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The effect of reservoirs on the climatology of warm-season thunderstorms in Southeast Texas, USA

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ABSTRACT: Although ample research suggests that urban environments and their associated land use/land cover modify convective precipitation patterns, little research has explored the role of human-made bodies of water – artificial reservoirs – on thunderstorm climatology. This study provides the first radar-derived climatological analysis of the impact of artificial reservoirs on warm-season convective initiation (CI) and associated thunderstorms. An area centred on three large reservoirs in Southeast Texas is examined to explore how the artificial bodies of water influence the spatiotemporal nature of deep, moist convection. A thunderstorm day and CI climatology for the study domain is constructed utilizing composite radar reflectivity data from 1997 to 2013. The results illustrate enhanced (reduced) convective activity on the edges of (atop) the reservoirs. The presence of the reservoirs also induced increased variability in thunderstorm occurrence compared to areas with no reservoirs. In addition, spatial analytical testing yields statistically significant higher densities of CI events on the southern shores of the reservoirs. Evidence that relatively small bodies of water can influence regional convective patterns and modify the risk of thunderstorm hazards is presented.

KEY WORDS reservoirs; thunderstorms; climatology

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1. Introduction

Human-made reservoirs are used for a variety of societal functions, including fisheries, recreation, navigation, water resources, flood control, and hydropower (Hossain *et al.*, 2010; Zhao and Shepherd, 2012). However, the impact of these impounded bodies of water on regional precipitation trends is not well understood (Durkee *et al.*, 2014). It is possible that they may represent a significant anthropogenic modification of local to regional-scale climate (Degu and Hossain, 2012). Another human-made modifier of regional climate – urbanization – has received considerable attention in the literature. Similarities exist between urban areas and reservoirs in the context of mesoscale modification of the atmosphere. Research has provided ample evidence that urban environments modify regional precipitation patterns by, for example, enhancing precipitation amounts downwind of the city (Shepherd, 2005; Han *et al.*, 2014). These patterns exist due, in part, to the formation of localized baroclinic conditions caused by thermodynamic discontinuities between urban and rural environments (Huff and Changnon, 1972; Miao and Chen, 2008), which are similar to sea and lake breezes (LBs) (Kingsmill, 1995; King *et al.*, 2003; Hill *et al.*, 2010; Sills *et al.*, 2011). Evidence of urban-influenced convective modification begs the question: *Do artificial reservoirs, like urban areas, affect the spatiotemporal nature of deep, moist convection (DMC)?* The impact of reservoirs on DMC could potentially manifest as (1) local maxima/minima in thunderstorm occurrences, and (2) local maxima/minima in convective initiation (CI) occurrences. In this investigation, radar reflectivity data are interrogated to find evidence of these possibilities. The research quantifies the effect of artificial bodies of water on the spatial and temporal distribution of DMC in a humid-subtropical region over a relatively long study period.

2. Background

Because of the vulnerabilities associated with the high-impact nature of convective weather near and around urban areas, the impacts on convection trends that urbanized locations place on their surrounding environments have made up a large portion of land use/land cover (LULC) research (Borden *et al.*, 2007). During the warm season, both observational and modelling research suggests that there is an increase in precipitation for locations near and downwind of the urban centre (Shepherd *et al.*, 2002; Niyogi *et al.*, 2011). Further, the size and geometry of urban 'footprints' impact the frequency and intensity of thunderstorm development (Ashley *et al.*, 2012; Shepherd *et al.*, 2013). These studies have established that convection can be modified by LULC.

Similarly, dam construction and affiliated impoundment of water have also been implicated as a modifier of regional precipitation patterns. LULC changes caused by the presence of dams impact both the regional hydrometeorology

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and precipitation patterns (Woldemichael *et al.*, 2012, 2013; Zhao and Shepherd, 2012; Durkee *et al.*, 2014), particularly when constructed in more arid climates like the western United States (Hossain, 2009). These human-made structures and the LULC changes associated with them provide favourable environments for CI and maintenance of storms because of the increases in soil moisture (Frye and Mote, 2010), cropland (Carleton *et al.*, 2001), and irrigation (Pielke and Zeng, 1989; DeAngelis *et al.*, 2010). As with urbanization, these variables can contribute to the formation of thermally induced boundaries that can modify the spatiotemporal characteristics of convection and precipitation (Hossain *et al.*, 2009).

The physical driver for a LB circulation is the differential heating between the water and the adjacent land. Thermal gradients as small as 1 °C have been observed to stimulate the formation of an LB (Asefi-Najafabady *et al.*, 2012) and most summertime instances of LB formation occur when $\Delta T \leq 12\,°\mathrm{C}$ (Laird *et al.*, 2001). Thus, it is not crucial for the temperature gradient to be exceptionally strong for LBs to form.

Additionally, the synoptic pattern is vital to the development and sustenance of LB circulations. In particular, LBs are highly sensitive to the orientation and speed of the background flow (Segal *et al.*, 1997). Low-to-moderate flow that opposes the onshore flow of the LB further intensifies the LB by enhancing local convergence (Arritt, 1993; Atkins and Wakimoto, 1997; Segal *et al.*, 1997). Moreover, low-to-moderate onshore flow allows for the LB to move further inland, often reaching distances greater than 20 km from the lake source. Conversely, the LB could be diffuse, deformed, or prevented from forming at all during days with strong background winds (Sills *et al.*, 2011). Asefi-Najafabady *et al.* (2012) assessed the influence of synoptic flow on LB formation by investigating two types of flow with respect to the major axis of the lake. They discovered that the LB was most intense when the flow was perpendicular to the major axis of the lake and wind speeds were less than or equal to 10 kts. When background flow surpassed this magnitude, the LB was advected away from the lake or destroyed. When background winds were oriented parallel to the lake's major axis and wind speeds were marginal, two distinct LB boundaries developed on both sides of the lake. Stronger background flow also disrupts LB formation associated with relatively small and circular bodies of water and LBs on the downwind side of these types of lakes typically penetrate farther inland (Blanchard and Lopez, 1985; Segal *et al.*, 1997; Crosman and Horel, 2010).

While much is known about the general characteristics of LBs, there is little in the literature that investigates the climatological importance of small lakes on CI. Much of the existing research has focused on large bodies of water (e.g. Great Lakes, oceans) and convergent boundaries, either between two LBs, a temperature or moisture boundary, or another forcing mechanism. Byers and Rodebush (1948) explored the occurrence of CI on the Florida peninsula and concluded that the interaction between sea breezes was the primary trigger for convection. This convergence between sea breezes was modelled by Pielke (1974), demonstrating that CI, on synoptically quiescent days, was controlled solely by the movement and convergence of sea breezes. Furthermore, convergent boundaries from the Great Lakes have been shown to influence CI and precipitation events (e.g. Harman and Hehr, 1972; King *et al.*, 2003).

3. Data and methods

3.1. Data

WSR-88D-derived products (Crum *et al.*, 1993) have two pertinent advantages over rain gauge data: (1) radar data boasts superior spatial coverage (Matyas, 2010) and (2) radar data allow researchers to differentiate effectively between stratiform and convective rainfall (Parker and Knievel, 2005; Matyas, 2010). In this investigation, we employ NOWrad$^{\mathrm{tm}}$ national composite data that span the continental United States (CONUS) and have 2.0×2.0 km spatial resolution and 5-min temporal resolution (Parker and Knievel, 2005). Weather Services International (WSI) produces these data by ingesting NEXRAD composite reflectivity every 5 min from each available federal radar installation in the CONUS. This data set provides spatially contiguous radar data in an accessible, pixel-based format. Further, this national mosaic product has data available from 1997 to 2013, which makes it an ideal data set for climatological radar studies.

Next, spatial synoptic classification (SSC; Sheridan, 2002) data were incorporated to systematically minimize the effect of large scale forcing on precipitation distribution around reservoirs (cf. Mote *et al.*, 2007; Ashley *et al.*, 2012; Stallins *et al.*, 2013). This is advantageous because synoptic-scale forcing can dissipate LB circulations or overwhelm the precipitation signal caused by reservoirs (Asefi-Najafabady *et al.*, 2012). Moreover, days labelled as moist tropical, or MT, typically have two of the ingredients (Doswell *et al.*, 1996) required to produce DMC: moisture and instability (Dixon and Mote, 2003; Mote *et al.*, 2007). The third necessary ingredient – lift to the level of free convection – is theoretically supplied by local forcing mechanisms such as LB fronts or localized convergence.

Finally, 700-hPa wind direction and speed from daily weather balloon launches at 1200 UTC for KSHV were acquired. Past studies have used this level as a steering wind proxy because of its similarity to deep-layer winds in barotropic conditions associated with warm-season subtropical highs in the southern United States (e.g. Rose *et al.*, 2008). Furthermore, this level is typically above the boundary layer and, as a result, less sensitive to diurnal phases.

3.2. Study area

Our study focused on three large artificial reservoirs in southeastern Texas (Figure 1). We were motivated to examine the effect of these particular reservoirs on DMC for a number of reasons, including anecdotal observations of the reservoirs' moderating effects on cumulus clouds

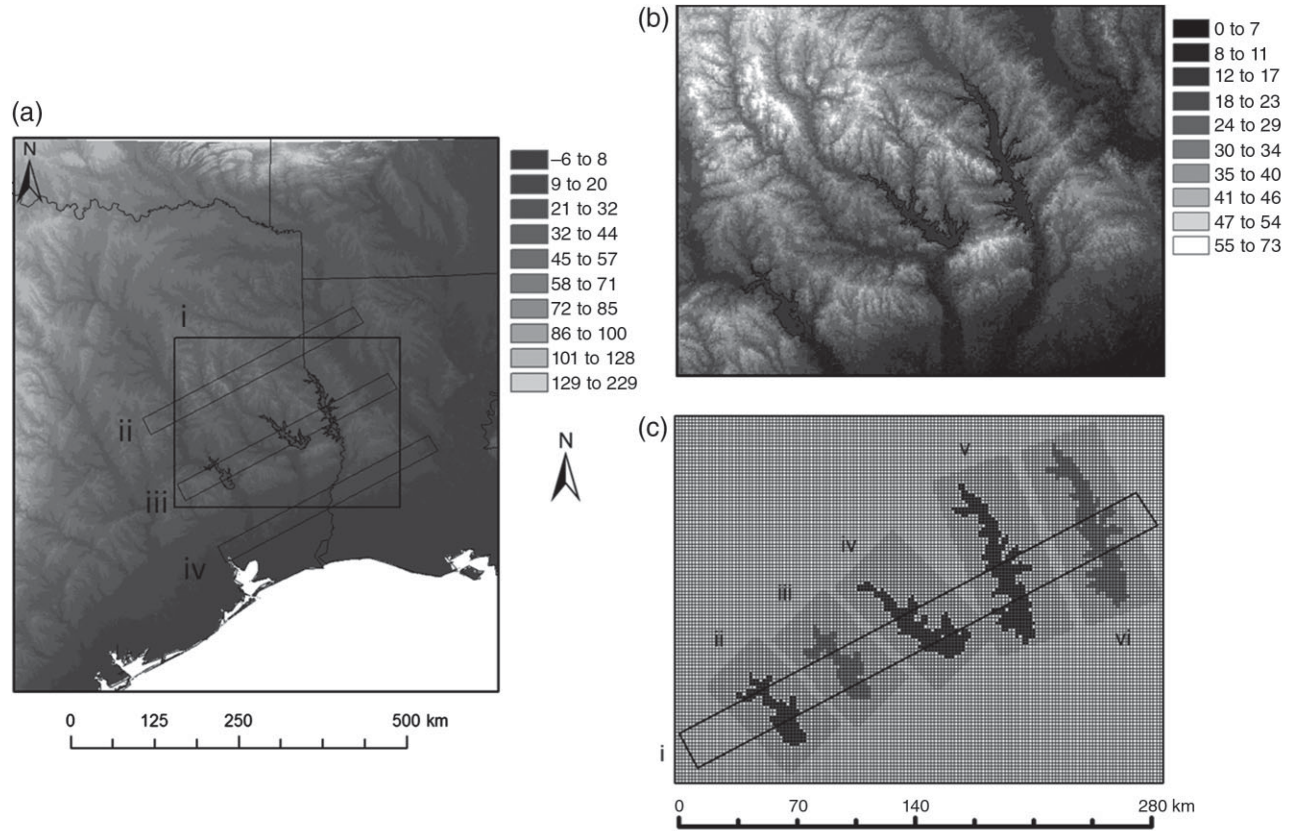

Figure 1. Regional (a) and study area (ai, b) elevation in metres above sea level. Rectangular polygons (aii–iv, ci) were placed across the study area to compare 'cross sections' of thunderstorm day counts per 2-km pixel. The 2-km grids in panel (c) were partitioned into four different classifications for statistical testing: background (lightest grey), near-reservoir (second-lightest grey), control-reservoir (second-darkest grey), and reservoir (darkest grey). Specifically, panel (c) includes Lake Livingston (cii), Sam Rayburn Lake (civ), Toledo Bend Reservoir (cv), and control reservoirs (ciii and cvi).

during summer days (e.g. Figure 2; M. Berry, 2014; personal communication); the area is dominated by a relatively static MT air mass during the warm season, reducing the influence from transitional synoptic regimes that may overwhelm LULC effects; that these reservoirs are embedded in the east Texas Piney Woods physiographic region, which is an area with large expanses of protected national forest land and only subtle shifts in LULC; provides three distinct reservoirs to assess, including the largest (Toledo Bend) reservoir by total surface area in the Southeast United States.

The study region is characterized by a gradual rise in elevation from the southeast to the northwest (Figure 1). Convective activity in southeastern Texas and extreme western Louisiana is influenced by the Gulf of Mexico (Changnon, 2001). Not only does the Gulf provide an ample source of moisture for convection but also land-ocean circulations typically develop daily because of the diurnal cycle of temperatures on land (Byers and Rodebush, 1948; Burpee, 1979; Changnon, 2001; Trier *et al.*, 2010). Compared to the rest of the United States, the region experiences the highest daily average thunderstorm rainfall (≥13 mm) and is second in average annual thunderstorm rainfall (70–90 mm) to southern Florida (Changnon, 2001). Thunderstorms produce more than 60% of the total regional rainfall, which is typical of areas around the Gulf of Mexico. Monthly rainfall ranges from 50–150 mm in August to 100–200 mm in June (PRISM Climate Group, 2004).

3.3. Selection of candidate days

Candidate days for analysis were chosen from 1564 warm-season (May–September) days from 1997 to 2013. First, the SSC was examined and filtered for days that were categorized as moist tropical, moist tropical +, or moist tropical ++ for the closest available SSC station to the reservoirs (KSHV, The National Weather Service office in Shreveport, Louisiana, USA). To capture the diurnal cycle of convection, an MT day was defined as a period starting at 1200 UTC on the SSC MT date and ending at 1155 UTC on the following calendar day. From this subset of warm-season, MT days, further analysis was performed.

3.4. Grid cell labelling

To assess whether or not reservoirs influenced thunderstorm activity, we compared event counts per grid cell between areas over and near each reservoir. Using shapefiles from the Global Lakes and Wetlands Dataset (GWLD; Lehner and Döll, 2004), we labelled grids associated with counts of events as 'over-reservoir' if they intersected

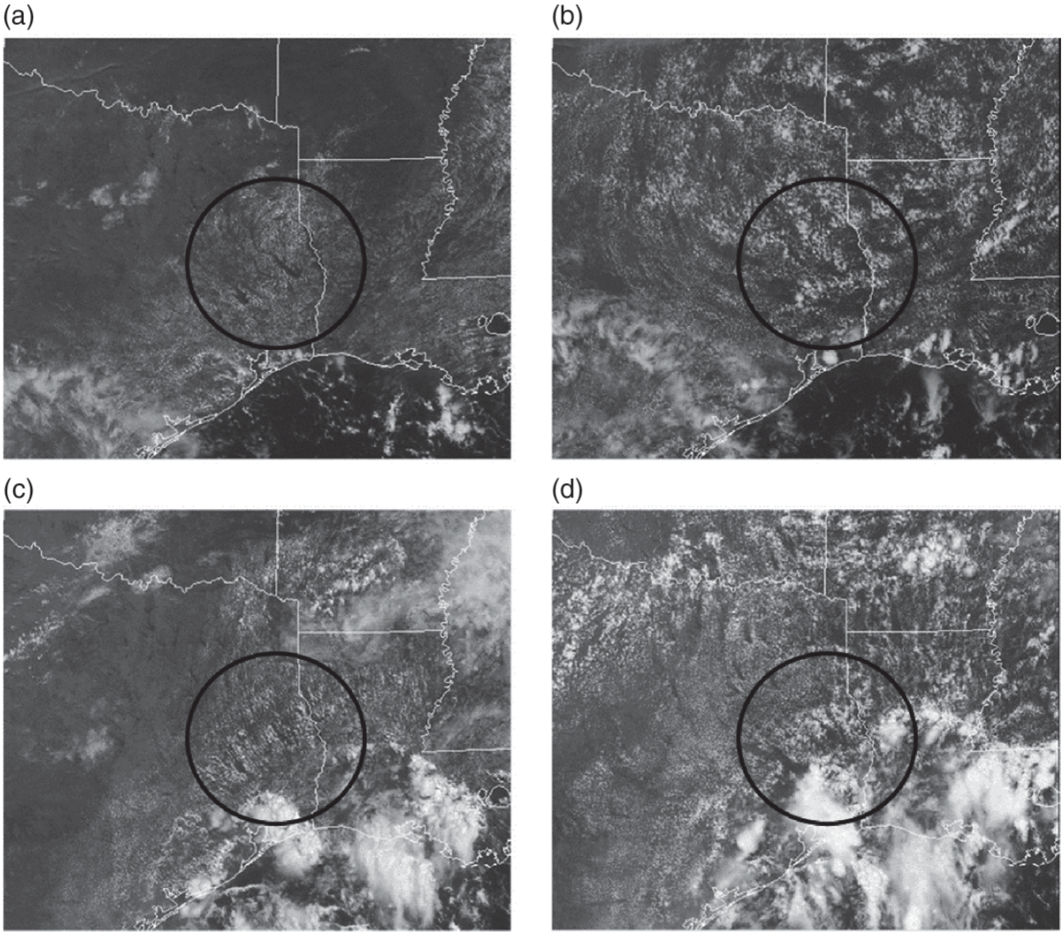

Figure 2. Visible satellite imagery from (a) 1615 UTC and (b) 1945 UTC 22 August 2013, as well as (c) 1515 UTC and (d) 1815 UTC 29 July 2011. The area encompassing the three reservoirs is circled in (a–d), revealing cumulus development suppression over-reservoirs (source: UCAR Image archive).

or were completely contained by the boundary of any of the three reservoirs. To label 'near-reservoir' grids, we created a box around each reservoir that contained a sample of 'near-reservoir' grids (i.e. grids that did not touch the reservoir). Using 2- by 2-km grid cells as an example, Figure 1(c) shows how each grid was labelled as 'over-reservoir' or 'near-reservoir'. Lowry (1998) urged those exploring urban effects on precipitation to consider including control regions in their methodological design. For example, Ashley *et al.* (2012) tested the effects of urban areas on convection against more natural variability by using similarly sized buffers over urban and rural areas to capture thunderstorm occurrence counts. Similarly, this study generated two control regions (the 'Toledo Bend control' and the 'Lake Livingston control') to test the natural variability of the area near the reservoirs. The Lake Livingston control (Figure 1(ciii)) and the Toledo Bend control (Figure 1(cvi)) are duplicates of their real reservoir counterparts (Figure 1(cii) and (cv), respectively) displaced into adjacent areas with no notable reservoirs. This process was also similar to Ashley *et al.* (2012) where thunderstorm occurrence counts over urban LULC was distinguished from counts over the surrounding non-urban LULC.

3.5. Thunderstorm day definition

To put the effect of the study area reservoirs on convection into a regional perspective, a climatology of radar-derived thunderstorm days (Falconer, 1984) was produced for a region including eastern Texas and parts of Oklahoma, Louisiana, and Arkansas (Figure 1(a)). As in Bentley *et al.* (2010) and Ashley *et al.* (2012), to record a thunderstorm day, a pixel must have experienced at least one occurrence of a reflectivity value over 40 dBZ for any given MT day period. Ultimately, each day may have pixels with no thunderstorm occurrences and those with several thunderstorm occurrences. Thus, each daily sum matrix was thresholded for values greater than zero and then added to the matrix representing the thunderstorm day count for the period of record.

3.6. CI detection

CI, in this study, was defined as the first occurrence of a convective pixel (or pixels; $\geq$40 dBz) in an area at least 30 km away from existing convection. A further qualifier was that this CI event must develop into a thunderstorm that lasts at least 30 min (seven scans). An algorithm (cf. Haberlie *et al.*, 2015) was developed to objectively and automatically detect and store the starting location of each event in the study area. The temporal and the spatial thresholds used to identify isolated CI events are similar to recent studies, including those that have automatically detected CI in sequences of reflectivity images (e.g. Weckwerth *et al.*, 2011; Kain *et al.*, 2013; Burghardt *et al.*, 2014; Clark *et al.*, 2014; Fabry and Cazenave, 2014; and Lock and Houston, 2014).

4. Results

4.1. Radar-derived thunderstorm day climatology

4.1.1. Situational analysis

To assess the temporal pattern of convective activity in the study region, we compared thunderstorm day counts between three pairs of temporal periods: (1) days when 700 hPa winds were 10 kts or less at 1200 UTC and those days that were greater than 10 kts, (2) daytime (1200–2355 UTC) and night-time (0000–1155 UTC), and (3) days with southerly (90°–270°) and northerly (270°–90°) 700 hPa winds at the 1200 UTC KSHV sounding (Figure 3). Subjective examination of the maps revealed spatial discontinuities including lower thunderstorm day counts that approximate the location and shape of three man-made reservoirs in southeastern Texas. Namely, the spatial gradient of thunderstorm day counts near the reservoirs is strongest when (1) 700 hPa winds were less than or equal to 10 kts; (2) during the day; and (3) when 700 hPa winds had any southerly component.

We also compared the thunderstorm day counts between grid cells over the reservoirs and grid cells near the reservoirs [i.e. Figure 1(cii), (civ), and (cv)] using the Kolmogorov–Smirnov (K-S) test (Kolmogorov, 1933; Smirnov, 1948), with results summarized in Table 1. The K-S test is used to assess if the distributions from two samples (e.g. over-reservoir *vs* over-land) are dissimilar. One caveat of this approach when used with spatial data is that the sampled observations used may not be independent and further verification of the results is necessary to avoid incorrectly rejecting the null hypothesis (e.g. that the reservoirs have no climatological effect on DMC). Thus, we complimented the statistical results with subjective visual interpretation and a local spatial autocorrelation test, the latter of which can be used to visualize spatial clustering of relatively high and low values (cf. Haberlie *et al.*, 2015). Overall, the difference in mean thunderstorm day counts (i.e. 'over-reservoir' mean minus 'near-reservoir' mean) was smaller when winds were greater than 10 kts at 700 hPa and at night. There was little distinction between means when comparing days with any southern or northern component of the wind direction at 700 hPa. Sam Rayburn Lake experienced the smallest reservoir/near-reservoir differences for all of the situations tested and the biggest mean difference observed was 16.8 less thunderstorm days over the Toledo Bend Reservoir when comparing counts during the day (i.e. 1200–2355 UTC). For the controls, the smallest differences were found when winds were less than or equal to 10 kts, at night, and when winds at 700 hPa had any southern component. Typically, the 'over-reservoir' mean thunderstorm day counts were greater than the 'near-reservoir' counts for the controls. This may be a consequence of the actual reservoirs depressing thunderstorm day counts in the 'near-reservoir' regions of the controls. Variability of thunderstorm day counts was higher for the Toledo Bend Reservoir and Lake Livingston regions compared to their control counterparts for both the 'over-reservoir' and 'near-reservoir' grids, especially when winds were less than or equal to 10 kts at 700 hPa. This suggests that the reservoirs disrupt the climatological transition from relatively high to relatively low thunderstorm occurrence as distance from the Gulf of Mexico increases.

The exploratory results are sufficiently explained by the existing literature. Regional winds have been reported to disrupt LB formation after becoming relatively strong (e.g. >11 kts; Asefi-Najafabady *et al.*, 2012), and our results suggest that this effect is evident on a climatological time scale. Moreover, during the day, the temperature difference between the reservoir surface and the surrounding land maximizes, allowing for stronger LB and areas of enhanced lift (Arritt, 1987; Asefi-Najafabady *et al.*, 2012). Lastly, southerly winds at 700 hPa are correlated with onshore flow in the region and, as a result, enhanced low-level moisture transport from the Gulf of Mexico, which may result in environments more favourable for convective development. Although the mean thunderstorm day counts reported in Table 1 suggest that 700 hPa wind direction is not overly influential when considering reservoir effects on convection, visual assessment of Figure 3 reveals that differences may exist between the two subsets of days. These subjective results are corroborated by two decades of observations by a senior forecaster at NWS Shreveport, Louisiana, who noted that cumulus suppression over the lakes was most apparent on days with southerly flow (M. Berry, 2014; personal communication). Thus, only MT days during the warm season where 700 hPa winds had no northerly component (i.e. 90°–270°) and had a magnitude of less than or equal to 10 kts at the 1200 UTC sounding were analysed further. Ultimately, 358 days met the criteria described above with 47 945 unique 5-min radar images included in the subsequent analysis.

4.1.2. Spatiotemporal analysis of thunderstorm day counts

A spatial climatology of thunderstorm day counts for the region is illustrated in Figure 4. From 1200 UTC to 1800 UTC (Figure 4(a) and (b)), thunderstorm day occurrences decrease the further the grid cell is from the Gulf of Mexico, a signal that is associated with the sea breeze/land breeze circulations (Byers and Rodebush, 1948; Burpee, 1979; Blanchard and Lopez, 1985; Easterling and Robinson, 1985; Lericos *et al.*, 2002; Smith *et al.*, 2005; Hill *et al.*, 2010). From 1800–0000 UTC (Figure 4(c) and (d)), thunderstorm day counts increase over land and decrease over the ocean. Overall, thunderstorm days (from 1200

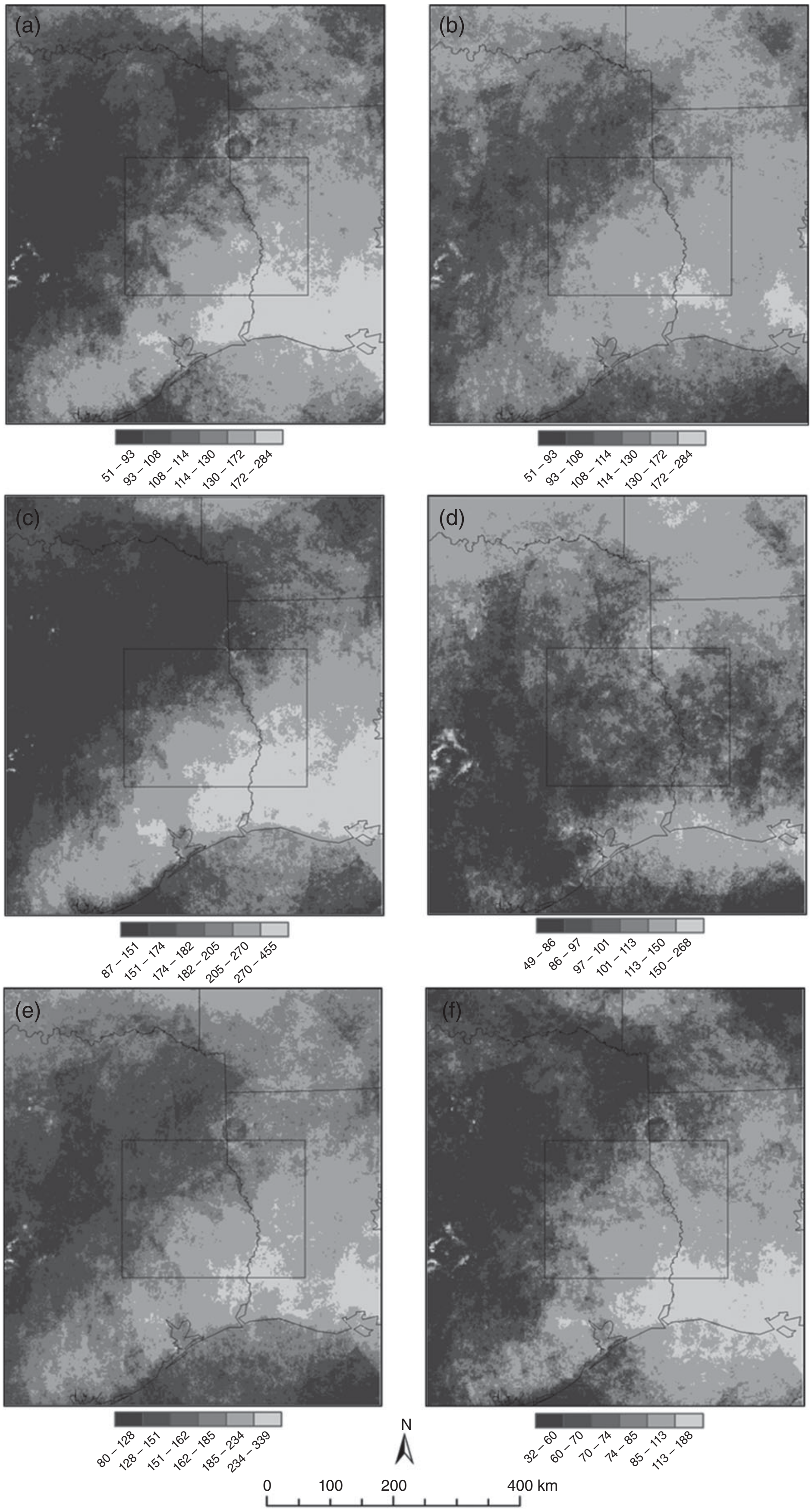

Figure 3. Thunderstorm day counts for each 2- by 2-km grid on MT days with 700 hPa winds at 1200 UTC that were (a) ≤10 kts or (b) >10 kts, occurred between (c) 1200 and 0000 UTC or (d) 0000 and 1200 UTC, and days with 700 hPa winds at 1200 UTC that were from (e) 90° to 270° (south) or (f) 270° to 90° (north). The rectangle in the east central portion of each panel is the study area.

Table 1. Comparison of over-reservoir and near-reservoir mean thunderstorm day counts per grid cell for days with 700 hPa winds greater than and less than or equal to 10 kts, thunderstorm occurrence during the day and at night, and days with 700 hPa winds with any southern or northern component.

	Over-reservoir		Near-reservoir		Difference	*p*-Value
	TD_m	TD_{sd}	TD_m	TD_{sd}		
All reservoirs						
700 hPa ≤ 10 kts	124.6	17.0	130.4	18.2	−5.8	<0.001
700 hPa > 10 kts	138.8	10.8	138.4	10.8	0.4	0.130
1200–2355 UTC	205.0	26.5	211.8	30.8	−6.8	<0.001
0000–1155 UTC	95.6	6.9	97.2	9.2	−1.6	<0.001
South at 700 hPa	178.6	20.1	180.6	20.3	−2.0	0.042
North at 700 hPa	85.5	7.3	88.2	8.3	−2.7	<0.001
Lake Livingston						
700 hPa ≤ 10 kts	113.7	12.7	122.3	15.6	−8.6	<0.001
700 hPa > 10 kts	135.5	8.1	137.4	9.6	−1.9	0.190
1200–2355 UTC	196.4	14.7	210.4	24.2	−14.0	<0.001
0000–1155 UTC	92.9	6.6	91.4	7.7	1.5	0.080
South at 700 hPa	168.5	14.5	174.8	16.7	−6.3	0.002
North at 700 hPa	82.6	7.7	85.1	9.6	−2.5	0.020
All control reservoirs						
700 hPa ≤ 10 kts	137.9	13.1	138.7	14.4	−0.8	0.487
700 hPa > 10 kts	149.4	10.2	143.3	12.3	6.1	<0.001
1200–2355 UTC	234.0	25.6	225.3	30.2	8.7	<0.001
0000–1155 UTC	98.1	7.1	99.1	8.2	−1.0	0.220
South at 700 hPa	198.5	16.9	193.3	19.2	5.2	<0.001
North at 700 hPa	90.0	7.9	88.9	8.0	1.1	0.001
Livingston control						
700 hPa ≤ 10 kts	135.6	7.7	137.1	11.3	−1.5	0.006
700 hPa > 10 kts	144.8	4.1	142.0	8.1	2.8	<0.001
1200–2355 UTC	230.2	9.5	226.3	19.6	3.9	0.003
0000–1155 UTC	94.5	6.0	95.9	4.9	−1.4	0.007
South at 700 hPa	188.5	4.4	187.7	11.3	0.8	0.006
North at 700 hPa	93.2	6.1	92.0	7.3	1.2	0.002
Toledo Bend Reservoir						
700 hPa ≤ 10 kts	125.9	16.4	134.0	18.3	−8.1	<0.001
700 hPa > 10 kts	134.6	10.9	136.8	11.5	−2.2	0.057
1200–2355 UTC	193.4	28.3	210.2	35.6	−16.8	0.003
0000–1155 UTC	96.8	8.0	101.2	10.4	−4.4	<0.001
South at 700 hPa	175.2	20.3	181.4	22.3	−6.2	<0.001
North at 700 hPa	85.2	6.5	89.9	7.3	−4.7	<0.001
Sam Rayburn Lake						
700 hPa ≤ 10 kts	129.9	17.3	131.7	18.0	−1.8	0.383
700 hPa > 10 kts	147.2	6.7	141.2	10.2	6.0	<0.001
1200–2355 UTC	220.4	23.0	214.7	28.5	5.7	<0.001
0000–1155 UTC	95.5	4.4	96.5	5.7	−1.0	0.003
South at 700 hPa	190.2	17.3	184.6	19.2	5.6	0.002
North at 700 hPa	87.8	7.4	88.4	7.9	−0.6	0.555
Toledo Bend control						
700 hPa ≤ 10 kts	138.9	14.7	139.7	15.9	−0.8	0.280
700 hPa > 10 kts	151.5	11.4	144.0	14.2	7.5	<0.001
1200–2355 UTC	235.8	30.2	224.8	35.0	11.0	<0.001
0000–1155 UTC	100.0	6.8	101.0	9.0	−1.0	0.043
South at 700 hPa	203.2	18.6	196.6	22.0	6.6	<0.001
North at 700 hPa	88.5	8.2	87.0	7.9	1.5	0.041

The grey highlighted rows denote significantly ($\alpha = 0.05$) different thunderstorm day count distributions. TDm is mean thunderstorm day count and TDsd is the standard deviation of thunderstorm day counts for each region and situation.

to 0000 UTC) for each pixel in the region ranged from 15 to 156 days, representing 4 and 44%, respectively, of all the days that were considered (358). Focusing on the reservoirs, their effects are evident even on a regional scale, particularly from 1800 to 0000 UTC.

A sample of thunderstorm day counts across the centre of the study region (Figure 1(ci)) showed further evidence of thunderstorm day depressions over the reservoirs (Figure 5). Moving from southwest to northeast across the reservoirs, noticeable drops in thunderstorm day counts coincided with grids that were over the reservoirs (Figure 5). This drop in thunderstorm day counts was not apparent in the strip northwest or southeast of the polygon over the reservoirs. This ‘rain shadow’

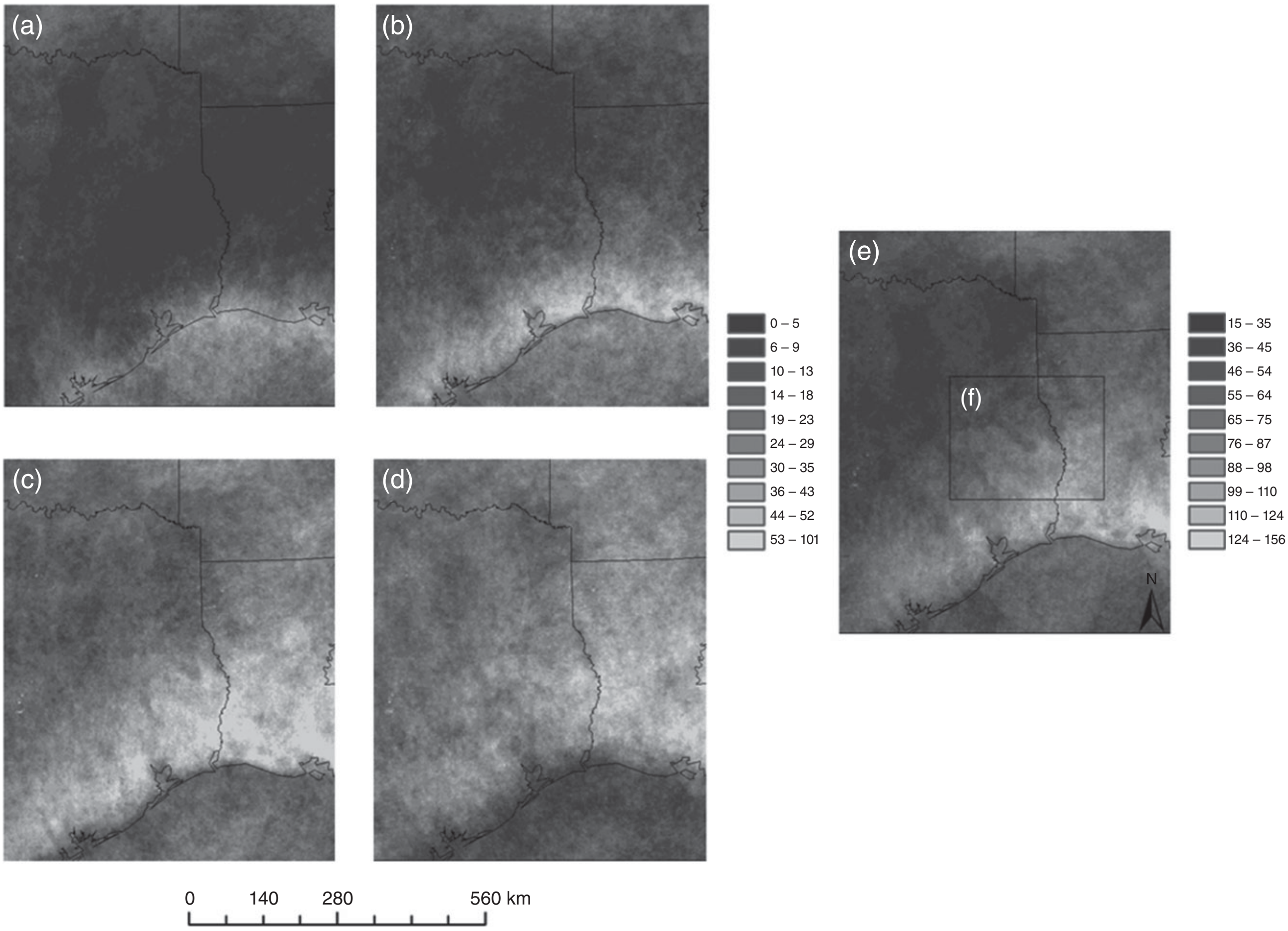

Figure 4. Thunderstorm day counts for each 2- by 2-km grid cell in the region for (a) 12–15z, (b) 15–18z, (c) 18–21z, (d) 21–00z (d), and (e) 12–00z. The analysis was performed for moist tropical days with light winds (≤10 kts) and no northerly component (90°–270°) of the wind at 700 hPa. The study area is delineated by a rectangle (f).

has been previously noted with large lakes in synoptically quiescent regimes near the Gulf of Mexico (e.g. Blanchard and Lopez, 1985; Smith *et al.*, 2005; Hill *et al.*, 2010). For example, suppression of thunderstorm activity has been observed over and downwind of Lake Okeechobee (Blanchard and Lopez, 1985; Lericos *et al.*, 2002) and Lake Pontchartrain (Smith *et al.*, 2005; Hill *et al.*, 2010). An examination of the standard deviation of thunderstorm day counts presented in Table 1 also show that areas over and near the reservoirs typically experience more variability in DMC activity. Figure 5 also illustrates this variability with a difference of over 60 thunderstorm days in just 25 km near and over Toledo Bend Reservoir. It is clear that the reservoirs disrupt the gradual decrease in thunderstorm day counts moving away from the Gulf of Mexico.

To test differences in thunderstorm day counts over the reservoirs and over the surrounding land, we used the non-parametric K-S test and cumulative probability distributions (Figure 6). Test results suggest that the Toledo Bend control (Figure 1(cvi)) had more thunderstorm days over the surrogate ‘reservoir’ ($p < 0.001$) and that there was a significantly lower mean thunderstorm day count over the Lake Livingston control (Figure 1(ciii); $p = 0.02$). Of the real reservoirs (Figure 6(a)–(c)), only Lake Livingston (Figure 6(c)) had significantly less thunderstorm days than the surrounding land ($p < 0.001$). Variance in thunderstorm day counts for Sam Rayburn Lake (Figure 1(civ)) and the Toledo Bend Reservoir (Figure 1(cv)) grids was higher than the surrounding over-land grids (Figure 1(civ) and (cv)), suggesting that extreme low and high counts occur over these reservoirs more often than the adjacent land. Indeed, a cumulative probability distribution shows that Toledo Bend Reservoir (Figure 6(a)) has more high and low values than the over-land grids. Although the *p*-value produced by the K-S test for Toledo Bend Reservoir suggests that the distribution of over-reservoir and over-land grid counts is different, the sign of this difference is uncertain. For both tests, the thunderstorm day counts over Lake Livingston and Toledo Bend Reservoir were significantly lower than over their control counterparts ($p < 0.001$).

4.2. CI climatology

To examine further for evidence of reservoir influence on convection, the spatial distribution of objectively determined CI points was analysed for the study region (Figure 1(ai)). As with the thunderstorm day climatology,

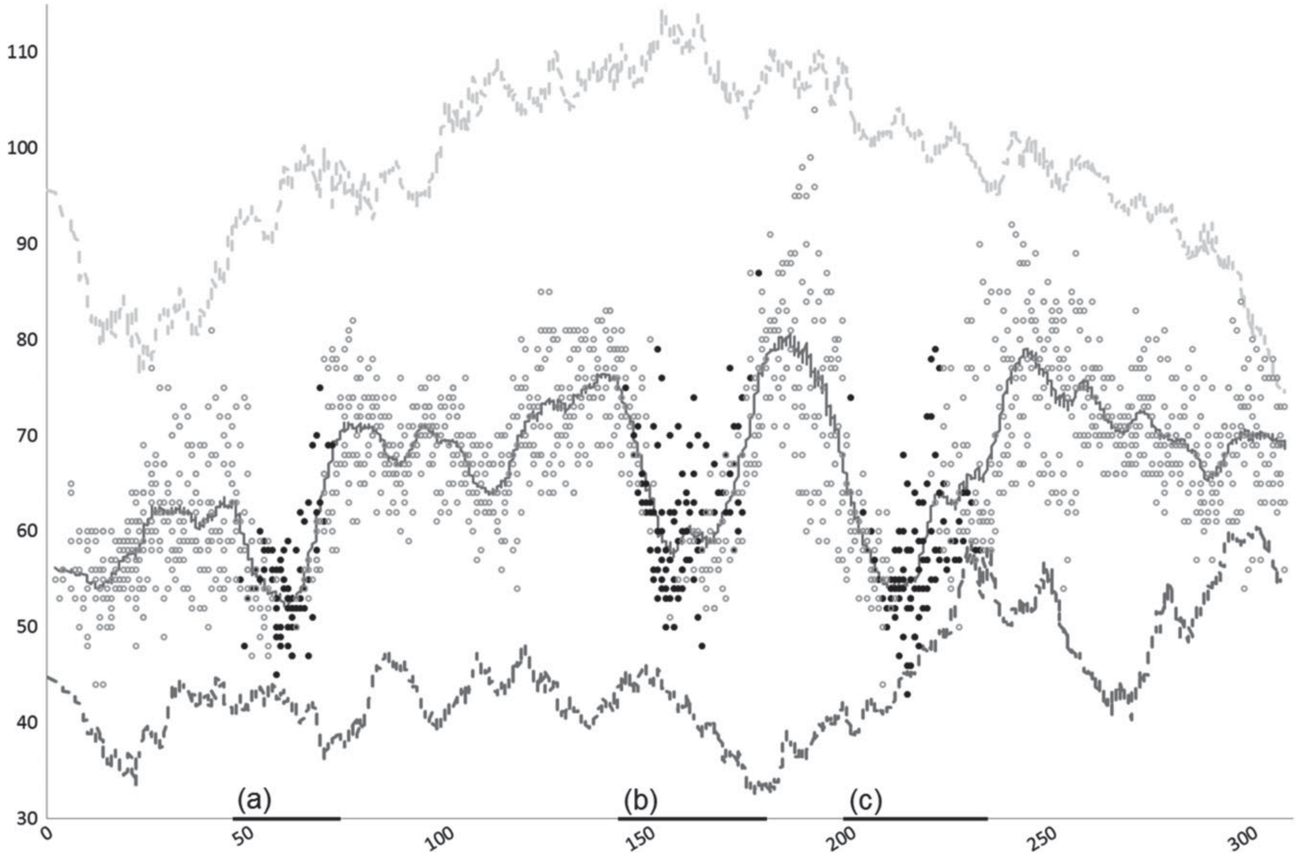

Figure 5. A horizontal cross section of thunderstorm day counts per 2-km grid cell with running averages for three regions – northern (dark grey dotted line), reservoir (dark grey solid line), and southern (light grey dotted line) as delineated in Figure 1(aii–iv), respectively. The y-axis is thunderstorm day counts and the x-axis is distance, in km, from the southwestern edge of the polygons (Figure 1(aii–iv)). The analysis was performed for moist tropical days with winds ≤10 kts and no northerly component (90°–270°) at 700 hPa. Data were only plotted for the reservoir strip (Figure 1(aiii)). The black (grey) circles represent thunderstorm day counts for reservoir (non-reservoir) grid cells. The horizontal extent of each reservoir is represented by the black line on the horizontal axis – specifically (a) Lake Livingston, (b) Sam Rayburn Lake, and (c) Toledo Bend Reservoir.

the CI climatology focuses on the time period between 1200 and 0000 UTC (Figure 7). For the days that were examined, there were 5987 unique CI events in the study area (i.e. Figure 1(ai)). CI occurrences peaked between 1900 and 2200 UTC with an abrupt increase in events after 1600 UTC (Figure 8). Other studies have reported similar temporal distributions of CI events, with relatively inactive morning hours, followed by a spike during mid-day to evening, and ending the day with a gradual decrease in events (Weckwerth *et al.*, 2011; Fabry and Cazenave, 2014). Comparisons can also be made to overall thunderstorm climatologies; however, specific regions experience peaks and valleys in thunderstorm occurrences (and presumably CI occurrences) at different times (Blanchard and Lopez, 1985; Easterling and Robinson, 1985; Parker and Ahijevych, 2007; Fabry and Cazenave, 2014). Notably, higher early- to mid-morning thunderstorm day counts associated with the sea breeze do not translate to higher CI counts during these hours. This suggests that, in these situations, convection moves into the area from the south and east rather than forming near the reservoirs.

In general, the CI point density decreases from southeast to northwest (Figure 7(a)). High CI point density is evident on the Gulf side of the two eastern reservoirs and low density exists over the centre all of the reservoirs. This could be climatological evidence of two ‘converging boundaries’ (Byers and Rodebush, 1948), the sea breeze and LB, interacting and producing locally enhanced convergence that leads to CI. Alternatively, this may be due to the southerly synoptic-scale flow interacting with the southernmost portion of the LB. A more in-depth analysis, including observational and modelling case studies, would be needed to confirm that this is the case. Next, hotspot clustering (Getis-Ord Gi*; Getis and Ord, 1992) was performed on the 6-km grids using CI count per grid as the statistical variable (Figure 7(b)). Getis-Ord Gi* is a useful tool for uncovering local spatial autocorrelation. It is employed in the spatial sciences for a number of applications that examine (1) how similar the value of a spatial unit is to its neighbours and (2) if the value associated with the spatial unit is significantly higher or lower compared to other regional values. A 6-km grid was chosen for the CI analysis because smaller, 2-km grid resolution produced exponential distributions due to the high number of low counts, such as 0s and 1s, per grid cell. Six kilometre grids sufficiently balanced the need for a non-exponential distribution of CI counts while still retaining high enough

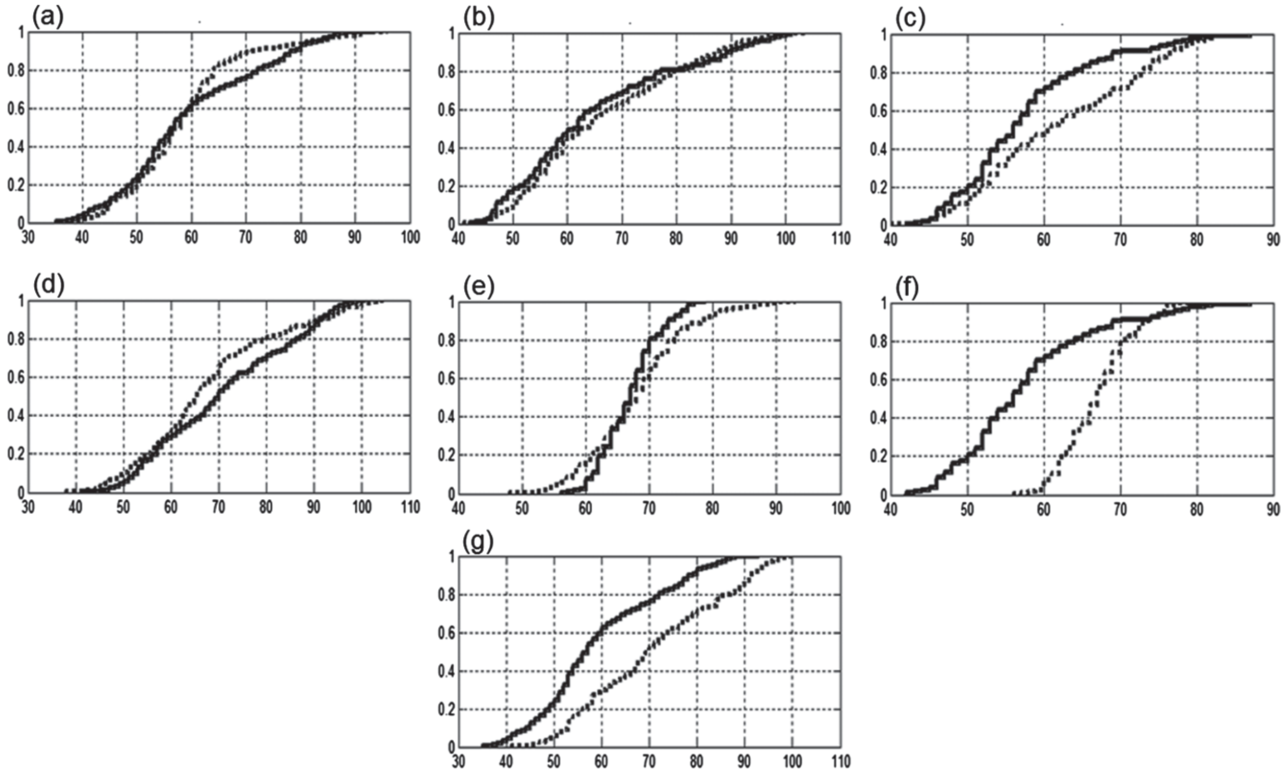

Figure 6. Cumulative probability distribution plots for thunderstorm day counts comparing lake (solid line) and land/control (dotted line) grids for (a) Toledo Bend Reservoir, (b) Sam Rayburn Lake, (c) Lake Livingston, (d) Toledo Bend Control, (e) Lake Livingston Control. Further comparisons are (f) Lake Livingston over-reservoir grids (solid) *versus* Lake Livingston control over-reservoir grids (dotted), and (g) Toledo Bend Reservoir over-reservoir grids (solid) *versus* Toledo Bend control over-reservoirs grids (dotted). The x-axis is the count value and the y-axis is the percent of observations lower than the value on the x-axis.

resolution to draw conclusions about potential reservoir influences. This analysis suggests that the high point density on the Gulf side of the two eastern reservoirs is significant and not noise. There are also some significant low density clusters that are situated over the reservoir, with Sam Rayburn Lake showing the most obvious dispersion of all three reservoirs. A cross-section analysis (not shown) reveals evidence of lower CI counts over the reservoirs compared to the adjacent over-land grids. These results are consistent with what has been found near natural, larger, land-locked bodies of water, such as the Great Lakes (Harman and Hehr, 1972; King *et al.*, 2003). Most importantly, these findings suggest some areas near the reservoirs are at higher risk of being exposed the dramatic changes in sensible weather conditions associated with CI.

5. Summary and conclusions

This study was the first to examine a relatively long period of radar data to uncover thunderstorm and CI distributions near human-made reservoirs in the United States. Seventeen years of radar data were processed to extract these events on days with conditional instability and predominantly mesoscale forcing for ascent. First, a diurnal climatology of thunderstorm and CI events was generated for the study area. Next, using over- and near-reservoir samples of convective behaviour, the effects of the three study area reservoirs were quantified.

The results suggest that human-made reservoirs modify the behaviour of ‘air mass’ thunderstorms during relatively quiescent synoptic conditions. The findings imply that the over-reservoir environment not only inhibits thunderstorm formation in some cases but also induces greater variability in thunderstorm activity. Although only a few reservoirs were tested, the thermally forced circulation between land-locked water bodies and the surrounding solid surfaces has been observed in many locations. Future work could explore the effects of other reservoirs using the methodological framework outlined herein.

On a broad scale, these results provide evidence of anthropogenic influence of thunderstorm risk. The importance of such findings can be applied to pursuits in regional climatology, regional planning, model verification and development, and operational mesoscale meteorology. Further, the methodology discussed in this article can be applied to any area with LULC discontinuities including urban/rural and crop/forest boundaries and other areas with varied terrain. The results of this study could also assist regional forecasters in anticipating convective storms and their affiliated hazards such as flash flooding and lightning. This information could then be conveyed to those seeking or participating in recreational activities near the reservoirs.

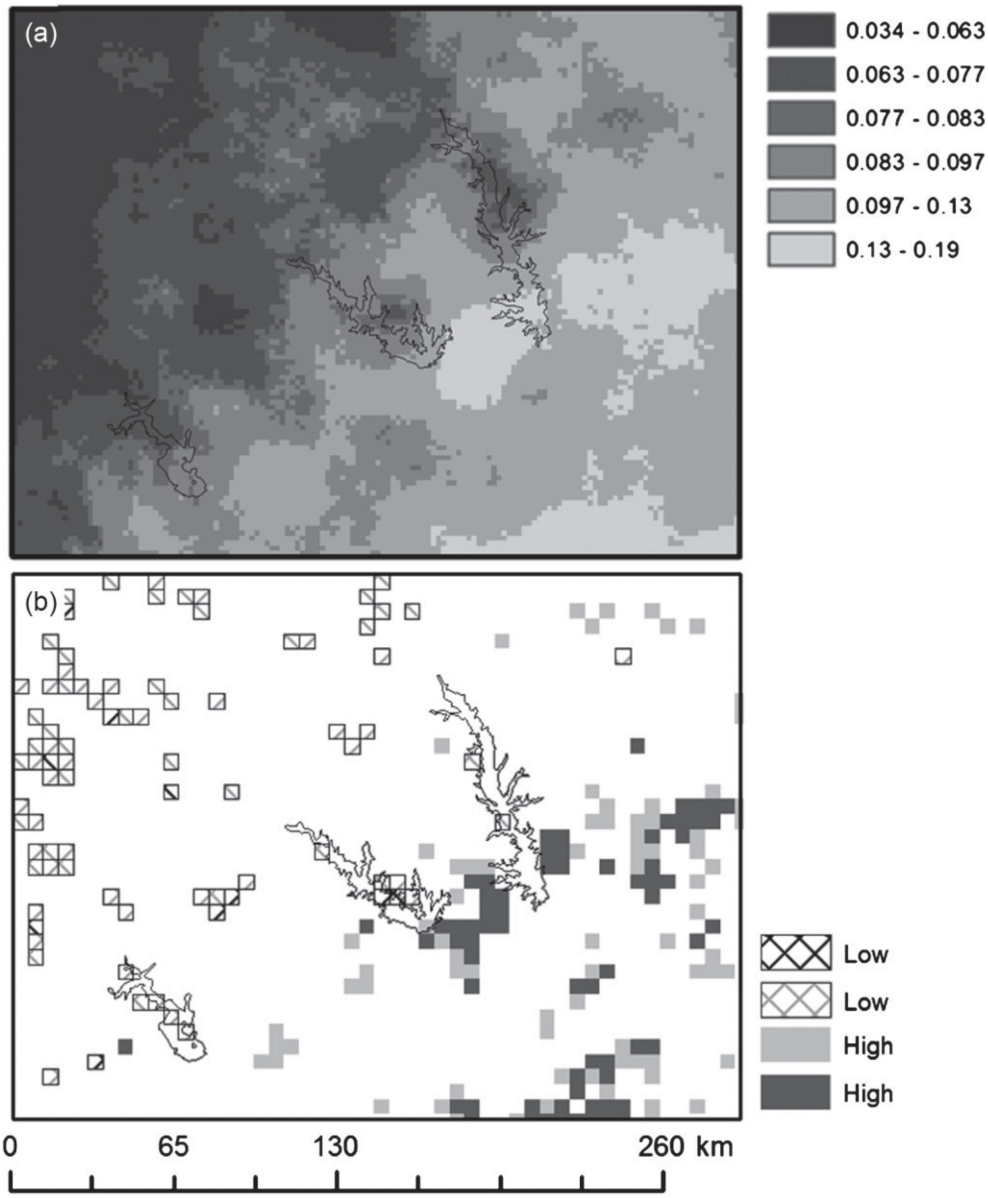

Figure 7. Maps of (a) CI point density (2-km grid cells, 20-km search radius) and (b) Getis Ord Gi* z-score (spatial autocorrelation) centred on the study area (Figure 1(ai)). Significantly low (hatched) and high (solid colour) z-score cells are categorized by $p < 0.05$ (grey) and $p < 0.01$ (dark grey).

While this study shows that man-made reservoirs can impact the climatology of DMC and CI, future work is needed to uncover more details about this relationship. Like existing urban studies, the size and shape of the reservoirs may influence the magnitude, or existence, of the effect of reservoirs on DMC. Future research should explore if there is a minimum size required to have an effect on thunderstorms, as was found for urban areas in Ashley *et al.* (2012). Other possible avenues of research could include considering the shape of the reservoirs to see if the ideas proposed by Shepherd *et al.* (2013) apply to city-sized bodies of water. Further, meteorological variables, such as instability and convective inhibition, could be employed to identify situations that are supportive of LB front induced CI or DMC enhancement. Models, in conjunction with observed case studies, could explore the possible interaction between the sea breeze and the LBs induced by the reservoirs.

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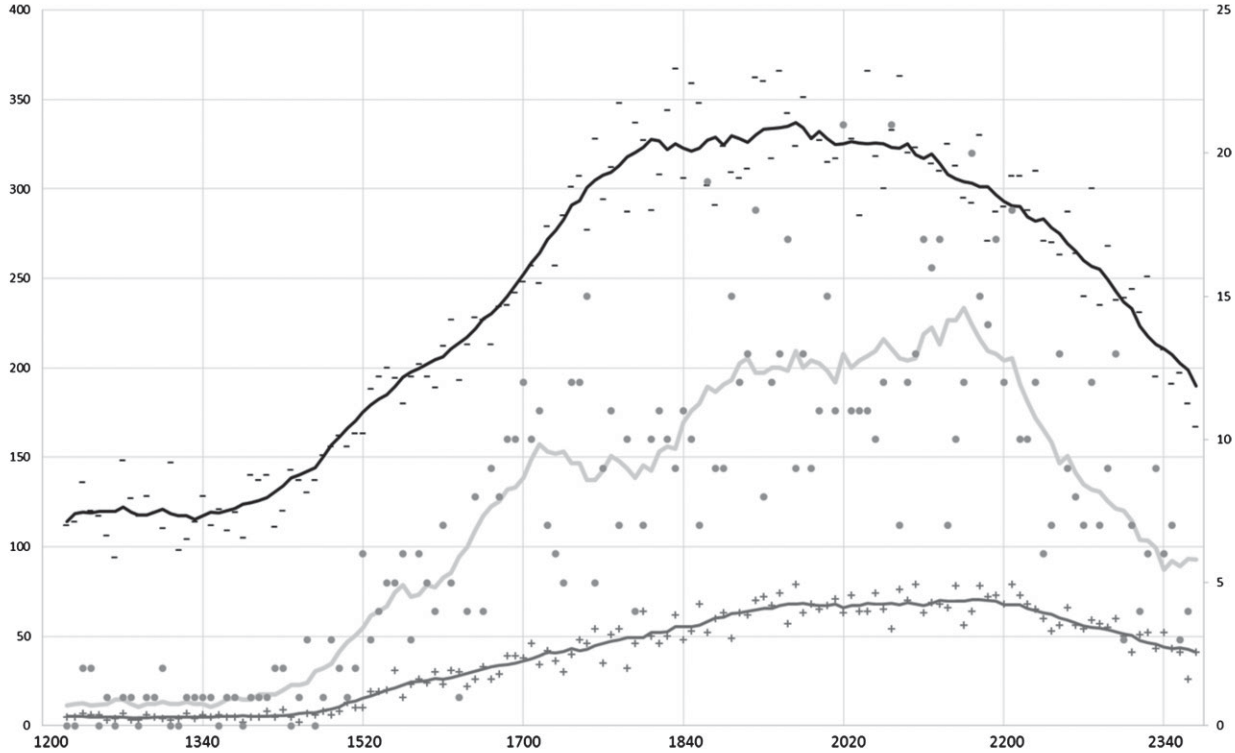

Figure 8. Count of CI events for the region (black dashes, left y-axis), the study area (grey crosses, left y-axis), and areas adjacent to the reservoirs (light grey circles, right y-axis) for every 5 min bin between 1200 UTC and 0000 UTC. The horizontal lines represent the 1-h running average value for each region.

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