Influence of the Madden–Julian Oscillation on Summertime Cloud-to-Ground Lightning Activity over the Continental United States

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(Manuscript received 30 March 2009, in final form 5 June 2009)

ABSTRACT

Summertime cloud-to-ground lightning strikes are responsible for the majority of wildfire ignitions across vast sections of the seasonally dry western United States. In this study, a strong connection between active phases of the Madden–Julian oscillation (MJO) and regional summertime lightning activity was found across the interior western United States. This intraseasonal mode of lightning activity emanates northward from the desert Southwest across the Great Basin and into the northern Rocky Mountains. The MJO is shown to provide favorable conditions for the northward propagation of widespread lightning activity through the amplification of the upper-level ridge over the western United States and the development of midtropospheric instability. Given the relative predictability of the MJO with long lead times, results allude to the potential for intraseasonal predictability of lightning activity and proactive fire management planning.

1. Introduction

Cloud-to-ground (CG) lightning has been recognized as a chief ignition mechanism for wildfire in the United States, especially in the West where up to two-thirds of wildfires are caused by lightning (Pyne et al. 1996). Summer wildland fire is most pronounced across the western United States as weather and fuel conditions align with ignition-based lighting strikes. While localized lightning activity associated with airmass thunderstorms can be problematic in fire ignition on local scales, regional outbreaks of enhanced lightning activity, or lightning busts, often overwhelm management in suppression efforts because of the shear number of fire starts. Regional wildfire outbreaks therefore require increased resources that mandate advanced lead times longer than those of deterministic weather forecasts.

Local tactical fire preparedness and resource prepositioning can be enhanced through improved predictability of lightning activity associated with synoptic-scale circulation patterns. Although synoptic conditions conducive to lightning activity vary widely across the continental United States, the fundamental atmospheric ingredients necessary for enhanced lightning activity include a convectively unstable midtroposphere (e.g., Burrows et al. 2005). Several studies have examined the synoptic conditions favorable for widespread lightning outbreaks across the interior western United States during summer (e.g., Rorig and Ferguson 1999). Watson et al. (1994) found that lightning activity over the desert Southwest is enhanced coincident with synoptic conditions associated with surges in the North American monsoon. Werth and Ochoa (1993) found that large lightning-ignited wildfires over the interior northwestern United States were associated with an amplification, and subsequent breakdown (and eastward movement) of the upper-level ridge over the West associated with an approaching shortwave disturbance. They showed that these synoptic conditions allow for a destabilization of the air mass as cool midtropospheric air is advected above the surface thermal trough. While the predictability of conditions conducive to lightning outbreaks across the western United States are limited to short time scales (e.g., 1–4 days), in this

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DOI: 10.1175/2009MWR3019.1

study we examine whether lightning activity across the continental United States, and the West in particular, is associated with lower-frequency modes in the climate system that may provide forecast skill beyond time scales of deterministic forecasts.

The predictability of atmospheric circulation patterns and extreme events straddling the weather–climate continuum constitutes one of the current major research and forecasting priorities. A better understanding of the processes that govern large-scale circulation patterns, synoptic regimes, and the likelihood of extreme events on intraseasonal time scales (10–90 days) is needed as decision-making processes require information that coincides with the gap between weather forecasts (e.g., associated with initial conditions) and climate forecasts (e.g., associated with boundary conditions). The Madden–Julian oscillation (MJO), the dominant mode of intraseasonal (20–90 days) variability in the tropics, represents an important, yet to-date relatively unexploited source of applied intraseasonal predictability. The MJO is characterized by an eastward-propagating Kelvin–Rossby wave in the tropics dominated by large-scale regions of enhanced and suppressed deep convection and precipitation across the tropical Indian and Pacific Oceans (Madden and Julian 1972). While the convective signal is confined to the tropics, the upper-tropospheric response to the MJO produces an effective Rossby wave source capable of fostering tropical–extratropical teleconnections through significant modulations in the midlatitude flow field and associated global energy and momentum fluxes (Matthews et al. 2004).

Although the impact of the MJO on Northern Hemisphere circulation regimes is most pronounced during boreal winter and spring, studies have documented its influence on North America during the summer (e.g., Higgins and Shi 2001). Lorenz and Hartmann (2006) found that the MJO affects the North American monsoon by preferentially modulating the amplitude of lower-tropospheric easterly waves, which in turn initiate a northward surge of low-level moisture into northern Mexico and southern Arizona. Coincidently, they note an amplification of the ridge over the West as part of a midlatitude wave emanating from the Pacific, and suggest that the coupling of the extratropical and tropical signatures associated with the MJO is needed to achieve sustained deep convection responsible for a monsoon surge. Northward surges of midlevel moisture and associated convection often penetrate northward into the Great Basin and northern Rocky Mountains. However, the poleward fringes of such convective surges often lack low-level moisture (at least initially), therein providing conditions ripe for lightning ignited fire outbreaks.

2. Data and methods

Daily cloud-to-ground (CG) lightning strike data for 1 June–30 September 1990–2007 were obtained from the National Lightning Detection Network (NLDN). The NLDN records the time, latitude, longitude, polarity, peak current, and multiplicity of CG lightning flashes, and has been shown to provide both accurate and effective detection of CG lightning for peak currents greater than 5 kA (Cummins et al. 1998). NLDN data were further aggregated onto $1^\circ \times 1^\circ$ grids traversing the continental United States.

Previous studies have noted temporal nonclimatic inhomogeneities in the NLDN (e.g., Orville et al. 2002). Noted changes in the geographic density and sensor sensitivity (e.g., associated with the detection of low peak current CG) have occurred over the period of record due to upgrades in the NLDN. The elimination of returns with positive CG strikes <10 kA, often associated with misidentified cloud flashes (Orville et al. 2002), is found to remove a majority of the temporal inhomogeneities in the record. The postprocessed NLDN dataset removes a bulk of the interannual step-function inhomogeneities, thereby providing a more physically realistic time history of lightning activity over the period of record.

We quantify the MJO using the real-time multivariate (RMM) index of Wheeler and Hendon (2004). The normalized combined empirical orthogonal function (EOF) of near-equatorial (15°S–15°N) 850-hPa zonal wind, 200-hPa zonal wind, and outgoing longwave radiation is used to create the index. The projection of daily data onto these EOFs after removing the annual cycle yields a principal component (PC) time series that provides a real-time MJO index valid across all seasons. The projection of the leading PCs forms a phase space plot that can be decomposed into amplitude and phase. The phases refer to the longitudinal position of the convective dipole, while the amplitude refers to the strength of the dynamic MJO signal.

The RMM index yields daily information on the MJO. However, it is important to distinguish between an active MJO, characterized by the relatively predictable coherent eastward propagation of enhanced convective activity, and an inactive MJO, characterized by an incoherent signal (e.g., associated with a weak signal and/or quasi-stationary signal). Similar to the methodology posed by Jones and Carvalo (2006) and Vecchi and Bond (2004), we define an active MJO by the presence of a large-amplitude signal that conforms to the canonical coherent eastward propagation of coupled convective and circulation fields. Unlike these previous studies, the RMM index is not prefiltered, thus making the results of this

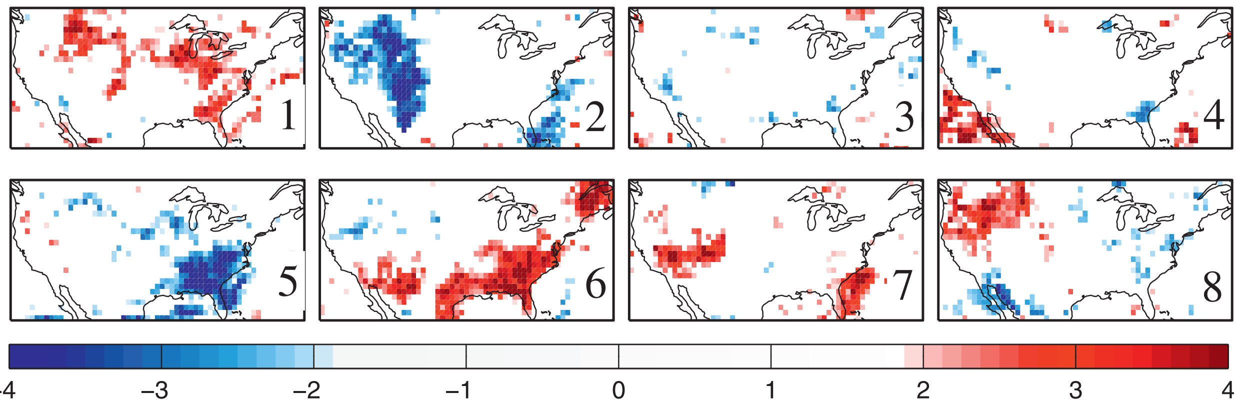

FIG. 1. Lightning frequency rank-order anomalies (z scores) stratified by RMM phase (denoted in lower-right corner). Red (blue) shading denotes areas of enhanced (suppressed) lighting activity for each RMM phase exceeding the 95% confidence interval.

study immediately applicable in a predictive sense. We qualify an active MJO by identifying a sequence of at least 21 days wherein the RMM phase space shows 1) amplitude >1, and 2) eastward phase propagation (e.g., anticyclonic in the phase–space plot). Since the RMM is not temporally filtered, we permit deviations in the above criteria of no more than 6 days in length. Periods meeting the above criteria are considered active, and daily RMM values are binned by their phase. Periods not meeting these criteria are considered to fall into the inactive MJO regime and are binned into the NULL phase.

For each phase of the MJO we examine the distribution of lightning frequency across the continental United States. Statistical significance is assessed by considering whether the observed lightning distribution for a particular phase differs from other phases. Because of the non-Gaussian distribution of lighting frequency, we employ the nonparametric Wilcoxon–Mann–Whitney rank-sum test (e.g., Wilks 1995). For each grid point and RMM phase we calculate a z score, and hereinafter refer only to results significant at the 95th percentile.

3. Results

Overall, the MJO is found to be active 31% of the time during JJAS, yielding an average of about 86 days (60–106 days) for each RMM phase over the period of record. Lightning frequency rank-order anomalies (i.e., z scores) binned by RMM phase for active periods of the MJO are shown in Fig. 1. Red (blue) coloring denotes locally enhanced (suppressed) lightning activity exceeding the 95% statistical significance level using the Wilcoxon–Mann–Whitney rank-sum test.

Significant anomalies are seen across the continental United States; however, features are most robust over the interior western and the southeastern part of the country. With the exception of the state of Florida, lightning activity across the southeastern United States from Louisiana to Virginia is suppressed (enhanced) coincident with RMM phase 5 (6). This is verified by noting that lightning frequency is increased over 60% during RMM phase 6 compared to phase 5 across the Southeast. Outside of RMM phases 5 and 6, there is no distinct spatially coherent feature indicative of changes in lightning activity over the southeastern United States with MJO activity.

By contrast, lightning activity over the interior western United States appears to be strongly linked to MJO activity. Intraseasonal variability in lightning activity associated with the MJO is manifested as a northward-propagating mode akin to northward surges in monsoon activity (e.g., Watson et al. 1994). Enhanced lightning activity occurs over northern Mexico and Arizona–New Mexico region during RMM phases 5 and 6, roughly corresponding to enhanced convective activity of the MJO near the Philippines. Widespread lightning activity proceeds northward in the ensuing period during phase 7, with enhanced activity encroaching much of Utah and western Colorado. Enhanced lightning activity continues its northward propagation over much of the northern Rockies, while lightning activity near the Gulf of California and over northern Mexico is suppressed during RMM phase 8. A widespread region of suppressed lightning activity dominates much of the interior West during the opposing phase of the MJO when convective activity in enhanced over the Indian Ocean (RMM phases 2–4).

Figure 2 shows a Hovmöller diagram of lightning frequency averaged over the interior West from 105°–115°W during the summer of 1993. The MJO was particularly active during the summer of 1993, as noted by the two full cycles completed over the 3-month period. Concomitant with the active MJO cycle in July–August

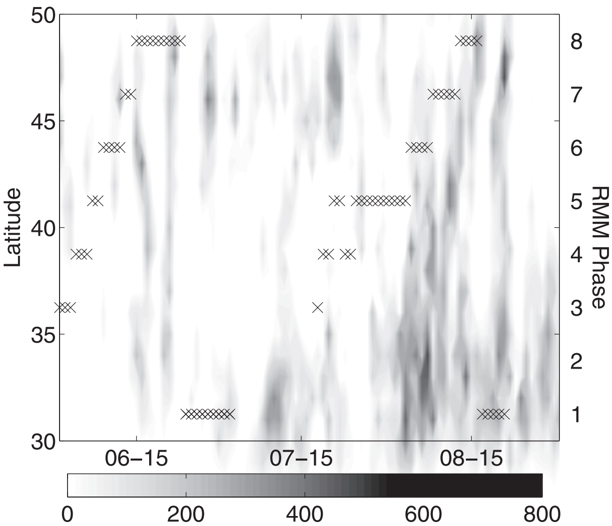

FIG. 2. Time vs latitude plot of daily lightning frequency zonally averaged over 105°–115°W for 1 Jun–31 Aug 1993. Active phases of the MJO are highlighted by an X according to the daily RMM phase (as shown on the right-hand axis), inactive periods are omitted.

there is a noted northward progression of enhanced lightning activity beginning over the southwestern deserts in early August during RMM phases 5–6 moving northward during the ensuring 10 days with the progression of the RMM to phases 7–8. The coherent northward intraseasonal progression of lighting activity over the interior West is consistent with prior analyses by Dettinger et al. (1999). They observed a northward-propagating intraseasonal mode with enhanced lightning activity propagating from the U.S.–Mexico border to the northern Rockies with a time scale of approximately 10 days.

Not all summertime MJO events enable and/or initiate northward-propagating lightning activity over the interior West. Likewise, northward-propagating lightning features are present during inactive periods of the MJO. Given the multitude of processes involved in generating summertime convection over the West, it is useful to provide insight into the link between this intraseasonal lightning behavior and that associated with the MJO. Lorenz and Hartmann (2006) found that the MJO has been linked to the initiation of low-level surges of moisture into the desert Southwest and precipitation across northern Mexico and southern Arizona. However, the influence of the MJO on northward surges of monsoonal activity propagating well into midlatitudes over the interior western United States has not been examined. We suggest that the combination of northward surges of midlevel moisture suggested by Lorenz and Hartmann (2006) and the modulation of the upper-level ridge over the West provide a mechanism for unstable atmospheric conditions to penetrate northward away from the monsoonal core region and toward the Great Basin and northern Rockies.

Composite analysis suggests that low-frequency modulations associated with the MJO create a favorable environment for instability and lightning occurrence across the interior western United States. The position and orientation of the upper-level ridge and midtropospheric instability concurrent with MJO phases are examined using daily data from National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis. Composite 500-hPa geopotential heights (contours) and midtroposphere instability anomalies [shaded, defined as 700–500-hPa temperature difference relative to June–September (JJAS) means, positive values denote larger temperature difference] binned by RMM phase are shown in Fig. 3. There is a noted amplification and eventual breakdown and eastward shift of the monsoonal ridge coincident with the northward propagation of enhanced lightning activity during RMM phases 6–8. The building of the upper-level ridge over the West allows for large surface radiative heating and the development of a coupled thermal low, therein priming the region for instability. As the ridge amplifies, the region of heating and instability follow northward. This corresponds well to the observed regions of enhanced convection over the desert Southwest and Great Basin. RMM phase 8 shows evidence of a breakdown of the ridge. Such composite features are broadly consistent with synoptic analysis by Werth and Ochoa (1993), who show that approaching midlatitude disturbances along the West Coast promote convective outbreaks over the northern Rockies. Lower-to-midtropospheric instability is enhanced by the highly amplified ridge that persists over the regions in the days prior, which leads to strong low-level heating, as well as the deepening of the long-wave pattern over the northeast Pacific, which can foster weak upper-level synoptic disturbances that lead to midlevel cooling. By contrast, the more zonal flow over the western United States evident in RMM phase 2 is associated with decreased midtropospheric instability and suppressed lightning activity over the interior West.

During JJAS, an active phase (e.g., RMM 6) occurs only around 4% of the time. However, we note that approximately one-third of all coherent northward-propagating widespread lightning busts over the interior West occur concurrent with RMM phases 6–8. These results support the findings of Dettinger et al. (1999), who geographically illustrate that a significant portion of the intraseasonal variance in lightning frequency exists in the 35–55-day band along a south–north corridor across the interior West.

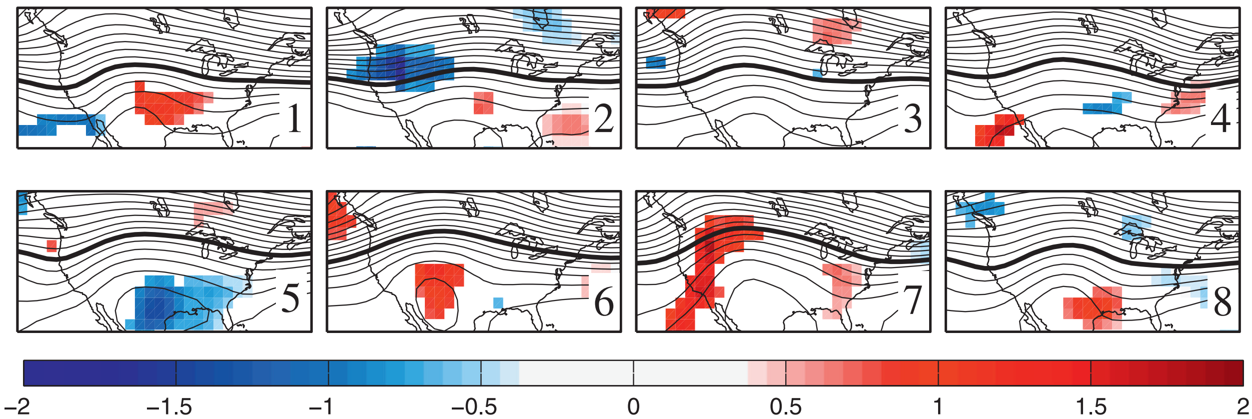

FIG. 3. Composite of 500-hPa geopotential height (contours every 20 m; 5800-m contour in boldface) and 700–500-hPa temperature (°C) difference anomalies (shading, values significant at the 95% confidence level are shown) stratified by RMM phases.

The MJO may provide a means to improve the predictability of lightning activity beyond typical synoptic time scales. Lightning activity over the Great Basin (37°–43°N, 110°–115°W) is significantly enhanced during RMM phase 7 (80% increase from JJAS daily mean), with suppressed activity during phase 2 (60% decrease). As the MJO provides forecast skill with a lead time of at least two weeks (Jiang et al. 2008) the ability to anticipate fluctuations in lightning activity over much of the interior West may be improved by utilizing the current and/or anticipated state of the MJO as a predictor such as provided by NOAA's Climate Prediction Center.

4. Discussion

Examination of daily gridded CG lightning data over the continental United States during summer reveals that lightning activity over the interior West is linked to active phases of the MJO. Enhanced lightning activity begins in northern Mexico and the southwestern United States (RMM phase 6). In the ensuing 5–10 days (phases 7–8) enhanced lightning activity propagates northward across the Great Basin and into the northern Rockies. By contrast, lightning activity over much of the interior West is suppressed during the opposing phase of the MJO (phases 2–4). The northward-propagating intraseasonal mode associated with the MJO follows the amplification and eventually breakdown and eastward displacement of the upper-level monsoonal ridge over the interior West. A region of midtropospheric instability follows the northward trajectory in response to strong radiative heating associated with ridge amplification over the West therein enabling the atmosphere to become unstable and create a favorable environment for lightning activity. Additional triggering mechanisms that promote additional instability and moisture needed for convection over the region include low-to-midlevel moisture advected northward from the core monsoonal region as well as transient midlatitude synoptic disturbances.

Although we have shown that lightning activity over parts of the continental United States is linked with the MJO, no mention is made here of whether the MJO is associated with variability in fire ignition potential (i.e., ''dry'' lightning). Lightning ignited fire starts depend on not only lightning, but also on meteorological and fuel conditions. Ignitions may not occur and spread significantly in the absence of low fuel moistures and dry windy conditions. An analogous analysis was performed on daily precipitation accumulations from the North American Regional Reanalysis (NARR), and results suggest a nearly identical pattern associated with the MJO for both lightning and precipitation (not shown). Further analysis reveals that while some surge events include widespread precipitation and moisture over the region, others include sparse precipitation totals accompanying lightning busts on the fringes of the primary monsoon core. Midlevel moisture from the monsoonal core often reaches much of the Great Basin prior to the advection of moisture at lower levels, therein enhancing midlevel instability and high-base convection, features that are conducive to lightning ignited fire outbreaks.

As the MJO is a recurrent intraseasonal phenomenon, the ability to utilize its information may enhance the predictability of weather and extreme events at lead times beyond those of deterministic numerical weather prediction (e.g., week 2–4 forecasts). Value-added products that bridge the intraseasonal time scale could be utilized in operational probabilistic forecasting of natural wildfire starts, thereby providing a suite of predictive tools to assist decision makers. Enhanced intraseasonal predictability of conditions conducive to the ignition and spread of fires, including not only lightning strikes, but also additional fire-danger weather (e.g., heat waves, enhanced surface winds, low relative humidities), may provide additional lead time for improved use in fire management decision-making applications (e.g., resource allocation).

Acknowledgments. The authors appreciate the use of data from the National Lightning Detection Network (NLDN), which is owned and operated by Vaisala. We also thank Mike Dettinger, USGS/Scripps Institution of Oceanography for project inspiration in addition to the constructive comments provided by the anonymous reviewers. We acknowledge funding from the NOAA/RISA Program through the California Applications Program, Scripps Institution of Oceanography, and NSF Grant ATM-0801474.

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