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Synoptic evolution of Midwestern US Extreme dew point events

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ABSTRACT: Eight Midwestern extremely high dew point events were examined with respect to their synoptic characteristics and evolution. Individual and composite analyses of events suggest that there exists three predominant features associated with extreme dew point events. In nearly all cases, the evolution of the synoptic environment includes the development and propagation of low pressure from the high plains through the upper Great Lakes. The low pressure increases and backs the surface winds acting to advect low-level moisture from eastern Nebraska, Iowa, Missouri eastward into Illinois and Indiana. The progression of the low pressure and attendant frontal boundaries also acts to modulate the length of the extreme low-level dew point event. Healthy crops and sufficient soil moisture content throughout this large agricultural region were also evident during the periods of extreme low-level moisture. Finally, the vertical thermal profile of the atmosphere during extreme dew point events supports previous findings and highlights the importance of restricted low-level mixing as instrumental in allowing near-surface moisture to become trapped and increased. Copyright © 2007 Royal Meteorological Society

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1. Introduction

Midwestern extreme dew point events pose significant hazards to human and wildlife populations across the region. Summer heat waves are a common occurrence throughout the Midwest. Large amounts of low-level moisture can elevate heat stress to dangerous conditions and lead to many injuries and deaths. A severe example of this occurred during July 1995 when apparent temperatures in the upper Midwest exceeded 35 °C due to the combination of heat and humidity, and caused over 700 deaths in Chicago (Kunkel *et al*., 1996). Investigations of factors leading to these conditions concluded that evapotranspiration from crops and recently wetted soils assisted in providing a large supply of low-level moisture in the region (Kunkel *et al*., 1996; Karl and Knight, 1997). In a study that examined dew point levels in extreme Chicago heat waves over a 75-year period, Changnon *et al*. (2003) noted that changes in a number of agricultural practices (e.g. acres planted with corn and soybean, planting densities, improved hybrids and no till-farming techniques) have likely enhanced evapotranspiration and increased surface dew points.

Deep, moist convection is also aided by increased amounts of low-level moisture. The focusing of low-level moisture can assist in organizing thunderstorms into mesoscale convective systems (MCSs) that produce damaging winds, hail, and occasional tornadoes (Fritsch *et al*., 1986; Bentley and Mote, 1998; Bentley *et al*., 2000). A major activity corridor for the occurrence of warm season derechos, widespread convectively induced windstorms, is located through the upper Midwest (Johns and Hirt, 1987; Bentley and Mote, 1998). Without topographic or organized synoptic-scale forcing, evidence suggests that warm season MCSs initiate and propagate along and through regions of greatest low-level moisture availability (Johns and Hirt, 1987; Johns 1993; Stensrud and Fritsch, 1994; Bentley *et al*., 2000). It has been postulated that primary source regions for this low-level moisture during weak flow situations within the upper Midwest are due to evapotranspiration from crops and vegetation (Chang and Wetzel, 1991; Johns 1993; Bentley and Mote, 1998).

Previous investigations of land–atmosphere interactions in North America have primarily focused on the western and southern Great Plains, the intermountain west, and the desert southwest (Segal *et al*., 1989; Pielke *et al*., 1991). Land–atmosphere interactions in the upper Midwest have been largely ignored even though it is a major agricultural region (i.e. corn and soybean) and an area that experiences dangerous heat waves and frequent MCS development (Johns and Hirt, 1987; Kunkel *et al*., 1996; Bentley and Mote, 1998; Palecki *et al*., 2001). The upper Midwest exhibits a wide range of land surface types, from extensive crop and grasslands

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in the west and south to heavily forested regions and abundant lakes in the northern portions. These land-use types are also dynamic with major shifts currently ongoing throughout the region (e.g. rural to urban, pasture to row crops; Changnon *et al*., 2003; Kalnay and Cai, 2003). Modelling studies further suggest that land–atmosphere interactions in mid-continental locations are important factors in determining the magnitude of global warming-induced climate changes (Menzel *et al*., 1992; Wetherald and Manabe, 1995).

Evidence suggests that low-level moisture is increasing in the upper Midwest (Sparks *et al*., 2002; Changnon *et al*., 2007). Assessment of warm season dew point characteristics at Rockford and Chicago, Illinois, indicate that there were significant increases in the number of hours and days and number of hours per day when extreme dew points (greater than 24 °C) occurred during the 1980–2000 period in comparison to that of 1959–1979. Dew-point temperatures also significantly increased during heat waves that have occurred since 1980 (especially in the mid/late 1990s). Gaffen and Ross (1998) found similar trends when examining changes in extreme apparent temperatures and high heat events in the central and eastern US. A recent investigation identified nine Midwestern high dew point events for the period from 1960–2000 (Changnon *et al*., 2007). Only one of the nine events occurred before 1986, with four of the events occurring from 1995 to 2000. This investigation will examine the evolution of synoptic environments during the eight most recent extreme dew point events identified and analysed by Changnon *et al*. (2007) with a goal of determining atmospheric environments leading to the distribution and focusing of low-level atmospheric moisture.

2. Data and methodology

The identification of extreme dew point events was conducted utilizing an extensively quality-controlled dataset consisting of 46 first-order stations (Figure 1; Sandstrom

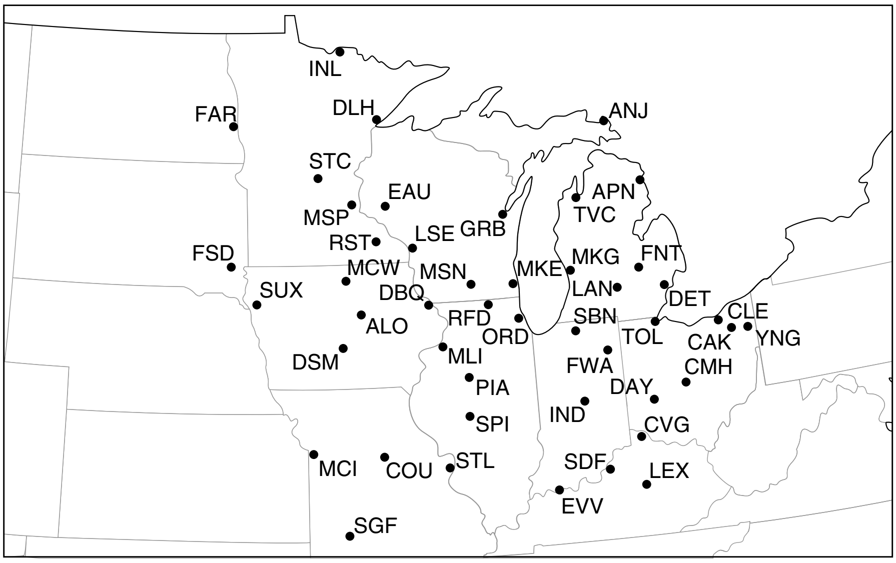

Figure 1. First-order stations used in the analysis (after, Changnon *et al*., 2007).

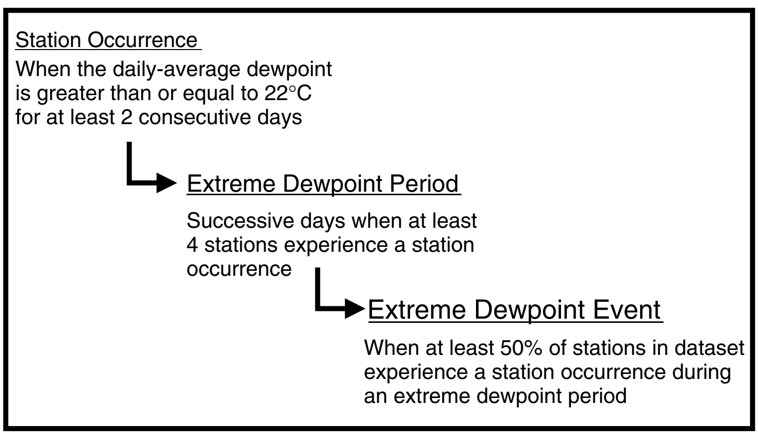

Figure 2. Decision-tree for choosing extreme dew point events.

et al., 2004). The data emanating from these stations was found to be the most complete and homogeneous in the region for the period 1960–2000 (Sandstrom *et al*., 2004). The identification criteria for defining an extreme dew point event utilizes both a temporal and spatial component, examining the number of days a station experiences an extreme dew point, and also the number of stations meeting the extreme dew point threshold (Figure 2; Changnon *et al*., 2007). Although at least 50% of the stations in the study region needed to exhibit a station occurrence in order for inclusion as an extreme dew point event, the majority of extreme dew-point events actually contained a much higher station percentage. The ten northern-most stations in the dataset were used to identify only the 24–28 July 1997 extreme dew point event (Figure 1). Therefore the identification criteria primarily relied upon 36 out of the 46 stations in the dataset to identify extreme dew point events.

Over the forty-year period, nine extreme dew point events were identified utilizing the before-mentioned criteria (Changnon *et al*., 2007). The event occurring in 1968 could not be analysed due to data limitations. Therefore, eight of the nine events were analysed in this investigation (Table I).

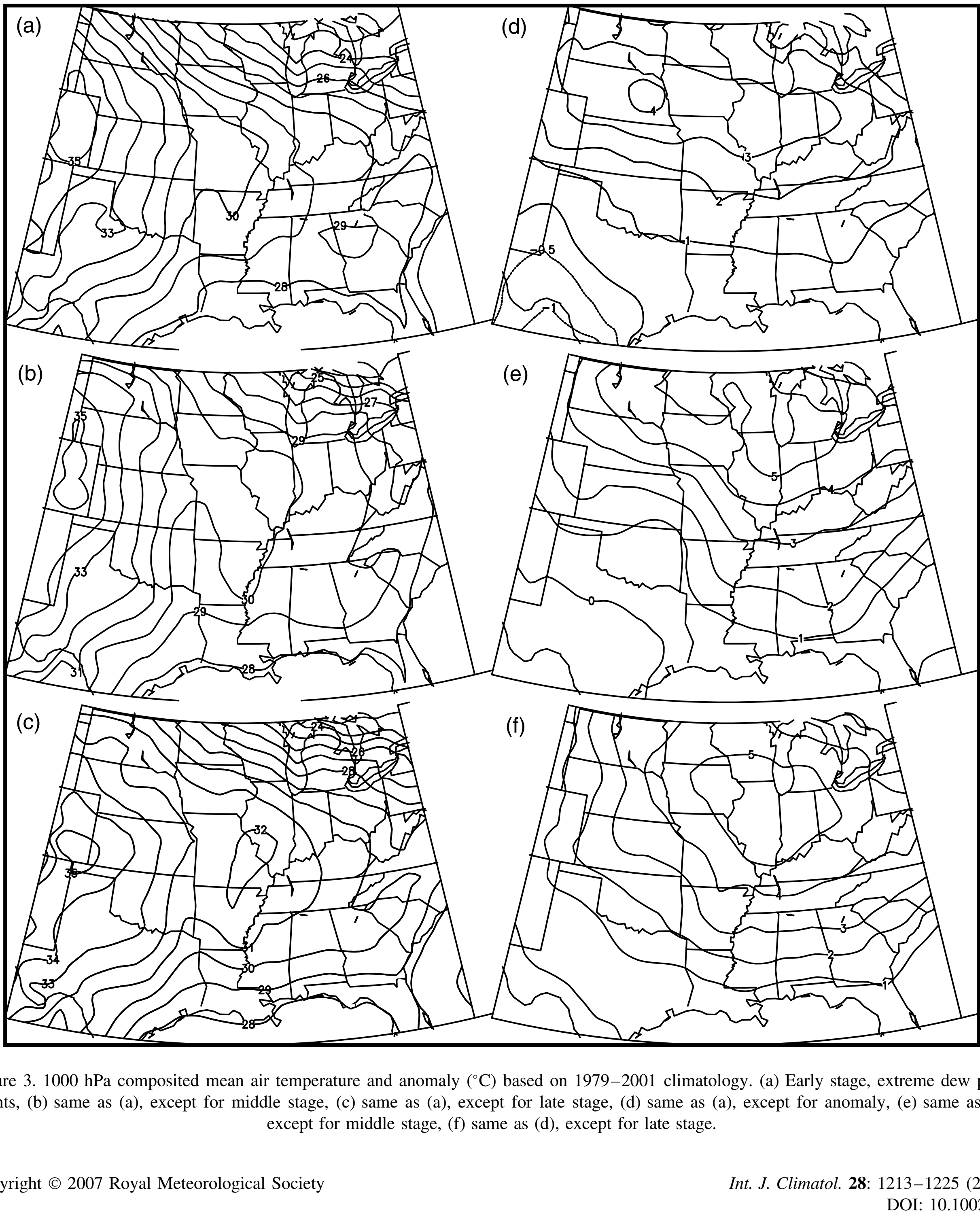

Figure 3. 1000 hPa composited mean air temperature and anomaly (°C) based on 1979–2001 climatology. (a) Early stage, extreme dew point events, (b) same as (a), except for middle stage, (c) same as (a), except for late stage, (d) same as (a), except for anomaly, (e) same as (d), except for middle stage, (f) same as (d), except for late stage.

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Table I. Dates of Midwestern extreme dew point events and *dry heat events*.

Period of event	Number of days	Number of stations involved
14–20 July 1986	7	36
24 July – 3 August 1987	11	31
8–17 August 1988	10	28
12–16 July 1995	5	38
11–20 August 1995	10	37
24–28 July 1997	5	24
2–6 July 1999	5	40
19–31 July 1999	13	31

Surface and upper-air data used to construct the daily and 3-hourly composites were obtained from the North American regional reanalysis (NARR), a long-term, consistent, high-resolution climate dataset that improves upon earlier global re-analysis datasets in both resolution and accuracy (Mesinger *et al*., 2006). The NARR is a 32-km/45-layer regional re-analysis based on the ETA model 3D-VAR data assimilation system and provides analyses beginning in 1979 (Mesinger *et al*., 2006). Variables utilized from the NARR analyses include temperature, geopotential height, specific humidity, accumulated precipitation, soil moisture, and turbulent kinetic energy (TKE). TKE is a measure of kinetic energy generated by the turbulent component of atmospheric circulations. Turbulence is modulated

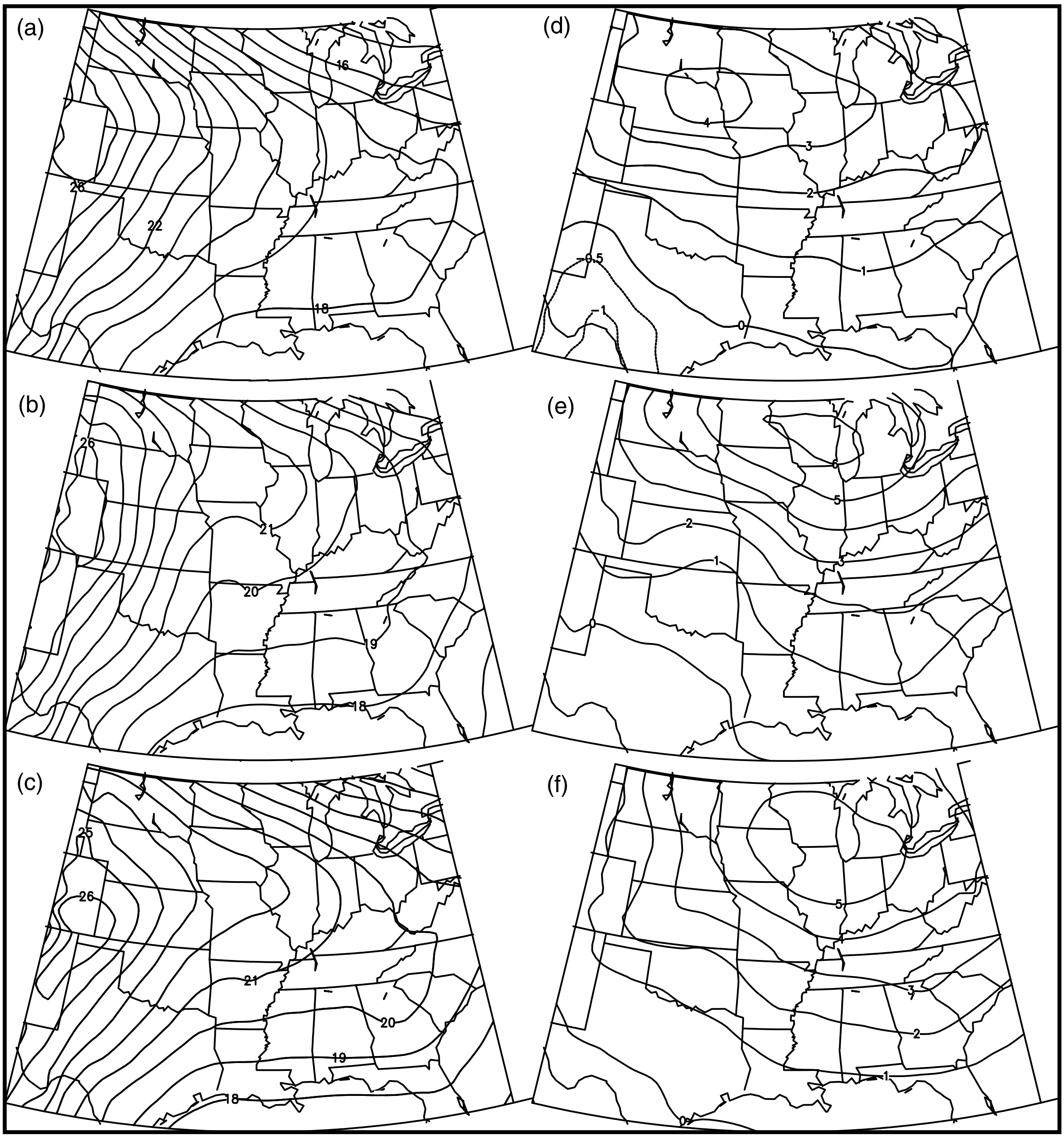

Figure 4. Same as Figure 3, except for 850 hPa temperature.

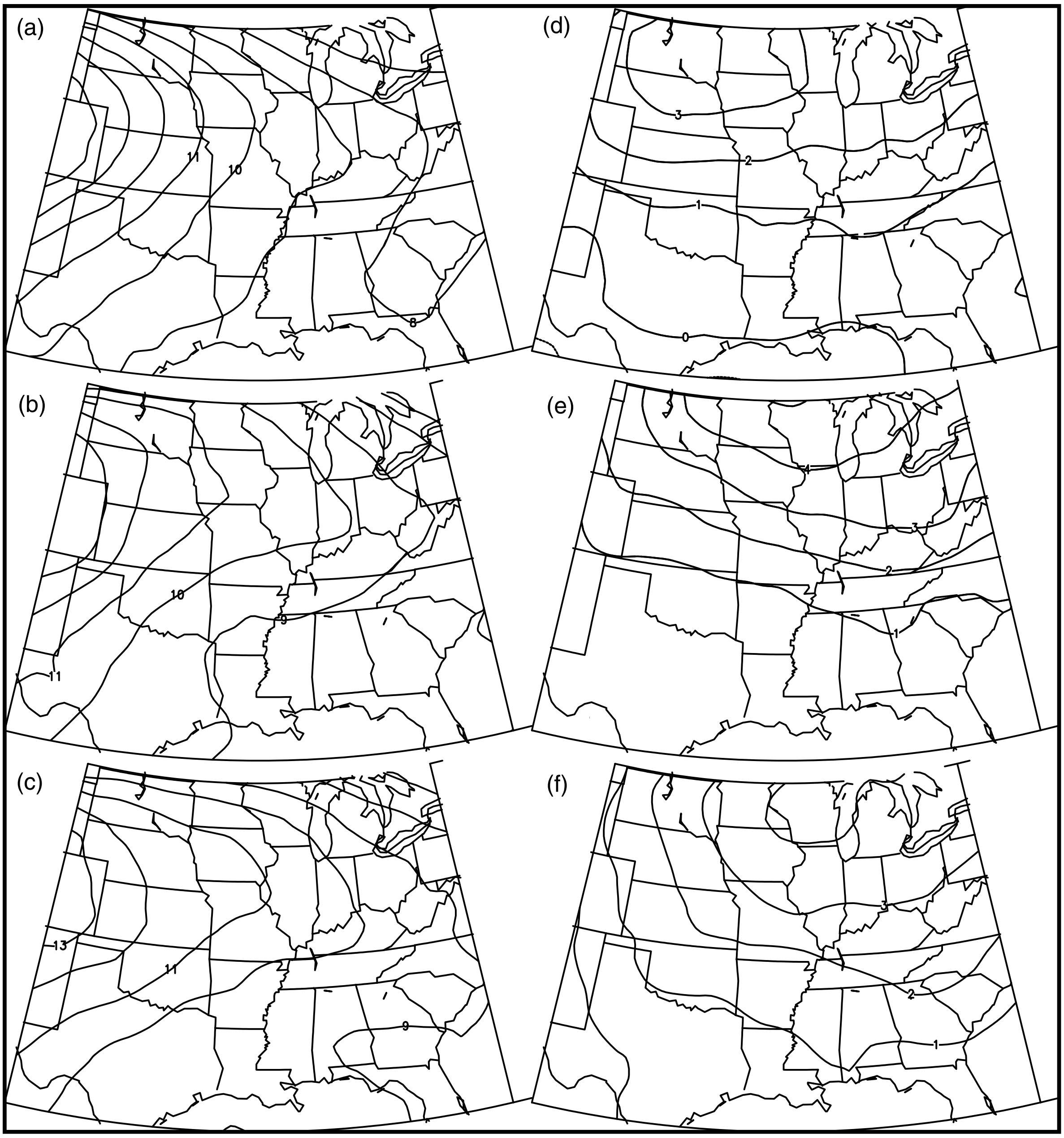

Figure 5. Same as Figure 4, except for 700 hPa temperature.

by buoyancy and wind shear, both leading to vertical motions and mixing within the planetary boundary layer (PBL). Large shears in thermally unstable atmospheric conditions tend to increase TKE while a thermally stable environment with weak shear reduces TKE. Therefore, TKE is a useful variable in assessing the amount of mixing within the PBL (Heilman *et al*., 2003; Sorbjan, 2003).

Hourly surface weather data from the National Weather Service were also gridded and plotted in 6-hourly intervals from one day prior to the extreme dew point event until dissipation using the GEMPAK software package. These data were used in order to determine whether commonalities existed among events prior to compositing. Visual inspection of each event indicated that similar synoptic features were prevalent and that composite analyses would be beneficial in determining predominant synoptic environments.

Extreme dew point events were composited in three stages: early, middle, and late. If an event contained an odd number of days, then three days spaced equally through the event representing these stages were chosen for the composite analysis. For example, the second (early), fourth (middle) and sixth (late) days would be chosen for an event lasting seven days. If the event consisted of an even number of days, each of the three stages would encompass a two-day composite equally spaced through the event. The hours chosen for the three stages of each event were identified by determining the hour when the maximum number of stations recorded an extreme dew point (see Table II in Changnon *et al*., 2007).

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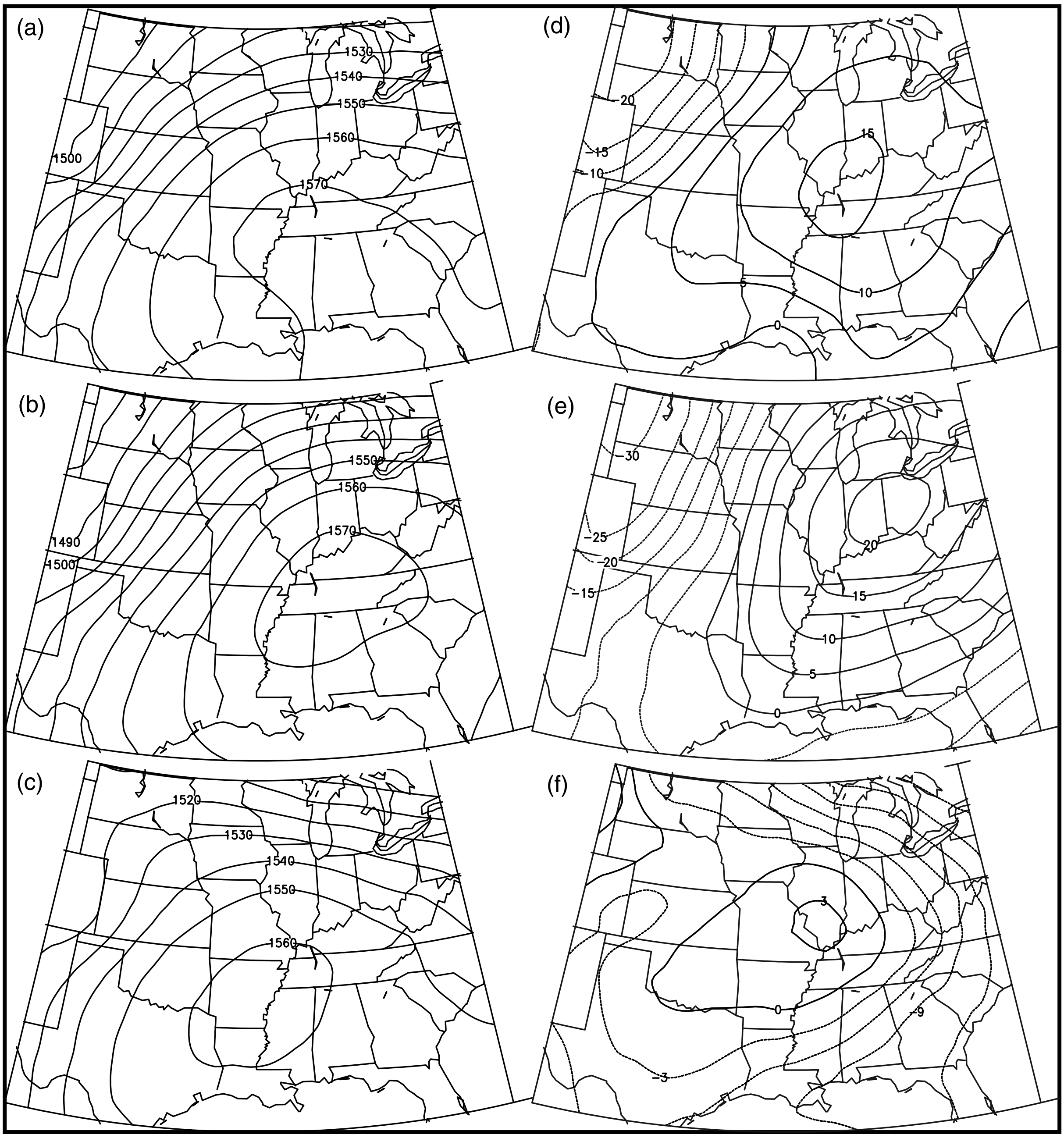

Figure 6. 850 hPa composited mean geopotential height and anomaly (gpm) based on 1979–2001 climatology. (a) Early stage, extreme dew point events, (b) same as (a), except for middle stage, (c) same as (a), except for late stage, (d) same as (a), except for anomaly, (e) same as (d), except for middle stage, (f) same as (d), except for late stage.

3. Results

The relative strength of the capping inversion during extreme dew point events is illustrated when examining low- to mid-level isotherms (Figures 3–5). Composited 1000 hPa isotherms indicate an anomalously warm near-surface atmosphere (Figure 3(a), (b) and (c)). This is especially evident in the early and middle stages of the event. When comparing these composites to a 23-year average of 1000 hPa temperatures, anomalies range from 3 to 5 °C for the extreme dew point events. A similar magnitude and location of anomalously high temperatures is evident when examining 850 hPa isotherms (Figure 4). The region of warmest air develops over Nebraska and Iowa and gradually shifts east until residing over Illinois and Indiana during the later stages (Figures 3(f) and 4(f)). At 700 hPa, the anomalously warm air develops and progresses over the upper Midwest, further north than lower levels (Figure 5). Using the 10 °C isotherm as an approximate location of the capping inversion, the entire region becomes capped during the middle stage with the greatest extent of air above 10 °C occurring by the late stage. However, the thermal gradient at 700 hPa does begin to increase over Wisconsin and Michigan in the late stage. This is indicative of the ridge axis de-amplifying and shifting south. The extent of the anomalously warm air throughout the low levels during extreme dew point events would restrict mixing

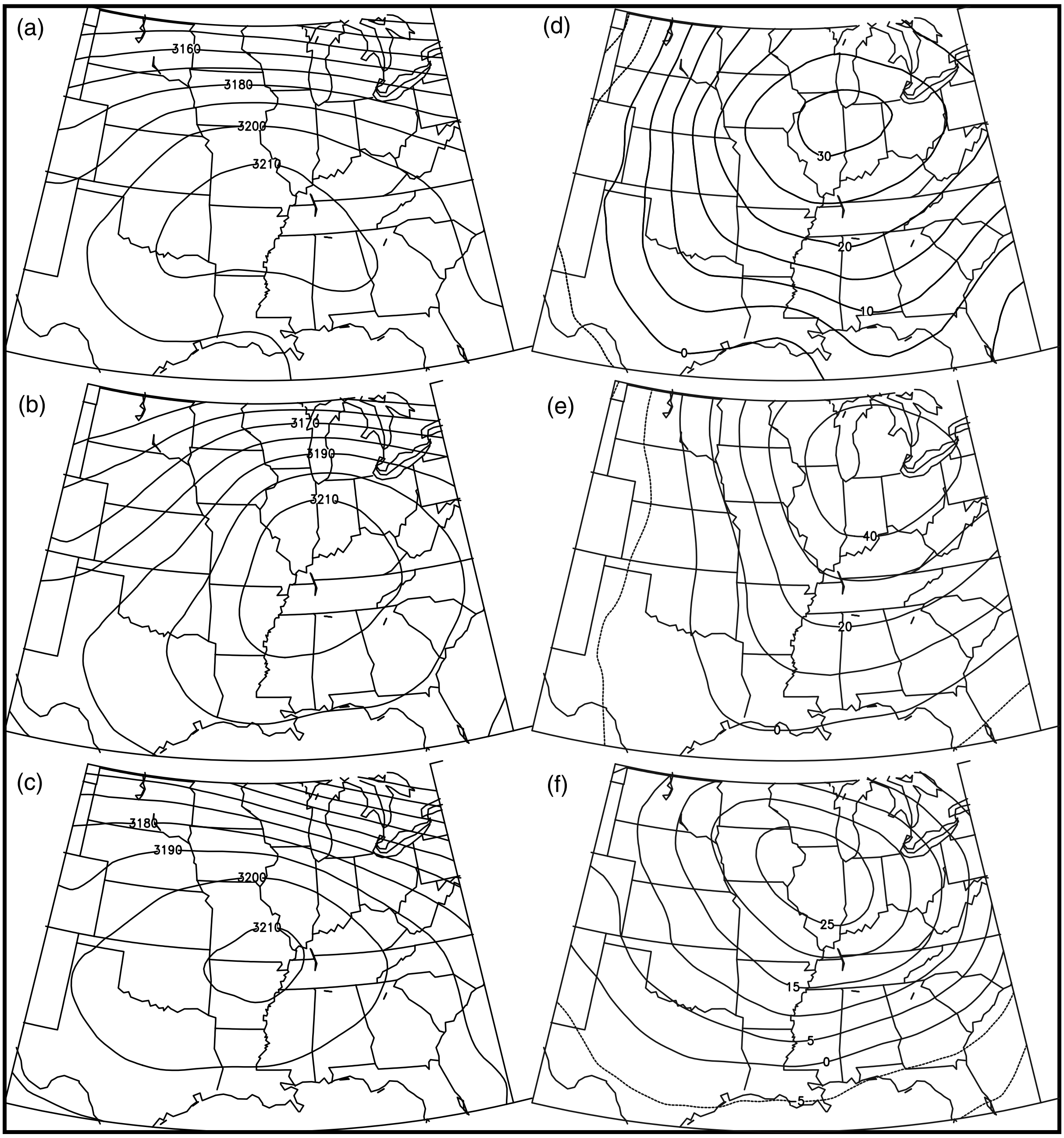

Figure 7. Same as Figure 6, except for 700 hPa geopotential height.

by strengthening a capping inversion similar to that identified by Kunkel *et al*. (1996). The strength of this inversion layer would subsequently trap any low-level moisture being produced through evapotranspiration.

The 850 hPa height fields for extreme dew point events illustrate the development of a trough along the western periphery of the Midwestern ridge (Figure 6). The development of the trough acts to amplify the Midwestern ridge and then suppresses it southward through the middle and late stages (Figure 6). By the late stage, the ridge is anchored over Arkansas and has also weakened considerably as evident in the composite anomaly (Figure 6(c) and (f)). The evolution of the height field suggests that extreme dew point events are characterized by disturbances propagating through the upper Midwest thereby suppressing the ridge southward and backing the flow westward through time. Further evidence of this persistent evolution during extreme dew point events is illustrated in the 700 and 500 hPa height fields (Figures 7 and 8) as well as surface analyses (Figure 9).

The 700 hPa ridge axis drifts eastward and then retrogrades and shifts southward during extreme dew point events (Figure 7). Given the height gradient and northwesterly flow found on the northern periphery of the 700 hPa ridge, it is likely that this is also the storm track (Figure 7(a), (b) and (c)). Similar to the 850 hPa height field, the ridge also weakens considerably in the late stage

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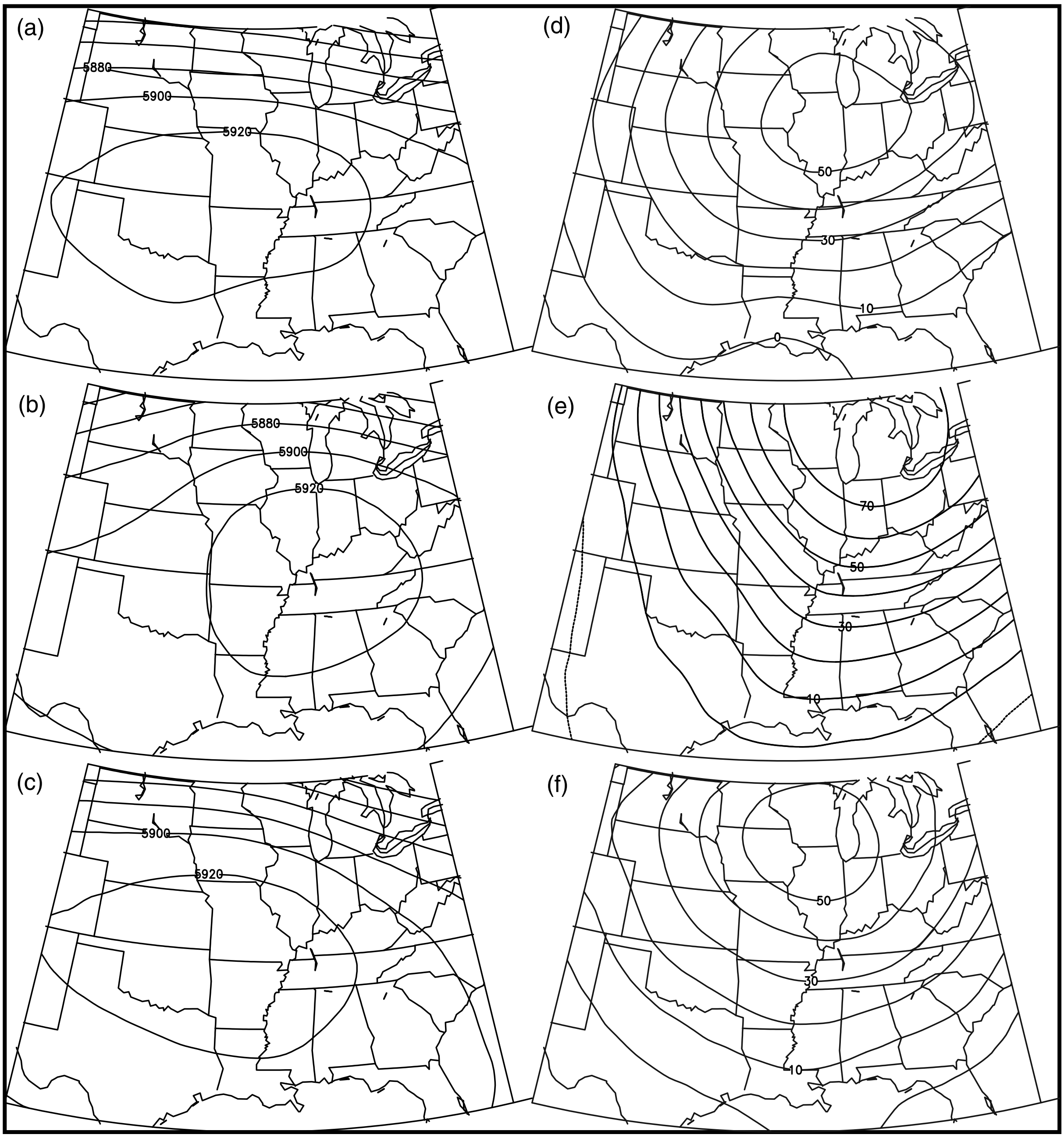

Figure 8. Same as Figure 7, except for 500 hPa geopotential height.

as disturbances progress over the ridge axis (Figure 7(f)). The surface accumulated precipitation composite analysis also illustrates a persistent migration of rainfall producing systems over the northern periphery of the ridge (Figure 10). At 500 hPa, ridge orientation during extreme dew point events resembles the classic 'ring-of-fire' convective situation with persistent formation of mesoscale convective systems propagating through the upper Midwest (Figure 8). As a shortwave rotates over the ridge axis, the ridge is deformed southward and re-amplifies northward once the shortwave moves eastward.

When examining the surface analyses of each event, the development of low pressure in the upper Great Plains and its subsequent propagation out of the lee–trough and through the upper Midwest was a characteristic of extreme dew point events (Figure 9(a), (b) and (c)). While moisture transport was found to remain maximized west of the region experiencing extreme dew points, the intensification of southerly flow in response to the developing surface low ejecting out of the lee-side trough in Nebraska led to an increase in dew points throughout the Midwest (Figure 9(a) and (b)). Therefore, moisture advection from the Gulf of Mexico cannot be completely ruled out as a contributor to low-level moisture. However, evidence suggests that shallow mixing depths, adequate soil moisture and enhanced evapotranspiration are essential in producing extreme dew point events.

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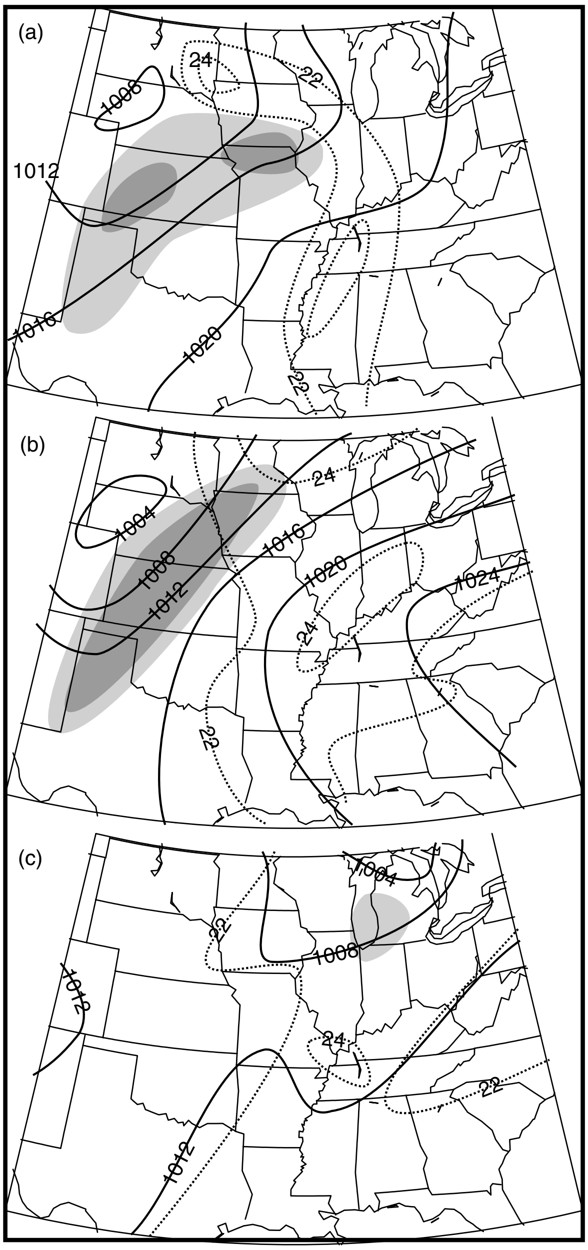

Figure 9. Isobars (hPa), isodrosotherms (°C, dashed lines) and surface moisture transport (12 kg s^{-1} m^{-1} light shade, 15 kg s^{-1} m^{-1} darker shade). (a) 15 July 1986, 1800 UTC (early stage, extreme dew point event), (b) 4 July 1999, 1200 UTC (middle stage, extreme dew point event), (c) 2 August 1987, 1200 UTC (late stage, extreme dew point event).

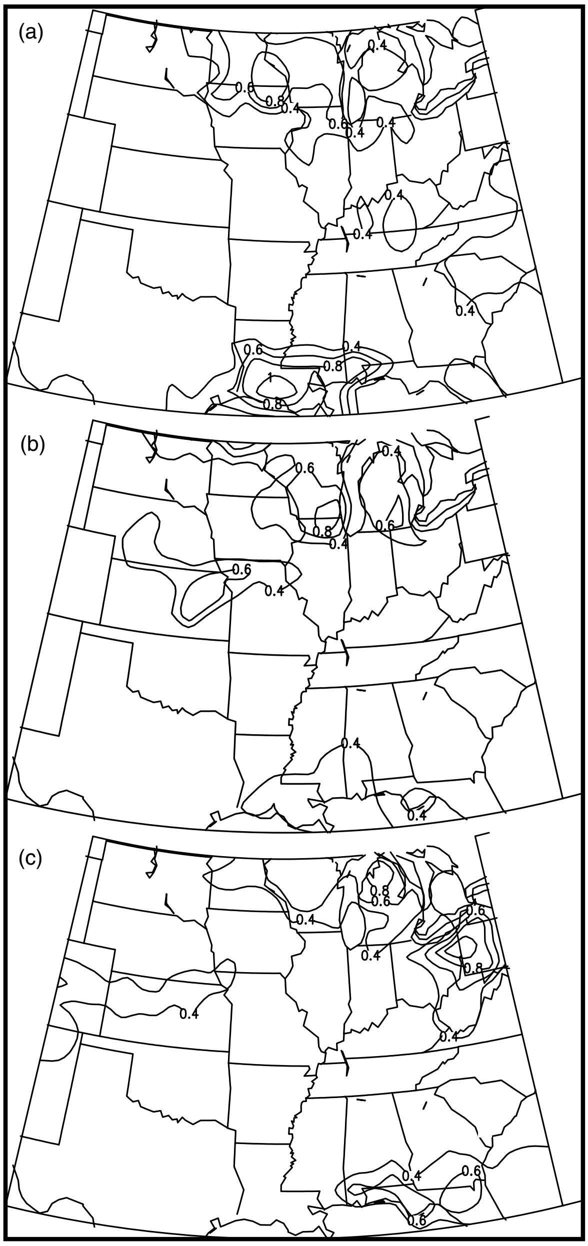

Figure 10. Daily surface accumulated precipitation (cm) composited means. (a) early stage, extreme dew point events, (b) same as (a), except for middle stage, (c) same as (a), except for late stage.

The centre of a region of enhanced low-level moisture during extreme dew point events is located over Iowa and Missouri in the early composite of 1000 hPa specific humidity (17g kg^{-1} to 18g kg^{-1}; Figure 11(a)). This is co-located with an area of moisture transport produced by the tightening pressure gradient in response to developing low pressure in western Nebraska (Figure 9(a)). During the evolution of the extreme dew point event, winds back southwesterly which focuses and advects this moisture throughout the Midwest (Figure 11(b) and (e)). Note that in the early and middle stages of extreme dew point events, the area of enhanced low-level moisture is located throughout the Midwest and appears separated from low-level moisture emanating from the Gulf of Mexico (Figure 11(a) and (b)). As the flow continues to back southwesterly in response to the migratory shortwave, the low-level moisture spreads throughout the Midwest with a region of specific humidities equal to or greater than 18 g kg^{-1} encompassing several states (Figure 11(c) and (f)). With the flow backing westward, it is unlikely that the increase and expansion of the low-level moisture field is due to advection from the Gulf of Mexico. Evidence suggests that this increase of low-level moisture is due to regional advection (i.e. from Iowa/Missouri/eastern Kansas to Illinois/Indiana) and a focusing of available moisture already trapped within a shallow mixing layer. The source of the

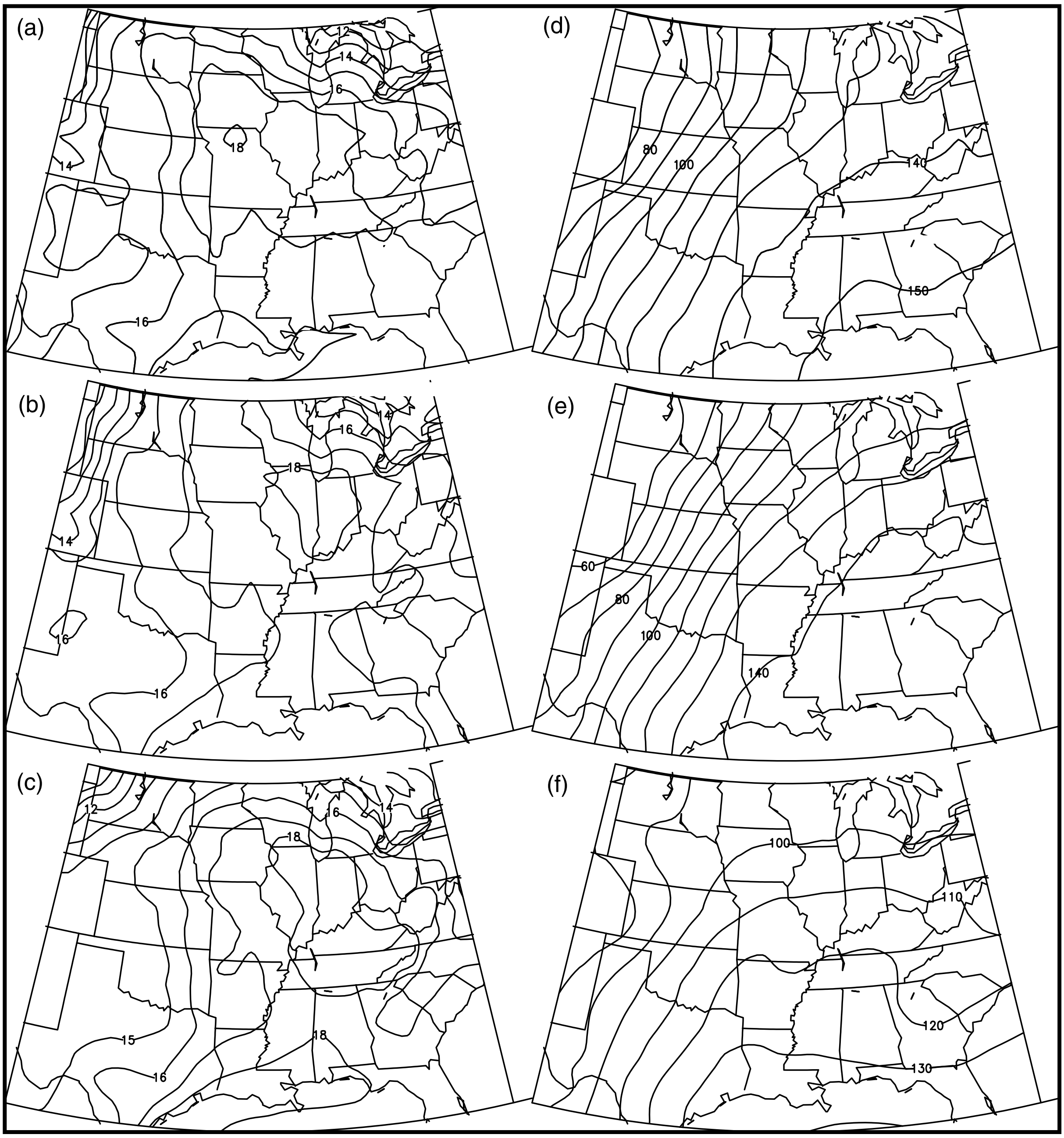

Figure 11. 1000 hPa composited means. (a) specific humidity (g kg^{-1}) early stage, extreme dew point events, (b) same as (a), except for middle stage, (c) same as (a), except for late stage, (d) geopotential height (gpm) early stage, extreme dew point events, (e) same as (d), except for middle stage, (f) same as (d), except for late stage.

advected and focused moisture is likely from evapotranspiration due to intensive agriculture during extreme dew point events throughout Iowa, Missouri, Illinois and Indiana.

An examination of soil moisture for the extreme dew point events illustrates the amount of near surface water available for input into the PBL through evapotranspiration (Figure 12). A region of high soil moisture runs from eastern Kansas through western Missouri and southern Iowa during the early stage of the events. This region is also the locus for advection of low-level moisture into the upper Midwest via southwesterly flow ahead of the developing lee trough (Figure 9). Kunkel *et al.* (1996) found similar evidence of PBL moistening when calculating potential evapotranspiration during the 1995 event.

In order to assess mixing within the PBL during extreme dew point events, composites were constructed of TKE at 900 hPa (Figure 13). Evidence suggests that the evolution in the number of stations experiencing extreme dew point temperatures is related to PBL mixing (or lack thereof) through reducing or increasing evapotranspired moisture. There appears to be a uniform region of relatively low values of TKE ($<0.25-0.275$ J kg^{-1}) throughout the Midwest up until the period when the

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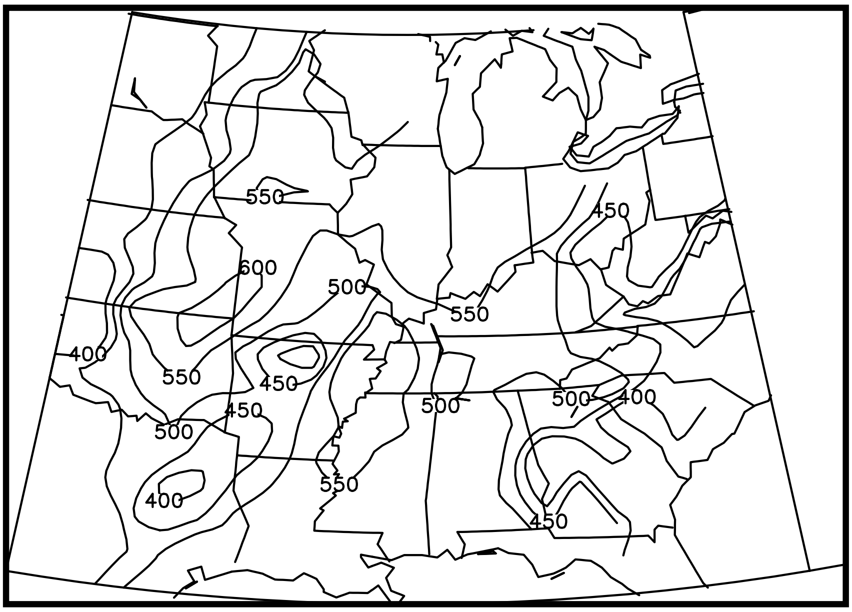

Figure 12. Soil moisture content (0–2 m; kg m^{-2}) composited mean, early stage, extreme dew point events.

maximum number of stations reported a high dew point event (Figure 13(a) through (d)). These low TKE values suggest that PBL mixing was suppressed at this time. Limited mixing continues until immediately prior to the time when the *maximum* number of stations reported an extreme dew point. TKE then significantly increases immediately *after* the 3-hperiod when the *maximum* number of stations reported an extreme dew point (Figure 13(e) and (f)). TKE more than doubles from 0.4 J kg^{-1} at the time when the maximum number of stations reported an extreme dew point to values greater than 0.9 J kg^{-1} in the later 3-h periods. During the morning hours after sunrise and when mixing is limited, the number of stations experiencing extreme dew point temperatures gradually increase (Figure 13(b), (c) and (d)). Evidence suggests that once greater PBL mixing commences a reduction in the buildup of extreme low-level moisture occurs.

4. Conclusions

We investigated eight extreme dew point events in order to ascertain the predominant factors behind their formation. A summary of major findings follows.

- In nearly all cases, the evolution of the synoptic environment associated with extreme dew point events includes the development and propagation of low pressure from the high plains through the upper Great Lakes. The low pressure increases and backs the surface winds and advects low-level moisture from eastern Kansas, Iowa, and Missouri eastward into Illinois and Indiana during the event. The surface wind field acts to advect and also focus the low-level moisture already trapped within the PBL throughout the Midwest, likely enhancing the apparent temperatures throughout the region. The progression of the low pressure also acts to modulate the length of the event as thunderstorms often propagated through the Midwest as the low pressure moved through the Great Lakes. In some cases, this low pressure development and evolution took place in several days, while in other events it took over one week. In a few events, it took the development and propagation of several low pressure centres before the ridge was suppressed southward far enough to end the extreme dew point event in the Midwest.
- Examination of soil moisture over the region for extreme dew point events illustrates that evapotranspiration over eastern Kansas, Iowa, and Missouri would provide a rich source of PBL moisture. The surface analyses indicated that low-level flow would advect moisture from this region into the Midwest.
- The vertical thermal profile of the atmosphere during extreme dew point events along with analysis of TKE further highlights the importance of restricted low-level mixing in the PBL as instrumental in allowing near-surface moisture to increase.

The major mechanisms listed above act in concert to create dangerous combinations of low-level warm air and moisture. If one of these ingredients is missing, it is likely that extreme amounts of low-level moisture will not develop and focus over the region. Meteorologists and climatologists should monitor soil moisture and vegetative health in the region as well as ridge amplification, the development of shallow mixing layers, and increasing winds behind high pressure (in response to developing lee-side low pressure) as indicators of the initiation of an extreme dew point event.

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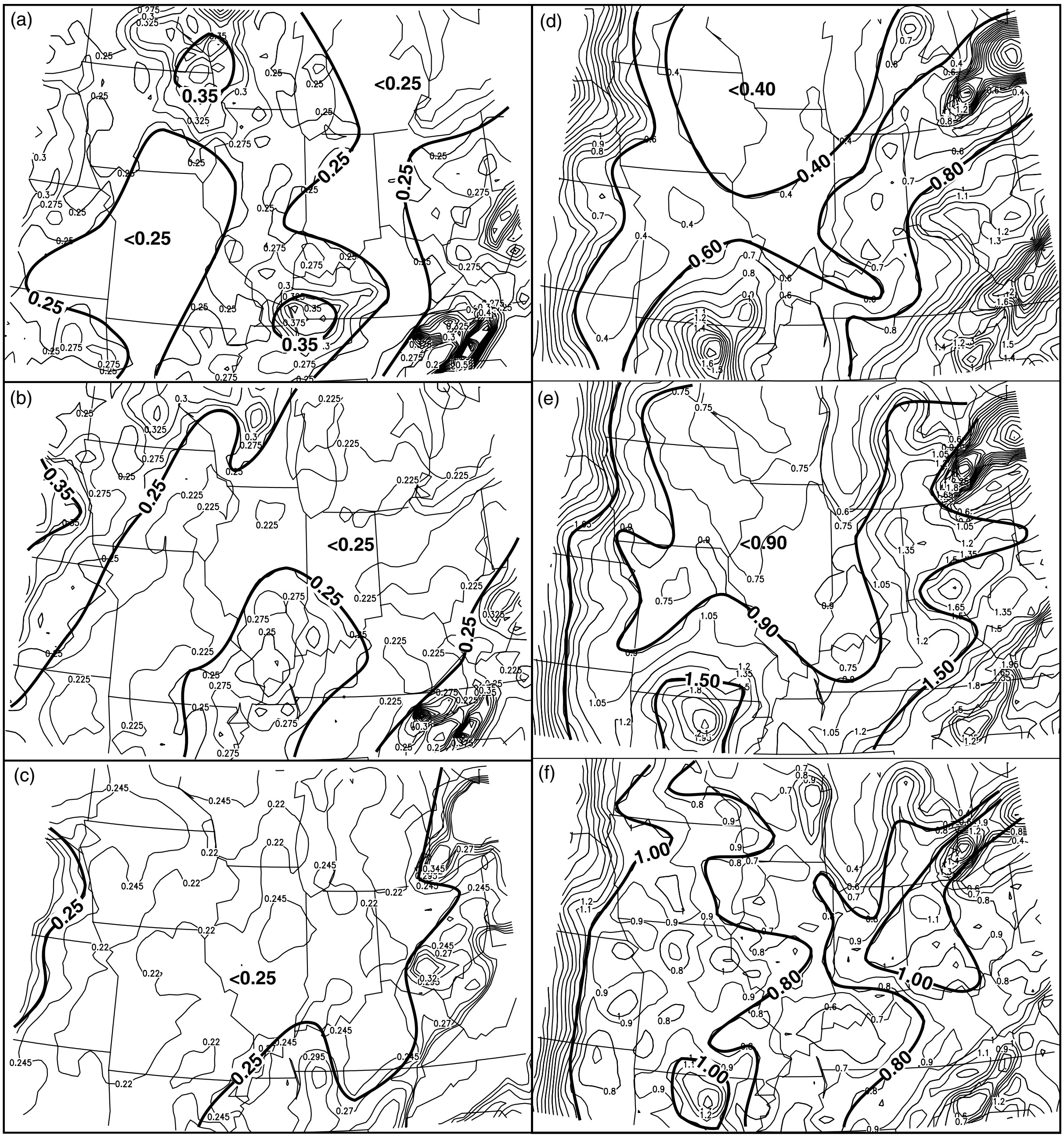

Figure 13. Composite analysis of 900 hPa turbulent kinetic energy (TKE; j kg-1) during the five most extreme dew point events. (a) TKE 3 h before the minimum number of stations reported a high dew point, (b) same as (a), except for during the hour when the minimum number of stations reported a high dew point, (c) same as (a), except for 3 h before the maximum number of stations reported a high dew point, (d) same as (a), except for during the hour when the maximum number of stations reported a high dew point, (e) same as (a), except for 3 h after the maximum number of stations reported a high dew point, (f) same as (a), except for 6 h after the maximum number of stations reported a high dew point.

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References

Bentley ML, Mote TL. 1998. A climatology of derecho producing mesoscale convective systems in the central and eastern United States, 1986-95. Part I: temporal and spatial distribution. *Bulletin of the American Meteorological Society* **79**: 2527–2540.

Bentley ML, Mote TL, Byrd SF. 2000. A synoptic climatology of derecho producing mesoscale convective systems in the north-central Plains. *International Journal of Climatology* **20**: 1329–1349.

Chang JT, Wetzel PJ. 1991. Effects of spatial variations of soil moisture and vegetation on the evolution of a prestorm environment: A case study. *Monthly Weather Review* **119**: 1368–1390.

Changnon DM, Sandstrom M, Schaffer C. 2003. Relating changes in agricultural practices to increasing dew points in extreme Chicago heat waves. *Climate Research* **24**: 243–254.

Changnon DM, Sandstrom M, Bentley M. 2007. Midwestern high dew point events 1960–2000. *Physical Geography* **27**: 494–504.

Fritsch JM, Kane RJ, Chelius CR. 1986. Contribution of mesoscale convective weather systems to the warm season precipitation in the United States. *Journal of Applied Meteorology* **25**: 1333–1345.

Gaffen DJ, Ross RJ. 1998. Increased summertime heat stress in the U.S. *Nature* **396**: 529–530.

Heilman WE, Bian X, Charney J, Potter BE. 2003. Combining the Haines Index and turbulent kinetic energy for fire-weather

DOI: 10.1002/joc

predictions. 5th Symposium on fire and forest meteorology joint with 2nd International wildland fire ecology and fire management congress, 2003 November 16–20, Orlando, FL, American Meteorlogical Society: Boston, MA, available only on CD.

Johns RH. 1993. Meteorological conditions associated with bow echo development in convective storms. *Weather and Forecasting* **8**: 294–299.

Johns RH, Hirt WD. 1987. Derechos: widespread convectively induced windstorms. *Weather and Forecasting* **1**: 32–49.

Kalnay E, Cai M. 2003. Impact of urbanization and land-use change on climate. *Nature* **423**: 528–531.

Karl TR, Knight RW. 1997. The 1995 Chicago heat wave: How likely is a recurrence? *The Bulletin of the American Meteorological Society* **78**: 1107–1119.

Kunkel KE, Changnon SA, Reinke BC, Arritt RW. 1996. The July 1995 heat wave in the Midwest: A climatic perspective and critical weather factors. *The Bulletin of the American Meteorological Society* **77**: 1507–1518.

Menzel WP, Wylie DP, Strabala KI. 1992. Seasonal and diurnal changes in cirrus clouds as seen in four years of observations with the VAS. *Journal of Applied Meteorology* **31**: 370–385.

Mesinger F, DiMego G, Kalnay E, Mitchell K, Shafran PC, Ebisuzaki W, Jovic D, Woollen J, Rogers E, Berbery EH, Ek MB, Fan Y, Grumbine R, Higgins W, Li H, Lin Y, Manikin G, Parrish D, Shi W. 2006. North American regional reanalysis. *The Bulletin of the American Meteorological Society* **87**: 343–360.

Palecki MA, Chagnon SA, Kunkel KE. 2001. The nature and impacts of the July 1999 heat wave in the Midwestern United States: Learning from the lessons of 1995. *The Bulletin of the American Meteorological Society* **82**: 1353–1367.

Pielke RA, Dalu G, Snook JS, Lee TJ, Kittel TGF. 1991. Nonlinear influence of mesoscale land use on weather and climate. *Journal of Climate* **4**: 1053–1069.

Sandstrom MA, Lauritsen RG, Changnon D. 2004. A central U.S. summer extreme dew-point climatology (1949–2000). *Physical Geography* **25**: 191–207.

Segal M, Schreiber W, Kallos G, Pielke RA, Garratt J, Weaver A, Rodi J, Wilson J. 1989. The impact of crop areas in northeast Colorado on midsummer mesoscale thermal circulations. *Monthly Weather Review* **117**: 809.

Sorbjan Z. 2003. Air-Pollution Meteorology. Chapter 4 of *AIR QUALITY MODELLING Theories, Methodologies, Computational Techniques, and Available Databases and Software. Vol. I – Fundamentals*. EnviroComp Institute (http://www.envirocomp.org/).

Sparks J, Changnon D, Starke J. 2002. Changes in the frequency of extreme warm-season surface dew points in northeastern Illinois: Implications for cooling-system design and operation. *Journal of Applied Meteorology* **41**: 890–898.

Stensrud DJ, Fritsch JM. 1994. Mesoscale convective systems in weakly forced large-scale environments. Part III: Numerical simulations and implications for operational weather forecasting. *Monthly Weather Review* **122**: 2084–2104.

Wetherald RT, Manabe S. 1995. The mechanisms of summer dryness induced by greenhouse warming. *Journal of Climate* **8**: 3096–3108.

DOI: 10.1002/joc