An Objective Classification and Analysis of Upper-Level Coupling to the Great Plains Low-Level Jet over the Twentieth Century

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ABSTRACT

Low-level jets (LLJ) around the world critically support the food, water, and energy security in regions that they traverse. For the purposes of development planning and weather and climate prediction, it is important to improve understanding of how LLJs interact with the land surface and upper-atmospheric flow, and collectively, how LLJs have and may change over time. This study details the development and application of a new automated, dynamical objective classification of upper-atmospheric jet stream coupling based on a merging of the Bonner–Whiteman vertical wind shear classification and the finite-amplitude local wave activity diagnostic. The classification approach is transferable globally, but applied here only for the Great Plains (GP) LLJ (GPLLJ). The analysis spans the period from 1901 to 2010, enabled by the ECMWF climate-quality, coupled Earth reanalysis of the twentieth century. Overall, statistically significant declines in total GPLLJ event frequency over the twentieth century are detected across the entire GP corridor and attributed to declines in uncoupled GPLLJ frequency. Composites of lower- and upper-atmospheric flow are shown to capture major differences in the climatological, coupled GPLLJ, and uncoupled GPLLJ synoptic environments. Detailed analyses for southern, central, and northern GP subregions further highlight synoptic differences between weak and strong GPLLJs and provide quantification of correlations between total, coupled, and uncoupled GPLLJ frequencies and relevant atmospheric anomalies. Because uncoupled GPLLJs tend to be associated with decreased precipitation and low-level wind speed and enhanced U.S. ridge strength, this finding may suggest that support for drought over the twentieth century has waned.

1. Introduction

The Great Plains (GP) low-level jet (LLJ) is the primary transport mechanism of moisture-laden air from the Gulf of Mexico into the GP and is essential to the region's agricultural and wind energy sectors, hydroclimate, and severe weather regimes. Bonner (1968) first objectively defined the southerly GPLLJ based on its diurnal oscillation in speed, height, and direction. The GPLLJ has a well-defined corridor (Texas to South Dakota) with a diurnal

cycle that peaks after local midnight (Bonner 1968). Unlike the South American LLJ, its frequency peaks in the warm season (e.g., Marengo et al. 2004; Jones and Carvalho 2018). Its warm-season predominance contributes to GP summertime precipitation maximums (e.g., Higgins et al. 1997; Yang et al. 2007; Squitieri and Gallus 2016a,b), which help sustain a \$100 billion yr⁻¹ crop and livestock industry (Basara et al. 2013; Melillo et al. 2014), and its strong winds fuel more than 45% of the U.S.'s wind energy production (AWEA 2018). GPLLJ variability plays a critical role in regional weather and climate extremes, from daily severe weather outbreaks (Uccellini and Johnson 1979; Muñoz and Enfield 2011) to seasonal floods and droughts (Weaver et al. 2009; Hodges and Pu 2019) to decadal drought variability (McCabe et al. 2004; Kam et al. 2014; Yu et al. 2017) such as the historical Dust Bowl drought of 1932–38 (e.g., Schubert et al. 2004).

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The socioeconomic importance of the GPLLJ has contributed to its prominence as a research topic over the past 50 years, yet it remains incompletely understood (e.g., Shapiro et al. 2016). Proposed mechanisms of the GPLLJ have historically addressed its boundary layer, terrain-linked attributes. Popular mechanistic explanations include those of Blackadar (1957), Wexler (1961), and Holton (1967). Blackadar (1957) explains the diurnal variation of the southerly GPLLJ through inertial wind and surface friction arguments related to the nocturnal decoupling of the boundary layer. Wexler (1961) uses the combined effects of orographic blocking and the summertime westward extension of the Bermuda high to explain the east–west placement and seasonality of the GPLLJ. Holton (1967) shows that the diurnal thermal fluctuations over the GP sloping terrain act to diurnally vary low-level pressure gradients and thermal winds and thus, modulate the GPLLJ position, diurnal cycle, strength, and vertical profile. Careful examination would suggest that all three mechanisms (i.e., Blackadar 1957; Wexler 1961; Holton 1967), are important and no theory alone can completely explain the GPLLJ (e.g., Shapiro et al. 2016). The Sierra Oriental/Rocky Mountain cordillera clearly plays a central role in terms of time-mean mechanical blocking (e.g., Wexler 1961; Ting and Wang 2006) and slope-driven thermal forcing (Holton 1967), which may be diurnally enhanced by nocturnal boundary layer decoupling (Blackadar 1957).

We propose that these aforementioned boundary layer development mechanisms for the GPLLJ are secondary in nature to the large-scale, upper-level synoptic flow patterns that serve as their common prerequisite. This idea is in fact not new. Taking a manual weather map analysis approach, Uccellini (1980) introduced the coupled and uncoupled GPLLJ nomenclature in a study of 15 GPLLJ cases spanning a wide range in strength of coupling with the jet stream at 300 hPa. Broadly, coupled GPLLJs were associated with a trough to the west and a ridge to the east (Fig. 1a) and uncoupled GPLLJs were associated with a ridge (Fig. 1b) or zonal flow (Fig. 1c) and weak winds aloft. Synoptic/coupled jets are transient in time with forcing that is independent of and likely dominates the effect of local terrain-linked mechanisms discussed above. Over longer periods of time integration, a correlation with the Wexler (1961) mechanism can be expected because the latter is the culmination of synoptic sequencing. Boundary layer/uncoupled jets are driven by local terrain-linked mechanisms but require quiescent synoptic conditions to form (Uccellini 1980). As we will show, the distinction between coupled and uncoupled jets is clear, although in about 4% of cases the distinction is more nuanced.

FIG. 1. Representative examples of the three synoptic regimes conducive to Great Plains low-level jets (GPLLJ) taken from the CERA-20C: (a) 24 May 2010: coupled, (b) 15 Aug 1993: uncoupled ridge, and (c) 11 Jul 1993: uncoupled zonal. Each plot shows the 0600 UTC 850 hPa meridional wind (color map) and 500 hPa geopotential height (contours). The contour interval is 6 dam.

This study demonstrates and applies a new LLJ classification in the construction of a twentieth-century climatology of coupled and uncoupled LLJs. Specifically, the Uccellini (1980) manual approach is updated with an

objective, automatable framework that merges the conventional Bonner–Whiteman LLJ classification (Bonner 1968; Whiteman et al. 1997) with the dynamically derived, local finite-amplitude wave activity diagnostic of Huang and Nakamura (2016). The climatology and ensuing analysis is based on the full available record of the climate-quality, European Centre for Medium-Range Weather Forecasts coupled Earth reanalysis of the twentieth century (CERA-20C, 1901–2010; Laloyaux et al. 2018). Thus, we extend and improve upon the work of Uccellini (1980) and offer an important long-term context of LLJ upper-atmospheric and lower, land–atmospheric coupling.

The relative frequency of coupled and uncoupled jets provides critical insight into the relative sensitivity (and predictability) of the GPLLJ in the context of changes in: weather regime sequencing, ocean SST-forced atmospheric circulation, as well as the local-land response. Such changes could include changes in east–west soil moisture gradients (Fast and McCordle 1990) and soil moisture availability (Frye and Mote 2010) over the GP, a westward shift in the Bermuda high (Wexler 1961; Ortegren et al. 2011; Zhu and Liang 2013), variations in Arctic sea ice extent (Budikova et al. 2017), and seasonal-to-multidecadal oscillations in sea surface temperatures (McCabe et al. 2004; Kam et al. 2014; Yu et al. 2017), which have the effect of shifting the mid-latitude storm tracks. Evaluating coupling to the upper-level jet is also key to unraveling the physical mechanisms of GPLLJs. The degree of coupling could very well serve as a conditional control on the relative role or efficiency of land forcing mechanisms. Improved modeling and prediction of the GPLLJ hinges on a more comprehensive understanding of its underlying forcings and their complex interactions over a range of spatiotemporal scales. A long-term analysis of the GPLLJ in this context has yet to be undertaken until now.

This study was motivated by a need to better characterize and understand GPLLJ dynamics from the perspective of terrain and upper-level coupling and to quantify how in this regard GPLLJ dynamics may have changed in recent history. The aims, therefore, are threefold: 1) to develop a robust new automated classification of GPLLJs based on a dynamical assessment of upper-level coupling; 2) to fully characterize the synoptic environment typical of each GPLLJ class event, specifically with regard to wind, atmospheric moisture convergence, and precipitation; and 3) to present a synthesis of GPLLJ spatiotemporal variability over the most recent century.

Section 2 outlines the data and methods. Results are presented for case studies of coupled/uncoupled GPLLJs, climatological features of GPLLJs, the synoptic environment of typical coupled/uncoupled GPLLJs, twentieth-century trends, and regional Dust Bowl anomalies in

sections 3a–e, respectively. Section 4 concludes with a discussion and summary.

2. Data and methods

a. CERA-20C

CERA-20C (Laloyaux et al. 2018) is a 10-member ensemble of land–atmosphere–wave–ocean–sea ice coupled reanalyses covering the period from 1901 to 2010. CERA-20C has a horizontal resolution of 1.125° (~ 125 km) with 3-hourly output available at 37 pressure levels and 4 soil levels. All forecasts (including precipitation and vertically integrated moisture divergence) are integrated daily from 1800 UTC. The CERA consists of the IFS, version Cy41r2, atmospheric model coupled to the Nucleus for European Modeling of the Ocean (NEMO; Madec 2008), version 3.4, model and Louvain-la-Neuve Sea Ice Model (LIM2; Fichefet and Maqueda 1997; Bouillon et al. 2009). CERA implements 4D-Var (atmosphere) and 3D-Var (ocean) to assimilate surface and mean sea level pressures from the International Surface Pressure Databank, version 3.2.6 (ISPDv3.2.6), and ICOADSv2.5.1, surface marine winds from ICOADSv2.5.1, as well as ocean temperature and salinity profiles (Laloyaux et al. 2017). The system's land, ocean, wave, and sea ice models run without observational constraint but the coupled model ensures a dynamically consistent Earth system representation at any given time. Atmospheric observations and model physical tendencies are perturbed to generate the atmosphere ensemble, whereas the positions of in situ observations are perturbed to generate the ocean ensemble (Feng et al. 2018). Because each ensemble member is an equally probable realization and due to computational constraints, this study considers only the first ensemble member. Note that this ensemble member was downloaded prior to 29 January 2019 using the veteran ECMWF interpolation library (EMOSLIB) spatial interpolation default setting. Additionally, the analysis requires only the following model fields: meridional and zonal wind, geopotential height, vertically integrated moisture divergence, and precipitation.

b. Study region and period

A LLJ classification is developed and applied over the contiguous United States (25° – 50° N, 50° – 130° W) using the full 110-yr (1901–2010) CERA-20C, extended summer season [May through September (MJJAS)] data record. Within CONUS, a GP region is defined, hereafter, to span 29.25° – 49.5° N, 96.75° – 102.375° W with an initial focus on the site of the U.S. Department of Energy Atmospheric Radiation Measurement Southern Great Plains Climate Research Facility (ARM-SGP; 36.68° N; 97.58° W; Sisterson et al. 2016). The GP region

is further divided into three subregions, each spanning an area of 6.75° latitude and 5.625° longitude and centered at latitudes of 32.625° , 39.375° , and 46.125°N for the southern, central, and northern GP, respectively. Of the 3-hourly analyses available, the 500 hPa geopotential height is used from all times to establish dynamical jet classification thresholds, although the majority of the study focuses on 0600 UTC fields, as this time is found to correspond most closely with the diurnal frequency peak of MJJAS total GPLLJ events in CERA-20C (see Fig. S1 in the online supplemental material). Forecasts of accumulated vertically integrated moisture divergence and precipitation for 0000–1200 UTC are included to represent hydroclimate effects. Precipitation will be reported as mm day^{-1} .

c. Dynamically derived LLJ classification

For individual events or studies spanning less than a few years, a subjective analysis of weather maps is a reasonable approach to categorize LLJs according to the degree of upper-level coupling (e.g., Uccellini 1980; Mitchell et al. 1995; Arritt et al. 1997; Walters and Winkler 2001; Hodges and Pu 2019). However, such an approach is less suited to an analysis of CERA-20C's 110-yr record. For this task, an automated and objective procedure is developed. The approach combines the Bonner–Whiteman (Bonner 1968; Whiteman et al. 1997) speed and low-level vertical wind shear-based classification with the 500 hPa geopotential height (Z500)–based local finite-amplitude wave activity diagnostic of Huang and Nakamura (2016). A brief overview of the classification, separately and combined, follows.

1) BONNER–WHITEMAN CLASSIFICATION

A Bonner–Whiteman (BW) GPLLJ is defined by its surface–700 hPa wind speed maximum ($\mathbf{V}_{\max}$) and vertical wind shear ($\Delta\mathbf{V}_z$), computed as the difference of ($\mathbf{V}_{\max}$) and the minimum wind speed found between the height of $\mathbf{V}_{\max}$ and the 700 hPa level. Figure 2a presents vertical wind profiles representative of each BW LLJ category taken from the CERA-20C record at the ARM-SGP site. As the magnitude of both $\mathbf{V}_{\max}$ and $\Delta\mathbf{V}_z$ increase, the categorical classification increases from BW1 to BW4 (Table 1). This study focuses on southerly GPLLJs, so the following additional criterion is added to the BW classification: $\mathbf{V}_{\max}$ must have a nonzero southerly component.

2) CYCLONIC AND ANTICYCLONIC LOCAL WAVE ACTIVITY

In this study, local finite-amplitude wave activity (LWA; Huang and Nakamura 2016) analysis is applied

to CERA-20C's Z500 field. LWA is a localization of the finite-amplitude wave activity diagnostic (FAWA; Nakamura and Zhu 2010; Nakamura and Solomon 2011). Whereas FAWA uses the strength and amplitude of quasigeostrophic potential vorticity (QGPV) and Z500 atmospheric waves to define zonal wave amplitudes around equivalent latitude (ϕ_e) bands, LWA is defined on a grid basis [e.g., $\text{LWA}(\lambda, \phi_e)$]. Previously, Z500-derived LWA has been successfully applied in studies of regional extreme hot- and cold-air outbreaks (Chen et al. 2015) and continental/regional scale wave events, similar to atmospheric blocking (Martineau et al. 2017). The Z500 field is used prolifically in weather forecasting to diagnose the likelihood of significant regional weather and hydrometeorological extreme events under prevailing larger-scale, synoptic patterns (e.g., Dole and Gordon 1983; Chen et al. 2015). The typical wavelengths of midlatitude cyclones and anticyclones ($O \sim 1000\text{ km}$) lend themselves well to the LWA diagnostic applied to the Z500 field. Moreover, Chen et al. (2015) demonstrate the relationship between low-level eddy heat fluxes and Z500 wave amplitude through temperature tendency equations. Generally, regions with large eddy heat fluxes, such as ahead of and within an advancing frontal system and along the GPLLJ corridor, correspond with regions of large LWA. A drawback to using Z500 as a nonconservative quantity in the LWA is that it encompasses the LWA tendency response to mean meridional circulations. This, however, should not limit the efficacy of the LWA for LLJ classification.

To differentiate uncoupled versus coupled LLJs, the LWA, computed at 500 hPa, may be decomposed into its constituent anticyclonic wave activity (AWA) and cyclonic wave activity (CWA) components, respectively, as

$$\text{LWA}(\lambda, \phi_e) = \text{AWA}(\lambda, \phi_e) + \text{CWA}(\lambda, \phi_e), \quad (1)$$

where λ is longitude and ϕ_e is time step–specific equivalent latitude as a function of Z500. The ϕ_e is defined as the latitude in which the area enclosed poleward of ϕ_e on a horizontal pressure surface is equal to the area enclosed poleward of the Z500 isoline in question (Butchart and Remsberg 1986; Chen et al. 2015, their Fig. 1). When summed around the Northern Hemisphere, the area enclosed between ϕ_e and the Z500 contour to the north (associated with anticyclones) is equal to the area enclosed between ϕ_e and the Z500 contour to the south (associated with cyclones), hence equally weighting the size of anticyclones and cyclones around the Northern Hemisphere for each ϕ_e at each time step. For more details, see Huang and Nakamura (2016) for the application of LWA to the QGPV field

FIG. 2. (a) 0600 UTC wind speed profiles at the ARM-SGP site [$\phi = 36.68^\circ\text{N}$ and $\lambda = 97.58^\circ\text{W}$; black dot in (b)] representative of each Bonner–Whiteman (BW) low-level jet (LLJ) category, from least (BW1) to greatest (BW4) speed and vertical shear (Table 1). (b) The synoptic environment corresponding to the BW2 event [red line in (a)] on 11 Aug 2007 as characterized by 500 hPa geopotential height (Z500; dam; black), cyclonic local wave activity (CWA; $\times 10^7 \text{ m}^2$; blue), and anticyclonic local wave activity (AWA; $\times 10^7 \text{ m}^2$; red). Z500 is plotted with a contour interval of 6 dam. AWA and CWA are plotted with contour intervals of $1 \times 10^7 \text{ m}^2$. The dashed line rectangle indicates the upstream CWA search domain corresponding to the ARM-SGP location. (c) Also for 11 Aug 2007, the 850 hPa meridional wind (V850; m s^{-1}) field with active regions of uncoupled LLJ activity according to the BW/LW merged classification outlined in gray. No coupled LLJ events are occurring on this day. All plotted fields are valid at 0600 UTC and taken directly or derived from CERA-20C.

and Chen et al. (2015) and Martineau et al. (2017) for applications of LWA to the Z500 field. For the current analysis, the three terms in (1) are computed over the Northern Hemisphere from 10° to 85°N . The two quantities on the RHS of (1), AWA and CWA, are plotted in Fig. 2b for 0600 UTC 11 August 2007. On this day, the Z500 contours (black) indicate a continental-scale ridge situated across the GP with weak upstream and downstream troughs. We show later this is a classic set up for an uncoupled LLJ (Fig. 2c, gray contour). The strength of the ridge is quantified by the AWA field (red), while the CWA field (blue) quantifies the strength of the flanking troughs to the east and west.

3) BW/LWA MERGED CLASSIFICATION

By merging the BW LLJ classification with the LWA analysis, a dynamically derived LLJ classification may be achieved that conveys both BW intensity and

whether the LLJ is coupled or uncoupled to the upper-level flow. For example, an uncoupled, BW1 event would be classified as UC1 and a coupled, BW4 event would be classified as C4.

First, all grid points are evaluated for the presence of a BW LLJ. If BW LLJ criteria are met for any BW intensity category (Table 1), at any grid point (λ_o , ϕ_o), where ϕ_o and λ_o are the latitude and longitude of a BW

TABLE 1. Maximum surface to 700 hPa wind speed ($\mathbf{V}_{\max}$) and wind shear ($\Delta \mathbf{V}_z$) criteria for LLJ events adapted from Bonner (1968) with the Whiteman et al. (1997) fourth category extension.

	$\mathbf{V}_{\max}$ (m s^{-1})	$\Delta \mathbf{V}_z$ (m s^{-1})
Bonner–Whiteman 1 (BW1)	≥ 10	≥ 5
Bonner–Whiteman 2 (BW2)	≥ 12	≥ 6
Bonner–Whiteman 3 (BW3)	≥ 16	≥ 8
Bonner–Whiteman 4 (BW4)	≥ 20	≥ 10

LLJ event, then a two-pass method is employed to determine the LLJ's dynamical type (coupled or uncoupled). AWA is used first to screen for uncoupled LLJs. If AWA ($\lambda_o, \phi_{e,o}$), where λ_o is the event longitude and $\phi_{e,o}$ is the equivalent latitude corresponding to the event latitude ϕ_o , exceeds a predefined threshold for that grid location, then the LLJ event is classified as uncoupled. Otherwise, a second pass is performed using the CWA. Specifically, a search for CWA greater than a predefined threshold is conducted over a grid-specific upstream rectangular box (black dashed box in Fig. 2b for the ARM-SGP site) with dimensions: (λ_o to $\lambda_o - \Delta\lambda$, $\phi_{e,o} \pm \Delta\phi_e$), where $\Delta\lambda = 12.375^\circ$ and $\Delta\phi_e = 4.5^\circ$. The magnitude of CWA west of the LLJ is indicative of its dynamical type because cyclone/coupled LLJs will be situated within the warm conveyor belt sector of an approaching frontal system, positioned between a trough to the west and a ridge to the east (Newton 1967, their Fig. 8). If neither AWA nor CWA values exceed their respective predefined thresholds for classification, then the event is classified as uncoupled. These types of events account for less than 4% of the total LLJ events and typically have weak geopotential height gradients and weak upper-level flow, hence weak to no upper-level coupling mechanism.

The AWA and CWA thresholds are grid-specific, time invariant constants defined from the 1901–2010 MJJAS CERA-20C AWA and CWA values (Fig. S2), following a regional adaptation of the hemispheric approach of Martineau et al. (2017). Whereas Martineau et al. (2017) sampled the latitudinal maximum wave activity at each longitude for the entire Northern Hemisphere, this study samples only the MJJAS daily maximum 3-hourly AWA ($AWA_{\max}$) in an expanded GP region where long-term mean MJJAS total LLJ (coupled and uncoupled) frequencies exceed approximately 10% (e.g., 24.75° – 49.5° N, 105.75° – 90° W; black box in Fig. S2a). A similar procedure is used for CWA, that is, MJJAS daily maximum 3-hourly CWA ($CWA_{\max}$), except the sample domain is located upstream and expanded northward and southward from the AWA sample domain (20.25° – 54° N, 118.125° – 90° W; black box in Fig. S2b). The positioning of the CWA thresholding box accounts for the relative location of LLJs in the warm sector of an approaching cyclone. Without an a priori reason to weight coupled and uncoupled event frequencies differently, we performed a sensitivity analysis of classification results using equal AWA and CWA threshold levels. Ultimately, the 75th percentile $AWA_{\max}$ and $CWA_{\max}$ thresholds were selected for use in the BW/LWA merged classification, since they yielded the closest correspondence with uncoupled-to-total jet ratios obtained from a 5-yr (2005–

10) manual weather-map-based classification. Notably, the 75th percentile CERA-20C $AWA_{\max}$ and $CWA_{\max}$ (hereafter, $AWA_{\max,75}$ and $CWA_{\max,75}$) values from our study agreed closely with the values from ERA-Interim computed for JJA 1979–2015 (Martineau et al. 2017). Percentiles for $CWA_{\max}$ are insensitive to the exact placement of the CWA domain, according to the threshold field (Fig. S2b), which shows relative uniformity across most of the United States. To ensure that the coupled LLJs are associated with large-scale, organized synoptic events, only BW LLJs for which local- $CWA_{\max,75}$ values are met at the majority of grids, that is, exceeding 50%, in the upstream CWA box are classified as coupled LLJs.

Results of the BW/LWA merged classification for 11 August 2007 show uncoupled (gray contour) LLJ events across the GP and western Atlantic. The objective classification results are confirmed with a visual synoptic weather map assessment. Namely, the large-scale ridge across the United States suggests an uncoupled LLJ in the GP, and the lack of strong AWA or CWA values suggests an uncoupled LLJ over the Atlantic off the Georgia coast. A manual weather map classification approach was conducted on 5 years of data to verify the robustness of the automated objective classification. In fact, it was in doing so that the necessity of the second pass (CWA) classification was realized. It turns out that in the case of zonal flow in Fig. 1c, that is, weak AWA values at ($\lambda_o, \phi_{e,o}$) and weak CWA values within (λ_o to $\lambda_o - \Delta\lambda$; $\phi_{e,o} \pm \Delta\phi_e$), a second pass is necessary in order to correctly identify these events as uncoupled. The complete BW/LWA merged classification dataset is available through the National Center for Atmospheric Research (NCAR) Research Data Archive (<https://rda.ucar.edu/>; Burrows et al. 2019).

d. Composites

Composite anomaly (from CERA-20C, MJJAS 1901–2010 time mean) maps are constructed to illustrate synoptic patterns associated with active GPLLJ events at the ARM-SGP site. Additional composite anomaly maps illustrate how these synoptic patterns tend to vary when the GPLLJ is active farther south and north. Most composites are conditioned on GPLLJ occurrence (or not) across a north–south transect encompassing the ARM-SGP site. The ARM-SGP has a few noteworthy attributes: 1) it is situated approximately 5° S of the predominant GPLLJ exit region and close to the 37° N, 95° – 100° W GPLLJ frequency maximum identified by Bonner (1968), and 2) it is well instrumented for weather and climate model evaluation studies (e.g., Berg and Lamb 2016; Liu et al. 2013; Dirmeyer et al. 2006; Ruiz-Barradas and Nigam 2013). For these reasons,

ARM-SGP constitutes a useful and familiar frame of reference. The set of variable fields analyzed includes atmospheric fields, such as 850 hPa meridional wind (V850), vertically integrated moisture divergence (VIMD), and precipitation (P) due to their relevance to wind and water resources assessment. Other variable fields such as 250 hPa meridional wind (V250), Z500, CWA, and AWA portray the synoptic features associated with GPLLJ events. All composites are constructed from the MJJAS 1901–2010 0600 UTC CERA-20C record and conditioned upon GPLLJ activity at various grid point locations. Student's t tests are performed on the composite anomaly plots against climatological mean fields to test for statistical significance at the 99% confidence level.

e. Trend analysis

A two-sided Mann–Kendall trend test (Kendall 1975; Mann 1945) and Theil–Sen slope estimator (Sen 1968; Theil 1950a,b,c) are used to test for trend significance and estimate the slope magnitude, respectively. If the original series is found to have significant lag-1 serial correlation at the $\alpha = 0.05$ level, then it is removed with a modified trend-free prewhitening (TFPW; Yue et al. 2002) procedure. Finally, we test the field significance (e.g., Livezey and Chen 1983) of the trends at the $\alpha = 0.05$ level following the false discovery rate (FDR) approach as described by Benjamini and Hochberg (1995). For a single (grid cell) time series, the type I family-wise error rate (FWER) is equal to the local significance level ($\alpha = 0.05$). However, each additional (grid cell) comparison over the domain causes the FWER to increase in a cumulative manner. The FDR procedure controls this multiplicity (selection) effect by requiring local p values be less than or equal to a rescaled global significance level

$$p_i \leq \frac{i}{m} \alpha_{\text{global}}, \quad (2)$$

where $p_1 \leq p_2 \leq \dots \leq p_m$ are the ordered local p values, m is the number of tests (cells: $m = 1562$ cells in the CONUS domain), and α_{global} is set in our case to 0.05. The overall analysis methodology follows closely to that of Ferguson and Mocko (2017), which thoroughly detail the procedure.

3. Results

a. Merged classification proof of concept

The synoptic-scale differences between a typical coupled and uncoupled GPLLJ are well characterized through concurrent plots of V250, Z500, and V850 fields. Figure 3 presents these fields for two cases: the 3 July

2010 coupled and 10 July 2009 uncoupled GPLLJ events. The locations of coupled and uncoupled LLJ activity according to the BW/LWA merged classification are outlined in black and gray, respectively. It will be shown that these objectively defined jet classifications are consistent with the classification outcome of a subjective analysis based on traditional weather map diagnostics.

At the 850 hPa level, both events are characterized by strong southerly flow that turns more cyclonically in the coupled case and more anticyclonically in the uncoupled case. At the 500 and 250 hPa levels, the two events differentiate themselves considerably. The coupled event is dominated by a large-scale pressure gradient that reverses the climatological upper-level flow and positions the V250 maximum on the GPLLJ's western flank. In contrast, the upper-level flow of the uncoupled event is dominated by a continental-scale ridge driving West Coast southerlies and GP-to-East Coast northerlies. This pattern is not conducive to upper-level coupling and therefore implies the support of low-level flow by boundary layer and terrain-linked processes. The upper-level northerlies off the west and northeast coast are also quite pronounced in the coupled event, suggesting potential upstream support from Pacific internal variability (i.e., the Pacific–North American pattern) and/or downstream support from Atlantic variability (i.e., the North Atlantic Oscillation), respectively. The Z500-derived AWA (red contours) and CWA (blue contours) fields tell a similar story. Elevated AWA values are associated with the ridge in the uncoupled case (Fig. 3e) and large upstream CWA (blue contours) values correspond with the cyclone in the coupled case (Fig. 3b).

Four additional coupled and uncoupled GPLLJ events, deliberately selected to capture a broad range of subclass variability, are presented to further demonstrate the robustness of the proposed classification (Fig. 4). Specifically, BW/LWA merged classification results are superimposed on Z500, AWA, and CWA fields from which they were derived. The coupled events consist of West Coast troughs of varying strengths and locations, one containing a closed cyclone (Fig. 4c), two with downstream ridging from the southeast United States into the Great Lakes (Figs. 4a,c), and two with downstream troughing along the East Coast to the western Atlantic (Figs. 4b,d). Notably, each of the coupled GPLLJs shown extend from southern Texas northward across the GP into Canada.

The uncoupled GPLLJ events shown consist of both uncoupled ridge events and a more zonally elongated event (Figs. 4e–h). The events on 23 August 2010 and 23 June 2010 exemplify classic, ridge-dominated and terrain-influenced GPLLJs with ridge patterns

FIG. 3. A synoptic summary of the (a)–(c) 3 Jul 2010 coupled and (d)–(f) 10 Jul 2009 uncoupled ridge LLJ events as represented in CERA-20C. Shown are the (a),(d) 250 hPa meridional wind (V250); (b),(e) Z500 (black), anti-cyclonic local wave activity (AWA; red), and cyclonic local wave activity (CWA; blue) with contour intervals of 6 dam, $2 \times 10^7 \text{ m}^2$ and $2 \times 10^7 \text{ m}^2$, respectively; and (c),(f) V850 (color map), C, UC with regions of coupled (C; black) and uncoupled (UC; gray) LLJ activity demarcated. All fields are valid at 0600 UTC.

extending across the United States and LLJ events occurring to varying eastward and northward extents. By contrast, the event on 27 June 2000 exemplifies an uncoupled zonal GPLLJ event with moderate Z500 gradients, and weak-to-no-wave-activity signal in the GP or upstream domain. Such uncoupled zonal GPLLJ events are relatively rare, comprising less than 4% of all GPLLJ events, and tend not to meet either AWA or CWA thresholds; they are classified as uncoupled by default in the current implementation of the BW/LWA merged classification. The ten events presented thus far in Figs. 3 and 4 demonstrate the robustness of the objective BW/LWA merged classification that has been devised.

b. Geographic and temporal distributions of GPLLJ class frequency

The frequency of coupled and uncoupled class GPLLJs, and of their constituent subclass (C1–4, UC1–4) events, is computed for MJJAS using the 110-yr (1901–2010) CERA-20C record (Fig. 5). In contrast to the coupled GPLLJ frequency, which maximizes in Kansas and decreases toward the northwest, regardless of jet

subclass (strength), uncoupled GPLLJ frequency maximizes in south-central Texas and decreases northward. Uncoupled jet frequency exceeds coupled jet frequency in the southern and northern GP, whereas coupled jets are more common from the central GP east-northeastward to the Great Lakes (Fig. 6b). Overall, the most common GPLLJs are moderate C2 and UC2 events. Relatively stronger and less common C3 and UC3 jets tend to occur within a narrow corridor spanning 103° – 99° W. Within this corridor, strong coupled jets are more likely between 35° and 45° N, whereas strong uncoupled jets occur over a broader range from 25° to 50° N. Extreme C4 and UC4 jets, which are associated with severe weather outbreaks, such as flash floods, occur most often in western Oklahoma, Kansas, central Nebraska, and northern Texas (i.e., 2%–4%; Fig. S3). It is interesting to note that whereas the total GPLLJ (C + UC) frequency distribution in Fig. 6a is aligned south–north, the frequency distribution of coupled events tilts cyclonically from the southeast to the northwest, consistent with a dampening of the inertial oscillation of a boundary layer GPLLJ (Fig. 5d). Likewise, the frequency distribution of uncoupled events turns

FIG. 4. Typical (a)–(d) coupled and (e)–(h) uncoupled GPLLJ events, according to the BW/LWA merged classification. Black and gray shading denotes grid points of coupled and uncoupled LLJ activity, respectively. For each panel, contours represent Z500 (black) with a contour interval of 6 dam, CWA (blue) and AWA (red)—both with a contour interval of $5 \times 10^7 \text{ m}^2$, all at 500 hPa.

slightly anticyclonically from the south-southwest to north-northeast, consistent with a prevailing role of the inertial oscillation (Fig. 5h).

Figure 7 illustrates variations in monthly total, uncoupled, and coupled GPLLJ frequency statistics across the southern, central, and northern GP. For example, GPLLJs occur on 48%, 62%, 60%, 53%, and 44% of MJJAS days in the southern GP, respectively (Fig. 7c). The regions share a warm-season minimum GPLLJ frequency in May; however, maximum GPLLJ frequency varies from early summer (June) in the southern GP, to midsummer (July) in the central GP, to late summer (August) in the northern GP. In general, the uncoupled GPLLJ fraction follows the seasonality of total GPLLJ frequency. Its value ranges from 33% in May in the central GP (Fig. 7b) to 97% in July in the southern GP (Fig. 7c). In fact, the uncoupled (coupled) GPLLJ fraction peaks (minimizes) in July across all

regions. Notably, coupled GPLLJ fraction is greatest in the central GP.

c. Synoptic environments of the GPLLJ

1) CLIMATOLOGY

It is critical to understand and quantify the large-scale atmospheric forcing and hydroclimatological effects of GPLLJ events as distinguished from the background climatology. Figure 8 depicts the MJJAS synoptic climatology over the CONUS through time-averaged (1901–2010) fields of: V850, V250, Z500, AWA, CWA, VIMD, and P . VIMD and P are accumulated from 0000 to 1200 UTC; the remaining fields are instantaneous at 0600 UTC. The V850 mean field shows persistence of both the southerly GPLLJs as well as northerly California coast LLJs. In contrast to both of these lower-level flows, V250 is southerly over the West Coast and

FIG. 5. Frequency (% of MJJAS days) of (a)–(c) coupled LLJ subclasses one through three (C1–C3) and (e)–(g) uncoupled LLJ subclasses one through three (UC1–UC3) based on the CERA-20C 1901–2010 0600 UTC reanalysis. (d),(h) Frequency of all coupled (C1–C4) and uncoupled LLJ (UC1–UC4) events, respectively. Note that the color bar differs for (d),(h). Uncoupled and coupled subclass four LLJ (UC4, C4) event frequency is generally less than 4% across the domain (see Fig. S3).

FIG. 6. As in Fig. 5, but for the (a) total frequency (% of MJAS days) of LLJ events and (b) fraction of total LLJ events that are uncoupled. The three black boxes in (a) define GP subregions used for monthly frequency (Fig. 7) and trend (Fig. 16) analyses. The black contour in (b) corresponds to a value of 0.5, and values are only plotted where total LLJ frequency exceeds 10%.

northerly from the Great Lakes through the GP, indicative of a climatological ridge. The ridge structure extends into the midlevels with Z500 showing a weak trough–ridge–trough structure across the CONUS (Fig. 8c). The trough and ridge regions are accentuated by maximums in the derived CWA and AWA fields, respectively (Fig. 8d). Under this climatological airflow pattern, the GPLLJ is situated in a region of northwesterly flow with weak Z500 gradients that are unfavorable for upper-level jet coupling. Shifting to VIMD, the climatology shows positive VIMD along the Rocky Mountain Front Range from Mexico to Montana and convergence across the GP, Gulf of Mexico, and southwest Atlantic. An implicit dryline is positioned at the 100°W meridian with moisture divergence to the west and convergence to the east (Fig. 8e). An east–west gradient in mean P across the CONUS is found, consistent with observations. A local P maximum lies near the intersection of Kansas, Nebraska, Iowa, and Missouri state boundaries. Consistent with negative VIMD, major P maximums are located over the Gulf of Mexico and southwest Atlantic.

2) COUPLED AND UNCOUPLED GPLLJ ANOMALY COMPOSITES

For each of the MJAS fields used to compose the climatology (Fig. 8), two anomaly composites are calculated (i.e., conditional mean minus climatological mean) for the subsets of all coupled (Fig. 9) and uncoupled (Fig. 10) GPLLJ events. The composites are conditioned on GPLLJ detection/classification at the ARM-SGP site. To facilitate further comparison of the

GPLLJ classes, composite difference fields (coupled minus uncoupled) are also provided in the supplemental material (Fig. S4).

The coupled GPLLJ V850 anomaly composites detail an enhancement and northeasterly extension of the GPLLJ from southern Texas and the Gulf of Mexico through the United States (Fig. 9a). Anomalous northerly flow along the West Coast and East Coast and extending from Colorado through Montana are also enhanced. From a hydroclimate perspective, coupled GPLLJs increase VIMD in the central GP and western Atlantic and decrease VIMD along the Colorado–New Mexico border and in a large southwest–northeast-oriented swath that extends from eastern Texas to Maine and beyond (Fig. 9e). The resultant P anomaly fields feature anomalous drying extending from the southern GP to the western Atlantic and anomalous wetting throughout the northern GP and upper-Midwest centered on Iowa ($\phi \approx 42^\circ\text{N}$, $\lambda \approx 93^\circ\text{W}$; Fig. 9f). The local P maximum in Iowa corresponds to the exit region of the anomalous V850 winds (Fig. 9a). Aloft, the V250, Z500, and CWA fields are opposing the climatological patterns with: anomalous northerly flow along the West Coast and southerly flow through the GP (Fig. 9b), mid-level anomalous troughing throughout the west (Fig. 9c), and enhanced CWA values in the northwest (Fig. 9d)—all conditions favorable for jet stream coupling.

Relative to the coupled V850 anomaly composite, uncoupled GPLLJ V850 anomalies exhibit a more spatially confined and northward-oriented enhancement, weaker northerly anomalies from Colorado to Montana, and stronger northerly anomalies in the eastern third of

FIG. 7. Climatological mean monthly area-averaged ($\lambda = 102.375^{\circ}$ – 96.75° W) total (bar) and uncoupled (line) GPLLJ frequencies for the (a) northern GP (NGP; $\phi = 42.75^{\circ}$ – 49.5° N), (b) central GP (CGP; $\phi = 36^{\circ}$ – 42.75° N), and (c) southern GP (SGP; $\phi = 29.25^{\circ}$ – 36° N), based on CERA-20C 1901–2010 0600 UTC reanalysis. The uncoupled GPLLJ event percentage of all GPLLJ events for each month and subregion is notated at the base of each bar. The coupled GPLLJ frequency is the difference of the total and uncoupled GPLLJ frequencies. Vertical lines denote the corresponding 95% bootstrapped confidence intervals calculated from 100 000 realizations.

the United States from the Gulf of Mexico into Canada (Fig. 10a). Thus, with uncoupled jets, there is a weakening of southerly low-level wind support for moisture advection from the Gulf of Mexico, and this is reflected

in the hydroclimatic anomalies, as well. Positive moisture divergence anomalies span the GP coincident with increased convergence over the northwestern Gulf of Mexico (Fig. 10e). The VIMD anomalies correspond with P deficits from the western Atlantic into the southern and central GP with maximum drying just east of the ARM-SGP site; a weak region of anomalous wetting is shown to span from Minnesota to Wisconsin (Fig. 10f) near the exit region of the anomalous V850 wind (Fig. 10a).

In summary, the upper-level flow pattern for coupled GPLLJs opposes the climatological flow, whereas uncoupled GPLLJs enhance the climatological flow. Specifically, uncoupled GPLLJ V250, Z500, and AWA anomaly composite fields demonstrate the following features: enhanced northerlies in the west and enhanced southerlies from the GP to the east (Fig. 10b), CONUS-scale ridging centered north of the ARM-SGP site (Fig. 10c), and anomalously large AWA values throughout CONUS (Fig. 10d). With a westward displacement of the upper-level southerlies, these conditions favor boundary layer/terrain-linked GPLLJs. The resulting P anomalies, and any persistence of this uncoupled GPLLJ pattern that can result from weather training linked to low-frequency (SST) variability, has the potential to trigger or intensify drought in these regions (Fig. 10f). Conversely, persistence of coupled GPLLJs and associated prolonged wetness has the potential to trigger and intensify floods.

3) CONTRASTING C1, C3, UC1, AND UC3 EVENTS ACROSS THE GREAT PLAINS

The synoptic environment conducive to coupled and uncoupled GPLLJ classes can and does vary according to location along the (generally) south–north GPLLJ corridor, as well as strength (subclass) of the GPLLJ. Figures 11–14 present GPLLJ anomaly V850, V250, Z500, and P composite fields, respectively, corresponding to C1, UC1, C3, and UC3 subclass GPLLJ events at 32.625° , 39.375° , and 46.125° N along the 97.58° W meridian. The sample size statistics corresponding to these composite conditioning locations are provided in Table 2. In this section, the focus will be on contrasting C1 and UC1 events and C3 and UC3 events because level 1 (C1, UC1) results are consistent with level 2 (C2, UC2) events (not shown) and the limited sample size of level 4 (C4, UC4) events precludes their use in a statistically meaningful comparison (Fig. S3).

Following from the BW/LWA merged subclassification criteria (Table 1), it is not surprising to find that the magnitude and extent—in both latitudinal and longitudinal directions—of level 3 V850 anomalies exceed those of level 1 anomalies (Fig. 11). Interestingly, uncoupled

FIG. 8. Climatological mean MJJAS (a) 0600 UTC V850, (b) 0600 UTC V250, (c) 0600 UTC Z500, (d) 0600 UTC 500 hPa AWA (red) and CWA (blue), (e) 0000–1200 UTC accumulated vertically integrated moisture divergence (VIMD), and (f) 0000–1200 UTC accumulated precipitation (P)—all calculated from the CERA-20C 1901–2010 reanalysis. The contour interval in (c) is 3 dam. The contour intervals for both AWA and CWA are both $0.5 \times 10^7 \text{ m}^2$, with the lowest contours removed for greater figure clarity.

GPLLJ V850 tend to maximize farther west of the location of jet conditioning, relative to coupled jets of comparative strength, and especially for weak (level 1) jets. The V850 anomaly differences between classes of the same jet type (e.g., C1, UC1; C3, UC3) are accentuated by the southern and northern jet composites. A latitudinal dependence within each subclass also exists. Coupled GPLLJ events (C1 and C3) at the southern and northern analysis points are relatively stronger compared with the central analysis point, while V850 anomalies for uncoupled GPLLJ events (UC1 and UC3) are relatively stronger as the analysis point moves northward. These generalities break down for UC3 events at the southern analysis point and begin to take on attributes of C1 GPLLJs, suggesting both boundary layer (land–atmosphere) processes and upper-level support are necessary for the strongest uncoupled GPLLJs occurring in the southern GP.

V250 (Fig. 12) and Z500 (Fig. 13) anomaly fields highlight large upper-level airflow configuration variations between GPLLJ subclasses according to the latitude of jet conditioning. Coupled GPLLJs are characterized by strong West Coast northerly anomalies, GP southerly anomalies, and western U.S. anomalous troughs (strongest at the southern and northern GP analysis point). In contrast, uncoupled GPLLJs are characterized by northwestern U.S. southerly anomalies, GP to central and eastern

U.S. northerly anomalies, and northern GP anomalous ridging (strongest for the central and northern GP analysis points). In general, the anomalies for level 3 events exceed those of level 1 events for each subclass and analysis location. Similar to the V850 anomaly composites, both the V250 and Z500 anomaly fields for UC3 events at the southern analysis point begin to converge on the C1 events.

Anomaly composites of Z500-derived CWA and AWA (Figs. S5–S6) underscore the V250 and Z500 anomaly composite takeaways. Namely, anomaly composites of CWA and AWA show an increase in CWA for coupled GPLLJ cases and increase in AWA for uncoupled GPLLJ cases. The CWA anomalies (Fig. S5) are strongest for coupled southern GPLLJs, while the AWA anomalies (Fig. S6) are strongest for uncoupled central GPLLJs. Again, the UC3 anomaly signal in AWA begins to converge toward the C1 anomaly signal at the southern GP analysis location.

Last, P anomaly composites provide insight into the different hydroclimatic impacts associated with GPLLJ classes and subclasses (Fig. 14). Relative to level 1 GPLLJ events, P anomalies are more pronounced for level 3 GPLLJ events. For coupled GPLLJ events, wet anomalies are generally located north and east of the analysis point and dry anomalies are generally south of the analysis location extending into the Gulf of Mexico, western Atlantic, and northeast United States. GPLLJ-related P anomalies

FIG. 9. As in Fig. 8, but for the anomaly (from CERA-20C 1901–2010 MJJAS 0600 UTC time mean) composites computed from the sample of 5033 days with coupled GPLLJ (C1–C4) occurrences at the ARM-SGP site, the location of which is denoted by the black dot in (a)–(f). The contour interval for CWA is $0.5 \times 10^7 \text{ m}^2$. Stippling in each panel represents Student's *t*-test significance at 99%. Note that the Z500 anomaly field is plotted with a color map here.

are particularly strong for jets at the southern analysis point. C3 GPLLJ events there produce anomalous drying patterns throughout the Gulf of Mexico and southwest Atlantic. In contrast, uncoupled GPLLJs are characterized

by anomalous drying across much of the United States. The largest precipitation deficits over land, linked with active central GPLLJs, extend from the Ohio River valley east and northeasterly (Fig. 14b). Some positive *P* anomalies

FIG. 10. As in Fig. 9, but for the uncoupled GPLLJ anomaly computed from the sample of 2754 days with uncoupled GPLLJ (UC1–UC4) occurrences at the ARM-SGP site. Note the contour intervals in (d) are also the same as in Fig. 9.

FIG. 11. GPLLJ subclass (i.e., C1, UC1, C3, and UC3) V850 anomaly fields (from CERA-20C 1901–2010 MJAS 0600 UTC time mean) corresponding to sample sets composed of GPLLJs incident at (a) 46.125°, (b) 39.375°, and (c) 32.625°N at 97.58°W. The largest black dot in each panel indicates the location of GPLLJ classification used in the composite construction. C1, UC1, C3, and UC3 composite anomalies are shown in the first, second, third, and fourth column, respectively. The number of contributing events per location/subclass is detailed in Table 2.

in the central and midwestern United States do appear for strong UC3 southern GPLLJs; however, C3 GPLLJs there produce stronger wetting anomalies that are concentrated across the GP regions with a noticeable tertiary

local P anomaly maximum over Wyoming and Montana. Overall, for C1, C3, and UC3 GPLLJ events, P anomaly patterns (wetting or drying) across CONUS are largest for the southern GPLLJ events. For interested readers, the

FIG. 12. As in Fig. 11, but for the V250 anomaly.

FIG. 13. As in Fig. 11, but for the Z500 anomaly.

VIMD anomaly fields may be found in the supplemental material (Fig. S7).

d. Twentieth-century GPLLJ trends and their impacts

The preceding analyses have contributed to an objective and robust characterization of airflow and P anomalies associated with coupled and uncoupled GPLLJ classes and their composing strength subclasses.

Having established that important distinctions exist, the next step is to quantify how the frequency of events in each class has changed over the twentieth century (i.e., CERA-20C's period of record). Trend analyses are conducted on the full coupled (C1 to C4), uncoupled (UC1 to UC4), and total (C + UC) GPLLJ event frequency time series. Considering the anomaly composites discussed earlier (Figs. 11–14), shifts in the frequency of

FIG. 14. As in Fig. 11, but for the 0000–1200 UTC accumulated P anomaly. Note that GPLLJ events were classified at 0600 UTC.

TABLE 2. Summary of CERA-20C 1901–2010 MJJAS 0600 UTC GPLLJ events occurring at the three grid points: (46.125°N, 97.58°W), (39.375°N, 97.58°W), and (32.625°N, 97.58°W), on which synoptic composites in Figs. 11–14 are based.

	Coupled 1 (C1)	Coupled 2 (C2)	Coupled 3 (C3)	Coupled 4 (C4)	Coupled (C)
46.125°N	271	367	257	133	1028
39.375°N	977	1524	1028	702	4231
32.625°N	235	432	268	60	995
	Uncoupled 1 (UC1)	Uncoupled 2 (UC2)	Uncoupled 3 (UC3)	Uncoupled 4 (UC4)	Uncoupled (UC)
46.125°N	733	1226	689	280	2928
39.375°N	650	1104	704	270	2728
32.625°N	2558	3680	1064	163	7465

coupled and/or uncoupled GPLLJs and/or their ratio are liable to correspond with regional climate change. All trends are calculated as the Theil–Sen slope and significance at the $\alpha = 0.05$ level is evaluated according to the Mann–Kendall τ (see section 2e). Out of an abundance of concern for sample size constraints on statistical robustness, trend analyses for GPLLJ subclasses are not discussed.

Figure 15 shows for the GP and Midwest, significant long-term (1901–2010) declines in MJJAS total GPLLJ frequencies largely attributable to declines in uncoupled GPLLJ frequencies. The largest rates of decline in total and uncoupled GPLLJ frequency are concentrated within the GP corridor, with local maxima of 40 events $(110 \text{ yr})^{-1}$ reduction from 1901 to 2010 located in central Texas and western North Dakota. Trends in coupled GPLLJ frequency are less widespread with some significant but weak increases over eastern North Dakota and western Minnesota and decreases over the eastern central GP (Fig. 15a). Regions that have experienced significant long-term declines in MJJAS GPLLJ frequency have experienced concomitant significant declines in southerly V850, VIMD, and P (Fig. S8).

Area-averaged coupled, uncoupled, and total GPLLJ frequency time series are presented for the southern, central, and northern GP subregions (Fig. 16). The time series illustrate low-frequency variability on time scales of 5–8 years against the backdrop of significant long-term linear decreasing trends in total and uncoupled GPLLJ occurrences and insignificant increasing trends in coupled GPLLJ occurrences for each subregion. The magnitude of the long-term trend in total GPLLJ frequency ranges from -14.2 to -18.8 events $(110 \text{ yr})^{-1}$ in the northern and southern GP subregions, respectively. Time series of uncoupled and coupled GPLLJ frequency are indirectly correlated, with Kendall's τ of -0.256 , -0.128 , and -0.221 (from north to south), which are all significant at 95% confidence. A running trend analysis of uncoupled GPLLJ frequency was conducted using start years between 1901 and 2000 and end years

between 1910 and 2010 (Fig. 17). The long-term trends ending in 2010 are significant for starting years 1901–66, 1901–76, and 1901–68 for the southern, central, and northern GP, respectively (Fig. 17).

Stacked Hovmöller (longitudinally averaged from 102.375° to 96.75°W) anomaly diagrams comprising the suite of key synoptic fields discussed herein effectively illustrate interannual univariate variability, multivariate covariability and long-term trends between total, coupled and uncoupled GPLLJ frequency, synoptic environment, and surface hydrology between 25° and 50°N. Total GPLLJ frequencies showcase negative long-term trends for latitudes north of 29° (Fig. 18a), which is reflected in significant reductions in uncoupled GPLLJ frequencies (Fig. 18c). Mixed trends for coupled GPLLJ frequencies indicate a reduction (enhancement) of event frequency between 40° and 45°N (45°–50°N) (Fig. 18b). Concurrent with total and uncoupled GPLLJ frequency trends, significant decreasing trends are found for V850 and VIMD anomaly fields (Figs. 18d,e). In particular, V850 shows a significant reduction at all latitudes. Although the long-term trends in VIMD indicate significant decreases in VIMD from 30° to 48°N, P shows anomalous drying (wetting) from 45° to 50°N (25°–28°N), a shift that may reflect long-term decreasing trends in V850 and associated moisture fluxes from the Gulf of Mexico.

Additional Hovmöller diagrams corresponding to mid- and upper-level synoptics provided in Fig. 19 further support the interpretation of fields in Fig. 18. V250 shows significant positive (increased upper-level southerlies) trends from 25° to 34°N (Fig. 19a), which occur at latitudes that Z500 show increasing (higher height) trends (Fig. 19d). At higher latitudes (40°–50°N) Z500 is negatively trending indicating an enhanced prevalence for troughs. Trends of CWA and AWA demonstrate significant increases and decreases at all latitudes, respectively, an indication of a general reduction in cyclone strength (or increase in anticyclone strength) across the entire GP (Figs. 19b,c).

A quantitative summary of the long-term (1901–2010) MJJAS GPLLJ frequency–synoptic field correlations

FIG. 15. Long-term (1901–2010) trends in the MJJAS (a) coupled (C1–C4; C), (b) uncoupled (UC1–UC4; UC), and (c) total LLJ (C + UC) events as computed from CERA-20C 0600 UTC reanalysis. Trends are estimated using a Theil–Sen line after trend-free prewhitening (see section 2a). Stippling denotes field significance of the Mann–Kendall τ correlation at 95% confidence. Only grid points with total LLJ event frequency exceeding 10% or 15.3 days yr^{-1} are included in the analysis.

and regression coefficients for the southern, central, and northern GP is provided in Table 3. Besides V250 winds, significant mean field correlations with total GPLLJ frequency are most often explained by significant correlations with uncoupled GPLLJ frequency. The

frequency of uncoupled GPLLJs is found to be significantly and negatively (positively) correlated with the MJJAS P (VIMD) throughout the GP. As could have been expected, the largest correlations ($\tau = 0.162$ – 0.419) in each region are found between V850 and GPLLJ frequencies. V250 is positively correlated with coupled GPLLJ frequency in all subregions (significant in all subregions), while V250 is negatively correlated to uncoupled GPLLJ frequency in all subregions (significant in the southern GP). AWA is significantly anticorrelated with coupled GPLLJ frequency in all subregions, while CWA is significantly correlated with coupled GPLLJ frequency in the southern GP. Conversely, significant negative (positive) correlation between CWA (AWA) and uncoupled GPLLJ frequency is found for each GP region. As an example, the slopes for uncoupled GPLLJ frequency and AWA are positive and range from 4.027 to $7.352 \times 10^5 \text{ m}^2$ per additional GPLLJ event day, whereas the slopes for uncoupled GPLLJ frequency and CWA are negative and range from -0.258 to $-0.1.823 \times 10^5 \text{ m}^2$ per additional GPLLJ event day. Overall the table shows that GPLLJ hydrological impacts are mainly focused in the central and southern GP and most significant impacts are tied to changes in uncoupled GPLLJ frequency.

e. The Dust Bowl: 1932–38

Until this point, the analysis has primarily focused on CERA-20C's long-term (1901–2010) trends in GPLLJ frequencies, synoptic conditions, and hydrology. Of course, it is equally important to investigate GPLLJs in the context of subperiod variability. In this section, we provide an interpretation of the 1932–38 Dust Bowl drought of record (e.g., Schubert et al. 2004) in the context of coupled and uncoupled GPLLJ event frequencies. Although CERA-20C misplaces the Dust Bowl north by approximately 6° relative to observations (Fig. S9; Schubert et al. 2004, their Fig. 1), the event's mechanistic forcing is well represented (Figs. 18 and 19).

The affected region (36° – 50°N , 110° – 90°W) experienced below-average coupled GPLLJ frequency (Fig. 18b) and above-average uncoupled GPLLJ frequency (Fig. 18c), consistent with expectations (Figs. 9 and 10, Fig. S4). The synoptic environment of the central and northern GP consisted of anomalously weak (enhanced) CWA (AWA) values and positive Z500 anomalies (Figs. 19b–d). In the southern GP, below-average uncoupled GPLLJ frequency (Fig. 18c) and below-average V850 (Fig. 18d) served to support the drought by limiting northward Gulf of Mexico moisture transport, as evidenced by above-average VIMD and drying anomalies north of 36°N (Figs. 18e,f). Overall, large-scale synoptic ridging over the central and northern GP combined

FIG. 16. Time series of the MJJAS area-averaged total, coupled, and uncoupled GPLLJ event counts for (a) northern GP, (b) central GP, and (c) southern GP according to the classification of this study applied to the CERA-20C 1901–2010 0600 UTC reanalysis. Event count is shown as a 3-yr moving average from which a Theil–Sen slope is computed. Slopes that are significant at the 95% confidence level as determined by a Mann–Kendall test are dashed. The Theil–Sen slopes for total, coupled, and uncoupled GPLLJ event counts, respectively, in the northern GP are: -14.2 , 0.8 , and -15.2 ; in the central GP are: -15.8 , -1.1 , and -13.8 ; and in the southern GP are: -18.8 , 1.4 , and -19.9 —all in event count $(110 \text{ yr})^{-1}$.

with weakened lower-atmospheric moisture convergence strongly reinforced drought conditions (Figs. 18 and 19).

During the Dust Bowl, an important transition is observed around 1934 from stronger (1932–34) to weaker than average (1935–38) V850 (Fig. 18d) and strong to stronger upper-level ridging (Z500; Fig. 19d). This transition likely signals a change in the dynamics of uncoupled GPLLJ and synoptic/upper-level jet stream interactions. During 1932–34, we postulate that uncoupled GPLLJs initiated through dry land–atmosphere feedbacks were maintained by and contributed to the formation of an anomalously strong Z500 ridge over the central and northern GP. By 1935, however, the contribution of uncoupled GPLLJs to ridge building wanes and upper-level dynamical support for strong uncoupled GPLLJs becomes the more important signal. Accordingly, the role of the strong uncoupled GPLLJ appears to have switched from one of drought development in 1932–34 to one of drought maintenance from 1935 to 1938.

The potential role that multidecadal variability played in the drought's evolution, particularly with regard to

the contribution of conditions in the southern GP, is also worth discussing. The southern GP's (25° – 36° N, 110° – 90° W) time series contains a remarkable multidecadal signal with: a dry period in the 30 years (1901–31) preceding the Dust Bowl, a wet period from approximately 1932–40 during the Dust Bowl, and another dry period from 1941 to 1963 following the Dust Bowl (Fig. 18f). During dry periods, the southern GP experienced consistently above-average uncoupled GPLLJ frequency and V850. Anomalously strong V850 suggests a northward extension of the GPLLJ exit region, which enables anomalously high moisture transport/convergence in the north. In contrast, the central and northern GP (36° – 50° N, 110° – 90° W) underwent a wet period in the 30 years leading up to the Dust Bowl and have not experienced similar multidecadal variability. Thus, other variability sources may be more important, such as: decadal internal atmospheric variability (e.g., Hoerling et al. 2014), SST-forced variability (e.g., Trenberth et al. 1988; Schubert et al. 2004), or potentially for this event, land-cover modification that exacerbated drying conditions (e.g., Schubert et al. 2004).

FIG. 17. Thielen-Sen slope calculations (red for increasing trend and blue for decreasing trend) of CERA-20C MJJAS 0600 UTC area-averaged uncoupled (UC1–UC4) GPLLJ event frequency for the (a) northern GP (NGP; 42.75° – 49.5° N), (b) central GP (CGP; 36° – 42.75° N), and (c) southern GP (SGP; 29.25° – 36° N) according to the classification of this study. Slopes that are significant at the 95% confidence level as determined by a Mann–Kendall test are indicated by a larger filled circle.

4. Summary and discussion

This study advances the seminal GPLLJ work of Uccellini (1980), which through subjective analysis of upper-air weather maps classified 15 previous GPLLJ events as either coupled (type 1 in their analysis) or uncoupled to the upper-level flow (type 2 in their analysis). Specifically, this study objectifies and automates the classification and subsequently applies it in composite and long-term trend analyses spanning the twentieth-century using CERA-20C data. Despite its relatively coarse, ~ 125 km horizontal resolution and 3-hourly output, the CERA-20C's representation of the GPLLJ was determined to be sufficient for the purpose of this study.

Uccellini (1980) used the presence of an upper-level short- or long-wave trough upstream of the GPLLJ to differentiate coupled from uncoupled GPLLJs. Coupled GPLLJs were found—consistent with our work—to be characterized by enhanced: low-level temperature gradients, vertical ageostrophic transverse winds, 850 hPa winds, GP moisture convergence, and precipitation (Uccellini 1980). Our classification approach comprises an initial screening for elevated low-level winds and vertical wind shear (i.e., Bonner 1968; Whiteman et al. 1997) and a secondary quantification of midlevel ridging and troughing, which is an indicator of the upper-level flow pattern, using the local finite-amplitude wave activity metrics (AWA, CWA; Huang and Nakamura 2016) applied to the 500 hPa geopotential height (Chen et al. 2015; Martineau et al. 2017).

Differences between coupled and uncoupled GPLLJ composites (Fig. S4) show that, in contrast to uncoupled GPLLJ events, coupled GPLLJ events at the ARM-SGP site are characterized by 1) a V850 dipole across the GP with stronger northerlies (southerlies) to the west (east), 2) enhanced troughing across the CONUS characterized by stronger 250 hPa northerlies (southerlies) along the West Coast (from the southern GP northeastward to the Great Lakes) and weaker AWA values across CONUS, and 3) significantly reduced VIMD from the southern GP east- and northeastward to the coast resulting in greater (less) P in the central GP (western Atlantic and Gulf of Mexico). These general differences between coupled and uncoupled GPLLJ frequencies, synoptic environments, and their associated hydroclimate effects are borne out in an anomaly analysis of the Dust Bowl period of 1932–38 (Figs. 18 and 19 and Fig. S9).

This study has shown that the total and uncoupled GPLLJ frequencies have decreased over the past century at rates of up to 3.75 fewer events per decade (Fig. 15). These declines are concurrent with declines in

FIG. 18. Hovmöller (longitudinally averaged from 102.375° to 96.75°W) anomaly (from CERA-20C 1901–2010 MJJAS 0600 UTC time mean) diagrams for (a) total GPLLJ frequency, (b) C1–C4 (C) frequency, (c) UC1–UC4 (UC) frequency, (d) 0600 UTC V850, (e) 0000–1200 UTC accumulated VIMD, and (f) 0000–1200 UTC accumulated P for the region bound by 25°–50°N, 102.375°–96.75°W. 95% confidence in the long-term (1901–2010) trend at every degree of latitude, according to Mann–Kendall τ significance, is indicated on the left y axis of each panel by a filled circle—red for increasing and blue for decreasing trends. Black vertical lines in each panel delineate the Dust Bowl years of 1932–38 from Schubert et al. (2004). Note that the color map for P is reversed.

FIG. 19. As in Fig. 18, but for (a) V250, (b) CWA, (c) AWA, and (d) Z500.

GP extended summer (MJJA) precipitation and strength of low-level winds (Fig. 18 and Fig. S8) and carry extensive implications for the region's agriculture and energy sectors and hydroclimate in general. Although the exact dynamical mechanisms responsible for the GPLLJ are not the focus of this study, the separation of events into coupled and uncoupled classes enables a first quantification of the relative contributions of synoptic versus land-atmosphere (i.e., boundary layer) processes to GPLLJ development and maintenance. For the majority of uncoupled GPLLJ events, the synoptic environment is quiescent, dominated by a central GP ridge. With limited to no jet stream support, these GPLLJs are mostly governed by mesoscale land-atmosphere and terrain-linked dynamics (Blackadar 1957; Wexler 1961; Holton 1967). The story for strong uncoupled events (i.e., UC3, UC4), however, is different. Strong uncoupled

GPLLJs require middle- to upper-atmospheric support, especially in central Texas [far right in Figs. 12 and 13 row (c)]. To summarize, land-atmosphere processes are sufficient support for uncoupled GPLLJs of moderate magnitude (i.e., UC1, UC2), but strong uncoupled GPLLJs (i.e., UC3, UC4) require the combination of land-atmosphere and synoptic process support, particularly in the southern GP.

The new, objective dynamical LLJ classification developed herein may serve as a tool for renewed investigation of the GPLLJ in the context of synoptic control (e.g., Uccellini 1980). Alternatively, understanding the degree of low-level (terrain) coupling for a particular LLJ is instrumental in predicting whether regional land-atmosphere interactions (Song et al. 2005; Ford et al. 2015) may play a role in its evolution, and moreover, whether land data assimilation

TABLE 3. Interannual MJJAS Mann–Kendall (MK) τ and Theil–Sen slopes (m) for select fields of interest and total, uncoupled (UC), and coupled (C) GPLLJ frequencies for the period of 1901–2010. Statistics are computed separately for the northern, central, and southern GP. Boldface numbers indicate significance at the $\alpha = 0.05$ level. Units for the V850, V250, Z500, AWA, CWA, 0000–1200 UTC VIMD, and 0000–1200 UTC P slopes are m s^{-1} , m s^{-1} , dam , m^2 , m^2 , kg m^{-2} , and mm day^{-1} per additional GPLLJ event day, respectively.

Variable	Total GPLLJ		Uncoupled GPLLJ		Coupled GPLLJ	
	τ	m	τ	m	τ	m
Northern Great Plains (42.75°–49.5°N, 102.375°–96.75°W)						
V850	0.162	0.066	0.546	0.090	0.013	0.008
V250	0.061	0.053	−0.028	−0.011	0.178	0.227
Z500	0.008	0.061	0.576	1.745	−0.161	−1.932
AWA	−0.129	−3.887 × 10⁵	0.699	7.352 × 10⁵	−0.319	−13.250 × 10⁵
CWA	−0.136	−1.293 × 10⁵	−0.460	−1.823 × 10⁵	0.114	1.768 × 10 ⁵
VIMD	0.118	0.017	0.317	0.021	−0.062	−0.013
P	0.105	0.013	−0.066	−0.004	0.138	0.025
Central Great Plains (36°–42.75°N, 102.375°–96.75°W)						
V850	0.217	0.075	0.522	0.096	0.214	0.090
V250	0.198	0.125	−0.043	−0.015	0.289	0.210
Z500	−0.035	−0.109	0.392	0.724	−0.041	−0.143
AWA	−0.177	−3.602 × 10⁵	0.684	6.540 × 10⁵	−0.160	−3.932 × 10⁵
CWA	−0.064	−0.221 × 10 ⁵	−0.319	−0.612 × 10⁵	−0.030	−0.106 × 10 ⁵
VIMD	0.066	0.010	0.419	0.033	0.054	0.010
P	0.087	0.010	−0.301	0.018	0.100	0.013
Southern Great Plains (29.25°–36°N, 102.375°–96.75°W)						
V850	0.419	0.092	0.626	0.089	0.032	0.016
V250	0.086	0.033	−0.164	−0.039	0.369	0.263
Z500	0.016	0.025	0.108	0.112	−0.127	−0.394
AWA	−0.112	−1.516 × 10 ⁵	0.435	4.027 × 10⁵	−0.173	−5.313 × 10⁵
CWA	−0.160	−0.167 × 10⁵	−0.366	−0.258 × 10⁵	0.230	0.501 × 10⁵
VIMD	0.121	0.008	0.383	0.018	−0.074	−0.011
P	−0.072	−0.004	−0.303	−0.011	0.076	0.009

(e.g., Case et al. 2014; Kumar et al. 2006) holds promise for improved weather prediction of such events. The complete BW/LWA merged classification dataset is available through the National Center for Atmospheric Research (NCAR) Research Data Archive (<https://rda.ucar.edu/>). Further analyses along this path may eventually necessitate quantification of the degree of upper-level coupling as opposed to the simple binary classification presented here. In addition to this, sensitivity of the classification to the local wave activity thresholds will need to be considered and retuned in the context of the observed ratio of uncoupled to coupled events. At this time, we do not have a long-term observed truth for comparison against CERA-20C; however, satellite-era atmospheric reanalyses may be used for comparisons spanning the period since 1979.

It is important to point out that this study's LLJ classification is applicable to most atmospheric models (and reanalyses) and is transferrable globally. The required inputs are limited to 3-hourly (or finer) Z500 and vertically resolved low-level (0–300 hPa AGL) u and v winds. Unfortunately, as Danco and Martin (2018) reported, subdaily wind field outputs exist for only a very few ($n = 3$) CMIP5 models. Thus, modeling centers will need to

increase the availability of these fields to support more detailed LLJ studies. The classification should be readily transferrable to studies of Earth's other LLJs (e.g., Rife et al. 2010) with minimal modification to account for wind speed distribution, diurnal cycle, and Z500 field. Finally, in a multimodel intercomparison project (i.e., MIP) framework, researchers will need to apply a local rescaling as in Rife et al. (2010) of the Bonner (1968) and Whiteman et al. (1997) threshold levels as a bias-correction technique (e.g., Jones and Carvalho 2018).

The CERA-20C reanalysis provides unique opportunities to analyze the high-frequency GPLLJ variability in the context of the large-scale low-frequency synoptic environment. Although CERA-20C was explicitly constructed to minimize the impact of observational network changes on long-term trends (e.g., Thorne and Vose 2010; Laloyaux et al. 2018), the fact remains that assimilated observation counts are relatively suppressed in the early years and variable over time. Thus, results for early years should be subject to scrutiny and the presence of spurious breakpoints should still be tested rigorously (e.g., Ferguson and Villarini 2014).

In future work, predicting how the GPLLJ will be manifest in a changing climate is of socioeconomic

importance. It will be particularly important to understand both the short- and long-term, subseasonal-to-decadal, variability and its relationship to large-scale climate drivers. Most likely, the global atmospheric circulation will change, for example, sensitivity to NAO, Pacific–North American pattern (PNA), AMO, and PDO, to name a few, leading to changes in the lower- and upper-atmospheric winds across the GP. In fact, on subseasonal-to-interannual time scales, the NAO and PNA are both shown to influence GP low-level winds and precipitation through alterations in the low-level pressure gradient field (Weaver and Nigam 2008). On interannual-to-decadal time scales, it is also recently shown that the AMO and PDO have transitioned into phases more conducive for drought across the GP, that is, +AMO and –PDO (Kam et al. 2014). Variability at either time scale may alter the ratio of uncoupled to coupled GPLLJ events and concomitantly, the location and intensity of GP precipitation. These internal and SST-forced modes of atmospheric variability may be further identified and quantified by considering the remaining nine ensemble members from CERA-20C. Application of the automated BW/LWA merged classification scheme developed herein on the long-term CERA-20C ensemble will allow for a future comprehensive overview of the high- and low-frequency contributions to GPLLJ variability.

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