Investigating the Effect of the ‘‘Land between the Lakes’’ on Storm Patterns

JOSH DURKEE

Department of Geography, Western Kentucky University, Bowling Green, Kentucky

AHMED M. DEGU AND FAISAL HOSSAIN*

Department of Civil and Environmental Engineering, Tennessee Technological University, Cookeville, Tennessee

REZAUL MAHMOOD AND JESSE WINCHESTER

Department of Geography, Western Kentucky University, Bowling Green, Kentucky

THEMIS CHRONIS

Earth System Science Center, University of Alabama in Huntsville, Huntsville, Alabama

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ABSTRACT

The artificially created region around the ‘‘Land between the Lakes’’ (LBL) in Kentucky represents unique land use and land cover (LULC) heterogeneities. Over a distance of 100 km, the LULC comprises artificially created open water bodies (i.e., two parallel large run-on-river dams separated by the LBL), mountainous terrain, forest cover, and extensive agricultural land. Such heterogeneities increase (decrease) moisture supply and sensible heat, resulting in a differential air mass boundary that helps to initiate (inhibit) convection. Hence, the LBL can potentially modify precipitation formation. Historical anecdotes reveal a tendency for storms to dissipate or reintensify near the LBL. The specific scientific question pursued in this study is therefore the following: Has the unique development of two parallel run-on-river reservoirs and the surrounding LULC heterogeneity modified storm patterns in the region? Ten storm events during the growing season were selected. Two additional events, observed by the newly established high-resolution Kentucky Mesonet network, were also considered. Radar reflectivity images were visually inspected to understand the evolution of convective cells that originated or were modified near the LBL. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model was used to determine near-surface trajectories that led to the selected events. The spatial synoptic classification and merged Geostationary Operational Environmental Satellite (GOES) IR images were analyzed to determine the prevailing synoptic conditions on the event dates. Six storm events showed a pattern wherein the convective cells lost strength as it passed over the LBL in a northeasterly direction. In two events, Next Generation Weather Radar (NEXRAD) reflectivity imagery revealed enhancement of convection as the storm passed over the LBL toward the Mississippi valley. Further dissection of the storm morphology suggested that the thermodynamic environment may have played an important role for the eight events where modification of precipitation near LBL has been clearly observed.

1. Introduction

The ‘‘Land between the Lakes’’ (LBL) is an inland peninsula formed by two artificial lakes that are parallel and run-on-river reservoirs covering an area of 680 km^2 (Fig. 1). One artificial lake is Lake Kentucky on the Tennessee River and the other is Lake Barkley on the Cumberland River in western Kentucky. After the

* Current affiliation: Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington.

Corresponding author address: Dr. Faisal Hossain, Department of Civil and Environmental Engineering, University of Washington, 201 More Hall, Box 352700, Seattle, WA 98195.
E-mail: fhossain@uw.edu

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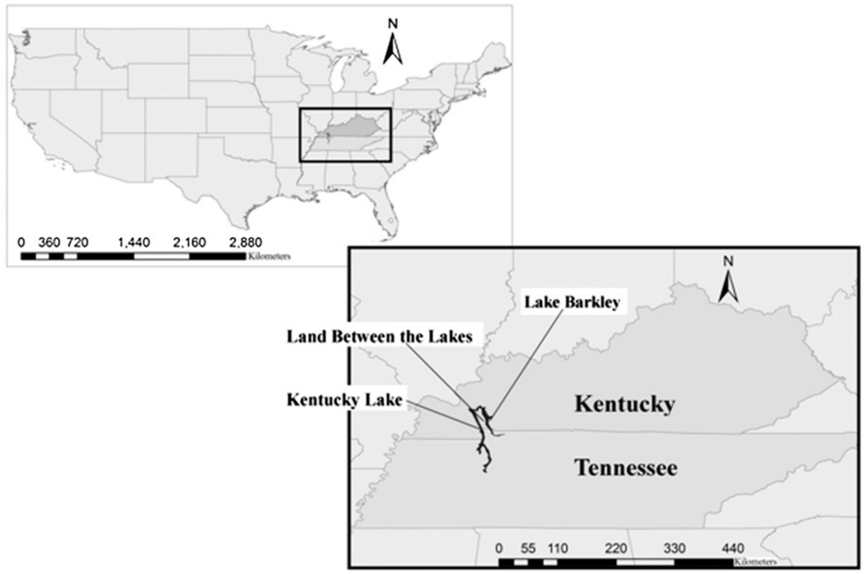

FIG. 1. Location of study area and LBL, Kentucky.

development of the LBL peninsula (hereinafter LBL) during the 1950s, anecdotes from the local inhabitants reported a marked change in precipitation patterns. The common thread of such anecdotes claims physical attenuation of an easterly moving convective storm near the LBL and reintensification after passing LBL downstream toward Hopkinsville, Kentucky.

Given the untested nature of the anecdotes, this study explored the role of the LBL and its surrounding land features on mesoscale storm systems. Land use and land cover (LULC) changes create heterogeneities in surface roughness, soil moisture, and vegetation cover. Such heterogeneities act as catalysts for differential heating that brings about different airmass boundaries to trigger deep convection. During daytime, vegetation cover and soil moisture can offset the energy balance by altering sensible and latent heat fluxes through inhibiting or increasing evapotranspiration (ET). Inhibition (increase) of ET occurs when soil moisture is limiting (saturated). Dry soil inhibits evapotranspiration and reduces moisture supply to the lower atmosphere leading to a warmer and drier condition. Such modifications in lower-atmospheric humidity and temperature can also affect development of convection [see Mahmood et al. (2010, 2014) for a comprehensive review of impact of LULC on weather and climate].

Various modeling studies report an increase in rainfall as a result of convection initiation due to LULC heterogeneities during free-atmospheric conditions (Yan and Anthes 1988; Pan et al. 1995; Pielke et al. 1999b; Pal and Eltahir 2001). Generally, if the synoptic environment is not conducive for large-scale vertical ascent, convective development is often linked to land surface features. Various model and observational studies also show the role of local-to-regional scale land surface variables and atmospheric interaction in understanding climate anomalies (Giorgi et al. 1996; Xue et al. 1996; Fennessy and Shukla 1999; Pielke et al. 1999a; Zangvil et al. 2004) and in improving forecasting capabilities (Huang and Van den Dool 1993; Durre et al. 2000; Mo 2003; Van den Dool et al. 2003; Alfaro et al. 2006). In this regard, the National Research Council (NRC) has suggested further study of regional radiative forcings due to LULC heterogeneities and its impact on regional climate (NRC 2005).

In semiarid regions, where convection is frequent, an increase in afternoon rainfall over drier soil has been reported that is due to increases in sensible heat (Taylor et al. 2012). However, no indication of a positive soil moisture feedback was shown in the observational analysis of Taylor et al. (2012). On the other hand, in a study of convective initiation across the southern Great Plains, Frye and Mote (2010) have shown variations in values of soil moisture and soil moisture gradients. Initiation of convection showed high variation throughout the range of soil moisture values in synoptically primed days. Hence, there is a critical role of soil moisture and soil moisture gradient for the mesoscale effect on convection (Frye and Mote 2010).

Various studies on the impact of open water (lake) on rainfall or snow storms have used radar data to identify convection cells that originate or become enhanced over the open water surface. Laird et al. (2009) examined nine

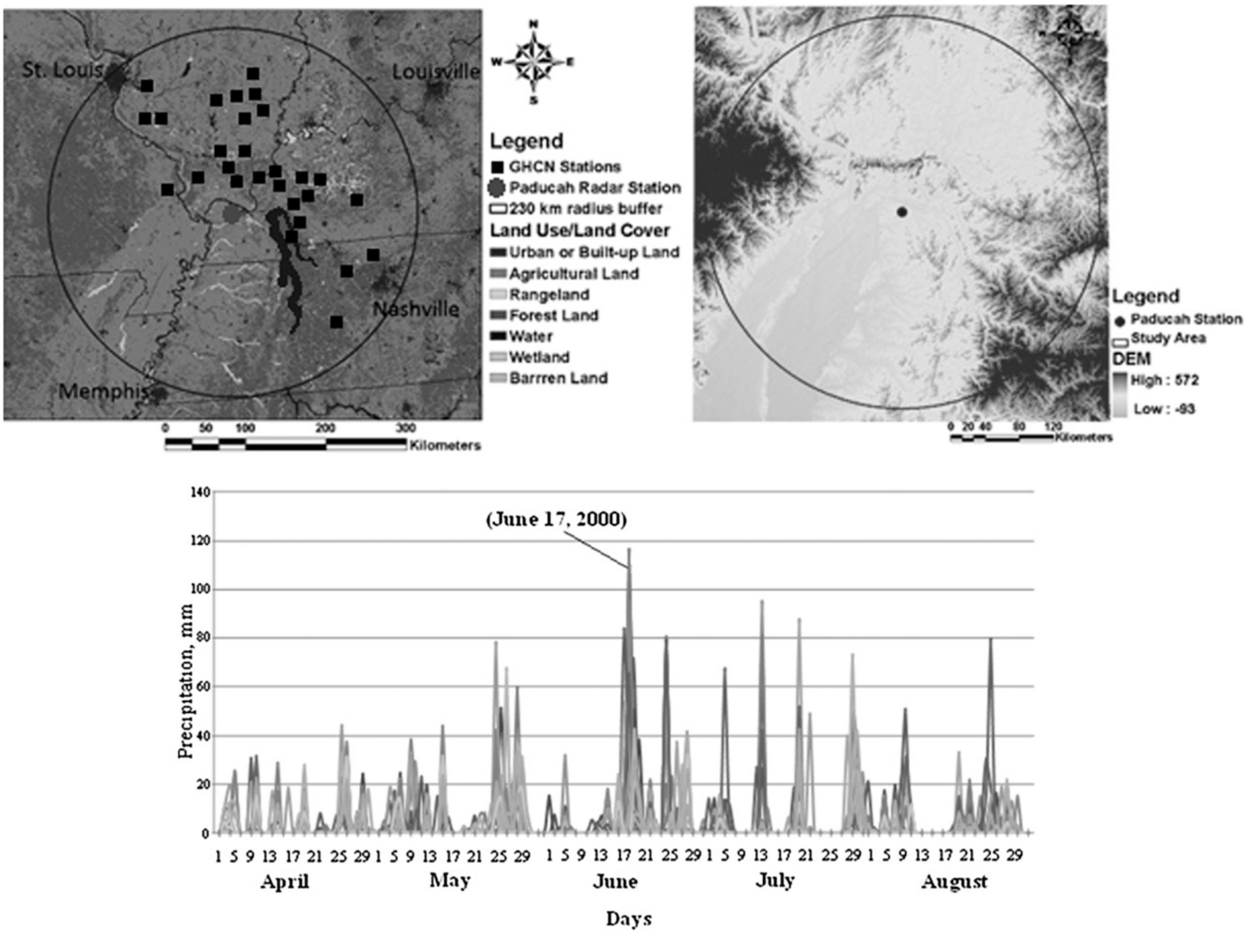

FIG. 2. (top) LULC pattern around (left) KPAH and (right) digital elevation model (DEM) analysis. The radar station is shown in the center of the circle drawn in black. GHCN precipitation stations are shown as black squares in the left panel. (bottom) Example daily rainfall hyetograph for the growing season of 2000 used in the selection of heaviest isolated episode for that year (17 Jun 2000).

winter seasons (1997–2005) of radar data from Burlington, Vermont, and identified 67 lake effect precipitation events due to Lake Champlain. Payer et al. (2007) also used Next Generation Weather Radar (NEXRAD) to analyze the evolution of snowbands over Lake Champlain. These studies showed the effectiveness of radar reflectivity images in identifying convection cells' origin, enhancement, or dissipation, particularly near water bodies.

Currently, the role of artificial reservoirs (also referred to as ''dams'' hereafter), such as the LBL, on mesoscale convection is not very well understood. Degu et al. (2011) have examined the impact of 92 large dams and associated LULC on precipitation patterns during the growing season. The authors primarily used North American Regional Reanalysis (NARR)-derived convective available potential energy (CAPE) and extreme precipitation percentiles drawn from Global Historical Climate Network (GHCN) to determine mesoscale convection. The local effect of the artificial reservoirs on summer precipitation was mostly observed for Mediterranean, semiarid, and arid climates. Degu et al. (2011) also reported a strong correlation between an increase in CAPE and extreme precipitation percentiles, implying possible storm intensifications. A more recent study by

TABLE 1. Selected events and their SSC.

Event	SSC
17 Jun 2000	Moist moderate (MM)
20 Jul 2001	Moist tropical (MT)
13 May 2002	Transitional (TR)
23 Aug 2003	MT
26 Aug 2004	Moist tropical plus (MT+)
26 Aug 2005	MT+
28 Aug 2006	MT
7 Jun 2007	Dry moderate (DM)
4 Apr 2008	TR
18 Jun 2009	MT+
11 Jul 2009	MM
2 Jul 2012	Not archived

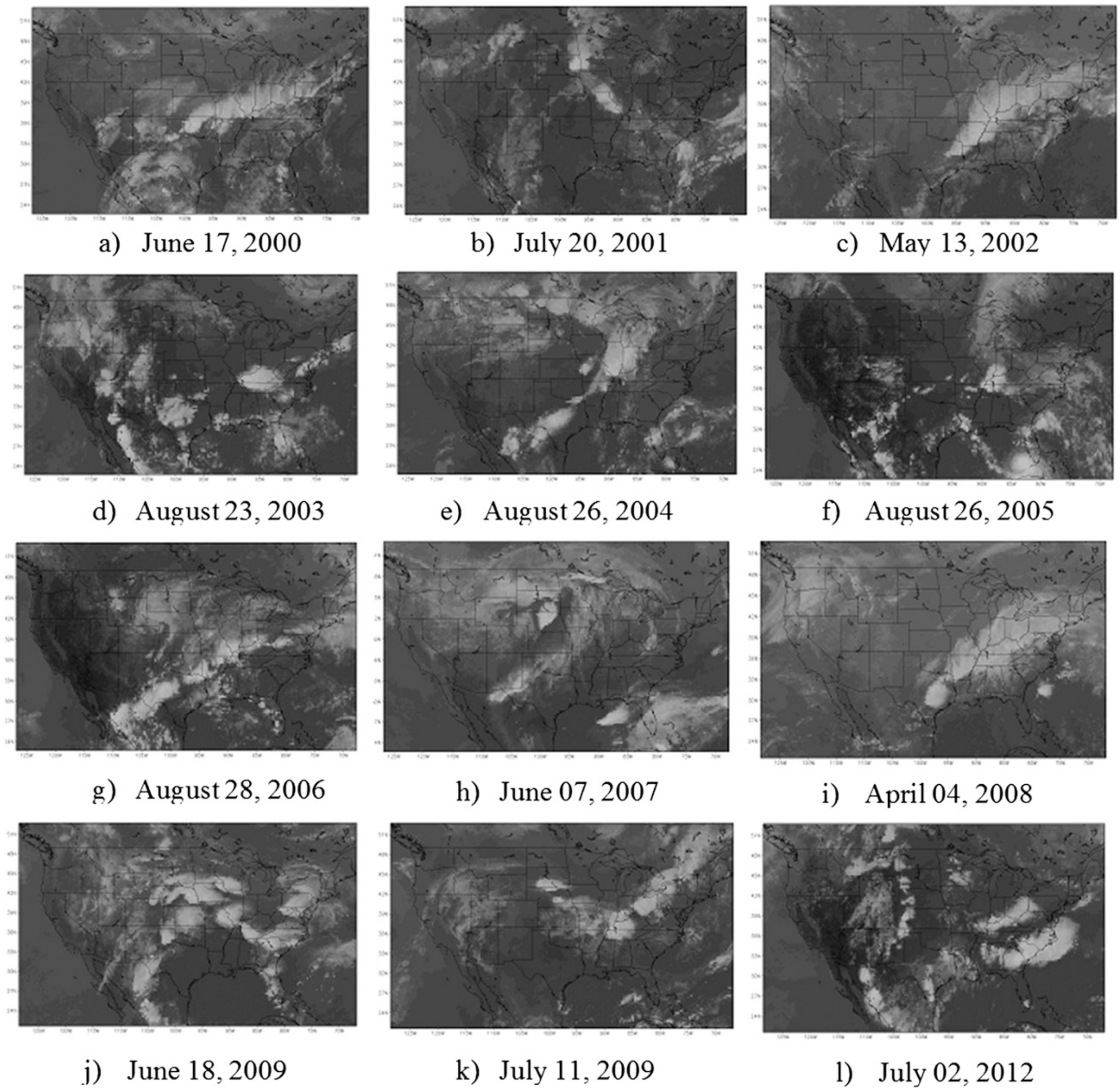

FIG. 3. GOES infrared satellite imagery for the selected events.

Degu and Hossain (2012) showed the impact of large artificial reservoirs on the frequency of downwind precipitation events during the growing season. That study showed the arid/semiarid region tends to increase moistening of the air by 5%–15% downwind of dams.

According to Jacquot (2009), there are approximately 845 000 dams and artificial reservoirs around the globe. Collectively, the surface area of these artificial reservoirs amounts to nearly 33% of total freshwater surface area for Earth. Many of these dams around the world have been constructed for various purposes such as irrigation, water supply, flood control, hydropower, and navigation. A study by Bates et al. (2008) indicated a steady increase in dam construction in developing countries that is expected to continue into the twenty-first century. Though the socioeconomic impact of dams is well documented, no study exists, to the best of the authors' knowledge, that has explored the impact of large reservoirs on the modification of precipitating systems at meteorological time scales. Almost all of the recent studies on artificial reservoirs have focused on precipitation modification at the climate scale (Degu et al. 2011; Degu and Hossain 2012; Woldemichael et al. 2012).

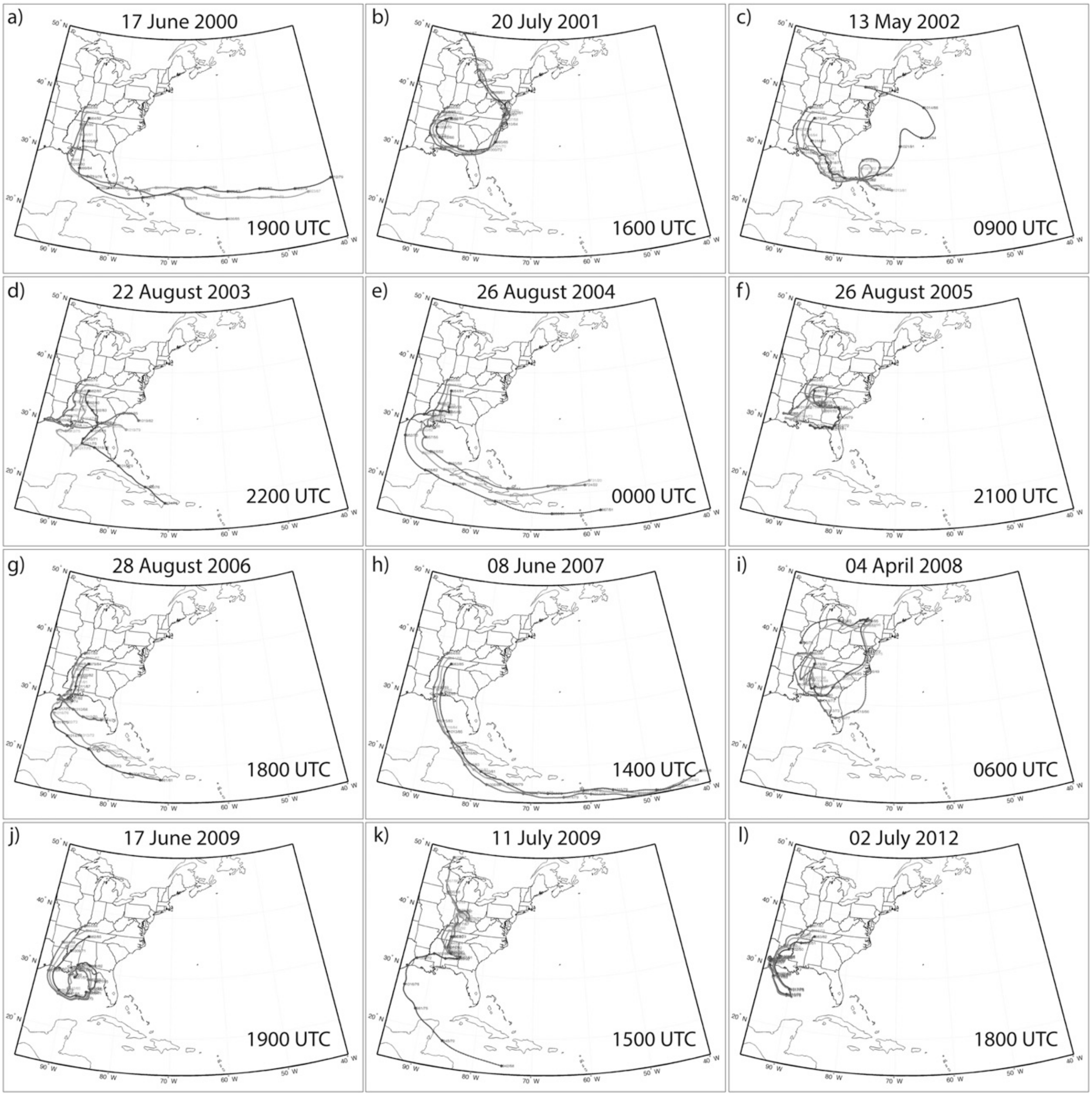

FIG. 4. HYSPLIT single-parcel, 10-day and 100-m AGL backward trajectories ending in the LBL domain.

In this exploratory study, therefore, the potential impact of the LBL on storm patterns at the meteorological scale is pursued. The motivation for this study can be summed up as follows. Since the construction of the two parallel run-on-river dams, the LBL has represented an artificial source of additional moisture to the natural precipitation process through evaporation. Combined with the unique land surface features that are also known to be conducive to mesoscale convection, the LBL could have a potential impact on the regional weather and precipitation patterns. Conceptually, the LBL has all the necessary LULC heterogeneities needed to sustain convection with the additional moisture supply from the artificial lakes. The key science question for this study is therefore the following: Has the unique development of two parallel run-on-river reservoirs and the surrounding LULC heterogeneity modified storm patterns in the region? The data and methodology are discussed in sections 2 and 3, respectively. This is followed by results and discussion in sections 4 and 5. The conclusions are presented in section 6.

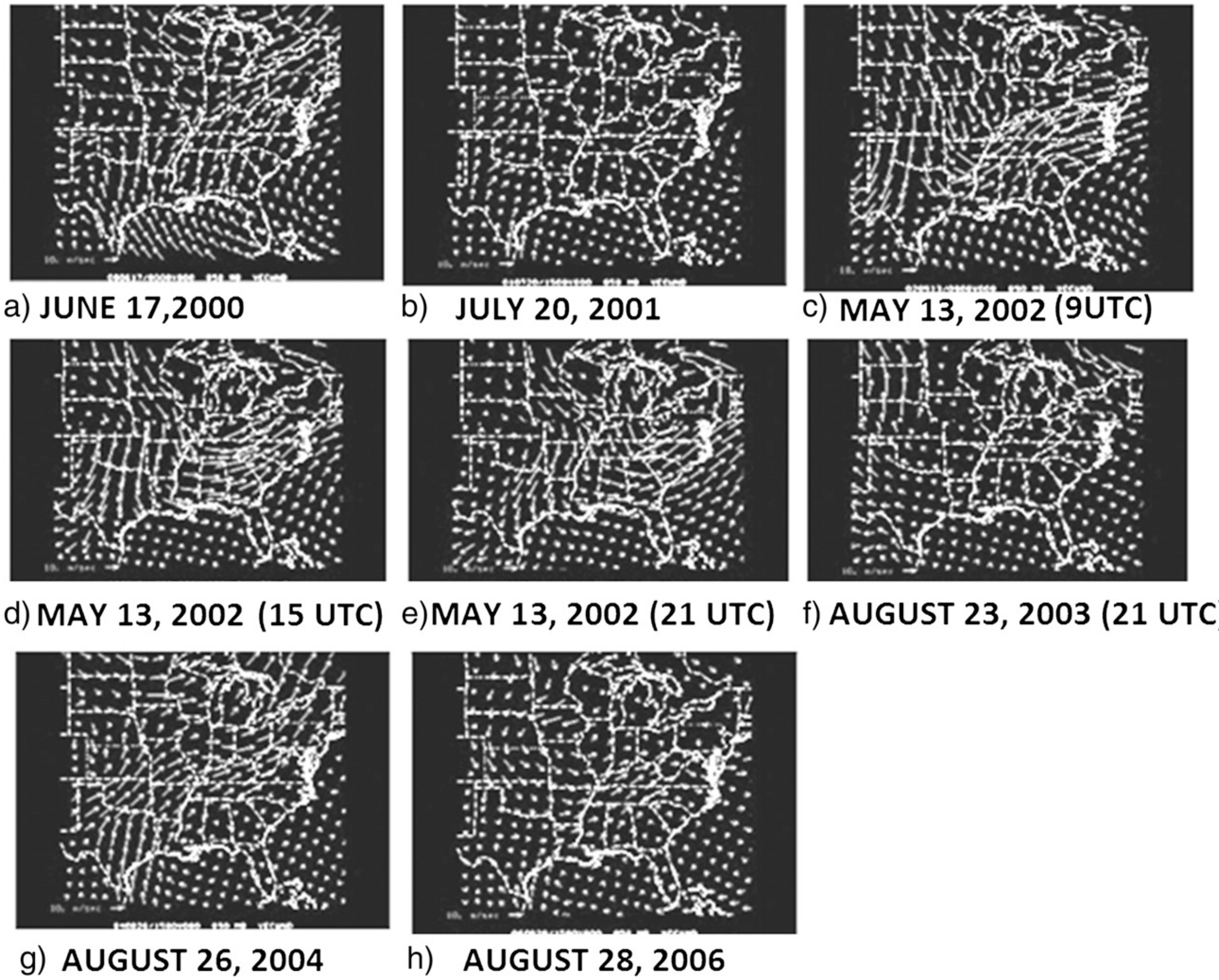

FIG. 5. NARR 850-hPa wind pattern.

2. Data and study region

Daily precipitation data for in situ stations shown in Fig. 2 were obtained from Cooperative Observer (COOP) and the GHCN. These data are available from the National Climatic Data Center (NCDC; http://www.class.ncdc.noaa.gov/saa/products/welcome). For the growing-season period (1 April–31 August) when mesoscale convection is most frequent, daily accumulated precipitation from these in situ stations spanning the period from 2000 to 2009 was analyzed for the selection of storm events used in this study. From these data, 10 event days (1 per year) were identified that represented temporally isolated (duration ~1 day) and heaviest rainfall episode (exceeding 100 mm of accumulation) for each year. For example, the lower panel of Fig. 2 explains how a storm was selected for the year 2001. Two more event days were added based on informal observational reports, as well as to take advantage of the high-resolution observational capability of the newly operationalized Kentucky Mesonet (KY Mesonet; www.kymesonet.org) network. The KY Mesonet was established by the Kentucky Climate Center of Western Kentucky University for automated monitoring of weather and climate across the state of Kentucky. This is a world-class research-grade network of 64 stations with redundant sensors. All data are quality assured and quality controlled (QA/QC) following established scientific standards with data collection frequency every 5 min. A quick look into the two recent events using KY Mesonet station records showed clear differences in precipitation received east and west of the LBL.

As mentioned earlier in the introduction section, the LBL and its surrounding land surface is the primary study region for understanding the impact of the LBL on mesoscale storm systems. The area surrounding LBL exhibits a large variety in LULC and topography (Fig. 2). The Mississippi River valley, located southwest of the LBL,

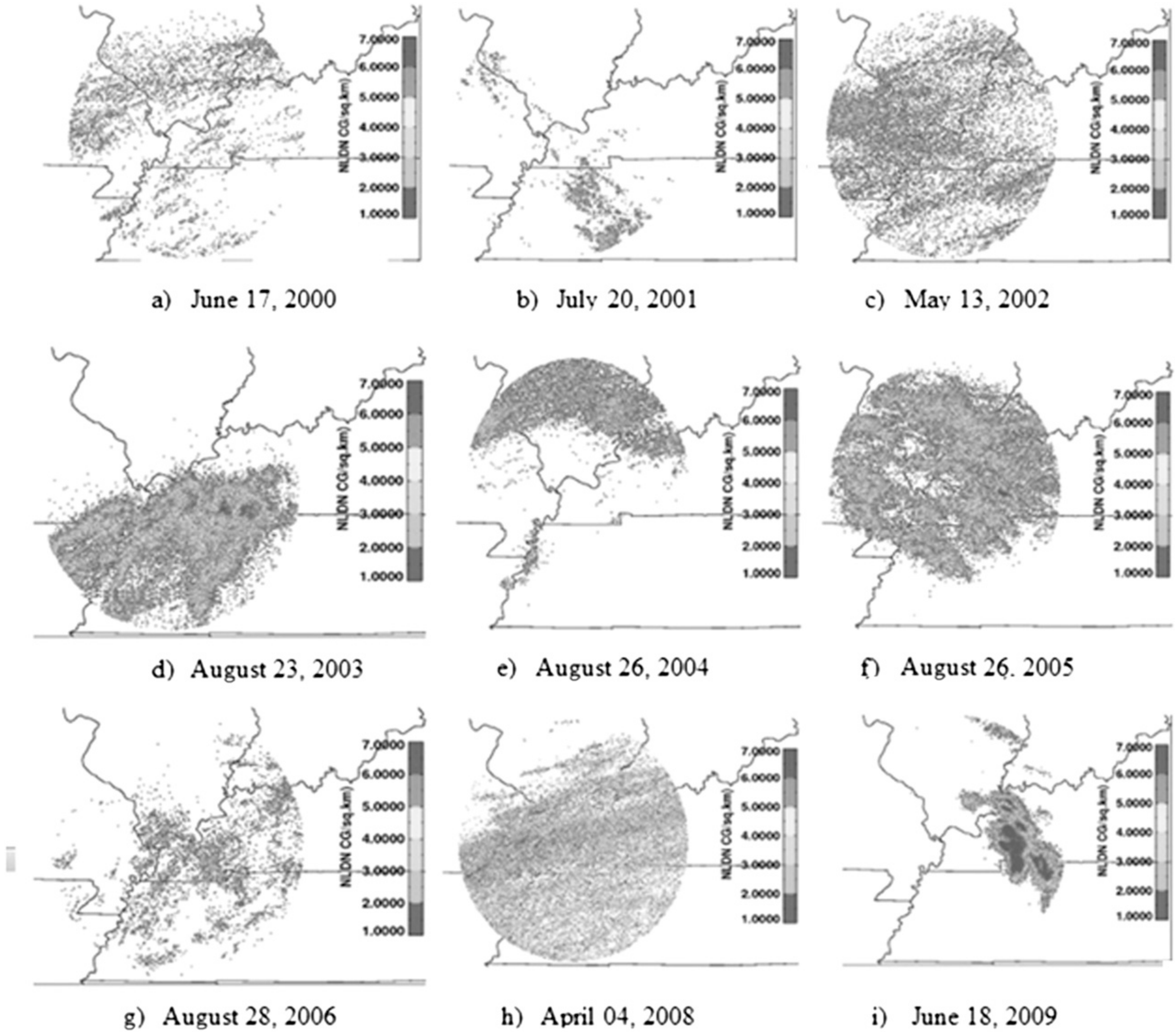

FIG. 6. NLDN C–G lightning density (strikes per kilometer squared) for the KPAH site horizontal swath coverage.

mainly consists of irrigated agricultural land. Farther west and northwest of the LBL, there is extensive forestland cover. On the eastern side of the LBL, the land use is mostly agricultural, although not under large-scale irrigation. Forested land also exists farther east of the LBL. Larger urban areas of various sizes, such as Louisville and Bowling Green, Kentucky; Evansville, Indiana; and Nashville, Tennessee, are located within a few hundred kilometers of the LBL (Fig. 2).

3. Methodology

a. General approach

The key features of the methodology can be summarized as follows. First, we selected a total of 12 storms during the growing season (April–August) from the in situ precipitation gauge data described in the previous section. Of these, 10 storm events were selected from the GHCN data. The remaining two were chosen from the newly established high-resolution Kentucky Mesonet network. Next, radar reflectivity images from the Paducah, Kentucky, NEXRAD site were visually inspected to understand the evolution of convection cells that originated or modified near the LBL. The dynamic space–time pattern of reflectivity was visualized using the General Meteorological Package (GEMPAK) and Gibson Ridge software. Each 5-min image was successively examined for convection cell modification (enhancement or dissipation). The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model was then used to identify low-level air-parcel sources for the selected events. HYSPLIT computes advection, stability, and dispersion of

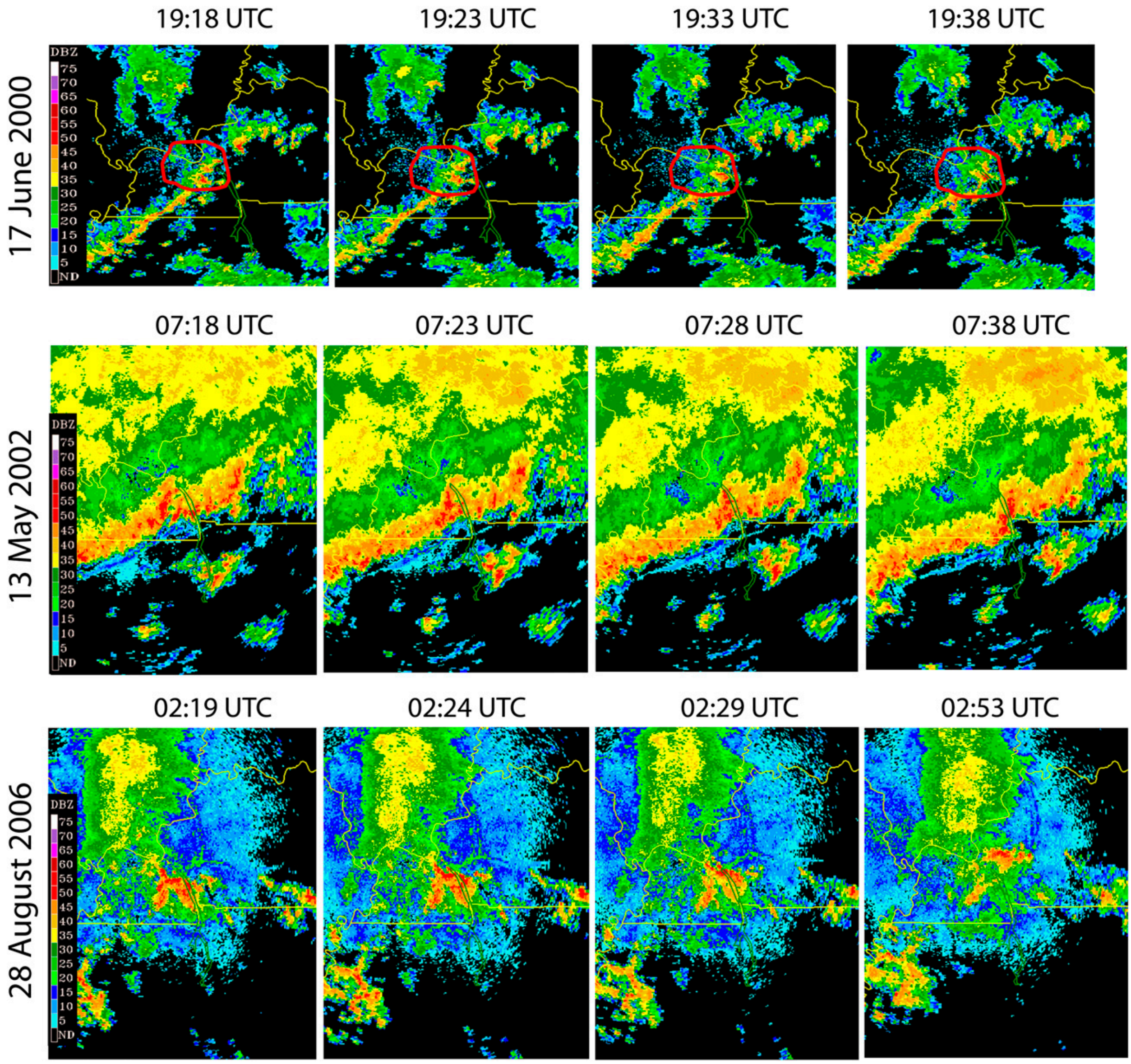

FIG. 7. Time evolution of NEXRAD radar imagery for selected events (category I). The red enclosed area in the top panels indicates the approximate location of the LBL.

chemicals and materials in the atmosphere by using forecasted meteorological data of regional or global models. HYSPLIT employs a Lagrangian approach to compute advection and diffusion of air parcel transportation. The spatial synoptic classification and merged Geostationary Operational Environmental Satellite (GOES) infrared (IR) images were analyzed to determine the prevailing synoptic conditions on the event dates.

b. Specific approach

Although no a priori synoptic condition screening was implemented to filter out the synoptically benign events from the selected 12 events, the synoptic condition was deduced later from spatial synoptic classification systems (SSC; see Table 1). The SSC classification system uses a manual as well as an automated classification to determine the dominant synoptic event and cross-checked with observed condition (http://sheridan.geog.kent.edu/ssc.html). Furthermore, 500-, 850-, and 1000-hPa and surface circulation features and surface-based CAPE and convective inhibition environments were analyzed from the 32-km-resolution NARR dataset using the Integrated Data Viewer. Together, these data showed the overall influence of the synoptic circulation

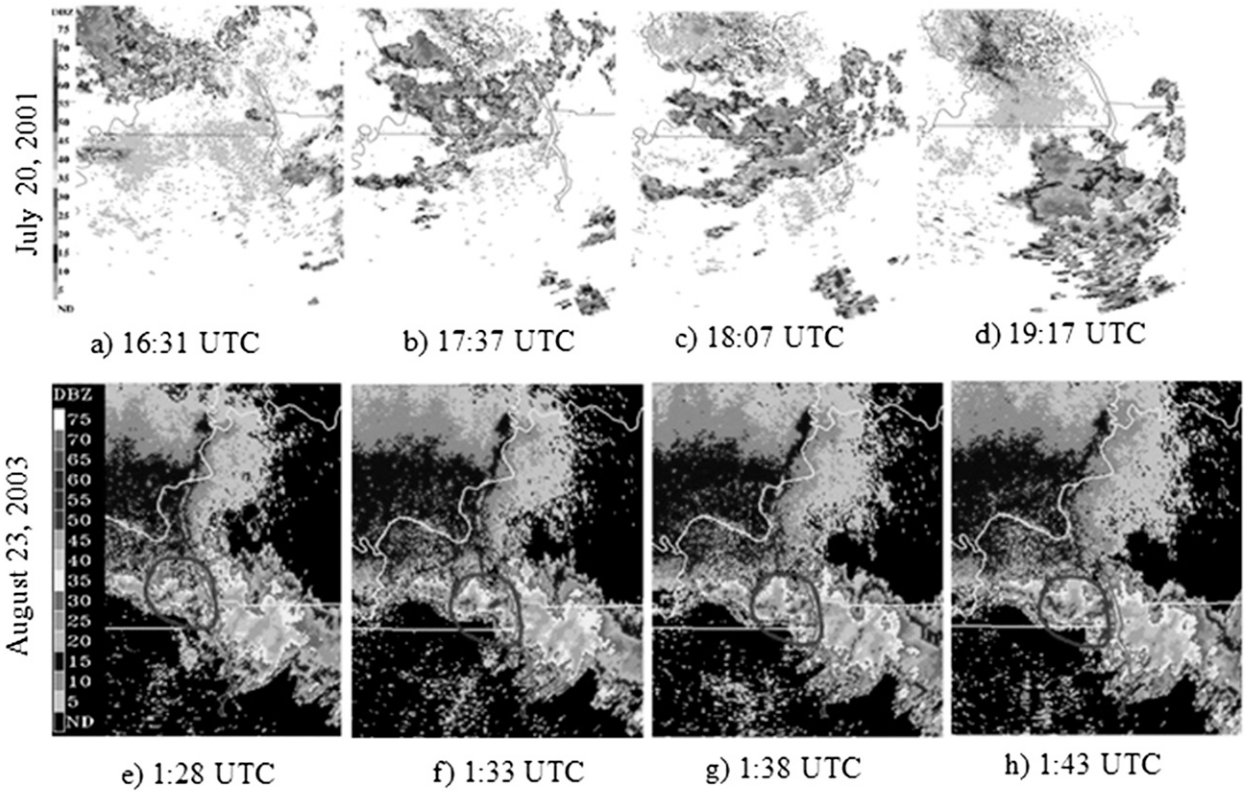

FIG. 8. As in Fig. 7, but for category II (and in black and white).

(or lack thereof) on convection in the LBL region. Regardless of the underlying synoptic condition, we hypothesize that the local effect of the LBL on convection could still be observed during the growing season (warm season) either as enhancement or dissipation of identified convection cells from radar reflectivity imagery (described later).

To further dissect the synoptic condition and the low-level circulation of the selected event days, cloud-top temperature data in the 10.3–11-μm band from the GOES IR sensor were examined (Fig. 3). The animated images were obtained through the Giovanni web portal developed by Goddard Earth Sciences Data and Information Services Center (GES DISC). The Giovanni web portal facilitates visualization, analysis, and access to vast amounts of earth science remote sensing data for selected event dates (http://disc.sci.gsfc.nasa.gov/daac-bin/hurricane_data_analysis_tool.pl). Such data were examined for cloud origin, development, and movement. (The animated GOES IR images are accessible to the reader from the online study site created by the authors at http://www.cae.tntech.edu/~amdegu42/LBL%20Study/).

Analyses of cloud-top temperature complemented the SSC description of the dominant synoptic condition. The low-level circulation for each event was determined using the HYSPLIT model (Draxler and Rolph 2013). This model has been used in tracking the origin of low-level air parcels in various climate characterizations and studies (e.g., Durkee et al. 2012). For this study, HYSPLIT was initialized using the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis data (2.5° grid) (Kalnay et al. 1996) and ran near-surface (100 m AGL) 10-day single-parcel backward trajectories for three locations in the LBL for each event, and for times specific to storms just entering the LBL (Fig. 4). Given the 2.5° resolution of the reanalysis data, we sampled five events with Eta Data Assimilation 40-km-resolution (EDAS40) data to subjectively determine potential considerable differences in output. Overall while some minor differences were noted, no major discrepancies were evident in the near-surface trajectories between the two output sets (not shown) and thus, the reanalysis output was utilized for this study. Wind vectors at 850 hPa were also obtained from NARR to determine the background low-level circulation during the day of the event (Fig. 5). The wind vectors were plotted using GEMPAK (Steenburgh et al. 2000).

For analysis of radar reflectivity and velocity data, nearly 3100 level II and III volume scans were obtained from the NEXRAD station located at Paducah (KPAH)

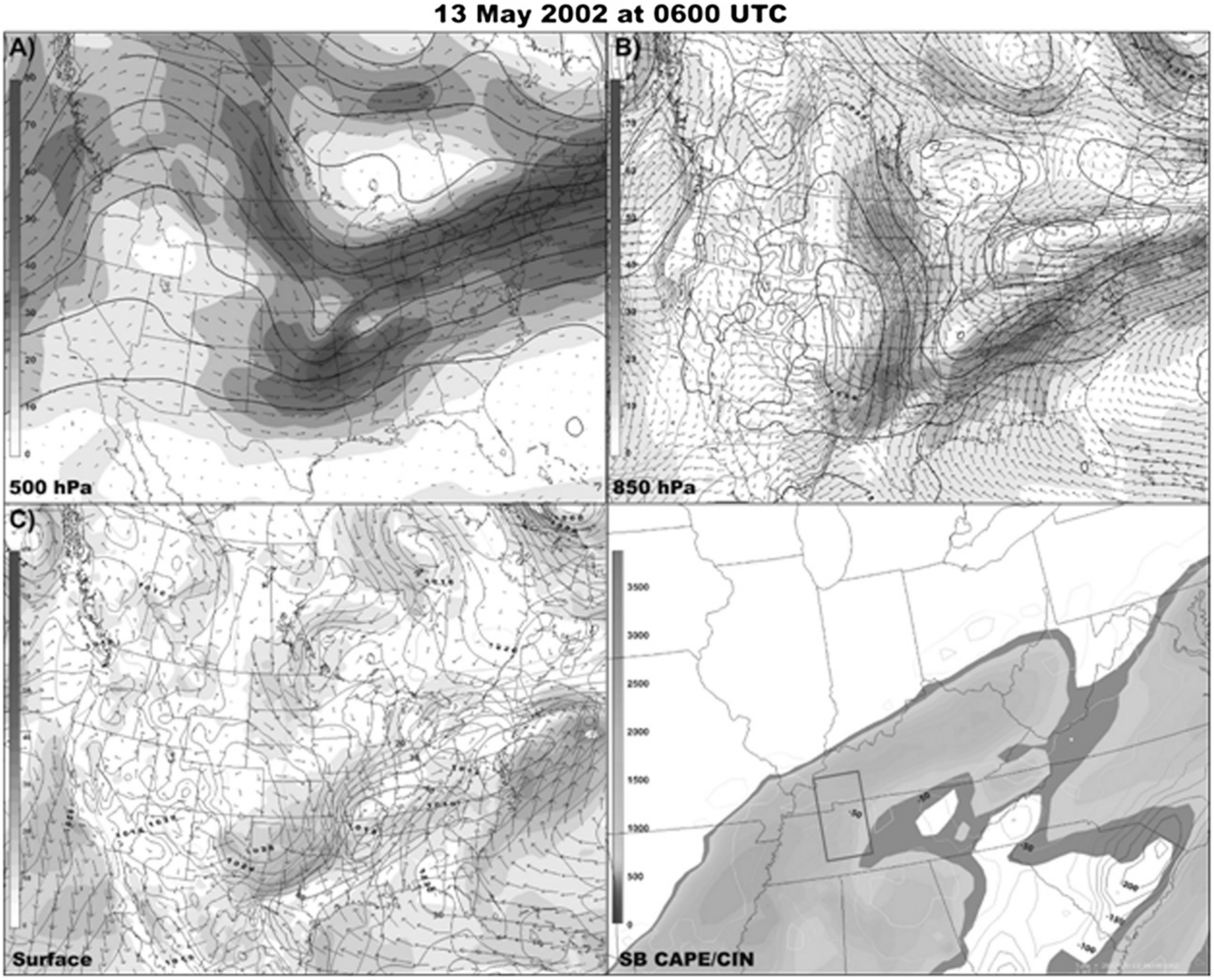

FIG. 9. Large-scale circulation features at 0600 UTC during the 13 May 2002 (category I) event showing (a) 500-hPa, (b) 850-hPa, and (c) surface geopotential heights (contours; gpm), wind pattern (arrows), and specific humidity [shading; kg kg^{-1} ($\times 10^{-3}$)]. (d) Surface-based (SB) CAPE (J kg^{-1}; shading) and convective inhibition (CIN; J kg^{-1}; contours); the gray box denotes the LBL domain.

and examined for convection cell evolution. Finally, as a proxy for cloud growth stage, cloud-to-ground (C–G) lightning density (C–G strokes per kilometer squared) from the National Lightning Detection Network (NLDN) was examined for each of the events. This analysis helped to infer the LULC type around the LBL where C–G strokes were more dominant (Fig. 6). Moreover, such data could indicate the LULC type that experienced preferential convection and rainfall modification.

4. Observational analysis

The observational data analysis of GOES IR data from the 10.3–11-μm band (Fig. 3) and HYSPLIT backward trajectory (Fig. 4) as well as the SSC description (Table 1) revealed that prevailing synoptic forcing existed in all the events considered for this study. This could have potentially masked the effect of the LBL in triggering convection locally. Radar reflectivity images did not reveal convection cells that originated over the LBL (Figs. 7 and 8). However, analyses of the radar imagery did reveal storm-cell modification over the LBL. Based on the evident convection modification, the selected events are described as belonging to one of the two following categories: category 1—events that showed convection cell dissipation after passing the LBL, and category 2—events where convection enhancement was observed adjacent, over, or after passing the LBL. These categorical events are discussed below from a preliminary observational standpoint.

a. Category I

The winds at 850 hPa as well as the GOES IR images of 17 June 2000 events showed a northeasterly storm

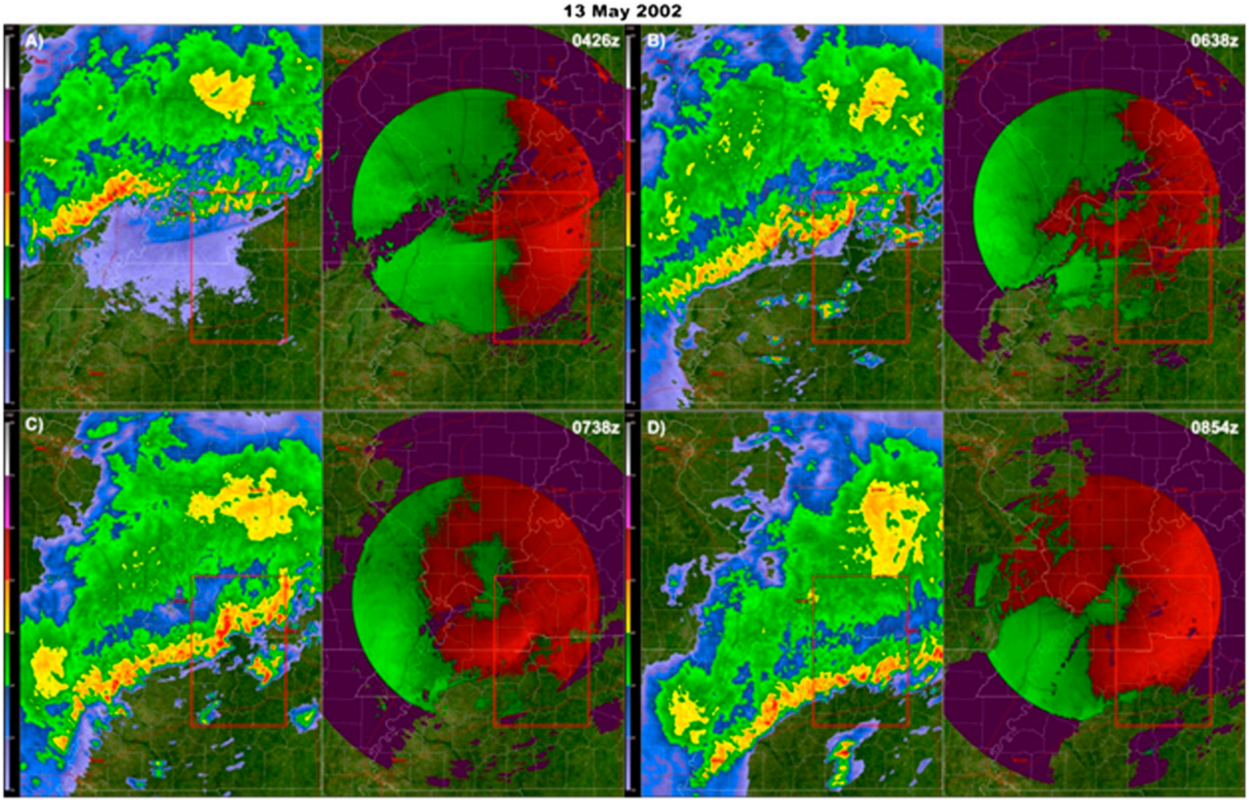

FIG. 10. Qualitative patterns of base reflectivity (left subpanels) and base velocity (right subpanels) from the KPAH site for (a) 0426, (b) 0638, (c) 0738, and (d) 0854 UTC 13 May 2002 (category I). The red boxes indicate the LBL domain.

on the NEXRAD radar. At 2149 UTC, the radar showed an enhanced convective cell to the west of the LBL (Fig. 6, upper panel) over the Mississippi valley. This cell moved toward the LBL and lost strength downstream of LBL. The HYSPLIT backward trajectory showed the initial near-surface trajectories for this event originated from the Atlantic and Gulf of Mexico. The radar image (Fig. 7, uppermost panels) as well as C–G lightning stroke density (Fig. 6a) showed most of the convection occurred north of Paducah away from LBL. A similar phenomenon was observed on 13 May 2002 event (Fig. 7, middle panels). This event was characterized by a shift in wind direction as observed in the 850-hPa circulation (Figs. 5c–e). The northeast wind gradually changed direction toward the southeast starting from 0900 UTC. At around 0713 UTC, a storm cell was observed to weaken as it passed the LBL. Similar to the 17 June 2000 event, the near-surface trajectories were shown to originate from the Atlantic and Gulf of Mexico (Fig. 4c). For this event, the C–G lightning stroke density (Fig. 6c) was observed to be distributed uniformly around the LBL.

For the 28 August 2006 event (Fig. 7, lower panel), it was observed that a storm cell was initially enhanced west of the LBL. From 0219 UTC onward, dissipation of convection began as it passed over the LBL over a 28-min period (Figs. 7i–l). The eastern region of the LBL showed a greater C–G lightning stroke density (Fig. 6g), suggesting higher convective activity as the storm headed farther east. The near-surface trajectories for this event also originated from the Caribbean and Gulf of Mexico (Fig. 4g). The GOES IR images showed a cloud band that stretched to the northeast (Fig. 3g). Generally, the 850-hPa winds showed the storm moving northeast over Mississippi valley, suggesting also moisture contribution from the highly irrigated regions (Fig. 5h). However, without the estimation of cloud volume change (not conducted in this study), the occurrence of moisture pickup from the LBL cannot be confidently established. For other events exhibiting dissipation near the LBL (i.e., 4 April 2008, 11 July 2009, and 18 July 2009), similar observations can be drawn. For these events, storms strengthened upwind of the LBL and then dissipated downwind.

b. *Category II*

Two out of the 12 events analyzed were determined as category II storm systems, whereby the storms

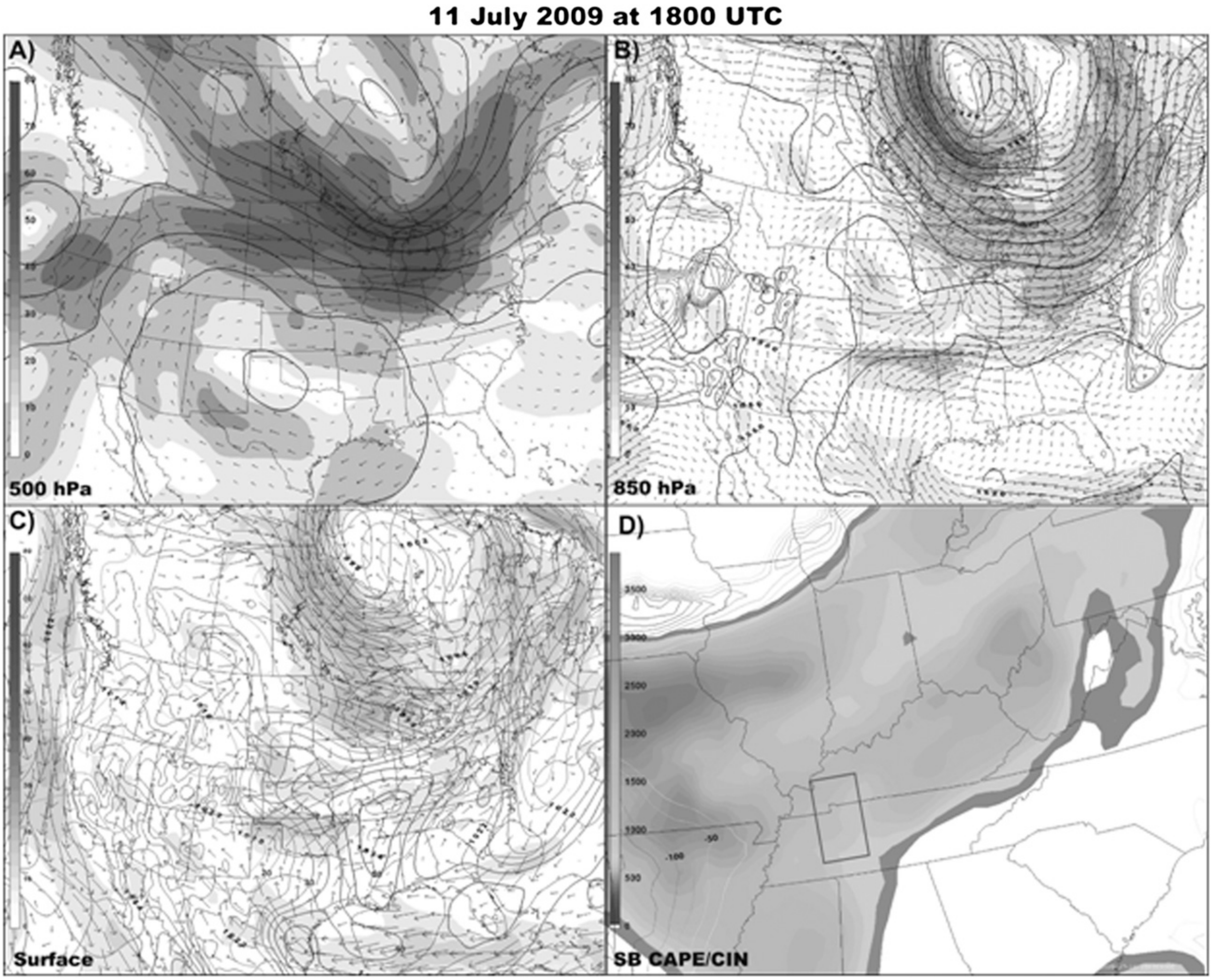

FIG. 11. As in Fig. 9, but for 11 Jul 2009 (category I).

strengthened downstream of the LBL. At 1320 UTC, the 20 July 2001 storm that was propagating southeast changed direction and headed south once it approached the LBL. This storm then started to dissipate before reaching the Paducah radar station. As it passed over LBL and the adjacent Mississippi valley, the storm regained intensity and a clear pattern of convection was formed at 1917 UTC (Fig. 8d). It is possible that the LBL provided enhanced moisture source, which helped strengthen the storm. The near-surface trajectories for this storm event were located just off the East Coast of the United States and Gulf Coast region (Fig. 4b). The GOES IR image showed clouds heading southeast over St. Louis, Missouri, toward the LBL (Fig. 3b). Radar reflectivity imagery revealed the convective nature of this storm (Fig. 8, upper panels).

The event of 23 August 2003 was characterized by a shift in a relatively weak 850-hPa wind circulation from southeast to southwest (Fig. 5f). According to the radar reflectivity imagery, a convective cell intensified after it crossed the LBL from the east at 0141 UTC. The near-surface trajectories originated just off the southeast U.S. coast and Caribbean region (Fig. 4d). Figure 8 (lower panel) provides a more pictorial sequence of the changing convection pattern. There appeared to be an isolated cloud over the Kentucky area as shown in the GOES IR image (Fig. 3d).

5. Discussion—Storm modification by LBL

Observational analysis in the previous section indicated that convection intensified and/or weakened as it passed over LBL. Furthermore, convection intensified and/or weakened under both, synoptically active and/or benign conditions. Herein, a synoptically active pattern is defined by an approaching upper-level trough and the

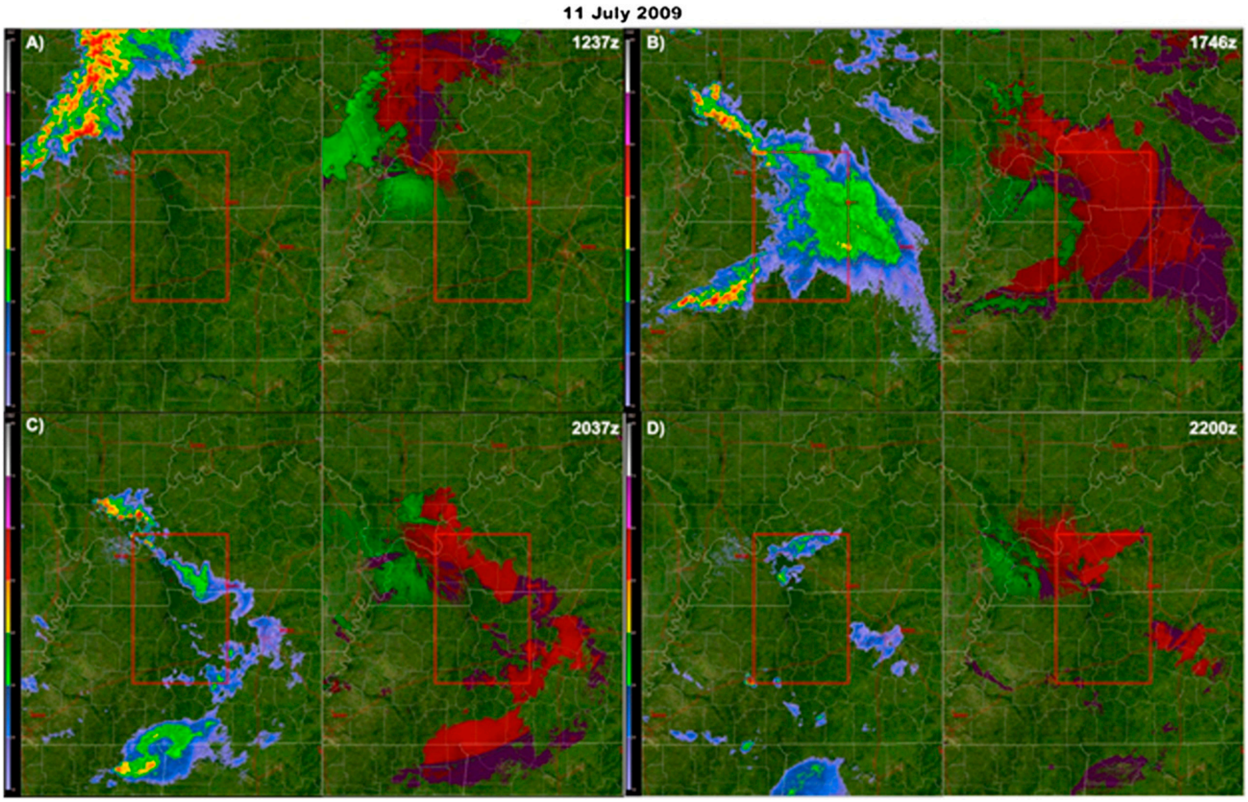

FIG. 12. As in Fig. 10, but for 11 Jul 2009 (category I).

passage of a surface cyclone and attendant fronts, with large-scale dynamical forcing for ascent. On the other hand, a synoptically benign environment is characterized by an upper-level ridge and the lack of a surface cyclone and attendant frontal boundaries near LBL, with little dynamical support for ascent. Upon these initial observations discussed in section 3, a total of four events were selected to analyze convective patterns that either weakened (category 1) or intensified (category 2) upon passing the LBL region, whereby each category contains events that took place during both synoptic characterizations. We analyzed the CAPE, convective inhibition (J kg^{-1}), and precipitable water (mm) for each of the four storms (see lower panels of Figs. 9, 11, 13, 15).

a. *Category I events*

1) 13 May 2002: Synoptically active event

A midlevel shortwave trough approached west of LBL with a surface low pressure center over southeast Missouri (Fig. 9). Radar analysis indicated convection ahead of the cold front within the warm sector was initially relatively strong. Also during this time, outflow started to dominate as the storm cluster began to produce multiple gust fronts as it approached the LBL (see Fig. 10a). Gust front interaction between two storm clusters led to storm intensification over the LBL (see Figs. 10b,c). These newly merged clusters became more linearly organized, while outflow outpaced the storms (see Fig. 10c) and weakened downwind of LBL.

From a thermodynamic perspective, the storm cluster moved into a CAPE region that lessened from ~1500 to ~800 J kg^{-1} over southeast Illinois to LBL, and into a region where convective inhibition increased downstream of LBL. Overall, a poststorm merged cluster that moved into a thermodynamic environment that was conducive for inhibiting overall storm growth potential may potentially explain the downstream weakening of the storm system.

Note that the atmospheric controls leading to precipitation are complex and nonlinear. If we simplify one aspect of this complex relationship, it can be suggested that CAPE, used here, is a useful indicator of atmospheric instability and convective development leading to precipitation. CAPE is physically linked to atmospheric moisture and energy. Higher latent energy fluxes and moist static energy could lead to higher CAPE and subsequently higher precipitation. In other words, we suggest that these lakes provide a considerable source of latent energy flux and moist static energy, which helps to attain

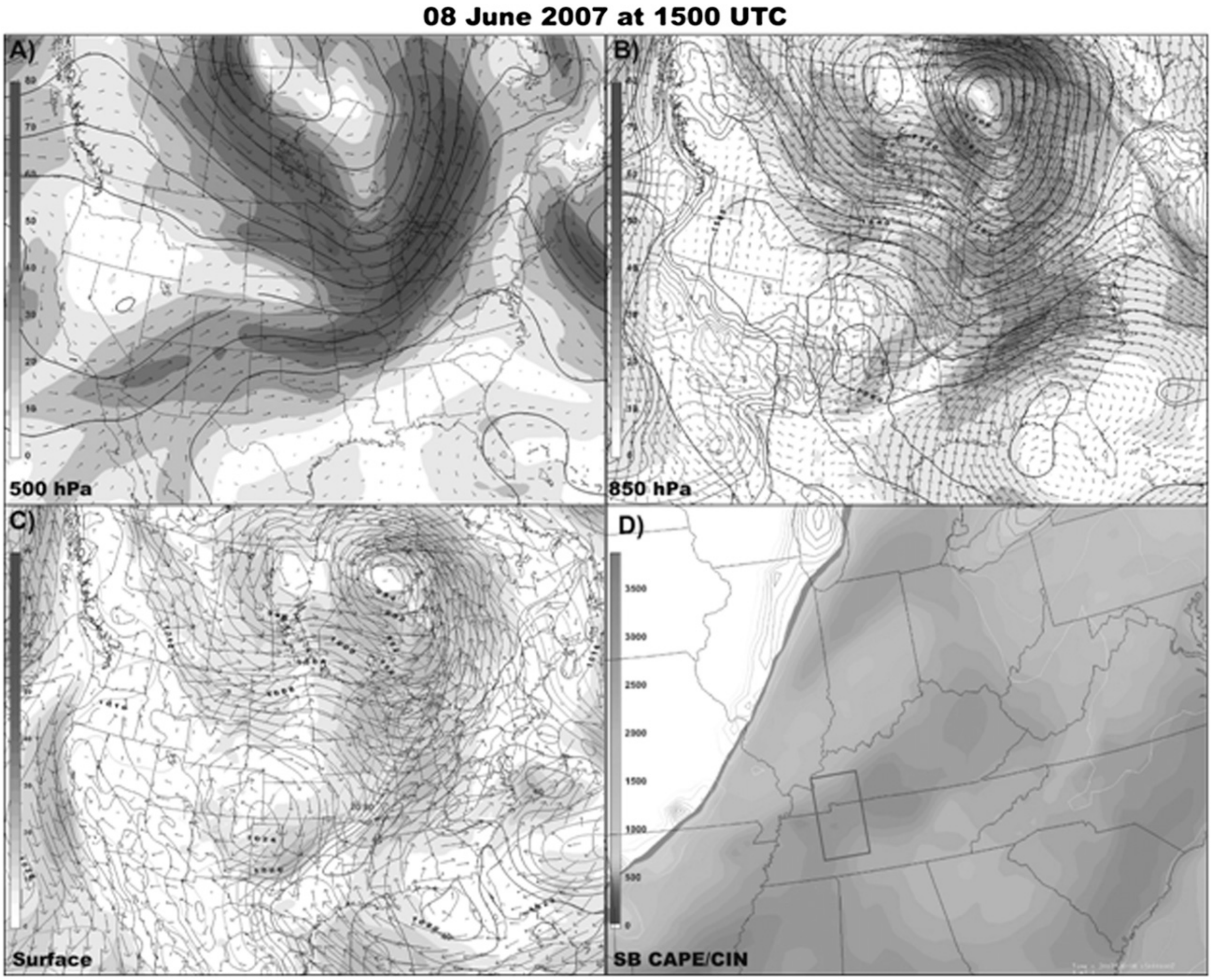

FIG. 13. As in Fig. 11, but for 8 Jun 2007 (category II).

high local CAPE leading to increased localized precipitation. In this particular case lower CAPE around the LBL inhibited already weakened convective development. On the other hand, some of the category II events with greater CAPE values and increased precipitation around the LBL were potentially linked to these enhanced fluxes. To determine the links between atmospheric instability and precipitation in these situations requires additional modeling analyses, which the authors are currently conducting.

It is also noted that when soil moisture is not restricted, CAPE increases with increased low-level heating during diurnal progression (associated with diurnal cycle of latent energy fluxes) (Quintanar et al. 2012). Quintanar et al. (2008) also showed that lower Bowen ratio (i.e., high latent energy flux) was associated with precipitation and coincided with the occurrences of high CAPE. Some studies suggest that surface latent and energy fluxes help to generate CAPE and also maintain its diurnal variation. However, our observation of data from the same study suggests precipitation onset was collocated with maximum CAPE values. Zangvil et al. (2004) also reported high and low CAPE values were coupled with low and high convective inhibition, respectively. Again this and the category II precipitation events around LBL generally resemble this thermodynamic state of the atmosphere. Additional discussions on CAPE and its physical link with convection are discussed in Pielke (2001).

2) 11 JULY 2009: SYNOPTICALLY BENIGN EVENT

A strong upper-tropospheric ridge was observed in the south and west of LBL, over the Texas Panhandle, with a passing trough axis over the Great Lakes. A weak boundary north of the LBL was the focal point for convection that moved south toward the LBL, following the upper circulation (Fig. 11). Radar analysis indicated a relatively strong storm cluster over southern Illinois

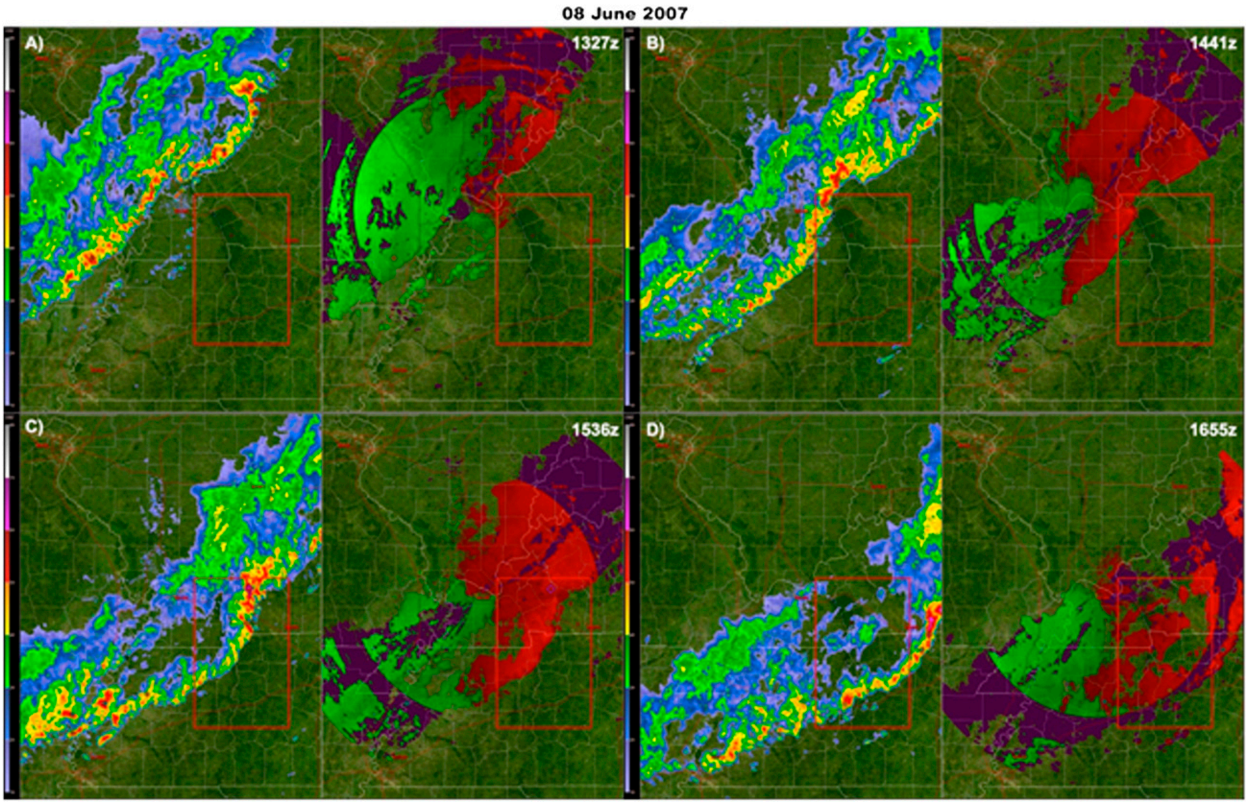

FIG. 14. As in Fig. 12, but for 8 Jun 2007 (category II).

(see Fig. 12a) that began to bow, disperse, and weaken as it entered the LBL (see Fig. 12b). The northern extent of this linear convective system moved along track the LBL and dissipated as it passed through the LBL region (see Figs. 12c,d).

From a thermodynamic perspective, the storms were much stronger over Illinois where CAPE values ranged from 1000 to 2000 J kg^{-1}, with midtropospheric lapse rates were ~7°C km^{-1} and little to no convective inhibition. Meanwhile, farther south over western Kentucky and the LBL, the static stability was considerably stronger, with midtropospheric lapse rates around 5.5°–6°C km^{-1}. Overall, downstream weakening may also be explained by a weak thermodynamic environment not conducive to overall potential for storm growth.

b. *Category II events*

1) 8 JUNE 2007: SYNOPTICALLY ACTIVE

A deep upper-tropospheric trough axis was located just west of the LBL, with a surface cold frontal boundary located just west of the LBL (Fig. 13). Radar analysis indicated a weakly organized squall line north and west of the LBL (Fig. 14a). As the line entered the LBL, the northern and southern extents of the system weakened, while the portion of the line that crossed LBL strengthened (reflectivity values increased from the range of 45–55 to 55–64 dB*Z*) (Figs. 14b–d). Another interesting feature is a weak flare up of convection over LBL behind the line (Fig. 14d).

From a thermodynamic perspective, convective inhibition eroded between the time of Figs. 14a and 14b, where the storms intensified. Moreover, the storms began to intensify along an increasing CAPE gradient with values near 2000 J kg^{-1} downstream of the LBL. Overall, the storm intensified as it propagated into a thermodynamic environment conducive to storm growth and potential. However, the focus of the intensification appeared to be over the LBL, with surrounding convection, which failed to maintain this intensity. As noted in the published literature (discussed in section 1), we suspect that potentially, a large amount of latent energy flux (i.e., low Bowen ratio) from the two reservoirs may have also played an important role in the intensification of these storms. The authors suggest that similar support for storm development through land surface–atmospheric interactions and lower-troposphere instability, was absent during the category I events. In other words, it is the combination of both influential

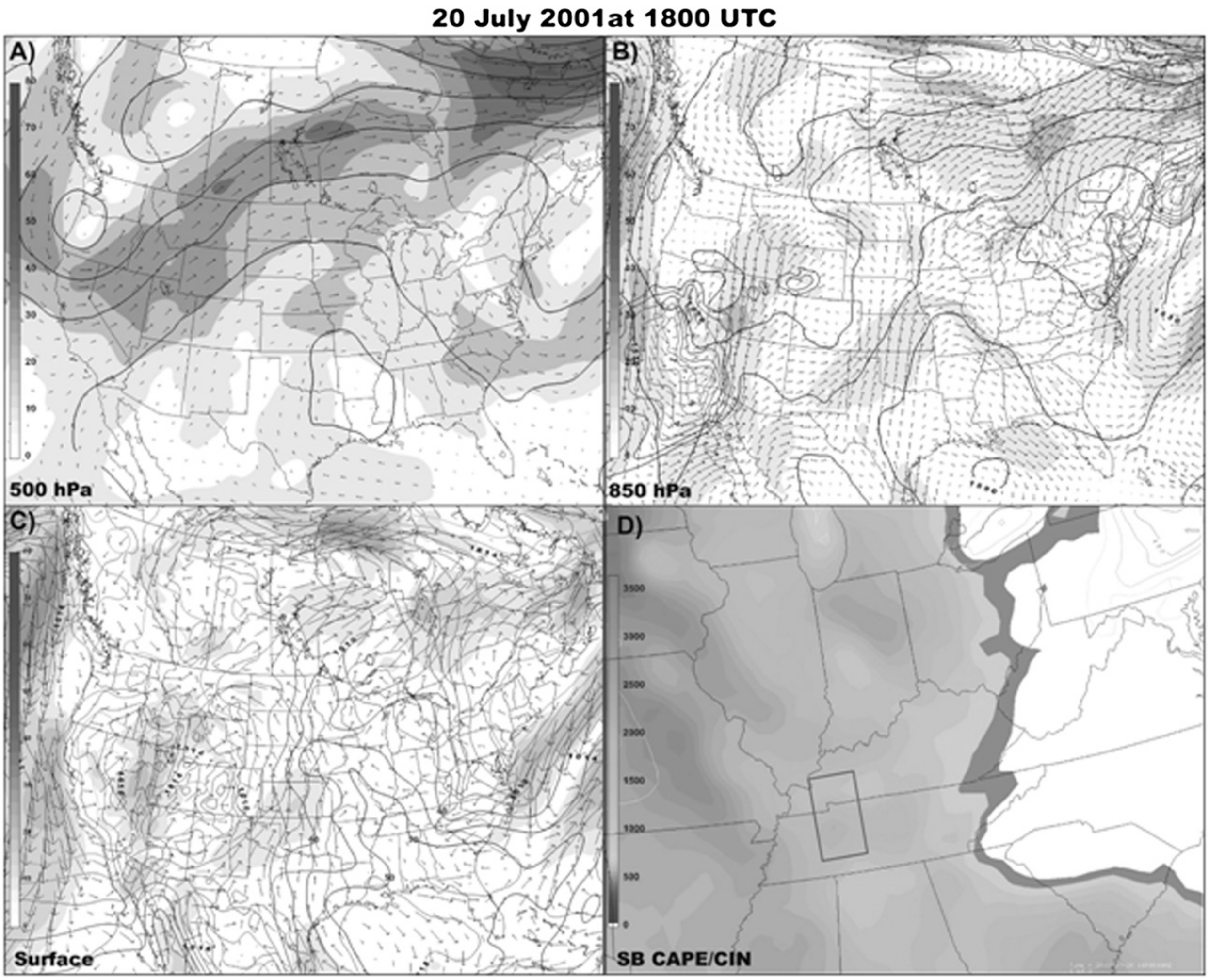

FIG. 15. As in Fig. 13, but for 20 Jul 2001 (category II).

factors (land surface interactions and lower-troposphere instability) that was critical.

2) 20 JULY 2001: SYNOPTICALLY BENIGN

A strong upper-tropospheric ridge was centered over the Arkansas, Louisiana, and Texas region, with no distinguishable surface boundaries in relative proximity to the study domain (Fig. 15). Radar analysis indicated a stream of convection approached LBL from the northwest, following the upper circulation (see Fig. 16a). As the storm passed through the LBL, convective intensity strengthened and organized into a cluster along the western portion of the LBL (see Figs. 16b–d). Meanwhile as these storms strengthened, scattered convection weakened along the eastern portion of the LBL as it approached. An interesting observation with this case was that these scattered storms weakened over the northern LBL region, as new convection initiated and intensified east and south (downstream) of the LBL (see Figs. 16b–d).

Radar reflectivity values increased west and south of the LBL, as indicated by the increased hail production and common cold-pool gust front (see velocity fields in Figs. 16b–d). From a thermodynamic perspective, this storm moved across a CAPE gradient of 2500–3000 J kg^{-1} across the LBL near 1500 UTC. However, by 1800 UTC CAPE decreased to ~1500 J kg^{-1} over LBL, with increased CAPE up to 2200 J kg^{-1} and virtually no convective inhibition downstream over Tennessee. As noted by the previous events, the thermodynamic environment likely played an important role in the storm morphology of these events. However, what is unique in the latter two cases is the collocation of increased convective intensity as it passed over the LBL. To that extent, it is plausible to consider that in conjunction with sufficient thermodynamic support for

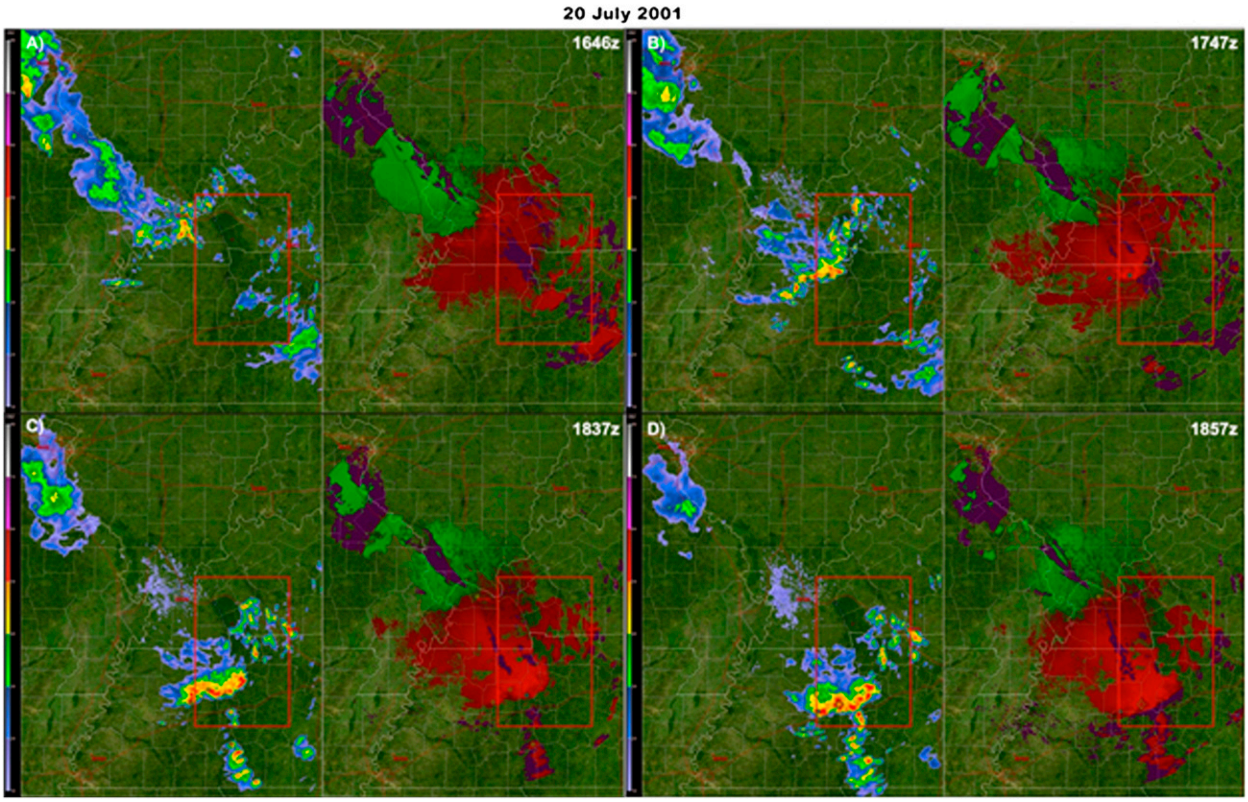

FIG. 16. As in Fig. 14, but for 20 Jul 2001 (category II).

the development and maintenance of convective storms, land surface–atmospheric interactions surrounding the LBL may act to modify the local convective behavior across this region.

6. Conclusions

This exploratory study examined the possible influence of the LBL surface heterogeneity on local convective intensities and resultant precipitation patterns. The study was conducted with the premise that the LULC heterogeneities in the neighborhood of LBL and the different airmass boundaries created as a result of LULC change in the region may possibly modify local convection morphology. Radar reflectivity data of 12 events were analyzed for modification of convection together with GOES IR, HYSPLIT, and C–G lightning data. In addition, this research provides an extension of previous scientific work on artificial reservoirs by Degu et al. (2011) and Degu and Hossain (2012).

This investigative study showed possible modification of convective storms due to development of the LBL and the surrounding LULC features. Of the analyzed 12 events, eight events showed potential signs of modification of convection cells over the LBL. Overall, it is plausible to consider that some of these storms strengthened downwind of the LBL as they headed into a more favorable thermodynamic environment. Although the remaining four events did not show a convincing modification of storms over the LBL, this study suggests that while the thermodynamic environment likely played a key role for all events, land surface–atmospheric interactions surrounding the LBL may also act to influence local convection.

The world has experienced extensive LULC change, particularly because of agricultural expansion and intensification with cropland, making up 11% of the total earth land area (Pielke et al. 2011). This change is likely to continue in developing countries for improving livelihood through building large dams for the purpose of irrigation for food production (Bates et al. 2008). This study provides evidence that supports the notion that local storm modification and resultant precipitation patterns across western Kentucky and Tennessee are possibly influenced by the presence of the LBL. The inadvertent human development activity of impounding the Tennessee and Cumberland Rivers has likely initiated regional climate change, which could alter the design and operation rules for water management in the near future. Hence, understanding the extent and how the LBL and surrounding LULC affect regional climate, especially on precipitation, is imperative for water resource management.

This study is not without its limitations. For example, some deep convection was short lived, often on the order of minutes. The selection of the events was based on daily accumulated precipitation, which could also be a result of long duration, light nonconvective precipitation. The method for selecting events based on daily totals could have also masked events that would have provided more information on convection initiation and/or modification. In addition, the high variability of LULC in the vicinity of the LBL, the limited set of data used, and the exclusive dependence on observations can often fail to pinpoint the responsible physical factors for convection modification. Numerical modeling of these events is therefore a natural extension of the current study. Such modeling can provide more physical explanation to identify the responsible LULC type and the extent to which the LBL affects convection. As an extension of this work, the authors are currently conducting simulations using the Weather Research and Forecasting model to better understand physical mechanisms and controls on precipitation around the LBL area.

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