anthropogenic activities such as burning of fossil fuels which have been documented to result in global warming (HPRCC 2013; Bathke et al. 2014). Nebraska with its continental climate, experiences a lot of variability in its climate from year to year. Long term historical records for Nebraska, prove that average annual temperatures have been changing over time and that the annual temperature has risen by about 0.6 °C (HPRCC 2013).

It is projected that by the end of this century with the range of representative concentration pathway scenarios (low to high), Nebraska's temperature is projected to increase from 2.22–2.78 to 4.44–5.00 °C. Additionally, the number of days above 55.6 °C (temperature stress days) is projected to increase by 13–15 to 22–25 additional days over the lower to higher spectrum of emissions (Bathke et al. 2014; Wilhite 2014). Occurrences of high temperatures will “become typical” (Wilhite 2014) by the middle of this century and the “number of warm nights” (Bathke et al. 2014; Wilhite 2014) is to be expected. The probability of frost during the growing season will reduce and the growing season will increase by approximately 2 weeks (Bathke et al. 2014; Wilhite 2014). With regard to rainfall, annual precipitation is projected to remain unchanged however, in the summer, rainfall is expected to decrease. The frequency and severity of droughts is expected to increase with increasing temperatures. For instance, in 2003 and 2012, Nebraska experienced drought during the growing season (April–October). During those years, increased water abstraction from the Ogallala aquifer for the purposes of irrigation, increased (Hornbeck and Keskin 2014). With these climatic projections and trends in mind, pragmatic decision-making among food producers will require the inclusion of the aforementioned climate predictions to assess the impacts of projected ambient CO₂ increments. Reliable weather predictions using both

regional and land surface models, are therefore very essential in a bid to adapt to climate variability and change.

Case Study of Nebraska

In order to compare and evaluate the two Land Surface Models (LSMs) coupled to a regional climate model, a region centered on the state of Nebraska was selected (Fig. 2.1). Seven of Nebraska's weather stations with long historical records of ground truth data were used for point weather data evaluations. These stations are shown in Fig. 2.1. The 3 years selected for the LSM comparison studies included: 2002, 2005 and 2008 which were dry, average and wet respectively. The level of wetness was based on statistical long-term historical HPRCC weather data.

The Precipitation-elevation Regressions on Independent Slopes Model (PRISM) daily estimated rainfall amounts (Daly et al. 1994) were utilized to evaluate spatial and temporal rainfall patterns. These datasets are provided at approximately 4.4 km spatial resolution gridded datasets and have been developed by scientists at the Spatial Climate Analysis Service of Oregon State University. They are available online at <http://www.ocs.orst.edu/prism/docs/meta/>. Daly et al. (1994) employed a statistical topographic-precipitation relationship to interpolate station observations and fill in rainfall distribution data for areas whose terrain is intricate.

Weather Research Forecast (WRF) runs were conducted for April through October for each of the individual 3 years. A horizontal grid size resolution of

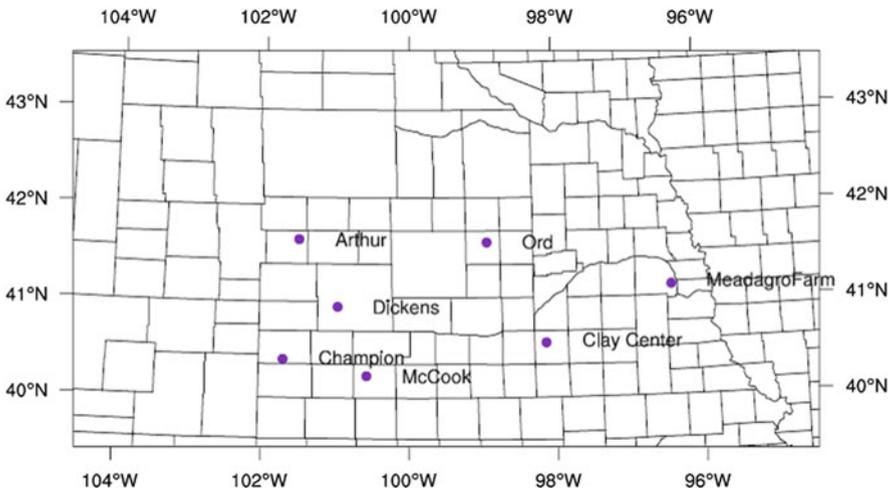


Fig. 2.1 Seven automated weather data network stations selected for evaluation of WRF-Noah and WRF-CLM3.5 weather prediction capabilities. *Source:* Author's figure developed using National Center for Atmospheric Research (NCAR) Command Language (NCL)

12 km and 27 vertical sigma levels were used in the runs. NCEP North American Regional Reanalysis (NARR) ds608.0 (<https://rda.ucar.edu/>) data, at 32 km horizontal resolution, were used for both lateral and lower boundary and initial conditions. The physics options that were applied for both the LSMs; CLM3.5 and Noah runs were similar apart from the number of soil layers and the surface layer option. For the CLM3.5 land surface model, 10 soil layers were included in the simulation while in the Noah runs 4 soil layers were simulated. The Noah land-surface model was represented using option 2 or the unified Noah land-surface model while option 5 was used to represent the CLM3.5 land surface model.

Both models used the WSM 5-class scheme (Hong et al. 2004) as the preferred microphysics option to estimate surface rainfall employing both its atmospheric moisture and heat tendencies. The shortwave radiation option chosen was that developed by Dudhia (1989) to estimate amount of energy absorbed, scattered and reflected from the surface relative to the cloud cover, vegetation, land surface characteristics such as albedo. The Rapid Radiative Transfer Model (RRTM) described longwave radiation transfer in the atmosphere to and from the earth's surface (Mlawer et al. 1997). The Monin–Obukhov surface layer scheme with its universal stability correction was selected for momentum, heat and moisture flux estimates. It was linked to the Yonsei University (YSU) boundary layer scheme that has an explicit entrainment layer that estimates transportation of mass, moisture, and energy. The new version of the Kain–Fritsch Scheme (tested in the Eta model) was selected for estimations in cloud formation, heat redistribution and precipitation estimations.

WRF Model

The Weather Research and Forecasting (WRF) Model, a mesoscale numerical weather prediction system, provides both operational forecasts and atmospheric research requirements (Skamarock et al. 2008). It shares several features with global climate models with respect to parameterizations of physics and dynamics. The main difference between GCMs and Regional Climate Models (RCMs) is the spatial and temporal resolutions at which they operate (smaller time steps and smaller grid point spacing for RCM). RCMs need to assimilate initial conditions and lateral boundary from reanalysis and/or GCMs (Evans et al. 2005). An essential feature of a regional climate model is the need to simulate land surface—atmosphere fluxes of energy, moisture, and momentum. This is typically handled via a Land Surface Model (LSM) component. WRF provides several LSM options. Available LSMs differ in their degree of complexity in estimating moisture and heat fluxes in various layers of the soil and in their “vegetation, root, and canopy effects and surface snow-cover predictions” (Skamarock et al. 2008, p. 73). The two specific ones evaluated in this study are described below.

Noah Land Surface Model

The Noah Scheme is one of the ‘second generation’ LSMs of the Advanced Research WRF (ARW) GCM that relies on both soil and vegetation processes for water budgets and surface energy closures (Wei et al. 2009). The model has evolved from the original Oregon State University (OSU) Land Model that was created in the 1980s (Mahrt and Pan 1984). It can simulate soil and land surface temperature, snow depth and snow water equivalent, both water and energy fluxes among others (Chen and Dudhia 2001; Ek et al. 2003; Feng et al. 2008). The model has four distinct soil layers (0.1, 0.3, 0.6 and 1.0 m) that reach a total depth of 2 m and one vegetation canopy layer. The Noah Scheme, which is commonly incorporated in WRF, utilizes the Penman equation to estimate potential evapotranspiration (PET). It has 16 soil and vegetation parameters that are employed to estimate soil temperature, soil moisture, snow cover and atmospheric feedbacks (Evans et al. 2005). In Noah; snow, vegetation and soil are all modeled as a single unit (Slater et al. 2007) over the whole grid box.

Community Land Model (Version 3.5): CLM3.5

The CLM3.5 is a sub-global vegetation land surface model (Collins et al. 2006) developed by the National Center for Atmospheric Research (NCAR) to serve as its Community Climate System Model (CCSM). It is a ‘third generation’ model and incorporates the influence of both nitrogen and carbon in the computations of water and energy fluxes. It was improved from the NCAR Community Land Model version 3 (CLM3) by adopting a sophisticated surface albedo scheme (Dickinson et al. 2006; Jin and Miller 2010) and enhancing its terrestrial water cycle (Oleson et al. 2008; Stöckli et al. 2008). The CLM3.5 improves the characterization of the land surface by subdividing each CLM3 cell into 8 sub-cells, thereby improving the accuracy of water and energy flux estimations between the land surface and atmosphere. Twenty-four land cover types and 10 soil layers are employed within the CLM3.5. Additionally cropped lands are characterized by their leaf area index, vegetation fraction and roughness height (Kueppers et al. 2008). The current vegetation dataset applied in CLM3.5 is based on a remotely sensed fractional vegetation cover dataset which is comprised of seven primary plant functional types (Bonan et al. 2002).

As this paper goes into publication, it is important to note that a new ‘official’ release of WRF3.5 is coupled to the newly released CLM4.0 (Kluzek 2013).

Results

Maximum and Minimum Temperature

The highest average temperature over the 2002, 2005 and 2008 Growing Seasons (GS) occurred during 2005 (Table 2.1). The lowest average GS temperatures recorded over the three study years 2002, 2005 and 2008 occurred in 2002. Minimum temperatures ranged between 280.6 and 285.2 K over the duration of the study (April–October) for all seven stations. In 2005, McCook, located in the south-western part of the state recorded the highest average GS temperature of 300.0 K while Arthur at the highest elevation recorded the lowest average maximum temperature (296.9 K) among the seven stations. During the year 2008; Arthur, Champion, Dickens, MeadagroFarm, Ord and Clay Center reported lower temperatures (0.56–1.29 K) than the 30-year climatological temperature recorded (source: hprcc.unl.edu Accessed 27th June 2013).

Precipitation

The year 2002 was a drought year in Nebraska, especially in the western parts. The average growing season (GS) rainfall for the seven stations was 318 mm in 2002. The year 2005 was moderate GS precipitation (467 mm) (Table 2.1) while the year 2008 received the highest amounts of GS precipitation (above normal—611 mm). The only CLM prediction that stood out conspicuously was in Champion in 2005 where the WRF-CLM3.5 prediction was about 260 mm above the actual observation while the WRF-Noah prediction stood at about 141 mm above the ground truth measurements. Apart from this incidence, WRF-CLM3.5 predicted rainfall totals compare much better to station observations than WRF-Noah. The largest over predictions by the Noah-WRF model occurred in 2005 for Clay Center (471 mm), Meadagrofarm (813 mm) and McCook (331 mm). WRF-CLM performed better with total rainfall predictions for Clay Center (+354 mm), Meadagrofarm (+492 mm) and McCook (+236 mm) above the observed values. The only significant rainfall total under-prediction by CLM and Noah LSMs occurred at Dickens Station in 2008.

Grid point precipitation estimate totals of the June, July and August [JJA] totals from both the WRF-CLM3.5 and WRF-Noah coupled models were compared to those from PRISM seasonal totals. Figure 2.2 illustrates the relative differences between WRF-Land Surface Model and PRISM observations for the years under study. WRF-CLM3.5 total GS rainfall predictions were lower than those of the WRF-Noah predictions. Over-predictions of about 2.5-fold, were generally common in the southeastern lower-elevation areas of Nebraska. However, the level of over-prediction was both quantitatively larger and spatially extended for the

Table 2.1 Precipitation, minimum and maximum temperature observations over the 2002, 2005, 2008 growing seasons (1st April–31st October) for Arthur, Champion, Clay Center, Dickens, McCook, MeadagroFarm, and Ord, Nebraska

Station	Actual observations											
	Precipitation (mm)			Minimum temperature degrees Kelvin			Maximum temperature degrees Kelvin					
	2002	2005	2008	2002	2005	2008	2002	2005	2008	2002	2005	2008
Arthur	Sum	262.000	407.714	412.289								
	Average	1.224	1.905	1.927	281.480	281.645	280.807	296.540	296.885	295.937		
Champion	Sum	193.534	420.520	446.278								
	Average	0.904	1.965	2.085	281.575	281.279	280.623	298.786	298.865	297.376		
ClayCenter	Sum	393.000	381.496	698.902								
	Average	1.836	1.783	3.266	283.957	284.511	283.198	297.821	298.987	296.626		
Dickens	Sum	191.754	560.846	624.080								
	Average	0.896	2.621	2.916	282.296	282.170	281.227	298.767	298.338	296.849		
McCook	Sum	300.485	428.996	571.244								
	Average	1.404	2.005	2.669	284.046	283.937	282.716	299.770	300.019	298.355		
Me adagro Farm	Sum	491.992	467.553	865.937								
	Average	2.299	2.185	4.046	284.712	285.220	284.023	298.447	299.317	297.291		
Ord	Sum	393.000	578.152	659.156								
	Average	1.836	2.702	3.080	283.365	283.557	282.346	297.481	298.134	296.389		
Average		317.966	463.611	611.127	283.062	283.189	282.134	298.230	298.648	296.975		

Notes: Data source: Daily precipitation, minimum and maximum temperatures for each station were obtained from the High Plains Regional Climate Center (HPRCC) www.hprcc.unl.edu. Table source: Sum and average station weather values for the growing season (April–October) were calculated by author

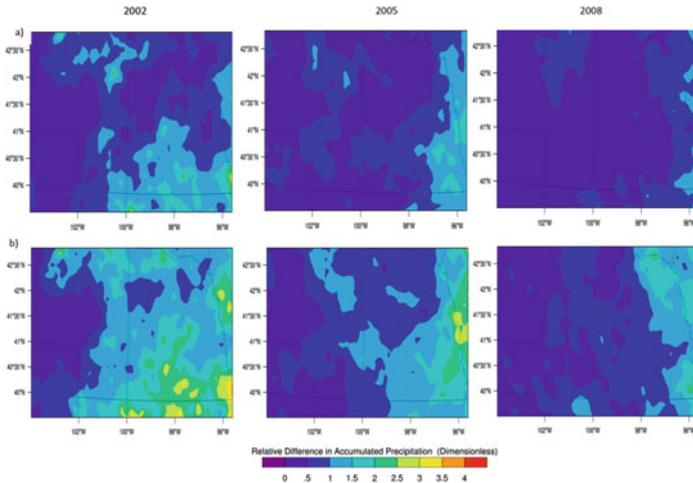


Fig. 2.2 Relative difference of (a) WRF-CLM and (b) WRF-Noah to Precipitation-elevation Regressions on Independent Slopes Model (PRISM) seasonal growing total precipitation (mm) over Nebraska during a dry year (2002), moderate year (2005) and wet year (2008). *Source* of observed data: Observed precipitation values from the Oregon State University, PRISM www.prism.oregonstate.edu were downloaded and summed for the growing season (April–October). *Source of graphics:* Relative differences were calculated and graphic visualizations were conducted by author using National Center for Atmospheric Research (NCAR) NCL

WRF-Noah precipitation model prediction results as compared to WRF-CLM3.5 precipitation totals and daily station observations.

Verification of Temporal and Spatial Distribution of WRF-LSM Coupled Temperature and Precipitation

The standard error of estimate (STEYX) associated with utilizing weather variables from a reference site to estimate data for adjacent sites was used to compare the corresponding ability of the WRF-CLM3.5 and CLM-Noah models ability to mimic the spatial structure of observed weather data. Using Champion as the reference site, the STEYX for precipitation, maximum and minimum temperature for the adjacent stations were calculated and plotted against the distance between Champion and the each of the other six stations (Fig. 2.3). STEYX increased with distance as expected. However, both the model results exhibited lower STEYX for maximum and minimum temperatures and did not adequately mimic the observed spatial variability resulting from non-uniform terrain, varied land use types and management; that may have resulted in complex atmospheric conditions on the ground.

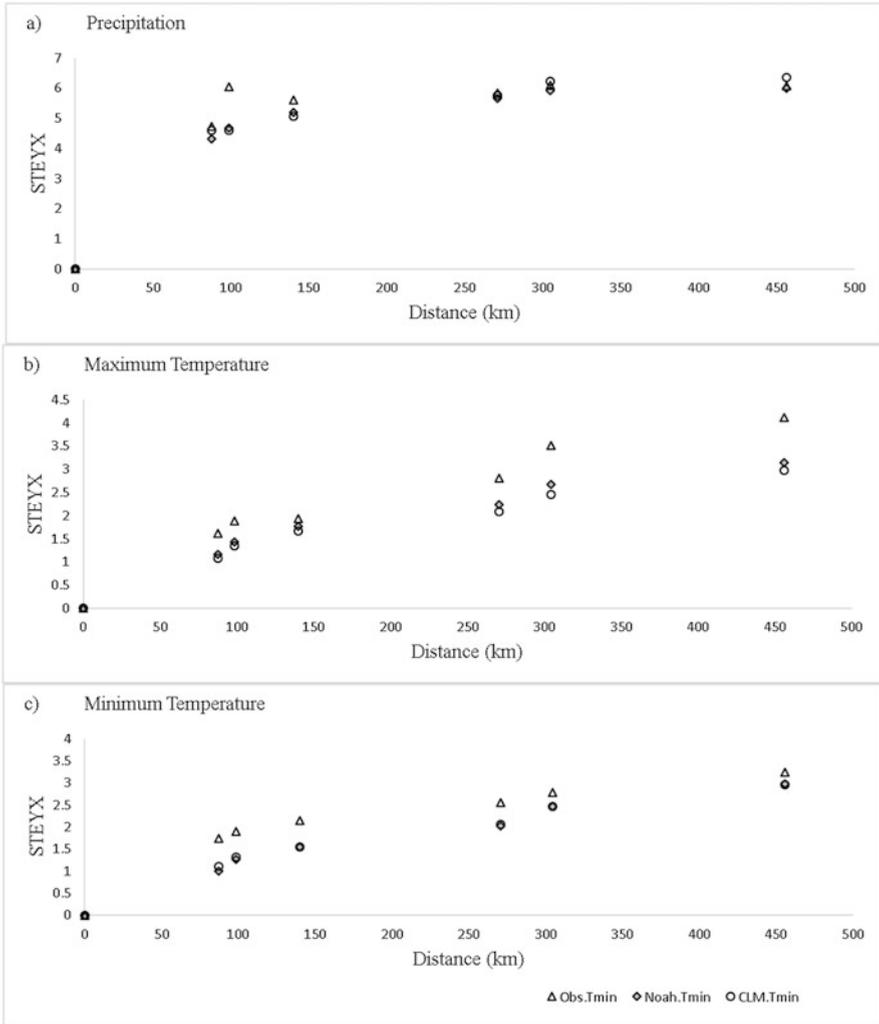


Fig. 2.3 Comparison of errogram for observed, WRF-CLM3.5 and WRF-Noah’s precipitation, minimum and maximum temperature observations over the 2002, 2005, 2008 growing seasons (1st April–31st October) for Arthur, Champion, Clay Center, Dickens, McCook, MeadagroFarm, and Ord, Nebraska. Source: Authors’ calculations

Discussion

Generally, there was a high correlation (>0.88) between the observed historical recorded temperature values and modeled predictions from both WRF-Noah and WRF-CLM3.5 for all the seven sites. However, WRF-CLM3.5 was always superior in predicting both daily maximum and minimum temperatures over the entire

growing season (GS) for all the weather stations with an average root mean square difference (RMSD) of 3.55 K as compared to RMSD of 4.14 K for WRF-Noah.

Model predictions of maximum temperature tended to be more accurate during the summer months of June, July and August when the atmosphere is more homogenous, with minimal occurrences of cold fronts. It was also noticeable when comparing monthly averages, that model predictions of minimum temperature were noticeably most accurate (for both models) in the months of May and October (data not shown here). However the WRF-Noah minimum temperature estimates were consistently higher than WRF-CLM3.5 and observed values for all weather stations. Overall, the models performed better at predicting maximum temperatures than minimum temperatures. However, WRF-CLM3.5 was more accurate than WRF-Noah in both minimum and maximum temperature predictions as depicted by higher correlations and lower RMSD values when compared to actual values.

Generally, both LSMs over-predicted rainfall. WRF-CLM3.5 rainfall predictions, however, were closer to actual ground truth observations and PRISM estimates. Nevertheless, better rainfall predictions were realized during the months of April and May when convective (parameterized) precipitation is less important. Duffy et al. (2003), as cited in Caldwell (2010), likewise noted that during the fall and winter precipitation, predictions improved when convective precipitation was of less importance. According to other regional climate model studies [such as Done et al. (2005)], predicting warm season rainfall in continental regions is much harder over the summer than during cooler times of the year. Done et al. (2005) simulated warm season rainfall using WRF and determined that “*the longer-timescale feedback mechanisms are not being represented accurately in climate simulations*”. Among candidate mechanisms that they recommended for further testing was convective cloud-radiation feedback (Done et al. 2005). The results of this study likewise demonstrate that precipitation estimates became more variable for both land surface models during the months of June, July and August (data not shown here).

The methods used by Regional Climate Models (RCMs) to generate precipitation are affected by boundary conditions and the model physics are very complicated and far from perfect. For example, other studies such as that conducted by Davis et al. (2006), concluded that WRF rain errors “suffer from a positive size bias that maximizes during the later afternoon”. Additionally, WRF-land surface models “dramatically overestimated” precipitation (Jin et al. 2010) in the western United States. The usefulness or utility of precipitation estimates from (RCMs) within crop growth models is hampered by the unrealistic intensity and frequency distributions of precipitation. In order to utilize data from RCMs, rainfall predictions need to be adjusted or corrected for biases. If corrected values are as close to reality as possible, there is promise for applying data from RCMs in crop yield simulation runs to make predictions into the future of agricultural production. The daily variations of rainfall affect crop growth significantly and crop growth simulations will only be as accurate as the input weather variables that drive the crop growth models.

This study also highlights the fact that even with perfect models, the nature of nonlinear atmospheric processes and initial boundary conditions have a large part to play in the data generated by the climate model. Inherent systematic biases exist within WRF model. The complexity of the land surfaces and changes in land use; are not adequately represented at the coarse spatial resolution of the models. The computations conducted by the models do not give accurate estimates of complex biophysical processes.

Conclusion

The study herein examined two land surface models (Noah and CLM3.5) coupled to a regional climate model, namely, WRF. Initial, lateral and boundary conditions were similar. What followed was the selection of an LSM scheme. The study did not examine any internal errors or biases that the regional climate model may have through its model physics.

Both LSMs performed well in predicting the maximum and minimum temperatures in 2002, 2005 and 2008. Generally, there was a high correlation (>0.88) between the observed historical temperature values and modeled predictions from both WRF-Noah and WRF-CLM3.5 for all the seven stations. However, WRF-CLM3.5 was always superior in predicting temperature as demonstrated by the lower standard errors over the entire growing season (GS) for all the weather stations. WRF-Noah minimum temperature estimates in particular were consistently higher than WRF-CLM3.5. Rainfall predictions by both models were not as reliable, based on evaluation for individual stations as well as spatially (state-wide). Both WRF-Noah and WRF-CLM3.5 models over predicted rainfall spatially and temporally. Generally, WRF-Land Surface model precipitation prediction skills tended to be lower in the south-eastern parts of the state. The systematic errors within the WRF model's convective schemes require more research.

From the overall comparisons of temperature and rainfall weather variables (results above), we are able to determine that coupling WRF to the CLM3.5 produces results or predictions that are more accurate than those of the WRF-Noah combination which is attributed to better soil moisture parameterizations within CLM3.5. Closer observations at specific monthly standard errors may help pinpoint areas of weakness within model computations, internal WRF model error biases and sensitivities of model parameterizations. It is envisioned that further comparisons with surface and atmospheric observations will guide the formation and revision of algorithms that reduce biases thereby improving the quality of global and regional climate models in the future.

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