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Surface radar-derived convective rainfall associations with Midwest US land surface conditions in summer seasons 1999 and 2000

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Abstract Previous research has suggested that spatial heterogeneities in soil moisture and/or vegetation cover promote the development of convective clouds. We examine the intensity of convective precipitation for the Midwest US Corn Belt in the summers of 1999 and 2000, which had contrasting synoptic circulation, atmospheric humidity, and soil moisture conditions. For days when synoptic scale atmospheric forcing is weak, we calculate a convective severity index (CSI) based on radar reflectivity composite values. Our results suggest that boundaries between soil types, and cropland and forest vegetation types in the western portion of the Corn Belt, enhance the development of convective precipitation. In the eastern part of the Corn Belt, less convection occurs, but we find a positive correlation between the intensity of convection and soil moisture conditions. Our results also demonstrate that the CSI is a simple yet effective technique for identifying where deep convection occurs relative to lighter precipitation.

1 Introduction

The extent to which land surface conditions affect the development of convective clouds and precipitation is a subject of contemporary climate research, especially for interior continental locations during the warm season (e.g., Carleton et al. 2008a, b). Modeling studies have investigated soil moisture influences on precipitation generation for both moist and dry environments over a range of spatial scales and have shown that the spatial heterogeneities can initiate convective rainfall when environmental (i.e., free atmosphere) winds are weak (Yan and Anthes 1988; Oglesby and Erickson 1989; Fast and McCorcle 1991; Chen and Avissar 1994a, b; Giorgi et al. 1996; Lynn et al. 1998). Other studies have shown that vegetation type plays an important role in increasing convective precipitation through the enhancement of evapotranspiration and alteration of the boundary-layer wind circulations (Blyth et al. 1994; Clark and Arritt 1995; Bonan 2001; Carleton et al. 2001). In particular, many of these studies have demonstrated that the boundaries between dry and moist soils, and cropland and forest land covers, can initiate mesoscale vertical air circulations that increase convective cloud development. However, few observational studies have investigated the resulting intensity of the convective precipitation.

Spatio-temporal differences in soil moisture content can affect the planetary boundary layer depth and other attributes, such as its stability, via the generation of "non-classical" (i.e., non-sea breeze) mesoscale circulations (NCMCs). Deep convection may be particularly favored over and near alternating bands of moist and dry soils (Yan and Anthes 1988; O'Neal 1996; Travis 1997; Brown and Arnold 1998; Lynn et al. 1998; LeMone et al. 2007). Chen and Avissar (1994a) explained that the lower Bowen ratio over wetter soils may induce a differential heating rate with respect to adjacent dry soils, giving rise to strengthened horizontal temperature gradients. Giorgi et al. (1996) stated that these local scale

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latent and sensible heat fluxes differentiated by surface type may be important in the development or persistence of droughts and wet periods. Atmospheric latent heat increases with greater evaporation of moisture from wet soils and provides additional moisture for cloud development and precipitation, as well as greater convective available potential energy. Alternately, when the atmosphere is sufficiently moist, dry soils can contribute to convective cloud formation through upward vertical motion due to increased surface sensible heat, or greater Bowen ratio (Rabin et al. 1990). When the atmospheric moisture content is low, a reduction in soil moisture may be associated with increased surface temperature, lower surface pressure, and increased ridging aloft, which tends to enhance the surface drying as a positive feedback loop (Oglesby and Erickson 1989).

Several studies suggest that vegetation cover also enhances convective development, especially over otherwise flat surfaces, and may promote precipitation (e.g., Anthes 1984). Clark and Arritt (1995) found that a modeled vegetation cover initiates convection due to its higher soil moisture content and reduces conduction of heat into the soil due to shading of the soil surface. O'Neal (1996) observed that convective clouds in the central USA occur more frequently over forested regions than over croplands. Blyth et al. (1994) modeled the boundary layer over forest-covered surfaces and found a 30% increase in precipitation amounts compared with bare soil. Half of this increase (i.e., 15%) was from the re-evaporation of precipitation, or "recycling", while the other half was attributed to the greater roughness length of trees, which leads to enhanced vertical motion of air. Carleton et al. (2001) investigated summertime convective cloud development in the US Midwest associated with croplands, forests, and cropland/forest boundaries and found evidence of NCMC development along the boundaries, given relatively low wind speeds in the free atmosphere.

Possibly because of the need to ensure a lack of topographic relief over wide areas, few empirical studies have sought to estimate the frequency and intensity of convection that is enhanced by quasi-linear heterogeneities in soil and vegetation types. Once comprised of a mix of forests and grasslands, the humid lowlands of the Midwest US Corn Belt (Fig. 1) is one such region of flat terrain. It comprises an important rain-fed agricultural region in the USA and is dominated by corn and soybean production. The heterogeneous mixture of croplands and forests (Figs. 2 and 3) causes moisture gradients to form near the land surface. Moisture gradients form where forests border croplands as the crops require and evapotranspire large amounts of water, contrasted with the situation for the remnant forests, especially in mid to late summer (Twine et al. 2004; Carleton et al. 2008b). Accordingly, Adegoke and

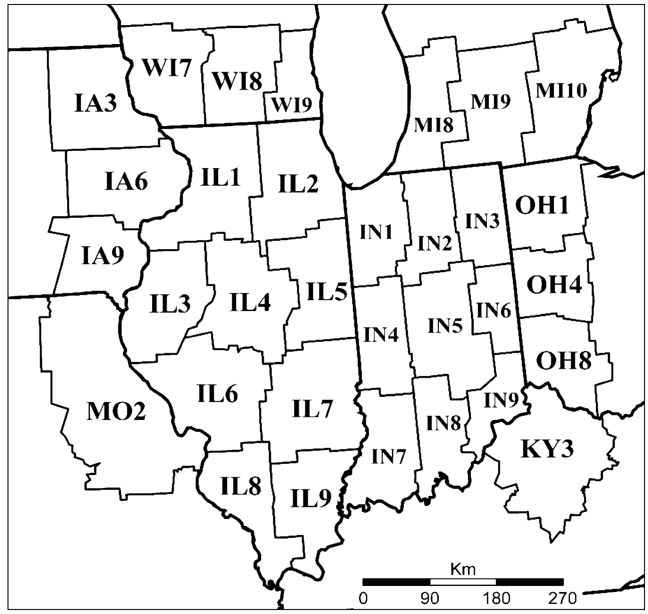


Fig. 1 Climate divisions comprising the Midwest US Corn Belt whose convective activity patterns are examined in the current study

Carleton (2000), among others, have further identified the Corn Belt as an ideal region for examining interactions between the land surface and the atmosphere, because of the heterogeneous arrangement of soil (Hollinger and Isard 1994) and vegetation (Bonan 2001). The area is also subject to interannual precipitation variations, the drought of 1988 and flood of 1993 being the two recent extreme examples (Giorgi et al. 1996). Several researchers have also found the adjacent Great Plains region of North America to be a good location in which to examine land surface/atmosphere interactions (e.g., Giorgi et al. 1996; Baidya Roy et al. 2003; Koster and Suarez 2004; Mahmood and Hubbard 2004). However, the Corn Belt is more humid and

Fig. 2 Example of heterogeneous arrangement of cropland and forest vegetation in the Midwest US Corn Belt; in this case, south-east Iowa

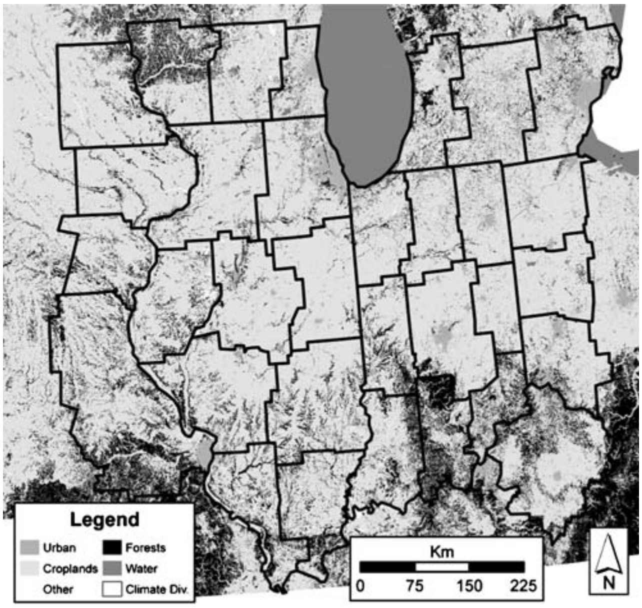


Fig. 3 Corn Belt region land use. Abrupt boundaries occur between agricultural and forested areas while many of the croplands are dotted with small forested patches

has lower rates of evaporation in contrast to the Great Plains (Carleton et al. 2008a).

This study investigates associations between the frequency and intensity of convection and soil and vegetation heterogeneities in the Corn Belt region at the climate division scale. We examine specifically the two consecutive summer seasons of 1999 and 2000, using combinations of radar reflectivity values, atmospheric synoptic data, soil moisture data, and land use/land cover information. These two summers present a good opportunity to examine the influence of the land surface on the formation of convective precipitation as they featured contrasting soil moisture patterns. From June to September 1999, dry conditions dominated the Corn Belt region. Climate forecasters had predicted the following summer of 2000 to be even drier, which prompted many farmers to change their crop schedules (Changnon 2002). However, the somewhat dry soil conditions present in June 2000 changed to normal and even moist conditions by the end of September 2000, due to large amounts of precipitation, especially in southern areas (Carleton et al. 2008a).

Because atmospheric dynamics exert a strong control on the development of precipitation (Oglesby and Erickson 1989; Fast and McCorcle 1991; Blyth et al. 1994; Clark and Arritt 1995; O'Neal 1996), we first identify days in summers 1999 and 2000 when strong synoptic scale forcing was absent. This is undertaken using the approach of Carleton et al. (2008a), which involves determining the category of mid-tropospheric (i.e., 500 hPa) vector wind speed (**V**(500)) for each day over the central part of the Corn Belt ("Central Corn Belt"). We then present the composite atmospheric conditions prevalent when convection occurs on this subset of days. Next, we perform a quantitative analysis of radar reflectivity data for the early morning through early evening periods on days having convection, to determine the frequency and intensity of convective precipitation within the Corn Belt region. For this purpose, we develop a convective severity index (CSI). The CSI represents an advancement on the binary and non-spatial classification procedure used in Carleton et al. (2008a, b) by considering all categories of convective intensity quantitatively. Our analysis also improves upon that of Carleton et al. (2008a, b) in that we analyze soil-type boundaries in addition to vegetation-type (forest, crop) boundaries within the Corn Belt region, for their influence on the CSI values. Our results suggest that the major boundaries between different soil types and vegetation types enhance the development of convective precipitation, particularly on days of relatively weak background wind speed.

2 Midwest study region

The Corn Belt study region comprises 32 climate divisions (Fig. 1), including all of Illinois and Indiana, and adjacent areas to the north, east, and west. This geographical area includes the Central Corn Belt subregion (Carleton et al. 2008a, b), as well as adjacent areas of natural forested vegetation, and is similar to the larger Midwest region examined for land surface–atmosphere interactions during the 1988 drought by Carleton et al. (1994). Our use of climate divisions allows a direct comparison with the weekly Palmer Drought Severity Index, which we use to infer subregional soil moisture conditions during the two summers, along with biweekly measurements of soil moisture for Illinois (Hollinger and Isard 1994). We aggregate the radar reflectivity data to the climate division scale in order to examine land surface–precipitation patterns at larger mesoscales, as suggested by the aforementioned studies, and given a general hypothesis that convection will develop over subareas of the Corn Belt having differences in atmospheric conditions and soil moisture content between the contrasting summers of 1999 and 2000. Because soil moisture content was generally lower during 1999, we expect the convective precipitation occurring to have lower rain rates, yielding lower CSI values, compared to summer 2000. In each year, the analysis period spans June 15–September 30, which is the season of greatest convection in this region. The following two sections discuss the spatial differences in soil moisture and atmospheric conditions in the Corn Belt between the two summers.

2.1 Vegetation and soil conditions

As previously mentioned, the majority of the study region features crops as the dominant vegetation type, but areas of forests exist in many of the climate divisions. To identify which climate divisions have the greatest probability of experiencing enhanced convective precipitation due to the presence of vegetation-type boundaries, we have placed each division into one of three groups: (1) presence of dense forests alongside croplands, (2) heterogeneous mixture of forests and croplands, and (3) less than 10% forest cover is present (Table 1). We expect the highest chance of enhanced convective precipitation to occur where dense areas of forests are located alongside croplands to both create a moisture gradient and where forests may enhance upwards vertical motion, such as within climate divisions IA3 (eastern border), WI7 (middle), and IL6 (western border). Climate divisions featuring less than 10% forest cover, such as IL5 and IN3, may have insufficient forest cover to produce significant moisture gradients. Any moisture gradients forming in climate divisions that feature 10–50% forest cover, but which have a spatial pattern where

Table 1 Characterization of each climate division according to the spatial arrangement of vegetation types and soil types

Climate division	Crop/forest boundary	Mixed crop/ forest	Croplands dominate	Soil-type boundary	Alternating soil-type bands	Dominant soil type
IA3	**X**			**X**		
IA6			X	X	X	
IA9		X			X	
MO2	X					X
WI7	**X**				**X**	
WI8		X		X		
WI9		X			X	
IL1			X		X	
IL2			X	X		
IL3		X			X	
IL4			X		X	
IL5			X			X
IL6	**X**				**X**	
IL7		X		X		
IL8		X				X
IL9		X				X
IN1			X		X	
IN2			X			X
IN3			X			X
IN4	X					X
IN5	X					X
IN6			X			X
IN7	X					X
IN8	X					X
IN9		X				X
MI8	X					X
MI9		X				X
MI10		X		X		
OH1			X			X
OH4			X	X		
OH8		X				X
KY3	X					X

Climate divisions in bold are most likely to experience the enhancement of convective precipitation due to the arrangement of vegetation and soils croplands and forests are heterogeneously mixed (e.g., IL7 and IN9), may feature moisture gradients that do not cover a sufficiently large area to significantly affect the development of convective precipitation.

A similar classification of climate divisions is performed based on the types of soil and their spatial arrangement (Table 1). Alfisols are the dominant soil type in the study region, with mollisols covering much of the western area (Fig. 4). Although both soils can retain high amounts of moisture, alfisols that typically support forested vegetation are generally more moist than mollisols, which traditionally support grasslands. In many areas where mollisols are the dominant soil type, narrow bands of alfisols are also present on scales of 20–30 km. Brown and Arnold (1998) and Travis (1997) suggested that these alternating bands of alfisols and mollisols help promote deep convection in Illinois and Wisconsin. Therefore, we expect heterogeneities in soil moisture to increase convective precipitation development particularly in the northwestern portion of the study region. We hypothesize that climate divisions featuring either a prominent boundary between two soil types (e.g., IA3 and IA6), or that have alternating bands of different soil types (e.g., IA6, IL6), have a higher likelihood of influencing the development of convective precipitation than climate divisions comprised of a single dominant soil type (e.g., IL5 and IN8; Table 1).

We utilize the Palmer Drought Severity Index (PDSI; Alley 1984) to indicate soil moisture at a climate division spatial scale for the entire study region. PDSI is calculated weekly from station precipitation and temperature data

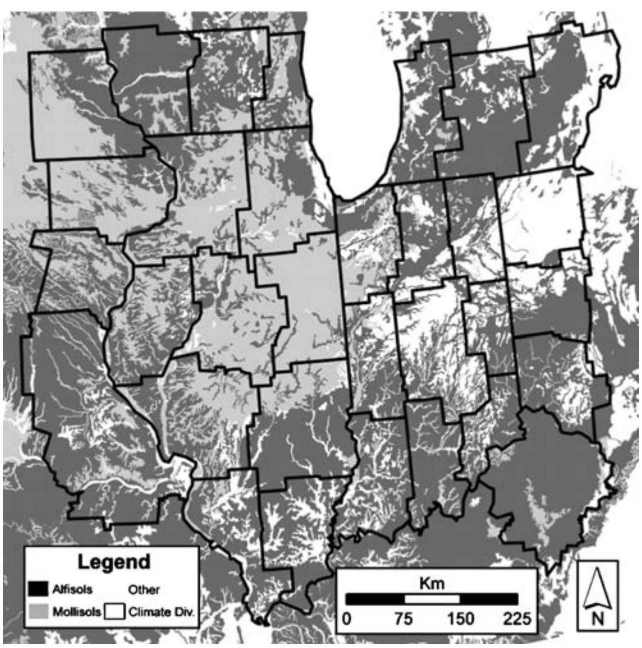


Fig. 4 Study area and surrounding region map of soil types illustrating prominent soil-type boundaries

using a form of the water balance equation. Differences in soil type may not influence the development of convective precipitation when soils within a climate division are wetter or drier than normal for the majority of the study period. Under these conditions, horizontal gradients in soil moisture will not form as all soils in the region may be uniformly wet or dry. When prolonged periods of dry conditions exist in a region, evapotranspiration rates may also decrease, which in turn would decrease the amount of moisture available in the lower troposphere to produce convective precipitation. Throughout June 1999, soils are moist in the northwest part of the study area but dry in the east (Fig. 5a). Maps of weekly PDSI values show that the western half of the study area changes from moist to dry during that summer, while the dry conditions in the eastern region intensify to extreme drought (Fig. 5b). At the beginning of summer 2000, most of the Corn Belt has normal to moderately dry soil moisture levels with moist conditions persisting in the north (Fig. 5c). By the end of the summer, moist conditions exist in the northern and three of the southern divisions, while close-to-normal conditions prevail elsewhere (Fig. 5d).

2.2 Atmospheric conditions

Because strong synoptic forcing likely masks or suppresses NCMCs (Fast and McCorcle 1991), we categorize the days within the two study summers according to **V** (500) (O'Neal 1996) into five classes ranging from weak to moderate to maximum. These classes (Table 2) are based on the spatial range of wind speed values across the Central Corn Belt associated with specific categories of **V** (300) for the same region classified by Carleton et al. (2008a). We stratify each day's combined afternoon and evening period coinciding with the time of maximum surface heating (Tian et al. 2005) into convective or non-convective, based on a qualitative evaluation of Next Generation Weather Radar (NEXRAD) composite radar images obtained online (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?WWNEXRAD~Images2). Days classified as non-convective either lack radar echoes or have very low level reflectivity values indicative of precipitation that would not reach the ground (i.e., virga; Carleton et al. 2008a). As shown in Carleton et al. (2008b), the primary determinant of whether convection develops on a given day in the Central Corn Belt is the sign of vertical motion in the free atmosphere: convection (no-convection) days typically have upward (downward) vertical motion at the 700-hPa level.

The frequency of days exhibiting each flow type and the co-occurrence of convective activity for both summers (Fig. 6) is similar to the results obtained by Carleton et al. (2008a), who utilized 14 fewer days for each summer's

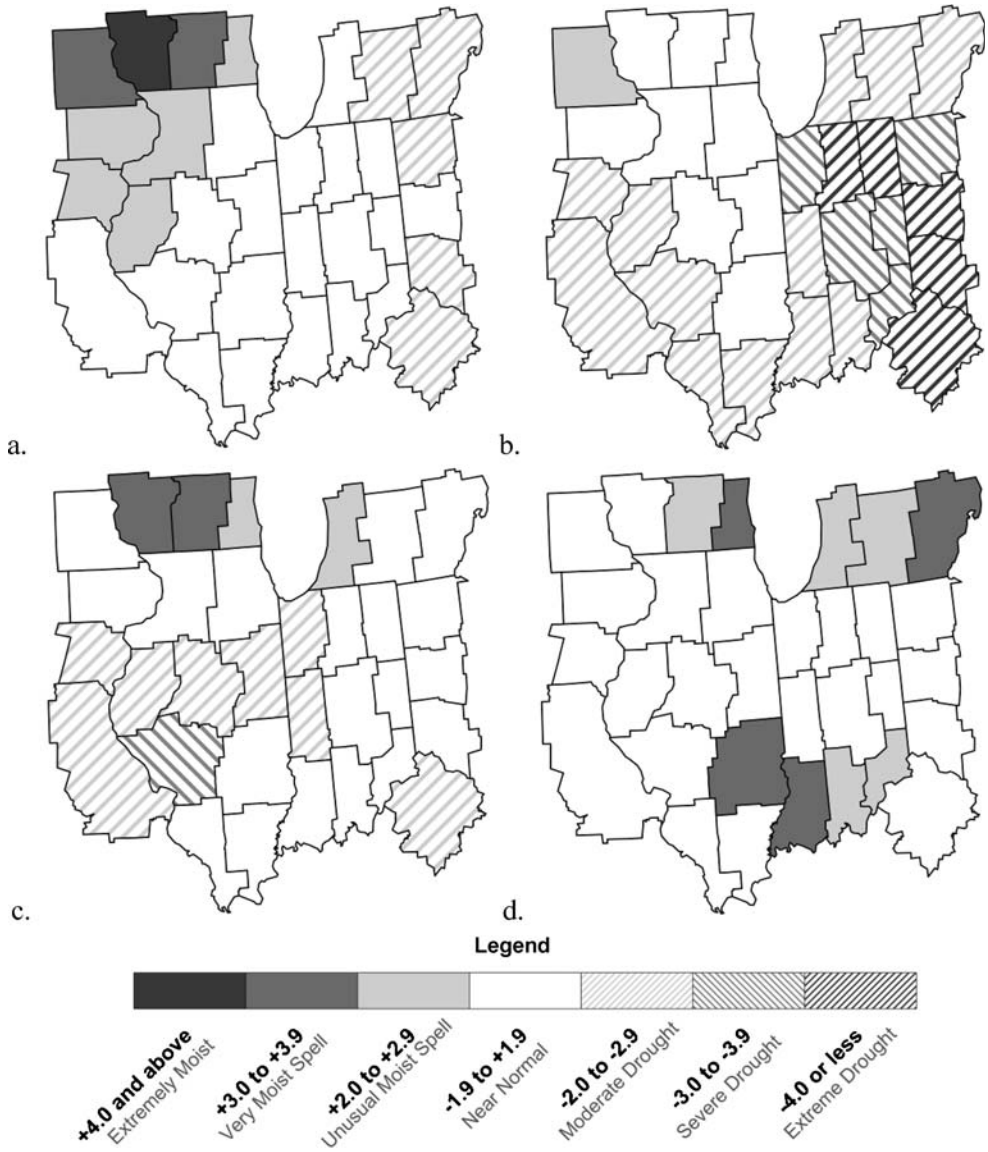


Fig. 5 Weekly Palmer Drought Severity Index maps for the start and end of each study summer: **a** June 12, 1999; **b** Sept. 30, 1999; **c** June 17, 2000; **d** Sept. 23, 2000

analysis (June 15–September 15). Convection is most enhanced on the primary flow-type days of weak, moderate, and maximum in 1999. During the summer of 2000, convection occurs most frequently during weak–moderate flow days. For the present analysis of convective intensity and its possible associations with land surface soil and vegetation conditions, we do not study the non-convective days. The synoptic atmospheric conditions associated with the non-convective day types are presented in Carleton et al. (2008a) and generally have reverse anomalies (e.g., positive values of omega, negative values of specific humidity) to those on deep convection days. Although Carleton et al. (2008a) found possible evidence of land surface forcing even on moderate-maximum and maximum days, which are strongly characterized by atmospheric dynamics (e.g., cyclonic vorticity, upper-air divergence), the current study confines the analysis to the weaker flow days. The convection that forms on the stronger flow days tends to be more widespread and organized and lasts longer than that forming due to land-surface interactions on weaker flow days.

To determine the synoptic atmospheric environments within which deep convection occurred during the weaker synoptic flow days, we composite the NCEP/NCAR

Table 2 Range of wind speeds at 500 hPa over the Corn Belt and average wind speed for each synoptic classification in ms^{-1}

Weak	Weak–moderate	Moderate	Moderate–maximum	Maximum
5-11	4–11	11–17	10–18	13–17
8.5	8.0	14.0	14.5	15.5

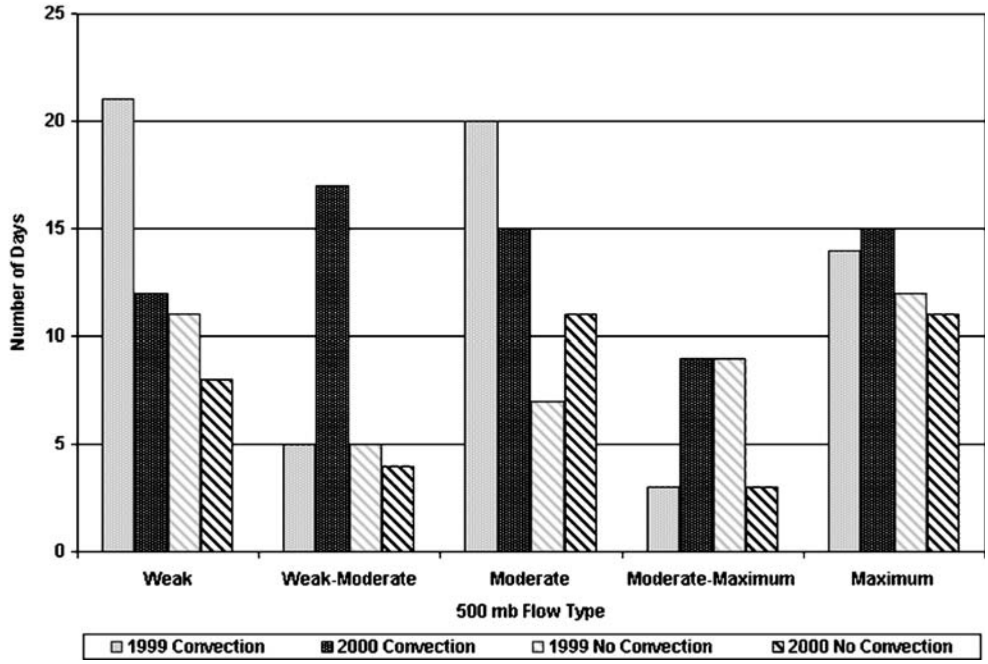


Fig. 6 Graph showing the number of days with and without convection that occurred under each synoptic flow type during the study period

reanalysis daily data (Kalnay et al. 1996) for several atmospheric variables, separately by flow strength category and for each summer. Specifically, we composite anomalies of the *u* wind component (west–east) at 500 hPa, *v* wind component (south–north) at 700 hPa, temperatures and geopotential heights at the 500, 700, and 850 hPa pressure levels; vector wind speeds and specific humidity at the surface and at 850 hPa; sea level pressure, surface temperatures, outgoing longwave radiation (OLR), and model-generated precipitation rates. The anomalies are calculated relative to the means for 1968–1996. Several of these variables are additional to those examined by Carleton et al. (2008a). We utilize the 2.5°×2.5° NCEP/NCAR reanalysis dataset as it is comparable in scale to the climate division radar analysis performed in the current study. We utilize OLR and precipitation rate anomaly data to determine where cumulonimbus clouds were most frequent in each summer and would have produced high rain rates for each atmospheric flow composite. We expect negative (positive) OLR and positive (negative) precipitation rate anomalies within climate divisions having high (low) CSI values. Additionally, we composite specific humidity anomalies at 1,000 and 850 hPa as we expect CSI to be higher where specific humidity anomalies at both 1,000 and 850 hPa are positive, than where moisture is either above normal at only one level, or below normal.

3 Radar analysis and the convective severity index

We determine the location and intensity of convective precipitation within the study area for the two summer seasons by utilizing hourly composite imagery of the NEXRAD network available online from the National Climatic Data Center for the daily periods of greatest surface heating: from 1200 UTC (7:00 AM LST) to 2300 UTC (6:00 PM LST). Although the spatial resolution of this composited radar reflectivity data is coarser than the native level II reflectivity data from which it is derived, it still has a higher temporal resolution than rain gauge measurements, allowing one to track convective precipitation both visually and numerically. It should be noted that a small percentage of the hourly data are missing (see Carleton et al. 2008a), but accommodations for missing data are made in the quantitative analysis of the radar reflectivity returns (see below). We utilize a computer program to accomplish several logistical steps related to the analysis of the NEXRAD data and preparatory to derivation of the CSI, as this provides an objective estimation of the convection present, rather than a less precise visual inspection of the data. First, the program automatically queries and obtains the hourly reflectivity composites from the NCDC website. Next, for each individual image, the program counts the pixels containing a given radar reflectivity level in each image by recognizing the HTML color code for each pixel (Table 3). Each colored pixel is allocated to its climate division by reference to an overlay map, and its intensity is recorded according to four categories of reflectivity: low (5–15 dBZ), medium–low (20–30 dBZ), medium–high (35–45 dBZ), and high (50+dBZ). The use of these four categories permits separation of heavy convection (i.e., highest category) from reflectivity values that might be produced by ground clutter or virga

Table 3 Color codes and their corresponding radar reflectivity values of the NEXRAD "composite" data used to quantify the severity of convection within the study region's climate divisions

Color	HTML color code	Reflectivity value (dBZ)
Cyan	#00FFFF	5
Sky blue	#6698FF	10
Light blue	#0000FF	15
Pastel green	#00FF00	20
Green3	#4CC417	25
Green4	#348017	30
Yellow	#FFFF00	35
Gold1	#FDD017	40
Orange	#FF8040	45
Red	#FF0000	50
Red2	#E41B17	55
Burgundy	#800000	60
Pink	#FF00FF	65
Dark purple	#800080	70

(i.e., lowest category). The numbers of pixels per intensity class are stored by category for each climate division in a geographic information system (GIS).

The CSI provides an area normalization procedure for radar reflectivity across all four intensity categories considered here. The CSI permits areas of heavy convective precipitation to be distinguished from areas receiving little or light precipitation, such as would be expected to fall from stratiform clouds (cf. Alfieri et al. 2008). Each intensity category is assigned a different weight based on its reflectivity range to indicate its importance in the CSI: thus, low (1), medium–low (10), medium–high (50), and high (100). The weights allow the final CSI number to distinguish lighter rainfall (low CSI values) covering large areas from very heavy rainfall (high CSI values), which typically is more localized. This weighting is important in the current study as convection developing in association with smaller-scale features, such as soil and vegetation-type boundaries, may not cover as large an area as convection that is more dynamically forced. The weighted category values are then summed and multiplied by the percent of the climate division having radar returns of any intensity to obtain a CSI that can be compared among climate divisions of different sizes. Although we employ the CSI at the climate division scale in the present study, the method could be utilized at more localized spatial scales in future investigations.

To include days when only 11 of the 12 hourly radar images are available, we calculate the average of the hourly CSI values so that each climate division has one CSI for each day within the study period. Although the averaged CSI values for these days may be slightly lower, this would only be the case if convection was present. Because fewer than 10% of the days in the study period are missing one of the radar images and fewer than half of these days occurred during weak or weak–moderate synoptic forcing, the averaging should not have significantly biased the results. This averaging also allows CSI values to be stratified by the daily **V**(500) categories previously established. Finally, we average CSI values among days with the same background flow strength for both years to obtain a composite seasonal value. The latter procedure allows us to spatially compare the severity of convection among climate divisions and to help identify groups of climate divisions where land surface conditions might have influenced convection during weaker background flow in the two summers.

4 Results

As expected, deep convection occurs more frequently and over a larger area as background wind speeds increase (Fig. 7). Despite the seasonal climate differences between the two summers, on days when synoptic scale forcing is weak or weak–moderate, similarities are evident when considering the regions having highest CSI values. The northwest corner (western portion) of the study region features the highest CSI values during weak (weak–moderate) flow days. Overall, the locations of high CSI occur where vegetation and soil-type boundaries exist and lower tropospheric moisture content is high. Relatively low CSI values exist over the eastern portion of the study region in both summers. We discuss results specific to several climate divisions in Section 5.

On days when synoptic forcing is weakest, the **V**(500) maximum is located farthest from the study region (Fig. 8a, b). During summer 2000, specific humidity, cloud coverage, and precipitation rate anomalies are higher than normal in the northwestern corner of the study region, particularly near the Illinois/Iowa/Wisconsin borders (Fig. 8d). Given that the lower troposphere is very moist, it is not surprising that the highest CSI values occur in this region, where cropland/forest and mollisol/alfisol boundaries also exist. During weak flow days in summer 1999, specific humidity values in the lower troposphere are below normal over most of the study region, and OLR values indicate that cloud coverage is less than normal (Fig. 8c). Under these drier atmospheric conditions, the boundaries between croplands and forests are expected to be ineffective at enhancing rainfall rates indicative of deep convection and, indeed, CSI values are lower than observed during weak flow days in 2000.

For both summers, on days of weak–moderate synoptic forcing, the region of highest **V**(500) wind anomalies is located northwest of the study region (Fig. 9a, b). Specific

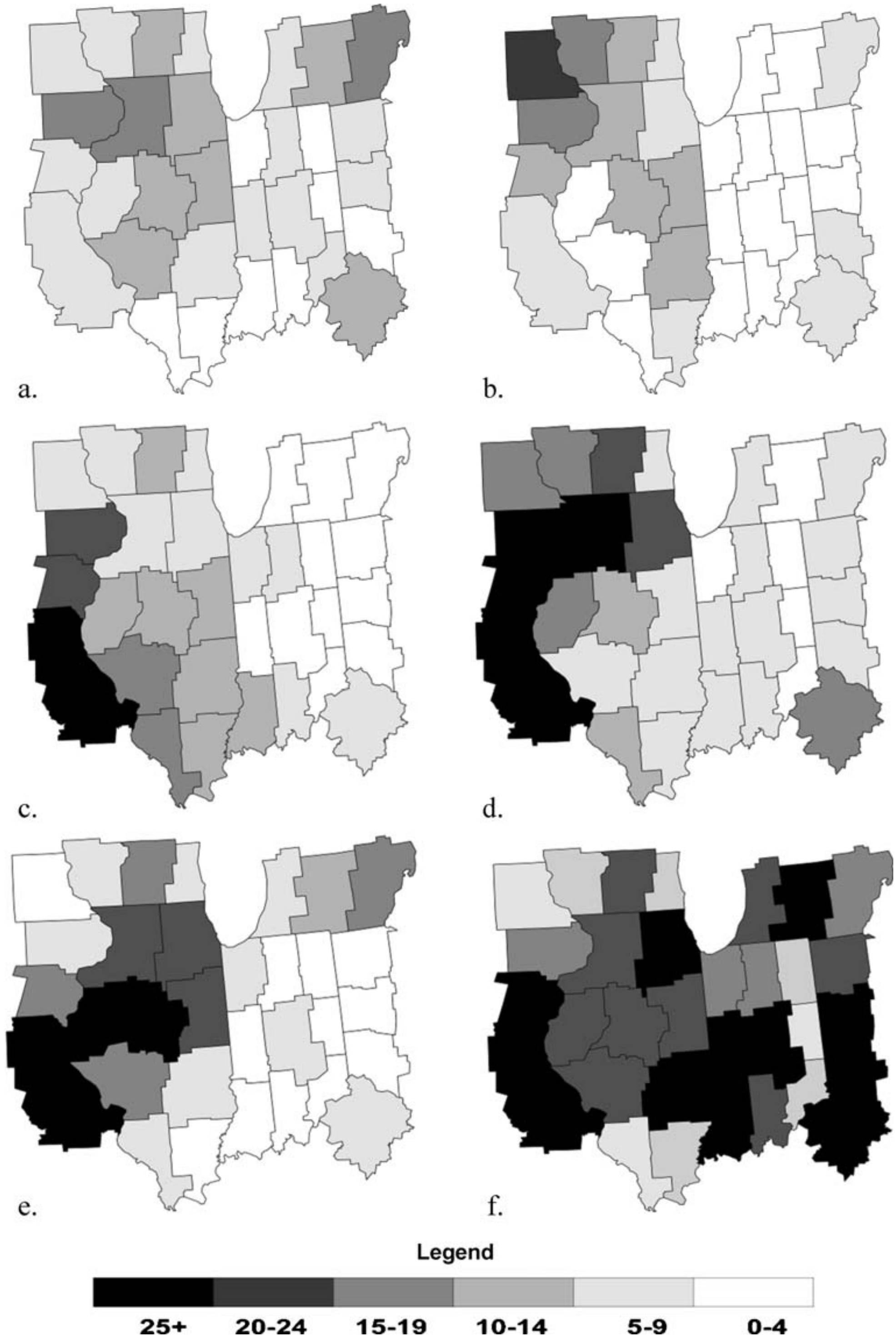
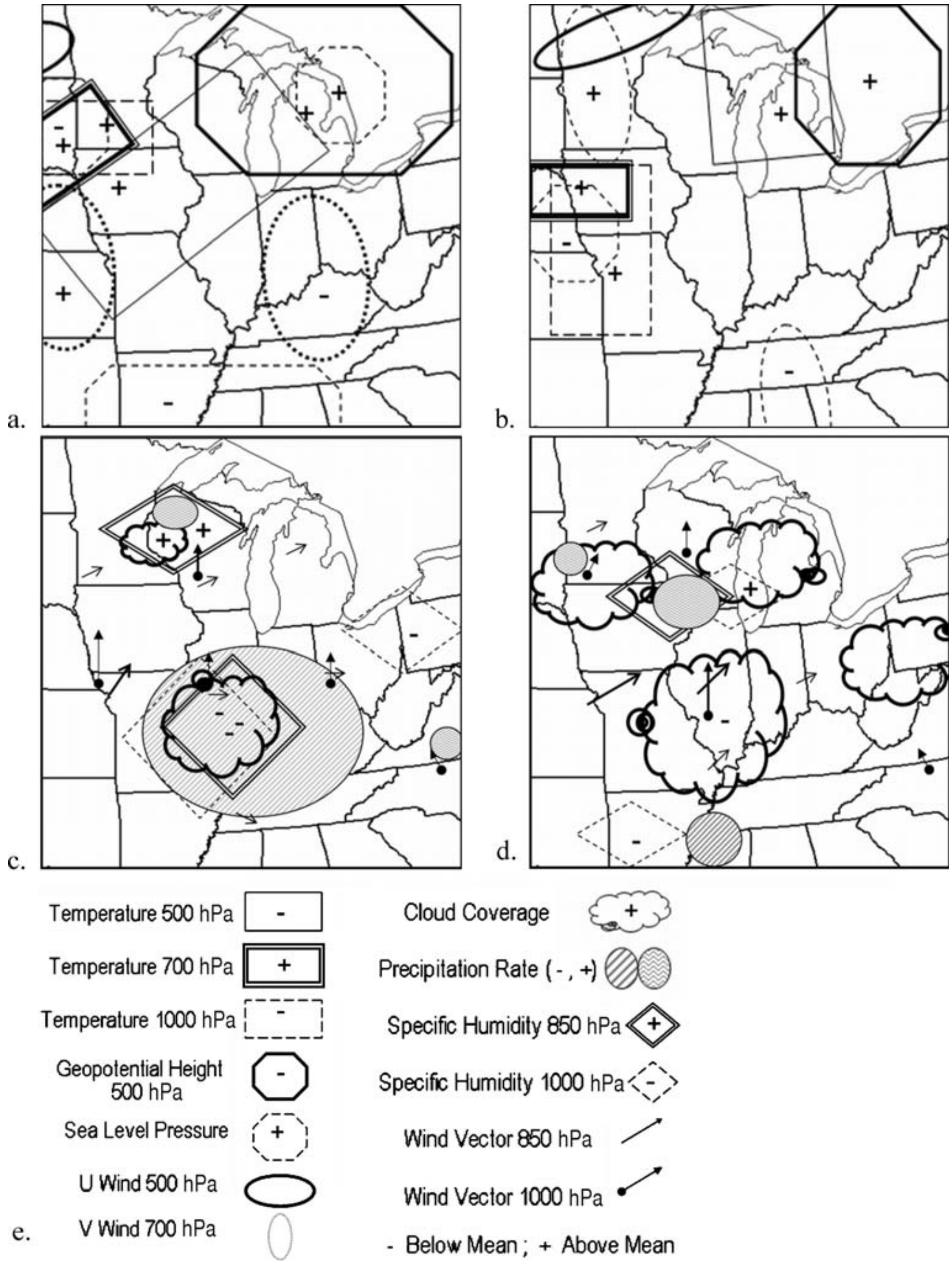


Fig. 7 Convective severity index (CSI) values for each climate division. Higher values indicate that deep convection occurs more frequently in a given climate division. **a** Weak flow 1999, **b** weak flow 2000, **c** weak–moderate flow 1999, **d** weak–moderate flow 2000, **e** moderate flow 1999, **f** moderate flow 2000

humidity values and cloud coverage are higher than normal over the western parts of the study region, although the maximum anomaly values are centered over southwestern (northwestern) Illinois in 1999 (2000; Fig. 9c, d). The peak in specific humidity values during 2000 occurs near the border between Illinois and Wisconsin (Fig. 9d), and CSI values indicate that this area experiences more deep convection during 2000 than during 1999. By contrast, climate divisions in northeast Indiana and northwest Ohio have very low CSI on weak and weak–moderate flow days during both summers.

CSI values are relatively low over the eastern portion of the Corn Belt on weak and weak–moderate flow days in both summers. To more closely investigate the possibility that soil moisture plays a bigger role in determining the amount of convection that will occur in this portion of the

Fig. 8 The geographical extents of peak anomaly values composited for days with weak synoptic scale forcing. Pressure, temperature, and mid tropospheric winds are shown for 1999 (**a**) and 2000 (**b**). Lower tropospheric moisture, winds, cloud coverage, and precipitation rates are for 1999 (**c**) and 2000 (**d**). *Symbols utilized in the figures* are labeled in **e**



Corn Belt, we compare the CSI values to soil moisture data at the 0–10-cm depth available each day from the modeled NCEP/NCAR reanalysis data. After estimating the average soil moisture value for each climate division, we rank the soil moisture and CSI values for each climate division from highest to lowest and calculate Spearman rank correlation coefficients for each ranked set. We perform the analysis for weak and weak–moderate flow days combined for both summers to increase the sample size. Many of the climate divisions in Indiana, as well as eastern Illinois and western Ohio, exhibit statistically significant positive correlations, meaning that CSI is high when soil moisture is also high (Table 4). Results are not statistically significant over the western portion of the study region, where CSI values are higher because deep convection is more frequent and covers a larger area than the eastern portion of the region. Higher humidity in the lower troposphere over the western Corn Belt may play a larger role than soil moisture in aiding the development of the deep convection there.

To confirm the possibility that relatively dry soil conditions existed alongside relatively moist soil conditions in parts of the Corn Belt during both summers, which might have influenced the development of convective precipitation, we obtain measurements of soil moisture at 0–10 cm depth from 17 stations in the Illinois Climate Network. Neutron probe measurements are available biweekly for the

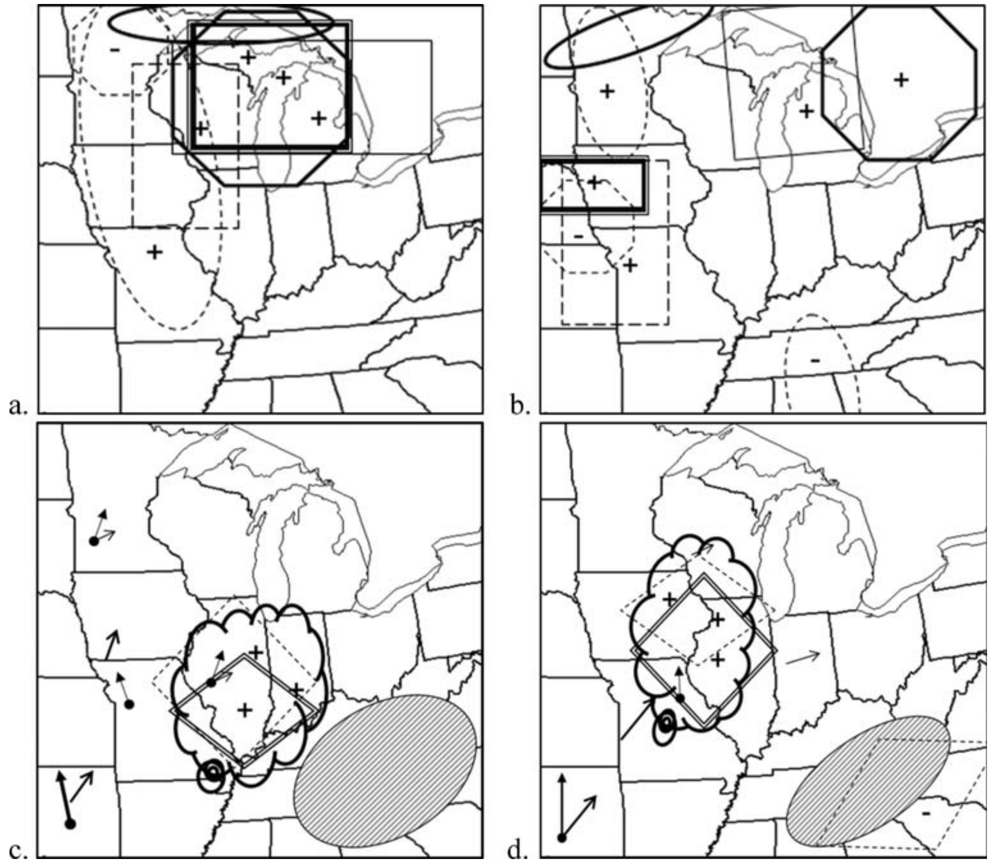


Fig. 9 As in Fig. 8 for days experiencing weak–moderate synoptic forcing (**a**–**d**)

summer months at several depths (Hollinger and Isard 1994). Comparing the soil moisture measurements for stations within each climate division to the PDSI values for the week that the soil moisture data were collected allows us to determine the range of soil moisture conditions that exist for each category of the PDSI (severe drought (−3 to −3.9), moderate drought (−2 to −2.9), etc.). We find that soil moisture can vary on a given day among locations in the same climate division and among stations in neighboring climate divisions, confirming that differences in soil moisture at high spatial resolutions exist within the Corn Belt region. Because relatively moist and dry soils can co-exist within a single climate division, a large range of soil moisture conditions can also occur for each category of the PDSI (Table 5). Even when PDSI values indicate dry conditions, a climate division may contain bands of moist soils that might help to initiate NCMCs promoting convective precipitation. The soil moisture measurements also confirm that soil moisture was lower in 1999 than in 2000 for each PDSI category in Illinois.

Table 4 Spearman rank correlation coefficients for ranked soil moisture and CSI values grouped by summer for days having weak and weak–moderate synoptic forcing

Weak and weak–moderate 1999		Weak and weak–moderate 2000	
Climate division	r_s	Climate division	r_s
IL8	**0.550**	IL2	**0.412**
IL9	*0.442*	IL5	**0.518**
IN2	*0.386*	IL7	**0.432**
IN4	**0.507**	IN1	**0.445**
IN5	**0.584**	IN4	**0.455**
IN7	*0.448*	IN5	**0.600**
IN8	**0.583**	IN8	**0.429**
IN9	**0.530**	IN9	**0.411**
MI10	*0.417*	OH1	**0.471**
KY3	**0.554**	OH4	*0.381*
		KY3	**0.528**

Values in bold are statistically significant at α=0.05, italics indicate significance at α=0.1

Comparing the radar-derived CSI values with the composite mean precipitation maps presented in Carleton et al. (2008a, their Fig. 5a, c), yields strong similarities in the locations of deep convection and high precipitation amounts, particularly for 1999. For weak flow days during summer 1999, mean precipitation is lowest in southeastern Iowa, northeastern Missouri, southern Illinois, Indiana, western Ohio, and southwestern Michigan. Carleton et al. (2008a) show that these regions recorded 0–6.7 mm of precipitation, and they correspond to CSI values of 9 or less

Table 5 Average, standard deviation, and ranges of soil moisture water equivalent values (millimeter) in Illinois for each PDSI category

PDSI category	Number of soil moisture observations	Average	Standard deviation	Range
1999 Data				
2 to 2.9	6	29.83	4.99	22.23–34.98
−1.9 to 1.9	122	25.66	9.76	7.47–44.15
−2 to −2.9	16	13.57	7.68	8.53–39.93
2000 Data				
3 to 3.9	3	38.33	5.31	33.64–44.09
2 to 2.9	8	37.37	6.82	27.41–46.02
−1.9 to 1.9	124	28.07	15.21	11.76–47.07
−2 to −2.9	7	29.41	8.16	18.94–33.46
−3 to −3.9	2	31.39	6.55	26.75–36.02

in the present study. Slightly more precipitation occurs in southeastern Michigan and northwestern Illinois (4.5–11.2 mm), and the CSI values for these areas total 15–19. As Carleton et al. (2008a) combined the mean precipitation for weak and weak–moderate days in summer 2000, direct comparisons between the two studies are not easily made. However, Carleton et al. (2008a) show that precipitation on weak and weak–moderate days averaged as high as 12.3 mm in eastern Iowa, northeastern Missouri, and northern Illinois. These regions had CSI values greater than 25 on weak–moderate days and 10–24 on weak flow days. The high average precipitation amounts in Indiana and southeastern Illinois indicated by Carleton et al. (2008a) for weak and weak–moderate days do not agree with the CSI values that we derive in the present study. A closer inspection of the radar reflectivity data between 1200 and 2300 UTC for each day shows that climate divisions IL7, IN7, and IN8 did not experience reflectivity values in excess of those occurring in surrounding climate divisions on any weak or weak–moderate day in 2000. Because Carleton et al. (2008a) utilize daily total precipitation from cooperative station rain gauges, the higher precipitation amounts could have occurred prior to or after the 1200–2300 UTC times that the present study uses to calculate the averaged CSI values.

Synoptic scale atmospheric forcing of deep convection becomes most evident during days classified as moderate flow, when the **V**(500) maximum winds are located adjacent to the study region (Fig. 10a, b; cf. Carleton et al. 2008a). Thus, it is not surprising that CSI values also are highest for these days (Fig. 7e, f). Relatively fast southerly winds at 850 hPa suggest that a low-level jet (LLJ) is important for the high amounts of lower tropospheric moisture and instability across the study region (Bonner 1968; Anderson and Arritt 2001; Zhu and Liang 2007), particularly during 2000 (Fig. 10d). Wind speeds at 850 hPa are twice as fast during moderate flow days of 2000 than during moderate flow days of 1999. Also on moderate flow days in summer 2000 contrasted with 1999, the entire study region has above average cloud coverage, indicated by below normal OLR values, and the CSI confirms that widespread deep convection develops across most of the study region, probably as a result of high moisture values at both 1,000 and 850 hPa (Fig. 10d). Because days when moderately strong synoptic scale atmospheric forcing exists do not provide an adequate opportunity to discern whether the land surface also contributes to the development of convective precipitation, we do not further discuss the results for the moderate flow days.

5 Focus on specific climate divisions

In Section 2.1, we identified the climate divisions where land-surface forcing is most likely to contribute to the development of convective precipitation as these divisions feature both a distinct boundary between croplands and forests, and boundaries between two different soil types. We based our selection of candidate climate divisions on the spatial arrangement of vegetation and soil types present (Table 1). This section discusses the results of our analysis for several of those divisions.

One climate division likely to experience land surface forcing on the development of convective precipitation is IA3 (Table 1). A distinct boundary between mollisols and alfisols runs through the middle of this division, and a forested area is located along its eastern edge while the rest of the division is dominated by croplands. The CSI values support our hypothesis that land-surface forcing of convective precipitation is highly likely in this climate division (Fig. 7). Division IA3 has the highest CSI value among all divisions in the study region under weak flow conditions in 2000, and high CSI values are also present during weak–moderate flow days in 2000. Above normal specific humidity in the lower troposphere (Fig. 8d) may have helped promote deeper convection over this climate division during these days in 2000. However, the results

Fig. 10 As in Fig. 8 for days experiencing moderate synoptic scale forcing (**a**–**d**)

also show that the soil moisture content as inferred from the PDSI is also an important consideration. During 1999, convection is less intense over this climate division than in 2000. PDSI values show that this area is unusually to extremely moist throughout the summer of 1999, and these uniformly moist conditions do not allow strong gradients in soil moisture to develop. Thus, CSI values for weak and weak–moderate flow days during 1999 are similar to one another but lower than the values in 2000 due to the uniformly moist soil conditions.

A similar explanation may also apply to climate division WI7. The dominant land-surface features here are a boundary between forests in the north and croplands in the south, and differences in soil type between the north that is dominated by alfisols and the south where mollisols alternate with alfisols. Like IA3, WI7 experiences normal moisture conditions for most of 2000 but is extremely moist in 1999. CSI values are higher in 2000 during both weak and weak–moderate days than in 1999 (Fig. 7), likely due to both the near-normal soil moisture conditions that allow gradients in soil moisture to develop, and the anomalously high amounts of moisture present in the lower troposphere in this part of the study region (Fig. 8d).

A climate division adjacent to IA3 that contains soil-type boundaries but experiences normal soil moisture conditions for the majority of both summers is IA6. Figure 2, taken in summer 2000, typifies the landscape in division (IA6). A boundary between mollisols and alfisols (eastern portion) and alternating bands of these soils both exist within IA6 (Fig. 4). These 20-km-wide bands may help supply the low-level moisture necessary to initiate weak convection, as Brown and Arnold (1998) suggested for similar boundaries in Illinois. The averaged CSI values are the same during weak flow days in 1999 and 2000 and are slightly higher during weak–moderate flow days in both summers likely due to higher specific humidity values in the lower troposphere. The similarities in CSI values for both summers suggest that gradients in soil moisture may indeed form within this climate division and help promote the development of convective precipitation. As more than 90% of this division is covered by croplands, we do not believe that differences in vegetation type played a significant role in enhancing convective precipitation.

Another climate division that we identify as a likely candidate for either soil moisture and/or vegetation-type influences on convective precipitation is IL6. This division features a densely forested area on its western border and mixture of forests and croplands throughout most of the division. Alfisols (mollisols) dominate the western (eastern) half of the division, and areas where soil types alternate exist in the middle of the division. Soil moisture conditions are normal during most of 1999, whereas they range from unusually dry to very moist during 2000. CSI values are slightly higher in 1999 than 2000 during weak flow days, and are nine points higher during weak–moderate days in 1999 when lower tropospheric specific humidity is anomalously high in this area. When soil moisture conditions are uniformly below normal, gradients in soil moisture may not exist in the region. Prolonged dry conditions also mean that transpiration is reduced, so that moisture gradients from different vegetation types also are less likely to occur. Both the reduced transpiration from plants and the inability of soil moisture gradients to form when conditions are wetter than normal, as well as when they are drier than normal, may help explain why deeper convection formed over the IL6 division in 1999 as opposed to 2000.

6 Discussion

The current study finds that differences in soil moisture across a soil-type boundary appear to enhance deep convection. We identify several locational examples in which convection preferentially develops over regions where mollisols are the dominant soil type, yet where they are mixed with smaller-scale bands of alfisols (e.g., IA6, IL1, IL6). In their modeling work, Yan and Anthes (1988) and Lynn et al. (1998) found that sea breeze-like fronts developed along the boundaries between wet and dry soil patches. Even though the circulation was strongest over dry land, the addition of moisture along the boundary of dry land with moist land allowed deep convection to form, producing high rain rates. Both sets of simulations found that convective rainfall was heaviest near alternating patches of dry and moist land if these are wider than 95 km. However, the observational analyses of O'Neal (1996) for the Midwest suggest that patches of different soil and vegetation complexes can affect convective cloud development as small as only 10 km wide. The bands of alfisols within the mollisols of eastern Iowa and western Illinois are approximately 15–30 km wide (Fig. 4). Our finding that heterogeneities in soil types coincide with the greater CSI values in these portions of the study region supports the work of previous researchers, including that of Brown and Arnold (1998) for Illinois.

Additionally, there are locational examples in the two study summers where convective precipitation is enhanced over climate divisions that feature a marked boundary between forests and croplands (e.g., IA3, WI7, IL6), rather than over regions where croplands alone occur (e.g., IN3). This finding also supports the work of O'Neal (1996), who observed that forested areas have more convective cloud coverage than croplands. Physical and physiological differences in vegetation types influence the transfer of moisture, heat, and momentum from the land surface into the atmosphere. Moisture gradients are maximized during the early summer when crops are immature and transpiring little moisture into the atmosphere, thereby creating a strong surface moisture gradient, while adjacent trees have higher transpiration rates. When crops mature in mid to late summer, they rapidly deplete soil moisture, which is then transferred to the atmosphere through evapotranspiration (cf. Bonan 2001; Carleton et al. 2008b). Through their deeper roots, forests also deplete soil moisture, but a high stomatal resistance means that transpiration rates are comparatively lower in the mid to late summer from trees than from crops. Blyth et al. (1994) found that forests may enhance rainfall due to the re-evaporation of intercepted rainfall, while Carleton et al. (2008b) add that differences in evapotranspiration rates of forests as compared to immature (mature) crops that produce low (high) evapotranspiration rates can also enhance rainfall. The change in roughness length between croplands and adjacent forests affects both the momentum and convective fluxes. Our present findings support these earlier studies: as inferred from the spatial associations of land-surface conditions with the CSI values, convective precipitation is enhanced by the presence of a heterogeneous land-surface cover within a given climate division.

The current study also finds that the amount of moisture present in the lower troposphere seems to have the largest influence on the range of CSI values measured, at least, for the two contrasting summers examined here. When specific humidity values in the lower troposphere are above normal, higher CSI values occur for the climate divisions that are co-located with the anomalously high moisture. When the atmosphere is moist, surface moisture from saturated soils and forest vegetation raises the latent heat flux; Segal et al. (1995) found that this increased latent heat flux rapidly destabilizes the atmosphere and leads to deep convection. Thus, conditions at both the land surface and in the lower troposphere can combine to produce heavy rainfall.

7 Conclusions and future research

This study's goal was to identify whether land-surface boundaries such as the alternating mollisols and alfisols in eastern Iowa and northwestern Illinois, and heterogeneities in vegetation type such as crop forest boundaries in southwestern Wisconsin, could together or separately enhance convective precipitation within the US Corn Belt during two recent summers having dissimilar atmospheric and surface moisture conditions. Because weaker flow days are an indicator of minimal synoptic scale forcing, they present the best opportunities to ascertain whether land-surface mesoscale heterogeneities enhance the development of deep convection within the study region. We first identified days during the summers of 1999 and 2000 when synoptic scale atmospheric forcing was weak to moderate. We examined the composite conditions in the mid and lower troposphere on each of these sets of days to identify properties that could aid or inhibit the development of convective precipitation, such as the presence of anomalous atmospheric moisture or a LLJ. Using NEX-RAD radar reflectivity returns, we then developed an index to determine quantitatively the severity of convective precipitation at a climate division scale. We averaged the CSI values temporally to uncover where the deepest convection occurred most frequently for a given back-ground wind speed category.

Our results indicate that under the two weakest synoptic flow regimes in the two summers studied (weak, weak–moderate), the boundaries between relatively moist and dry soils and between cropland and forest land covers both appear to enhance the development of convective precipitation in the western portion of the Corn Belt. We find that climate divisions IA3, WI7, IA6, and IL6 have the strongest evidence of land surface forcing on the development of convective precipitation due to the presence of soil-type and/or vegetation-type boundaries. Lower tropospheric moisture is a key factor in determining which land surfaces enhance convection on a given day. When humidity values at 1,000 and 850 hPa are anomalously high, convection forms over moist land, particularly where forests grow atop alfisol-type soils. Because alfisols better retain moisture than mollisols, they likely provide more latent heat to the atmosphere. However, where and when soil moisture values are anomalously moist or dry, gradients in soil moisture cannot form and thus do not enhance the development of convective precipitation. Less convection occurs overall in the eastern Corn Belt in both summers. On days when the Corn Belt experiences atmospheric forcing of at least moderate strength, convective development is enhanced by a LLJ (see also Carleton et al. 2008a).

These observational findings support those of previous researchers, especially model-generated results. Additional examination of the role of land-surface heterogeneities in enhancing convective precipitation within the US Corn Belt for a greater number of summer seasons clearly is warranted. Future research should investigate cropland/forest and alfisol/mollisol boundaries in IA3, WI7, IA6, and IL6 suggested by this study as being important for the development of convection at higher spatial resolutions. The analysis undertaken in the current study utilized a climate division spatial scale to accommodate the PDSI values along with the CSI and land surface conditions. Because the timing of convective development is at least partly dependent on the underlying surface, the time of day at which convective development begins or reaches peak intensity should also be examined. Allocating the development of convective precipitation to a particular land-surface boundary and time of day will aid precipitation forecasts in the Corn Belt and provide a more precise assessment of the amount of precipitation that heterogeneities in the land surface can induce under varying atmospheric conditions.

A future study for the Corn Belt region should also examine the lead-lag association between soil moisture and rainfall. Findell and Eltahir (2003) identified the role of soil moisture on the development of convection over Illinois and found that wet soils can help trigger deep convection. This enhanced convection, in turn, moistens the soils. For a larger number of summer seasons than examined here, rainfall data should be examined for days after soil moisture values become high to determine how often rainfall develops in response to wet soil conditions. This information could be combined with results generated by modeled soil moisture fields to further investigate the lead-lag association between convective precipitation and soil moisture.

Finally, the CSI developed in this study to help separate deep convection from lighter rainfall could usefully be applied to the quantitative analysis of radar reflectivity data in GIS frameworks for additional climate research projects. The CSI index provided important insights into which climate divisions comprising the Midwest US Corn Belt experienced the most frequent and intense convective precipitation for the two contrasting summer seasons. Because the CSI can be calculated for radar reflectivity values at various spatial scales, employing this technique with level II base reflectivity radar data should yield values at a spatial resolution of 2 km^2 and a temporal resolution of 5 or 6 min. Aggregating radar-derived convective activity over longer temporal scales such as weeks or months would facilitate higher-resolution comparisons of convective rain-fall rates for multiple seasons and across multiple years.

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