On the Surface-Convection Feedback during Drought Periods on the Canadian Prairies

Julian C. Brimelow and John M. Hanesiak*

Centre for Earth Observation Science, Department of Environment and Geography, University of Manitoba, Winnipeg, Manitoba, Canada

William R. Burrows

Cloud Physics and Severe Weather Research Section and Hydrometeorology and Arctic Lab, Meteorological Research Division, Science and Technology Branch, Environment Canada, Edmonton, Alberta, Canada

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ABSTRACT: Linkages between the terrestrial ecosystem and precipitation play a critical role in regulating regional weather and climate. These linkages can manifest themselves as positive or negative feedback loops, which may either favor or inhibit the triggering and intensity of thunderstorms. Although the Canadian Prairies terrestrial system has been identified as having the potential to exert a detectable influence on convective precipitation during the warm season, little work has been done in this area using in situ observations.

The authors present findings from a novel study designed to explore linkages between the normalized difference vegetation index (NDVI) and lightning duration (DUR) from the Canadian Lightning Detection Network for 38 census agricultural regions (CARs) on the Canadian Prairies. Statistics Canada divides the prairie agricultural zone into CARs (polygons of varying size and shape) for the purpose of calculating agricultural statistics. Here, DUR is used as a proxy for the intensity of thunderstorms. The results suggest that there is a significant relationship between NDVI and DUR, with higher NDVI values corresponding to longer lightning durations. This finding supports the hypothesis that the terrestrial ecosystem can influence convective precipitation during drought periods.

* Corresponding author address: John M. Hanesiak, Centre for Earth Observation Science, Department of Environment and Geography, University of Manitoba, Winnipeg MB R3T 2N2, Canada.
E-mail address: john_hanesiak@umanitoba.ca

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for thunderstorm activity. Statistical analyses were undertaken for 38 CARs for summers [June–August (JJA)] between 1999 and 2008. Specifically, coefficients of determination were calculated between pairs of standardized anomalies of DUR and NDVI by season and by month. Correlations were also calculated for CARs grouped by size and/or magnitude of the NDVI anomalies.

The main findings are as follows: 1) JJA lightning activity is overwhelmingly below average within larger dry areas (i.e., areas with below-average NDVI); that is, the linkages between NDVI and DUR increased significantly as both the area and magnitude of the dry anomaly increased. 2) In contrast, CARs with above-average NDVI did not consistently experience above-average lightning activity, regardless of the CAR size. 3) The lower threshold for the length scale of the dry anomalies required to affect the boundary layer sufficiently to reduce lightning activity was found to be approximately 150 km (~18,000 km²). 4) The authors’ analysis suggests that the surface-convection feedback appears to be a real phenomenon, in which drought tends to perpetuate drought with respect to convective storms and associated rainfall, within the limits found in 1) and 3).

**KEYWORDS:** NDVI; Lightning; Soil moisture; Land–atmosphere interaction

### 1. Introduction

Modeling studies have suggested that changes in moisture and energy fluxes associated with soil moisture and vegetation anomalies can contribute to the persistence of wet or dry conditions long after the precipitation anomaly that created them has passed, thereby perpetuating soil moisture anomalies and drought (e.g., Dirmeyer 1994; Beljaars et al. 1996; Schubert et al. 2004). The size and duration of anomalies of soil moisture in space and time are an important aspect in land–atmosphere interactions. At scales of a few kilometers, advection and turbulence mix out surface-induced variability in the convective boundary layer (CBL; Raupach and Finnigan 1995), so discontinuities must be long lived and cover a sufficiently large area before they can begin to significantly influence the evolution of the CBL (Avissar and Chen 1993; Lynn et al. 1995; Lynn et al. 1998) and attendant thunderstorm activity. Oglesby et al. (Oglesby et al. 2002) conducted modeling studies over the Mississippi basin and found that the magnitude of the soil moisture anomaly must be much larger than typical interannual variability for the anomalies to exert a strong influence on the atmosphere. Fennessy and Shukla (Fennessy and Shukla 1999) used model simulations to investigate the impact of soil moisture on precipitation. They found that the strength of the terrestrial–atmosphere linkage was governed by the magnitude of the soil moisture anomaly, soil wetness persistence, solar forcing, accessibility to other moisture sources, and large-scale dynamics.

Several theoretical studies have used scaling techniques to identify length scales at which heterogeneities are capable of affecting the convective boundary layer (e.g., Raupach and Finnigan 1995; Mahrt 2000). Depending on conditions, the critical length scale can vary between 50 and 130 km. Few observational studies have investigated links between the size of surface anomalies and convection. Taylor et al. (Taylor et al. 2003; Taylor et al. 2005) studied the link between soil moisture variability (inferred from thermal infrared satellite data) and antecedent
rainfall over the Sahel region in Africa. They noted that soil moisture variations on the order of several hundred kilometers could generate low-level circulations, which in turn modulated the presence of thunderstorm activity. Desai et al. (Desai et al. 2006) found that CBL depth responded to 50–100-km scale variations in surface energy flux over the southern Great Plains of the United States, with decreased influence of soil moisture on CBL depth at scales smaller than 100 km.

Vegetation is known to interact with the overlying atmosphere by influencing surface energy and hydrological budgets (e.g., Kaufmann et al. 2003; Siqueira et al. 2009). By transporting moisture from the root zone to the CBL, vegetation is a primary pathway for coupling the surface and the atmosphere (e.g., Tsvetsinskaya et al. 2001). Consequently, changes in phenology can have a marked effect on the partitioning of incoming solar radiation (e.g., Liu et al. 2006; Notaro et al. 2006) and on modulating fluxes of mass and momentum (Domínguez and Kumar 2008). Thus, the coupling between the terrestrial surface and overlying atmosphere is strongest during the warm season (Koster et al. 2004; Seneviratne et al. 2006).

As noted by Siqueira et al. (Siqueira et al. 2009), the linkages between soil moisture, vegetation, and convection have received much attention (e.g., Koster and Suarez 2004; Kim and Wang 2007) but remain a vexing research problem. The strength of the land–atmosphere interaction is difficult to quantify, but modeling studies (Koster et al. 2004; Koster et al. 2006) have identified certain terrestrial “hot spots” where linkages between the land surface and atmosphere are strong. The Great Plains of North America, including southern portions of the Canadian Prairies, is one such hot spot. Dirmeyer et al. (Dirmeyer et al. 2009) conducted an integrated analysis for quantifying land–atmosphere interactions, which was not based on climate model output. Specifically, they used observations of precipitation, reanalysis data [National Centers for Environmental Prediction–Department of Energy (NCEP–DOE)] of atmospheric variables, and soil moisture from the Global Soil Wetness Project. Their work identified the Great Plains and southern Canadian Prairies as hot spots for feedbacks in June–August (JJA). Hanesiak et al. (Hanesiak et al. 2009) determined that knowledge of root-zone soil moisture at the beginning of summer can provide some indication as to the severity of the upcoming storm season on the Canadian Prairies. Although the Canadian Prairies ecosystem has been identified as having the potential to exert a detectable influence on convective precipitation in the summer, little work has been undertaken on this topic.

Linkages between the terrestrial surface and the atmosphere can result in positive or negative feedback loops, which may either favor or inhibit the triggering and intensity of deep, moist convection (e.g., Findell and Eltahir 2003a; Findell and Eltahir 2003b). The amount of moisture in the CBL has important consequences concerning the initiation and intensity of thunderstorms (Segal et al. 1995). Johns et al. (Johns et al. 2000) concluded that evapotranspiration (ET) played a significant role in conditioning the prestorm boundary layer structure for violent tornadoes over the north-central United States. Raddatz and Cummine (Raddatz and Cummine 2003) investigated whether there was a link between crop phenology on the Canadian Prairies and the seasonal pattern of tornadoes. They concluded that the timing of the peak number of tornado days was found to change in step with the time of the maximum specific humidity and maturation of wheat.
Thunderstorms form an important part of the Canadian Prairies hydrological cycle. Statistics from Environment Canada indicate that up to 50% of the annual precipitation on the prairies falls during the summer months. Also, an analysis of sounding data from central Alberta by Reuter and Aktary (Reuter and Aktary 1995) found that 95% of the summer precipitation occurred on days when the potential for convective instability was present. The Canadian Prairies grassland ecoclimate region covers an estimated 480,000 km². Annual field crops (wheat, canola, and barley) cover about 60% of this area, with wheat accounting for about 50% of the cropped area (e.g., Hanesiak et al. 2009). Raddatz and Hanesiak (Raddatz and Hanesiak 2008) investigated almost 1000 significant summertime rain events (≥10 mm in 24 h) on the Canadian Prairies between 2000 and 2004. They found that 79% of the significant rain events were solely or partially convective [i.e., lightning was recorded by the Canadian Lightning Detection Network (CLDN) at some time during the accumulation period], whereas lightning was not recorded for the remaining 21%.

Most studies investigating linkages or feedbacks between the land surface, atmosphere, and precipitation have had to rely on modeled data. This is because precipitation and soil moisture are typically not adequately resolved at the spatial and temporal scales of summertime precipitation events. One dataset that has received virtually no attention in terms of elucidating land–atmosphere influences on convection is lightning flash data. These data are available at a higher spatial and temporal resolution than are the processes driving convection. Further, by combining lightning flash data with high-spatial-resolution (and real-time) estimates of normalized difference vegetation index (NDVI), one could, for the first time, explore land–atmosphere linkages without having to rely on output data from numerical models.

In this paper, the focus is on how land–atmosphere processes over the Canadian Prairies can condition the CBL so as to inhibit or facilitate thunderstorm activity. Specifically, we address the following questions: 1) Is there a link between NDVI and lightning activity on the Canadian Prairies? 2) What are the required thresholds in terms of both the size and magnitude of the NDVI anomaly to affect lightning activity? 3) What is the relationship between NDVI and plant-available root-zone soil moisture in association with questions 1 and 2?

To address questions 1 and 2, we use lightning flash data and NDVI data for a 10-yr period spanning 1999–2008 for 38 census agricultural regions (CARs) on the Canadian Prairies (Figure 1). Between 2000 and 2003, the Canadian Prairies region experienced one of the most severe droughts on record (e.g., Liu et al. 2004). The 1999–2008 period provides a unique opportunity to explore linkages between terrestrial land surface and thunderstorm activity during drought, normal, and pluvial conditions. Question 3 is addressed using in situ root-zone plant-available moisture observations in Alberta and simulated root-zone soil moisture together with NDVI data.

2. Data and methodology

2.1. CARs

Statistics Canada divides the agricultural zone on the Canadian Prairies into 43 CARs for the purpose of disseminating agricultural statistics. The CARs are random
Figure 1. Standardized anomalies of (top) NDVI and (bottom) DUR for JJA 2002. Irregular polygons represent the 38 CARs considered here. Black dots represent the locations of the three DroughtNet sites discussed in section 3.1.1.
polygons with areas ranging from 5000 km\(^2\) (equivalent radius of \(\sim 40\) km) to over 30 000 km\(^2\) (equivalent radius of \(\sim 100\) km). In this study, 38 CARs for which reliable NDVI data were available were used: some CARs spanning the Red River Valley in Manitoba were excluded because of frequent flooding that contaminated the NDVI data. Of the 38 CARs considered, 11 were located in Alberta, 20 were in Saskatchewan, and 7 were in Manitoba (see Figure 1).

### 2.2. Cloud-to-ground lightning data

The CLDN continuously records all lightning with peak current greater than 5 kA (3 kA after 2005) detected in North America north of 35\(^\circ\)N for east of 100\(^\circ\)W and north of 40\(^\circ\)N for west of 100\(^\circ\)W (Burrows et al. 2002). We used only cloud-to-ground (CG) lightning flashes in the present study. Detection efficiency of CG flashes for the CLDN over the prairie agricultural zone is \(\sim 90\%\), whereas the median stroke location accuracy is 500 m or better (Cummins et al. 1999).

To quantify the thunderstorm activity we used the lightning duration (DUR) within each CAR. The lightning duration is defined as the length of time (in hours) between 0930 and 1930 local solar time (LST) where flashes occurred “continuously”; that is, no more than 10 min was allowed to separate a flash and the next flash in a given series of flashes. If more than 10 min separated two flashes, then the time series was discontinued and a new time series was started when the next flash was recorded. Isolated or “singleton” flashes that occurred more than 10 min between different series were allocated a duration of 1 min. We used the 0930–1930 LST window to avoid issues with time zones and to focus on surface-based thunderstorms (rooted in the convective boundary layer), which typically develop in response to daytime heating, rather than nocturnal thunderstorms, which tend to be elevated. The lightning duration does not consider the location of the flashes, only when they occurred. The length of the series for each solar day in each CAR was summed to calculate monthly and seasonal totals. These data were used to calculate standardized anomalies [see Equation (1) in section 2.5].

Another metric that was considered for the purpose of quantifying the overall level of lightning activity was lightning flash density (LFD). However, LFD can be skewed by a few storms that have a high flash rate over an area. Some preliminary statistics indicated that correlations between DUR and NDVI were higher than between LFD and NDVI. Consequently, in this study, we focused on the lightning duration.

### 2.3. NDVI

Weekly NDVI data valid for each CAR during the growing season were downloaded from the Canadian Crop Condition Assessment Program (CCAP) Web site, which is operated by Statistics Canada. A land-use mask is applied in which a pixel is classified as crop/pasture if at least 50\% of that pixel is crop/pasture. Here, NDVI data for only those pixels classified as crops or pasture are included in the calculation of NDVI for each CAR. However, it is possible that pixels are classified as crop/pasture but may have 40\% forest cover. Sensitivity tests (not shown)
indicate that applying the mask is expected to have very little impact on the results, probably because most of the CARs are dominated by crops and/or pasture.

Statistics Canada uses data from National Oceanic and Atmospheric Administration satellites carrying the Advanced Very High Resolution Radiometer (AVHRR). A composite of AVHRR images covering a 7-day period removes most or all cloud effects (Latifovic et al. 2005). To further minimize errors that may have been introduced by clouds, pixels identified as being contaminated (i.e., if a sudden drop is immediately followed by a sudden increase in the following week) are corrected using statistical imputation (Bédard 2010). Corrections are also made to remove much of the atmospheric contamination and to minimize other effects (such as view angle and solar angle). We used the NDVI data as is from the CCAP Web site.

2.4. Root-zone soil moisture

We also explore the relationship between the root-zone relative plant-available water content (RZPAW) and the NDVI. Two sources of RZPAW are used: 1) in situ measurements from the Alberta Drought Monitoring Network (DroughtNet) (Figure 1) and 2) modeled root-zone soil moisture from the second-generation Prairie Agriculture Model (PAMII; Raddatz 1993). The drought monitoring network has been established over cropped land throughout Alberta starting in 2002. Hourly measurements of volumetric soil moisture content ($\theta$; in %) are made using calibrated ThetaProbe sensors (type ML2X). Measurements at DroughtNet sites are made every hour at four depths (5, 20, 50, and 100 cm). Details concerning the DroughtNet sites and the PAMII model can be found in Brimelow et al. (Brimelow et al. 2010). Data for the DroughtNet sites were provided by Alberta’s Department of Agriculture and Rural Development (R. Wright 2010, personal communication).

For the purpose of comparing in situ soil moisture measurements at the DroughtNet sites with the concomitant NDVI, we used NDVI data provided by CCAP at the township scale; that is, NDVI data are aggregated into 10 km by 10 km squares. NDVI data for the township in which each DroughtNet site is located were then used to calculate weekly standardized NDVI anomalies. The three sites were Vermilion (53.34°N, 110.88°W, 620 m), Killam (52.85°N, 111.87°W, 692 m), and Hussar (51.19°N, 112.50°W, 971 m). The same approach used by Brimelow et al. (Brimelow et al. 2010) was used to determine the permanent wilting point (PWP; $\theta_{pwp}$) and field capacity (FC; $\theta_{fc}$) at each site. Specifically, the PWP was estimated by selecting the mean lowest daily-mean $\theta$ observed at a 20-cm depth between 15 May and 30 September for the entire record; this typically spanned a 7-yr period. The FC was approximated by identifying the mean $\theta$ at 20 cm, 72 h after the time of maximum soil moisture content associated with a heavy precipitation event (>10 mm).

To determine whether the plants’ moisture requirements are being adequately satisfied, it is convenient to quantify the moisture in the root zone in terms of the relative plant-available water capacity (e.g., Anderson et al. 2000). The relative plant-available water content is equal to $[(\theta - \theta_{pwp})/(\theta_{fc} - \theta_{pwp})]$. RZPAW was calculated by using hourly $\theta$ data at each level, which were used to calculate daily means and then were used to calculate the daily root-zone soil moisture content.
between the surface and 100 cm. The equivalent soil moisture contents (in millimeters) for all the layers in the root zone were then integrated to obtain a bulk soil moisture amount, and the RZPAW was calculated using the water retention properties determined for each site.

Given that a prairie-wide soil moisture monitoring network is not in place, it is necessary to use model data to investigate the relationship between RZPAW and NDVI over several years and over a large area. PAMII was used to simulate the evolution of the root-zone soil moisture content and RZPAW during July and August for 1999–2005 for each CAR. The model was driven using observed rainfall; minimum and maximum temperatures from each site; and prognostic profiles of temperature, moisture, and winds from the regional version of the Canadian Global Environmental Multiscale (GEM; Côté et al. 1998) model. The surface dewpoint depression from the GEM model was used to calculate the near-surface vapor density required for the calculation of transpiration from the canopy. Daily RZPAW data were aggregated into monthly means for July and August. This period was selected because it is when the modeled root-zone extends to near 100 cm and also includes the time when the crops are maturing and sensitive to water deficits (Mkhabela et al. 2010).

2.5. Calculation of standardized anomalies and correlations

All monthly and seasonal NDVI and DUR data were standardized using the methodology employed by Koster and Suarez (Koster and Suarez 2004). Specifically, the monthly (June, July, and August) and seasonal (June–August) standardized anomalies were calculated as follows:

$$\Delta X_j = \frac{X_j - \bar{X}_j}{\sigma_j},$$

where $X_j$ is the value of NDVI (DUR) for a given month $j$ [a particular summer (JJA)], $\bar{X}_j$ is the mean value of $X$ over the 10 years, and $\sigma$ is the standard deviation for month $j$ over the 10 years.

The weekly NDVI data were used to calculate the monthly and seasonal means. The start and end dates for the season and monthly data varied slightly from year to year, with start dates ranging between 3 and 9 June and end dates ranging between 1 and 7 September. However, this factor was not expected to significantly affect the seasonal NDVI anomalies because there was typically very little change in NDVI values during these times.

The association between NDVI and DUR was quantified using the coefficient of determination $R^2$ between pairs of standardized anomalies of lightning duration ($\Delta$DUR) and NDVI ($\Delta$NDVI) for individual months and also by season (JJA) for a 10-yr period spanning 1999 through 2008. The statistical significance of the correlations was quantified using $p$ values of 1% ($\alpha = 0.01$) and 5% ($\alpha = 0.05$). A maximum sample size of 380 pairs (38 CARs $\times$ 10 years) was available for analysis. Here, a CAR season refers to one JJA period for one CAR. Correlation analysis was also undertaken using classes of CARs ranked by size. It is important
to keep in mind that the $R^2$ values do not speak to causality between ΔNDVI and ΔDUR.

3. Linkages between NDVI and DUR

In this section, we focus on how the areal extent of the NDVI anomaly, as well as the magnitude of the NDVI anomaly, is related to JJA lightning duration on the Canadian Prairies. Before doing so, we will investigate the relationship between RZPAW and NDVI.

3.1. Relationship between RZPAW and NDVI anomalies

The relationship between RZPAW and NDVI anomalies was investigated using two independent datasets consisting of in situ soil moisture observations and simulated soil moisture from the PAMII model.

3.1.1. Observed RZPAW and NDVI

Weekly-mean RZPAW values were calculated for 2003 using in situ soil moisture measurements for three DroughtNet sites in Alberta. The 2003 growing season was selected because it was a season in which two of the three DroughtNet sites with reliable data experienced a significant dry down that resulted in stressed vegetation (as shown by NDVI data). Standardized NDVI anomalies were calculated for the township in which each of the three DroughtNet sites are located for each week from early June though the end of August, using a baseline period of 1999–2008. Daily measurements of RZPAW from in situ observations were amalgamated into weekly means; the dates used to calculate the mean weekly RZPAW were those that coincided with the weekly observations for which NDVI data were available.

To investigate the response of NDVI to changes in 0–100-cm RZPAW, box plots were generated for several classes of RZPAW. For example, RZPAW < 40%, RZPAW between 40% and 60%, and RZPAW > 60%; RZPAW < 50%, RZPAW between 50% and 70%, and RZPAW > 70%; and RZPAW < 35%, RZPAW between 35% and 55%, and RZPAW > 55%. Here we only show the data for those RZPAW classes that showed the greatest degree of separation in the ΔNDVI data. Figure 2 shows that there was clear response of ΔNDVI to RZPAW at the three DroughtNet sites in the summer of 2003, with NDVI declining systematically as RZPAW decreased. Two sample Student’s $t$ tests found that the mean ΔNDVI observed for RZPAW less than 35% and the mean ΔNDVI observed for RZPAW between 35% and 55% were statistically different at the 95% confidence level. Similarly, the mean ΔNDVI observed for RZPAW greater than 55% and the mean ΔNDVI observed for RZPAW between 35% and 55% were statistically different at the 95% confidence level.

The interquartile range for the ΔNDVI values observed for RZPAW less than 35% ($N = 8$) was between $-1.37$ and $-0.47$ (median of $-0.77$), with the 95% confidence level for the mean between $-1.27$ and $-0.50$; that is, when RZPAW was less than 35%, ΔNDVI values were typically below $-0.5$ (i.e., the vegetation was stressed and less dense than normal). Apart from two outliers (both from
Vermilion), the ΔNDVI data for the intermediate range of RZPAW between 35% and 55% ($N=17$) were fairly tightly clustered. The interquartile range for these data was between $-0.42$ and $+0.08$ (median of $-0.13$), with the 95% confidence level for the mean between $-0.57$ and $+0.05$; that is, this range of RZPAW seemed to be associated with incipient moisture stress. For RZPAW greater than 55% ($N=14$), the ΔNDVI values were almost exclusively positive, with an interquartile range between $+0.14$ and $+0.75$ (median of $+0.45$) and with the 95% confidence level for the mean between $+0.27$ and $+0.63$. Thus, for RZPAW greater than 55%, vegetation was typically at near-normal to above-normal density.

Lagged correlations were calculated between the weekly observed RZPAW and ΔNDVI data for lags from 0 to 4 weeks and for 0-100-cm and 0-50-cm RZPAW. Here, only results for 0–100 cm are discussed because RZPAW in this layer had higher correlations than it did in the 0–50-cm layer. The data in Figure 3 suggest that, for all the sites, the $R^2$ between ΔNDVI and RZPAW increased when ΔNDVI lagged RZPAW by 1–2 weeks. Between 50% and 90% of the variance in NDVI could be explained by RZPAW depending on the time lags that were used. A caveat concerning the increase in $R^2$ when calculating lagged correlations: on account of the small sample sizes, the increases in $R^2$ were not found to be statistically significant after applying a Fisher $Z$ transform to the correlation coefficients ($r = \sqrt{R^2}$).

The $R^2$ values reported here are much higher than those found in the literature between RZPAW and NDVI (e.g., Adegoke and Carleton 2002; Wang et al. 2007). A likely reason for the higher $R^2$ values at Hussar and Killam is possibly because autocorrelation tests showed a statistically significant autocorrelation at a lag of 1 week in both the RZPAW and NDVI data. At Vermilion, there was an
autocorrelation for a 1-week lag in the NDVI data. Thus, the autocorrelation evident in our data is probably attributable to the fact that we are dealing with only one summer’s data and when a sustained dry-down period was observed. Had data been used for multiple seasons with more variable conditions, then we expect that the $R^2$ values would be more in line with values from similar studies.

3.1.2. Simulated RZPAW and NDVI

The soil moisture data in section 3.1.1 are only valid for one season and for three sites, and one could argue that they may not representative of the prairies. To address this, we used the PAMII model (run for sites located within the CARs) to quantify the variation of root-zone soil moisture over CARs between 1999 and 2005. PAMII has been shown to reasonably simulate root-zone soil moisture over the cropped grassland of the prairies. Specifically, Brimelow et al. (Brimelow et al. 2010) validated the PAMII model against in situ soil moisture data from DroughtNet sites and showed that the modeled root-zone PAW values were typically within 10% of the observations.

The mean monthly RZPAW values for stations located in all but three CARs (over far southern Alberta) were calculated. Soil moisture values for CARs over far southern Alberta were not included because RZPAW routinely drops below 30% in July and August at those sites and we wished to focus on the response of NDVI to RZPAW in those CARs that typically did not experience very low RZPAW (i.e., <30%). Depending on the year, simulated RZPAW data were available for between 85 and 115 sites across the Canadian Prairies. To increase the likelihood that point values of RZPAW from PAMII were representative of conditions over large CARs,
we only considered those Julys and Augusts that had uniform NDVI anomalies across the CARs (see section 3.3). Some CARs had up to four sites with simulated RZPAW but had drastically different RZPAW because of localized effects. If the simulated mean monthly RZPAW differed by more than 20% between sites, then those data were not included in the analysis. Daily simulated RZPAW data from all sites present in a CAR were then aggregated and then used to calculate the monthly-mean RZPAW for July and August, respectively.

The interquartile range of $\Delta$NDVI for those CARs experiencing uniformly above-average NDVI in July and August ($N = 68$) was between +0.9 and +1.4 (median of +1.1), with only one of the 68 CARs having a mean $\Delta$NDVI < +0.5 (i.e., 0.44). The interquartile range for those CARs experiencing uniformly below-average NDVI ($N = 48$) was between −1.0 and −1.9 (median of −1.5), with only one of the 68 CARs having a mean $\Delta$NDVI > −0.5 (i.e., −0.41).

Figure 4 shows the modeled RZPAW for CARs with contrasting vegetation health. The interquartile range for the RZPAW values observed in CARs experiencing below-average NDVI ($N = 48$) was between 19.8% and 37.0% (median of 26%), with the 95% confidence level for the mean between 25.3% and 32.5%. That is, when $\Delta$NDVI < −0.5, RZPAW values were typically below 40%. In contrast, the interquartile range for the RZPAW values observed for CARs experiencing uniform above-average NDVI ($N = 68$) was between 57.7% and 77.9% (median of 65%), with the 95% confidence level for the mean between 62.5% and 69.7%. That is, when $\Delta$NDVI > +0.5, RZPAW values were typically above 55%. The mean simulated RZPAW for CARs experiencing below-average NDVI in July and August and the mean RZPAW modeled for CARs experiencing above-average NDVI were statistically different at the 99% level.

These results are consistent with those from the comparison between $\Delta$NDVI and 0–100-cm RZPAW at the three DroughtNet sites. With both datasets suggesting
that stressed vegetation (\(\Delta NDVI < -0.5\)) is typically associated with \(RZPAW < 40\%\), whereas denser-than-average vegetation (\(\Delta NDVI > +0.5\)) is typically associated with \(RZPAW > 55\%\).

### 3.2. Effect of CAR size

The effect of CAR size on the association between \(\Delta NDVI\) and \(\Delta DUR\) was investigated by dividing the CARs into quartiles and then calculating \(R^2\) between seasonal \(\Delta NDVI\) and \(\Delta DUR\) for each quartile. CARs with both positive and negative summer \(\Delta NDVI\) were considered. Results are displayed in Table 1.

For all CARs, the \(R^2\) for JJA between 1999 and 2008 is 5.6\% (\(p\) value = 0.000). When one ranks the CARs by size, however, a systematic increase in \(R^2\) with increasing CAR size becomes evident. Specifically, \(R^2\) increases from only 2.5\% (\(p\) value = 0.135) for the lowest quartile class, to almost 13\% (\(p\) value = 0.001) for the top quartile class. Table 1 shows that \(R^2\) becomes statistically significant at the 99\% level of confidence when the class average equivalent radii approach 70 km, with the highest correlations obtained for those classes with mean equivalent radii greater than about 80 km. These data suggest that the size of the CAR is important in governing the strength of the relationship between NDVI and DUR and that, if the area is too small (equivalent radius less than about 75 km), the relationship breaks down.

### 3.3. Effect of both CAR size and magnitude of the NDVI anomaly

In the previous section, all CARs, regardless of the magnitude of \(\Delta NDVI\), were included in the analysis. We purport that the relationship between NDVI and DUR should increase as the magnitude of \(\Delta NDVI\) increases. To this end, we calculated correlation statistics for CAR seasons grouped according to the magnitude of \(\Delta NDVI\) for all CARs (regardless of size), for subsets of CARs with an equivalent radius in the top 50\% or lower 50\%, and finally for those CARs with an equivalent radius of at least 75 km. The results are summarized in Figure 5.
The thresholds for NDVI anomalies were based on observations from the literature and on the nature of the data and to ensure that the sample sizes were of sufficient number as to calculate reliable statistics. Philippon et al. (Philippon et al. 2007) defined areas experiencing low (high) photosynthetic activity as those regions where the standardized NDVI anomalies were $-0.5$ ($+0.5$). Similarly, we use thresholds of 0, $-0.5$, and $+1.0$ for the standardized NDVI anomalies.

Figure 5 clearly shows that both the size of the CAR class as well as the magnitude of the anomaly have important implications for the association between NDVI and DUR. Specifically, the values of $R^2$ and their statistical significance rise with increasing mean class radius and also as the magnitude of $\Delta$NDVI increases. The highest correlations (statistically significant at the 99% level of confidence) are only observed for those CARs with both large equivalent radii (top quartile and Req_75 km classes) and significant negative $\Delta$NDVI ($<-0.5$). In contrast, even large CAR classes with significant positive $\Delta$NDVI have much lower $R^2$ values than do those classes with negative $\Delta$NDVI, and they are only statistically significant (95% confidence level) for anomalies $>+0.5$ for the Req_75 class.

![Figure 5. Coefficient of determination between $\Delta$NDVI and $\Delta$DUR for JJA between 1999 and 2008 for various classes of $\Delta$NDVI and CAR area. Req_75 uniform refers to those CARs with equivalent radii of at least 75 km and uniform standardized NDVI anomalies in space and time (see text for details). Bars with diagonal hatching have coefficients of determination that are statistically significant at the 99% level of confidence, whereas those with vertical hatching are statistically significant at the 95% level of confidence.](image-url)
The marked increase in $R^2$ evident for large CAR classes with significant negative $\Delta$NDVI (i.e., severely stressed vegetation) suggests that a positive feedback mechanism may be operating over the course of the boreal summer over drought-affected regions, with drought conditions leading to less lightning activity. The very weak relationship between even large CAR classes with strong positive $\Delta$NDVI and concomitant $\Delta$DUR suggests that dense vegetation is neither a necessary nor a sufficient condition for above-average lightning duration. We will discuss why this might be in section 4.

3.4. Effects of spatial and temporal homogeneity of NDVI anomalies

To determine the effect of the uniformity and persistence of the NDVI anomalies on the relationship between NDVI and DUR, we identified those CARs that had uniform NDVI anomalies in both space and time. This was achieved in three steps. First, all CARs with JJA NDVI anomalies of at least 0.5 were identified in accordance with the findings of Philippon et al. (Philippon et al. 2007) discussed in section 3.3. Second, weekly NDVI anomaly data were inspected to determine whether nine consecutive weeks in JJA were present with positive or negative anomalies. This criterion was adopted to identify CARs with persistent NDVI anomalies that lasted the majority of the growing season; Fennessy and Shukla (Fennessy and Shukla 1999) noted that initial soil moisture anomalies persisted between 60 and 90 days after 1 June over most of the regions considered in their study. Increasing the threshold required for consecutive number of weeks significantly reduced the sample size, so 70% was found to yield a decent sample size while still identifying CARs that had NDVI departures for most of the JJA period. Third, weekly NDVI maps (with data aggregated into 10 km by 10 km squares) were visually inspected to determine whether the NDVI anomaly, for those weeks identified in step 2, was uniform across the CAR in question.

Applying these criteria reduced the number of CAR seasons available for analysis from 380 to 130. Most of the 130 CAR seasons had uniformly positive $\Delta$NDVI (91), with only 31 CAR seasons having uniformly negative $\Delta$NDVI. All of the CAR seasons with uniformly negative $\Delta$NDVI occurred between 2000 and 2004, which coincided with the drought period. Results for only two size classes—Req_75 and “all CARs”—are shown in Figure 6.

Although applying the uniformity criteria for all CARs (regardless of area) did increase the values of $R^2$ between seasonal (JJA) $\Delta$NDVI and concomitant $\Delta$DUR somewhat, the values remained well below statistically significant levels. Applying the condition of uniformity for the Req_75 class did slightly increase the $R^2$, as did increasing the magnitude of the negative anomaly. In contrast, correlations for positive $\Delta$NDVI versus $\Delta$DUR were not statistically significant at a 95% confidence level, and applying the condition of uniformity had no significant impact on the $R^2$ values, even for large CARs with uniformly positive $\Delta$NDVI $> +1.0$. These statistics suggest that patch size and the magnitude of the negative anomaly are probably more important for the association between $\Delta$NDVI and $\Delta$DUR than is the uniformity of the anomaly.

Another means of interpreting the data is to calculate the percentage of JJA seasons that have above- (or below-) average $\Delta$DUR for CARs that have positive or
negative $\Delta$NDVI for JJA. Figure 7 shows that almost 80% of those CAR seasons (for all sizes) with uniformly strongly negative $\Delta$NDVI ($\leq -1.0$) experienced below-average lightning duration, compared to only about 60% for CARs with nonuniform $\Delta$NDVI. The percentage of CARs with negative $\Delta$DUR also increased as CAR size increased and as the magnitude of the negative $\Delta$NDVI increased. Specifically, almost 90% of those CAR seasons with $\Delta$NDVI of $-0.5$ or lower had below-average $\Delta$DUR. The gap between the percentage of below-average $\Delta$DUR for all CARs with below-average $\Delta$NDVI and for the Req_75 class decreased when the uniformity criterion was applied, especially for CAR seasons with negative $\Delta$NDVI. This suggests that applying the uniformity criterion for CAR seasons with negative $\Delta$NDVI reduces the importance of area in modulating the relationship between $\Delta$NDVI and $\Delta$DUR. As found in section 3.3, Figure 7 shows that no clear trend is evident in $\Delta$DUR in CARs with positive $\Delta$NDVI, even for large CARs with spatially and temporally consistent positive $\Delta$NDVI. For all CAR seasons with positive $\Delta$NDVI, just over 50% of concomitant seasons have positive $\Delta$DUR, regardless of the magnitude of the positive $\Delta$NDVI. That is, the odds of a CAR season having above- or below-average DUR are about the same, regardless of the magnitude or uniformity of the positive NDVI anomaly.
3.5. Linkages between late June NDVI on July DUR

In this section, we investigated whether the state of the land surface in late June, as quantified by ΔNDVI, had any bearing on lightning duration in July. The start date of weeks used to calculate ΔNDVI varied between 23 and 29 June, with end dates between 28 June and 4 July. The $R^2$ values were calculated for CARs of varying size and of varying magnitude of ΔNDVI.

Figure 8 shows that, for CAR seasons with negative ΔNDVI, $R^2$ increases as ΔNDVI becomes more negative and as the CAR size increases. For large CARs [upper quartile (T25)] with June ΔNDVI $<-0.5$, almost 50% of the variance in July lightning duration is explained by late June ΔNDVI ($p$ value = 0.01). The association between late June ΔNDVI and July ΔDUR is weakest for the smallest 50% of CARs (B50). Thus, if the vegetation in late June is severely stressed over a large area, the concomitant July lightning duration is very likely to also be below average.

In contrast, the magnitude of a positive ΔNDVI in late June explains very little about July ΔDUR. Additionally, the values of $R^2$ decrease as the magnitude of the positive June ΔNDVI increases. The $R^2$ between June NDVI and July ΔDUR for Req.75 and T25 are statistically significant at the 95% confidence level, but only when one considers all CAR seasons with above-average late June ΔNDVI. These statistics suggest that lush vegetation in late June does not necessarily translate into positive ΔDUR in July.
3.6. Linkages between late June NDVI and early August NDVI

In this section, we investigated whether NDVI anomalies in late June persist into early August. July is the most active month for thunderstorms on the Canadian Prairies (Burrows et al. 2002), so anomalies in early August ΔNDVI should arise primarily in response to the amount of convective precipitation in July. Also, in section 3.4 it was found that negative ΔNDVI in late June were typically associated with below-average ΔDUR in July. Is this reflected in early August ΔNDVI, or is it masked by synoptic-scale nonconvective precipitation events? The weeks used to calculate ΔNDVI for June were the same as in section 3.4; the dates for early August ΔNDVI varied between 30 July and 4 August and between 4 and 10 August. The $R^2$ values were again calculated for CARs of varying size and of varying magnitudes of ΔNDVI.

Figure 9 shows that $R^2$ between late June ΔNDVI and early August ΔNDVI is only 0.11 ($p$ value = 0.01) for all CARs. However, as was the case for the association between late June ΔNDVI and July ΔDUR, the $R^2$ between late June ΔNDVI and early August ΔNDVI increased as the size of the CARs and the magnitude of the negative ΔNDVI increased. Specifically, for the T25 group, over 60% of the variance in early August ΔNDVI can be explained by late June ΔNDVI for seasons with late June ΔNDVI < −0.5 (and < −1.0). The weakest association was found for the smallest 50% of CARs. With the exception of the B50 class, all $R^2$ are significant at the 99% level of confidence for late June ΔNDVI < −0.5 (and < −1.0).

When grouped by positive June ΔNDVI, the $R^2$ between late June ΔNDVI and early August ΔNDVI are much lower for all size classes and anomaly classes than for negative late June ΔNDVI and early August ΔNDVI. For large CARs (T25), up to 35% of the variability in early August ΔNDVI can be explained by June ΔNDVI.

![Figure 8. Late June ΔNDVI vs July ΔDUR between 1999 and 2008. Bars with a single asterisk have coefficients of determination that are statistically significant at the 95% level of confidence, whereas those with two asterisks are statistically significant at the 99% level of confidence.](image-url)
for seasons with late June $\Delta$NDVI > +0.0 (and +0.5). Interestingly, the weakest association between late June $\Delta$NDVI and early August $\Delta$NDVI was found for seasons when $\Delta$NDVI > +1.0. This is essentially the opposite of what was observed for negative late June $\Delta$NDVI and early August $\Delta$NDVI. Reasons for this counterintuitive result are not clear. These data suggest that it is more likely that CARs with stressed vegetation in late June are much less likely to transition to lush vegetation by early August, especially for large CARs. However, more data are required to generalize this statement. Nonetheless, these data support the hypothesis that a positive feedback mechanism may be present between NDVI and DUR during drought years.

4. Discussion

4.1. Impact of magnitude and extent of NDVI anomalies on DUR

We expect that the association between anomalies at the terrestrial surface and attendant lightning activity will strengthen as the size of the anomaly increases and also as the magnitude of the anomaly increases. Our data indicate that the relationship between $\Delta$NDVI and $\Delta$DUR becomes statistically significant at the 99% level of confidence when the class average equivalent radii approach 70 km and that the highest $R^2$ obtained for those CARs with both large equivalent radii (top quartile and Req_75 classes) and significant negative $\Delta$NDVI (<−0.5). Thus, CAR area is critical in governing the strength of the relationship between NDVI and DUR, and, if the area is too small (R_eq less than about 75 km), the relationship breaks down.

The critical anomaly size identified here is consistent with estimates of critical patch size determined from both modeling studies and theoretical values. For
example, Raupach and Finnigan (Raupach and Finnigan 1995) used scaling techniques to identify length scales at which heterogeneities at the surface affect the CBL. They estimate the appropriate critical length scale to be the product of the mean horizontal wind speed in the CBL ($U$) and the entrainment time scale ($T$; time required for renewal of CBL by entrainment from the free atmosphere). For quiescent conditions in the CBL ($U \sim 3$ m s$^{-1}$ or $\sim 10$ km h$^{-1}$) and an entrainment time scale of about 12 h, the corresponding length scale ($L$) is 130 km (radius of 65 km). If $U$ increases to 5 m s$^{-1}$, then $L$ increases to just over 200 km. As noted earlier, Desai et al. (Desai et al. 2006) analyzed satellite-derived surface soil moisture data and measurements from aircraft and found that, over the southern Great Plains of the United States, CBL depth responded to 50–100-km scale variations in surface energy flux over the southern Great Plains of the United States, with decreased influence of soil moisture on CBL depth at scales smaller than 100 km. These data all suggest that the minimum equivalent radii of 70–80 km in this study perhaps represent the low end of the range at which NDVI anomalies become sufficiently large as to affect thunderstorm activity.

### 4.2. Asymmetric relationship between NDVI and DUR

An intriguing finding is the asymmetric relationship between NDVI and DUR. Specifically, the relationship between positive $\Delta$NDVI and $\Delta$DUR is very weak, even for large CAR classes with strong positive $\Delta$NDVI. Realization of thunderstorms requires three criteria to be satisfied: instability, low-level moisture, and a trigger. For drought conditions ($\Delta$NDVI $< -1.0$) the resultant reduction of moisture into the CBL from evapotranspiration reduces the amount of moisture available for thunderstorms (e.g., Jamieson et al. 1995). That is, a necessary criterion for convection (low-level moisture) has been weakened, which may explain the close relationship between those CAR seasons with $\Delta$NDVI $< -1.0$ and attendant $\Delta$DUR. Of course, the lack of low-level moisture does not always lead to no thunderstorms at all times, but it has a notable impact, as shown in our analysis. The opposite is not necessarily true for CAR seasons with positive $\Delta$NDVI. We purport that a possible reason for this asymmetric relationship is that the presence of abundant CBL moisture (years with NDVI $> +1.0$) from vegetation transpiring freely under ideal soil moisture conditions is a necessary but not sufficient condition for thunderstorms. One reason for this could be that the higher soil moisture may result in a cooler and more stable CBL, which may lead to reduced convection (e.g., Cook et al. 2006), or other processes that inhibit convection are at play (e.g., lack of a trigger or strong capping lid).

This hypothesis is illustrated by events in 2005, a pluvial summer on the prairies during which all CARs had above-average JJA $\Delta$NDVI. However, despite the dense vegetation in 2005, 10 of the 12 CARs with $\Delta$NDVI $\geq +1.0$ had $\Delta$DUR $< 0.0$. In contrast, only six CAR seasons between 1999 and 2008 had $\Delta$NDVI $\leq -1.0$ but $\Delta$DUR $> 0.0$, and of these only two had $R_{eq}$ of at least 75 km. North American Regional Reanalysis (NARR; Mesinger et al. 2006) anomaly data indicate that the summer of 2005 was predominantly cool and wet over the Canadian Prairies. NARR data also show that conditions were typically not favorable for
thunderstorms on account of the abnormally high convective inhibition and below-
average convective available potential energy (CAPE), especially over Alberta and
western Saskatchewan. In contrast, CAPE values were above average over southern
Manitoba. Enhanced ascent at 500 hPa was present over most of the
prairies. Thus, most of the rainfall, especially west of Manitoba, that led to positive
ΔNDVI in JJA 2005 was likely associated with synoptic-scale baroclinic systems.
This is supported by lightning duration data, with notable positive ΔDUR (> +0.5)
observed over only 7 of the 38 CARs (<20%) in 2005. Six of these were located
near the Saskatchewan–Manitoba border where NARR data suggest conditions
were more favorable for thunderstorms. These observations are consistent with
those made by Raddatz (Raddatz 2005), who noted that between 1997 and 2003 the
critical ingredients required for the realization of convection (e.g., lift and CAPE)
were less prevalent over drought CARs than pluvial CARs.

4.3. Relationship between NDVI and RZPAW

Values of $R^2$ calculated here between NDVI and RZPAW (0.50–0.90) are much
higher than those found in the literature. For example, Adegoke and Carleton
(Adegoke and Carleton 2002) calculated lagged $R^2$ between root-zone soil mois-
ture and NDVI of between 0.18 and 0.23. Wang et al. (Wang et al. 2007) calculated
$R^2$ values of 0.21 and 0.30 between detrended root-zone soil moisture and NDVI at
three sites in New Mexico, Arizona, and Texas. As discussed in section 3.1.1, the
high values of $R^2$ between NDVI and RZPAW appear to be in part attributable to
autocorrelation, so this caveat should be recognized before drawing definitive
conclusions concerning the lags. The dataset considered here is small (i.e., only
one season), and more data are required to make specific deductions concerning the
optimal lag between RZPAW and NDVI at these sites, for example.

With that said, the analysis here does show that NDVI is responding to
changes in the RZPAW. The data also suggest that the response in NDVI may be
strongest for lags between 1 and 3 weeks, with 2 weeks favored for the finer
textured clay loam soils (e.g., Hussar) and a 1-week lag favored for the coarser
sandy loam soils (e.g., Vermilion). The suggestion of a lagged response of NDVI
to RZPAW is consistent with similar research. For example, Adegoke and
Carleton (Adegoke and Carleton 2002) found the highest $R^2$ when NDVI lagged
root-zone soil moisture by 2 weeks. By comparison, Wang et al. (Wang et al. 2003)
found that the response time of grasses and crops in Kansas to heavy precipitation
events was 8–26 days, with the most common delay being 11–24 days (about 1–3
weeks).

Both observed and modeled datasets suggest that stressed vegetation (ΔNDVI <
−0.5) is typically associated with RZPAW < 40%. These findings are in good
agreement with data from controlled laboratory and field experiments, which have
shown that incipient moisture stress for most plants starts when the RZPAW
approaches 50% (e.g., Shen et al. 2002). Controlled laboratory and field experi-
ments show that notable losses of photosynthetic activity (Vico and Porporato
2008), increases in abscisic acid levels (Schurr et al. 1992), and reductions in
biomass growth (Mitchell et al. 2001) occur once the RZPAW declines below 30%.
5. Conclusions

Thunderstorms form a critical part of the Canadian Prairies hydrological cycle, with up to 50% of the annual precipitation sourced from summertime convective rainfall. Although the Canadian Prairies terrestrial system has been identified as having the potential to exert a detectable influence on convective precipitation in the summer, relatively little work has been dedicated to the impacts of land–atmosphere feedbacks on thunderstorm activity on the Canadian Prairies.

We introduced a novel approach of using lightning flash data with high-spatial-resolution (and real-time) estimates of NDVI to investigate linkages between vegetation density and concomitant and subsequent thunderstorm activity. The degree of association between NDVI and DUR was quantified using the coefficient of determination between pairs of standardized anomalies of lightning duration (ΔDUR) and NDVI (ΔNDVI) for individual summer months and also by season (JJA) for a 10-yr period spanning 1999 through 2008. Anomalies were calculated for 38 CARs on the Canadian Prairies. Linkages between root-zone plant-available soil moisture (RZPAW) and NDVI were investigated by comparing both observed and modeled RZPAW data with NDVI data. Primary research findings are as follows:

- CAR size is important in governing the strength of the relationship between NDVI and DUR. If the area of the anomaly is too small (area less than 18,000 km² or equivalent radius less than about 75 km), the relationship breaks down. Additionally, the relationship strengthens as the magnitude of the anomaly increases, and is especially strong when negative anomalies are larger than typical interannual variability (ΔNDVI ≤ −1.0).
- An asymmetric relationship exists between ΔNDVI and ΔDUR. Specifically, a positive feedback mechanism is evident over the course of the summer over drought-affected regions, with drought conditions leading to less thunderstorm activity. In contrast, a very weak relationship was found in pluvial regions, even over large CARs with strongly positive ΔNDVI. This suggests that positive ΔNDVI alone are not a necessary or a sufficient condition for above-average lightning duration.
- If the vegetation in late June is severely stressed over a large CAR, the July lightning duration over that CAR will likely be below average. In contrast, lush vegetation in late June does not necessarily translate into positive ΔDUR in July. However, analysis over more years is needed to generalize this statement.
- CARs with stressed vegetation in late June are much less likely to transition to lush vegetation by early August, especially for large CARs. These data support the hypothesis that a positive feedback mechanism is present between NDVI and DUR during drought years (2000–03).
- Both observed and modeled soil moisture datasets suggest that stressed vegetation (ΔNDVI < −0.5) is typically associated with RZPAW < 40%.

The findings presented here (i.e., patch size and anomaly magnitude) are consistent with and corroborate both theoretical studies and modeling work. Future work will
focus on how land–atmosphere processes (e.g., NDVI anomalies) over the Canadian Prairies can condition the CBL layer so as to inhibit or facilitate thunderstorm activity while also considering the role of synoptic-scale forcing on modulating summer thunderstorm activity.

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