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Pristine Nocturnal Convective Initiation: A Climatology and Preliminary Examination of Predictability

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Keywords
Atmosphere, North America, Forecasting techniques, Numerical weather prediction/forecasting, Operational forecasting, Model evaluation/performance

Disciplines
Atmospheric Sciences | Climate

Comments

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ABSTRACT

The prediction of convective initiation remains a challenge to forecasters in the Great Plains, especially for elevated events at night. This study examines a subset of 287 likely elevated nocturnal convective initiation events that occurred with little or no direct influence from surface boundaries or preexisting convection over a 4-month period of May–August during the summer of 2015. Events were first classified into one of four types based on apparent formation mechanisms and location relative to any low-level jet. A climatology of each of the four types was performed focusing on general spatial tendencies over a large Great Plains domain and initiation timing trends. Simulations from five convection-allowing models available during the Plains Elevated Convective At Night (PECAN) field campaign, along with four versions of a 4-km Weather Research and Forecasting (WRF) Model, were used to examine the predictability of these types of convective initiation. A dual-peak pattern for initiation timing was revealed, with one peak near 0400 UTC and another around 0700 UTC. The times and prominence of each peak shifted depending on the region analyzed. Positive thermal advection by the geostrophic wind was present in the majority of events for three types but not for the type occurring without a low-level jet. Models were more deficient with location than timing for the five PECAN models, with the four 4-km WRF Models showing similar location errors and problems with initiating convection at a lower altitude than observed.

1. Introduction

In the U.S. Great Plains, nocturnal convection, often in the form of mesoscale convective systems (MCSs), produces a large portion of the warm season rainfall (Wallace 1975; Maddox 1980; Fritsch and Maddox 1981; Maddox 1983; Velasco and Fritsch 1987; Miller and Fritsch 1991; Bentley and Mote 1998; Carbone et al. 2002; Parker 2008). MCSs often are associated with some nocturnal convective initiation (CI), even if the initiation stage occurs prior to sunset. MCSs can threaten public safety and property with high winds, hail, flooding, and occasionally tornadoes, despite their helpful role as the primary producer of warm season precipitation in the central United States (Maddox et al. 1979; Maddox 1980; Fritsch et al. 1986; Rochette and Moore 1996). Thus, correctly predicting the initiation of MCSs and other less organized convection is an integral part of forecasting for the Great Plains.

Prediction of the CI that leads to nighttime convection is challenging. Although previous studies had shown that quantitative precipitation forecast skill increased as the strength of the large-scale forcing increased (Jankov and Gallus 2004; Szoke et al. 2004), Duda and Gallus (2013) found that CI forecast skill in 3-km horizontal grid spacing versions of the Weather Research and Forecasting (WRF) Model did not follow such trends. Wilson and Roberts (2006), however, found that CI tended to be better predicted in a 10-km version of the Rapid Update Cycle (RUC) when the forcing mechanism was a synoptic-scale front rather than a smaller-scale feature like an outflow boundary. The challenge becomes even greater when the initiation takes place some distance away from any synoptic forcing feature. In these cases, smaller-scale features with lower predictability drive initiation, including indirect effects of surface boundaries such as positive thermal advection, as the Great Plains southerly low-level jet (LLJ) rises over those boundaries. The LLJ, a relatively narrow stream of air with a speed maximum occurring between 500 and 1000 m AGL and usually around 0600 UTC (Bonner and Peagle 1970; Mitchell et al. 1995; Song et al. 2005), is a major factor in the initiation of MCSs, which often evolve from nocturnal CI (Wallace 1975; Rochette and Moore 1996; Laing and Fritsch 1997).

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Great Plains forecasters have noted that elevated nocturnal CI often favors a few distinct and diverse modes (R. Roberts, National Center for Atmospheric Research, 2015, personal communication). These modes include a variety of situations, from areas of positive thermal advection at the nose of the LLJ to regions where no forcing mechanism is obvious. Nighttime elevated CI characteristics were examined by Wilson and Roberts (2006) for cases that occurred during the International H2O Project (IHOP) in 2002 (Weckwerth et al. 2004). They found elevated initiation episodes to be associated with the convergence of winds on the meso- and synoptic scales between 900 and 600 hPa, implying an active role by the LLJ. However, no definitive time-based pattern was observed for these cases, meaning simple LLJ explanations related to the temporal evolution of the LLJ are not appropriate. Colman (1990) performed a 4-yr climatology of elevated nocturnal CI but only considered cases on the cool side of boundaries. It was found that a diurnal variation of elevated convection existed, with the peak depending on the front type (closer to 1200 UTC for warm and stationary fronts, 0000 UTC for cold fronts). While these are both important findings, neither addresses the entire nocturnal elevated CI spectrum noted by forecasters, as both studies focused on either surface features or convergence zones. The present study includes forcing associated with LLJs.

Improved understanding of nocturnal elevated CI was one of the four main objectives during the Plains Elevated Convection At Night (PECAN) field campaign that took place between 1 June and 16 July 2015 (Geerts et al. 2017). The present study is centered temporally over the PECAN field phase, but the full study period has been expanded to encompass four warm season months, May–August 2015, to allow for a larger sample of events. A basic climatology of all likely elevated nocturnal CI events during this period is presented to reveal temporal and spatial trends. In addition, both operational and experimental convection-allowing models (CAMs) available to forecasters during the PECAN field phase, as well as several runs of a 4-km WRF-ARW model using four different planetary boundary layer (PBL) schemes, are verified to study the predictability of these initiation events. The goal of the present study is to identify the basic characteristics of and prediction deficiencies associated with nocturnal elevated CI.

2. Data and methodology

a. Classification of CI events

This study examines likely elevated pristine nocturnal CI (PNCI) cases during May–August of 2015. Several dates were chosen preliminarily using half-hourly mosaic radar images from the UCAR Meteorological Case Study Selection Kit Image Archive (UCAR 2014) to find CI within the domain during the 0000–1200 UTC period. After preliminary identification of possible PNCI cases, archived Level II NWS WSR-88D radar data were obtained from the National Centers for Environmental Information (NCEI) Hierarchical Data Storage System (HDSS) Access System (NCEI HAS). The overall domain spanned 28 radar sites and was split into three subdomains: upper plains, PECAN, and Texas (Fig. 1). The PECAN subdomain mirrors the effective study domain used during the field project. The upper plains subdomain lies north of the PECAN subdomain, while the Texas subdomain lies to the south. Level II data were analyzed using Gibson-Ridge Analyst version 2 (GR2Analyst 2.0).

Each preliminary event was examined to determine if it was truly PNCI, based on the criteria stated earlier. CI was said to have occurred if at least one cell reached 35 dBZ over a 4-km² area, as in Roberts and Rutledge (2003), Kain et al. (2013), and Johnson et al. (2016), and modified from 40 dBZ over 4 km² as in Wilson and Roberts (2006). The 35-dBZ threshold was chosen to reflect CI criteria used during the PECAN field campaign. The location of each event was noted, also using GR2Analyst 2.0. Since many events consisted of multiple cells initiating in varying orientations and possibly over short periods of time, the general centroid of the area encompassing all initiating cells during an event was determined and used to represent the initiation location for said event. Initiation time was defined as the first time a cell in the event reached the threshold of 35 dBZ over 4 km².

For events defined as PNCI, further classification into one of four types of PNCI was performed. These types were chosen by the PECAN CI science team based on conversations with NWS forecasters in the plains states, and PECAN forecasters were tasked with trying
to identify which of these types of CI might occur on a given night. Type 1 includes PNCI where both an LLJ (the specific criteria used to define an LLJ are described later) and surface boundary or front are present, such that the LLJ is likely causing convergence within an elevated frontal zone and resulting in positive thermal advection, with the PNCI occurring on the cold (usually north) side of the front (Fig. 2). In this case, note the core of the LLJ (Fig. 2b) crossing the stationary front (Fig. 2a) in a perpendicular fashion. This mode is very similar to the type 1 mesoscale convective complex (MCC) described in Maddox (1980), and the isentropic forcing mechanism driving this mode is further discussed in Trier (2003). Type 2 includes PNCI occurring within the LLJ itself, but not in conjunction with a surface or elevated front or boundary (Fig. 3). Note the line of storms forming along the right side of the LLJ (Fig. 3b), well ahead of the cold front to the northwest (Fig. 3a). Type 3 occurs in a semilinear orientation ahead of and at least quasi perpendicular to the leading edge of a forward-propagating MCS. Type 3 has also been referred to by forecasters as “T initiation,” because of its resemblance to the letter T (Fig. 4). It also resembles a “flipped” version of the “bow and arrow” style initiation discussed in Keene and Schumacher (2013); however, T initiation occurs ahead of the MCS and its gust front/cold pool. Finally, type 4 includes PNCI occurring without any obvious mesoscale cause and outside of or not associated with the LLJ. The type 4 case in Fig. 5 occurred ahead of the MCS, like a type 3 case, but with no preferred orientation and without LLJ influence (in this example, the weak wind maximum seen in Fig. 5b

**FIG. 1.** Domain for the climatology (solid gray) including the WSR-88D radars used as well as the PECAN model verification (dashed box), along with subdomains (inside solid gray, separated by dashed lines) for (a) the upper plains, (b) PECAN, and (c) TX. Red markers indicate NWS stations, and blue markers are military sites.
fails to meet a lateral shear requirement to be considered an LLJ). It is important to note that while type 4 initiation is herein described as occurring without any definitive mesoscale cause, it is possible that small-scale forcing mechanisms not identifiable with the data available, or other synoptic-scale factors, such as lift associated with cyclonic vorticity advection or low-level thermal advection, played a role.

To distinguish each event type, several criteria were considered. First, if an event was at least quasi linear in orientation, within 45° of being perpendicular to a pre-existing linear system, and downstream of that system and its associated outflows, it was immediately classified as type 3. To classify the remaining systems, 850-hPa winds were plotted next to represent LLJ location and orientation. While some in situ lower-troposphere wind data were available for several days during the PECAN field campaign via periodic rawinsonde launches at fixed and mobile sites, these data were not collected over a large enough area, at a fine enough spatial resolution, and over a long enough period (45 days for PECAN versus 120 days for the present study) to be useful in the present study. Thus, 13-km RAP analyses obtained from the NOAA National Operational Model Archive and Distribution System (NOMADS) were used as a proxy for in situ wind measurements, as in Thompson et al. (2003), Schumacher and Johnson (2009), Coniglio et al. (2010), and Snively and Gallus (2014). PNCI was defined to have occurred within an LLJ (and is therefore classified as type 1 or 2) if PNCI occurred within an area of flow exceeding 12 m s$^{-1}$ [similar to the Bonner I criteria; Bonner (1968)], with the flow field exhibiting a horizontal jetlike structure such that lateral shear exceeding 1 m s$^{-1}$ over 25 km was present on each side of the axis of

![Figure 2](image-url)

**Fig. 2.** Example of a type 1 system on 24 Jun with (a) WPC surface map analyzed at 0600 UTC, (b) wind speed (contoured every 3 m s$^{-1}$ from 12 to 30 m s$^{-1}$, with shading according to color bar) and wind barbs at 850 hPa for 0600 UTC, and radar reflectivity in dBZ (see color bar at bottom) at (c) 0500 and (d) 0600 UTC.
maximum flow at a distance not exceeding 400 km (areas where strong lateral shear appeared to be caused by the jet interacting with convective systems were excluded). For these LLJ-associated events, 3-hourly surface maps from the Weather Prediction Center (WPC) were examined to determine if fronts were also present that intersected the LLJ. If so, the events were classified as type 1; otherwise, they were classified as type 2. Type 2 events were further classified based on the location of PNCI relative to the cores of the associated LLJs, with subclassifications being nose, left, middle, right, and tail (Fig. 6). Finally, for the remaining events, where no LLJ was present in the vicinity of the PNCI, no surface boundary was present, and the PNCI did not result in the T-shape characteristic of a type 3 event, the event was classified as type 4. Because type 4 included all remaining PNCI events, no events were unclassifiable.

For all PNCI events, RAP analyses were used to compute thermal advection by the geostrophic wind at both 850 and 700 hPa. Analyses were performed using both the nearest grid point to the PNCI centroid, and an average over a $4^\circ \times 4^\circ$ latitude–longitude box centered on that grid point, similar to Jankov and Gallus (2004). A nine-point smoother available within GEMPAK was applied five times to the temperature field and a five-point smoother applied three times to the geostrophic wind prior to the computation of the advection to smooth small-scale features for which quasigeostrophic theory would not be valid.

### Model analysis

Two approaches to model verification and analysis were used. First, five high-resolution models available...
during the PECAN field campaign were verified. These included the 4-km WRF run by Colorado State University (CSU WRF: Precipitation Systems Research Group 2014), the Model for Prediction Across Scales (MPAS; National Center for Atmospheric Research 2016), the National Severe Storms Laboratory WRF (NSSL WRF; National Severe Storms Laboratory 2016), a 1-km deterministic WRF simulation run by the Multiscale Data Assimilation and Predictability Laboratory group (WRF-MAP; Johnson and Wang 2017), and the NCEP High-Resolution Rapid Refresh version 1 (HRRRv1; Earth System Research Laboratory 2016). Since many of these models were run regularly only during the PECAN field project, this verification was restricted to 1 June–16 July. Additionally, output for several of the models was archived with limited domains that encompassed mainly an area only slightly larger than the original PECAN study area (Fig. 1), restricting verification to that domain. It should be noted that during the summer of 2015, the HRRRv1 overmixed the boundary layer, which resulted in too much convection during the study period (C. Alexander, NOAA/ESRL, 2015, personal communication). However, since not all members of the PECAN forecasting team were aware of this problem until nearly the end of the project, we have chosen to keep the HRRRv1 in the verification as it was a tool used for forecasting during the project.

Model PNCI location and time were determined in the same way as the observed PNCI location and time. Absolute errors for both time and distance were computed, with the distance error based on the distance of the centroid of the modeled PNCI event from the centroid of the observed PNCI event. A series of 90% and 95% significance level Student’s *t* tests were performed on differences between each model and among the PNCI types. Hit rate, false alarm ratio, and threat score

![Image](https://example.com/image.png)

**Fig. 4.** As in **Fig. 2**, but for a type 3 system at (a) 0900, (b) 0900, (c) 0900, and (d) 1000 UTC 22 Jun. The black oval indicates the region of PNCI.
were calculated for each PECAN model and also for the entire group of models using the standard contingency table where hit rate is the fraction of observed PNCI events correctly forecast, false alarm ratio is the fraction of forecast PNCI events (models produced convection that met the PNCI criteria) that were not accompanied by any observed PNCI, and the threat score is the number of correct forecasts of PNCI occurrence divided by the sum of the total number of correct forecasts of PNCI occurrence (hits) plus false forecasts of PNCI occurrence (false alarms) plus observed PNCI events that were not forecast to occur (misses). To determine if a surface boundary was present, and thus if the falsely predicted convection was elevated, 2-m temperature and 10-m wind plots were analyzed for evidence of fronts or outflow boundaries. Additionally, WPC surface maps were used as supplements for the identification of fronts, since many of the archived PECAN model temperature and wind plots suffered from sparse contours and low temporal resolution.

For the second approach to model verification, a subset group of four PNCI events was simulated using a variety of PBL schemes, with the primary focus on differences in the elevation of the PNCI. One case was selected from each type, having a large spatial area (>5000 km²) and high density (less than 20 km between each individual cell) to allow for a better representation of the event when taking point soundings. The four cases were 24 June in eastern Nebraska and western Iowa (type 1; Figs. 2c,d), 6 July in eastern Nebraska (type 2; Figs. 3c,d), 22 June in southern Minnesota and northern Iowa (type 3; Figs. 4c,d), and 26 June in western Missouri (type 4; Figs. 5c,d). Each run used version 3.6.1 of the WRF-ARW model with 4-km horizontal grid spacing and 50 vertical levels. The domain spanned 1200 km × 1200 km and was centered on the initiation

Fig. 5. As in Fig. 2, but for a type 4 system at (a) 0600, (b) 0600, (c) 0630, and (d) 0730 UTC 26 Jun. The black circle indicates the region of PNCI.
location of the observed PNCI. Initial and lateral boundary conditions were provided every 6 h from 12-km North American Mesoscale Forecast System (NAM) analyses. Runs began at 1200 UTC the day of the nocturnal initiation event, to capture the diurnal evolution of the boundary layer prior to the nocturnal events. The four PBL schemes used included two local mixing schemes, Mellor–Yamada–Nakanishi–Niino level 2.5 (MYNN; Nakanishi and Niino 2009) and the quasi-normal scale elimination scheme (QNSE; Sukoriansky et al. 2005), as well as two nonlocal schemes, Yonsei University (YSU; Hong et al. 2006) and Asymmetric Convective Model version 2 (ACM2; Pleim 2007). The ACM2 is actually a hybrid local/nonlocal scheme, employing both local and nonlocal upward mixing and local downward mixing. Table 1 shows the remainder of the physics parameterizations used in each run.

Simulated radar reflectivity for the lowest level of the model was plotted using the wrf_user_getvar function in NCAR Command Language (NCL), which calculates reflectivity using intercept parameters for rain, snow, and graupel consistent with Reisner et al. (1998). NCL was then used to create sounding plots at both the location of the PNCI event in the model as well as the observed PNCI event. If a model did not produce the event, soundings were instead plotted relative to other major areas of observed convection that were present in the model. If the model failed to produce any convection at all, only soundings at the observed location were plotted. These model soundings were then compared to the RAP analysis soundings in a similar fashion.

3. Results

a. Climatology analysis

A climatology for May–August 2015 was performed for all 287 cases. Over the 4-month period (Fig. 7a), type 2 PNCI events were the most common, with 153 occurrences, followed by type 1 (60), type 4 (46), and type 3 (28). Results were similar by month (Fig. 7b), with type 2 the most common in each month, followed by type 1, type 4, and then type 3. Examining each individual type alone, the largest number of type 3 and 4 events was found to occur in June, while type 1 was most common in July. Type 2 was also common in July but the greatest

| Table 1. Physics package used for the four WRF-ARW simulations that examine the sensitivity to the choice of PBL scheme (PBL schemes tested are described in text). |
|---------------------------------|-----------------------------|
| Microphysics                   | Morrison                    |
| Longwave radiation             | New Goddard                 |
| Shortwave radiation            | New Goddard                 |
| Land surface                   | Noah land surface model     |
| Cumulus parameterization       | None                        |
| Urban surface                  | Urban canopy model          |

FIG. 7. Overall PNCI frequency by (a) type only and (b) type and month. Note that August totals are lower because hourly RAP analyses were missing during the first 8 days.
number happened in May. It is important to note that the lack of hourly RAP analyses from 1 to 8 August reduced the totals for that month. It also must be emphasized that this climatology is from one convective season only and may not be representative of other years.

Regarding the timing of the events, a clear peak existed for the full sample during the 0400–0500 UTC hour (Fig. 8a), with two subtle peaks occurring at 0700–0800 and 1000–1100 UTC. In the PECAN region, events had a much stronger twin-peak signal at 0400–0500 and 0700–0800 UTC (Fig. 8c) than for the full domain. The upper plains and Texas subdomains also exhibited dual-peak shapes (Figs. 8b and 8d, respectively); however, the structure was much less pronounced there, possibly because of the small sample sizes. All three subdomains showed an initial peak between 0300 and 0500 UTC.

Further analysis was performed to look at the timing of each individual type to see if any one type contributes more to the different peaks. For the whole domain, each type had at least a subtle peak between 0300 and 0500 UTC, corresponding with the major peak in the overall time analysis (Fig. 9a). The only exception was type 1,

![Fig. 8. Frequency of PNCI over time for (a) the entire domain and the (b) upper plains, (c) PECAN, and (d) TX subdomains.](image)

![Fig. 9. Frequency of PNCI over time, by PNCI type, for (a) the entire domain and (b) the PECAN subdomain.](image)
which had a small peak at 0200–0300 UTC and remained relatively constant through 0600 UTC. Since all four types had a peak at or near 0400 UTC, this implies that the peak in overall PNCI activity at this time was not driven by any one type in particular, which is interesting since only two of the four types are directly related to the LLJ that typically strengthens during the first half of the night (0000–0600 UTC). The strengthening of the LLJ could help trigger PNCI as it might lead to increasing thermal advection.

In fact, positive 850-hPa geostrophic thermal advection (averaged over a 4° latitude × 4° longitude region centered on the initiation centroid) was present at the time of initiation for the majority of all PNCI events (Fig. 10), with the mean thermal advection statistically significantly greater than zero (with 95% confidence) using a Student’s t test for all types except type 4. Similar results were obtained for 700 hPa (not shown) and for both levels using the gridpoint value closest to the centroid of the PNCI event instead of an area average, although for the gridpoint values, the fraction of strong cases was reduced by roughly 50% for all four types while the combined fraction of moderate and strong events remained relatively unchanged (not shown). Strong positive thermal advection (defined as a magnitude at least 10% of the peak value of 1.044 K h⁻¹ from the full sample of cases) was present for over 50% of all type 1–3 events, with at least moderate warm air advection (magnitude at least 1% of the peak value) occurring in roughly 80% of type 1 and 2 events and 75% of type 3. For type 4, only about half of the events had moderate or strong warm air advection. In these type 4 cases, despite the absence of an LLJ, flow was strong enough and/or oriented primarily perpendicular to the isotherms to yield substantial warm air advection. For the PNCI types most directly associated with LLJs (types 1 and 2), and for type 3, where an LLJ could be present, it is likely the strengthening of the LLJ enhanced positive thermal advection and resulted in the 0400 UTC peak. However, since the 0400 UTC peak was present also for type 4 events that happen without an LLJ (as defined in this research), the peak cannot be explained entirely by the strengthening of the LLJ.

The second minor peak at 0700–0800 UTC in the overall frequency graph existed in all four types as well, but not as clearly as the first peak. In fact, type 2 had a relative minimum at 0700–0800 UTC with peaks both an hour earlier and an hour later. Overall, types 3 and 4 were relatively constant from 0500 to 0900 UTC. Since the second maximum in the overall frequency graph is driven by the two types of PNCI where the LLJ is present without ongoing convection nearby, perhaps the movements or changes in strength of the LLJ are responsible. It was observed during the PECAN project that the temperature gradient at 850 hPa often had a strong component from west to east during the night. The typical veering of the LLJ during the night could help intensify or maintain positive thermal advection in such a scenario, as long as LLJ speeds were not weakening markedly. An analysis of the 41 type 1 and 2 events occurring during the secondary peak (0700–0900 UTC) for which RAP analyses were available found that the jet veered near the PNCI location in 38 of the 41 events (data were missing for one case) during the 2 h prior to PNCI, and positive thermal advection at 850 hPa intensified in 26 of the 36 events where this advection was positive at the time of PNCI (not shown). Because other factors besides thermal advection can contribute to vertical motion, a similar analysis was performed for 700-hPa omega. In 28 of the 41 cases, ascent strengthened, while in the six other cases ascent did not strengthen. Of the seven cases where downward motion was occurring near the PNCI, the downward motion weakened in five of them. Thus, in roughly 70% of these cases a veering LLJ was associated with strengthening ascent around the time of the secondary peak in PNCI, and in the majority of the remaining cases, the veering LLJ may have played a role in sustaining positive thermal advection that, although not increasing in magnitude, maintained ascent or weakened descent, making conditions more favorable for PNCI.

Because of small sample sizes, the upper plains and Texas subdomains are not shown. More cases did occur in the PECAN region, and that subdomain also exhibited two peaks among all four PNCI types (Fig. 9b).
However, the peaks occurred relatively coincident with each other, around 0300–0500 and 0700–0900 UTC, meaning no one CI type explains any individual peak. Also, since all types occurred at roughly the same time, LLJ development and behavior cannot necessarily be used to explain the occurrence of these peaks, since the same peaks were present in CI types that do not rely on the LLJ.

The general dual-peak nature observed during summer 2015 is interesting because Schumacher et al. (2008) and Reif and Bluestein (2017) also examined nocturnal elevated CI in a similar manner and found similar twin-peak structures. Both studies were much longer climatologies, examining over five years’ worth of data, supporting the dual-peak structure found in the present study.

Finally, the location of all PNCI events was plotted (Fig. 11) to determine if there are preferred regions for certain types of PNCI. A few subtle patterns can be noted if the region is divided into equal thirds by latitude (the north closely matches the upper plains subdomain defined earlier but the other two zones do not match the PECAN and Texas subdomains). First, type 1 events were much rarer in the south (9 events) than in the north (19 events) or central region (32 events). The lack of type 1 events in the south may be due to the time of year; it is possible that these events would be more common earlier in the year when frontal boundaries are more likely to exist in the south. Type 2 occurred more uniformly across the

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**FIG. 11.** Locations of each PNCI type over the entire period: types (a) 1, (b) 2, (c) 3, and (d) 4.
domain with a small maximum in the central region, where 69 events occurred compared to 42 in the north and 42 in the south. Types 3 and 4 were more common in the north (12 and 24 events, respectively), with type 3 being especially rare in the central area (six cases), and type 4 the rarest in the south (eight cases). Regarding temporal trends (Fig. 12), PNCI events were fairly evenly distributed over the domain for each month, except for a slight minimum in the extreme northern portions of the study domain in August. While June appears to have a minimum in the southern portion, it is likely an artifact of Tropical Storm Bill, and such a reduction in June would not likely be present in a longer-term climatology.

b. Analysis of high-resolution models available during PECAN

High-resolution models available during the PECAN field campaign included the CSU WRF, NSSL WRF, MPAS, WRF-MAP, and NCEP HRRRv1. Simulated radar output was examined for each model for each case that fell within the archived model domain. For the PECAN period, the general distribution of the four types of events was similar to that of the larger time
period over the larger region, with type 2 events dominating (31), followed by type 1 (16), type 4 (7), and type 3 (6). Considering the entire sample of five models, there were 99 times out of a possible 219 hits (60 PECAN events in five models, but 81 instances where events occurred outside a particular model’s domain or for which data were not available) when a particular model did not capture the CI event at all, with all models achieving a combined hit rate of 55%, false alarm ratio of 57%, and threat score of 32%. Individual model hit rates were between 39% and 64%, false alarm ratios were between 49% and 65%, and threat scores were between 23% and 38% (Table 2). Of particular interest is that type 2 CI was the only type where all five of the models on occasion failed to produce an event (Table 3 and 4). However, it must be noted that this result may not be that significant since over half of all events were classified as type 2 (Fig. 7).

The absolute error for initiation time was calculated, with negative (positive) numbers meaning the model initiated convection earlier (later) than was observed,

### Table 2. Hit rate, false alarm ratio, and threat score (see text for definitions) for each of the high-resolution PECAN models.

<table>
<thead>
<tr>
<th></th>
<th>NSSL WRF</th>
<th>MPAS</th>
<th>WRF-MAP</th>
<th>NCEP HRRRv1</th>
<th>CSU WRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hit rate (%)</td>
<td>52</td>
<td>58</td>
<td>57</td>
<td>39</td>
<td>64</td>
</tr>
<tr>
<td>False alarm ratio (%)</td>
<td>65</td>
<td>49</td>
<td>59</td>
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<td>Threat score (%)</td>
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### Table 3. Model verification of June PNCI events. An ex (X) indicates the model did not produce the observed initiation. N/A indicates the observed initiation occurred outside the archived model's domain or the archived image was unavailable.

<table>
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<tr>
<th>PNCI type</th>
<th>NSSL WRF</th>
<th>MPAS</th>
<th>WRF-MAP</th>
<th>NCEP HRRRv1</th>
<th>CSU WRF</th>
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and with 0 indicating the correct time of initiation (Fig. 13). Overall, the five models handled the timing of PNCI rather well, exhibiting a mostly bell-shaped curve (Fig. 13a); however, there was a bit of a skew toward later initiation. The mean absolute error was around 1 h for the NSSL WRF and MPAS models and around 1.7 h for the other three models. Individually, the NCEP HRRRv1 had a small tendency to initiate events earlier than observed (Fig. 13e), while the WRF-MAP (Fig. 13d) and CSU WRF results (Fig. 13f) were skewed toward later initiation than observed. However, it should be noted that examining individual models yields small sample sizes. A similar lack of model bias in initiating time was seen by Kain et al. (2013) and Johnson et al. (2016), who showed that the models seem to handle the timing of initiation fairly well.

Regarding the location of PNCI, the NSSL WRF and MPAS again performed best, with average distance errors of 77 and 87 km, respectively (Fig. 14a). Meanwhile, the WRF-MAP, NCEP HRRRv1, and CSU WRF performed worse, with an average distance error near 105 km for all three. However, it should be noted that examining individual models yields small sample sizes. A similar lack of model bias in initiating time was seen by Kain et al. (2013) and Johnson et al. (2016), who showed that the models seem to handle the timing of initiation fairly well.

According to the original location of PNCI, the NSSL WRF and MPAS again performed best, with average distance errors of 77 and 87 km, respectively (Fig. 14a). Meanwhile, the WRF-MAP, NCEP HRRRv1, and CSU WRF performed worse, with an average distance error near 105 km for all three. However, a Student’s t test found using 90% and 95% significance levels that only the NSSL WRF and the CSU WRF had significant differences in these distance errors, and only at the 90% significance level. Analyses of types suggest that forecasts of type 4 exhibited the highest distance errors of any PNCI types, while type 3 errors were lowest (Fig. 14b). The type 4 result is likely due to the very subtle forcing mechanisms that lead to this type of CI not being predicted correctly by the models. Meanwhile, the lowest errors for type 3 suggest that since type 3 is heavily reliant on the location of the parent linear systems, perhaps the models performed well when predicting these linear systems and the prediction of the location of type 3 PNCI is relatively easier once the parent system is captured. The five models performed relatively the same for the two LLJ-driven PNCI types, which makes sense since both are influenced by the same forcing mechanism. They did, however, appear to perform worse than the type 3 simulated events. It must be noted, however, that some sample sizes were small, and in Student’s t tests, no differences were statistically significant between any of the four types.

c. Analysis of WRF-simulated CI events

Sixteen total WRF-ARW simulations were run for four PNCI events that occurred during the study period, with four different PBL schemes used for each of the four PNCI events.

1) 24 June: Type 1

A type 1 frontal event occurred on 24 June, with a stationary front across northern Kansas, moving slowly northward overnight (Fig. 2a) while an LLJ, analyzed in the RAP analyses as exceeding 30 m s⁻¹, was oriented southwest to northeast across western and central Kansas, crossing the warm front just south of the Kansas–Nebraska border (Fig. 2b). This initiated convection north of the warm front over far eastern Nebraska and into western and central Iowa. Initially
storms were organized into several parallel lines stretching NW–SE, but they consolidated into a disorganized MCS (Figs. 2c,d).

Among the WRF runs, only the ACM2 PBL run did not produce the type 1 CI event at all (Figs. 15j–l). Because the Pleim–Xiu land surface scheme must be used when the ACM2 PBL scheme is used instead of the Noah land surface model used in the other three configurations, sensitivity tests were run with the other three PBL schemes also using the Pleim–Xiu scheme for the 24 June case. Simulations were not sensitive to this change in the land surface scheme, making it likely that the failure to produce CI in this case was directly related to the ACM2 scheme itself. The other three runs predicted the event remarkably well, despite being slightly farther west and organizing into one line instead of several parallel lines (Figs. 15a–i). All three then proceeded to develop the weakly organized MCS seen in the observations.

Modeled thermodynamic profiles were taken from the centroid of CI in the model at the time of initiation and compared to RAP soundings from the centroid of the observed PNCI event. In the case of the ACM2, since no PNCI formed, the sounding was taken from the same location as the RAP sounding used for the observed CI. One difference that all the models had when compared to the RAP analysis is that the level at which initiation likely occurred was lower in the models than it was in the RAP analysis. The operational RAP used 50 vertical levels, like the WRF configuration, but the output available for comparison had been interpolated to constant pressure levels every 25 hPa, so small differences in the placement of the levels could explain small differences between the soundings. The level at or just above 700 hPa became increasingly saturated over time (a good indicator of CI at that level) in the RAP analysis, while this saturation occurred at about 800–750 hPa in the WRF

![Figure 13](image-url)
models. Despite this difference, three of the four models did produce the PNCI. One difference between the ACM2 results and the other configurations was a slightly stronger inversion in the approximately 100-hPa layer just above the level that was becoming saturated, possibly inhibiting convection. With the ACM2 having only a slight difference in inversion strength yet being the only PBL scheme not to produce the event at all, CI is shown to be highly sensitive to which PBL scheme is used, as was also seen in Johnson et al. (2016).

2) 6 JULY: TYPE 2

The type 2 PNCI event on 6 July fell in the “right” subgroup of the type 2 events, meaning to the right of the LLJ axis. Convection initiated in a line just southwest of Omaha, Nebraska. Over time, the line grew longer, remained linear, and seemed to rotate about a north–south axis positioned over Omaha (Figs. 3c,d). By 0500 UTC the linear structure began to break down, with significantly more initiation occurring between the line and the approaching MCS to the northwest. This event was accompanied by another LLJ (Fig. 3b), although during this type 2 event, the LLJ was in its strengthening phase, with winds reaching 25 m s$^{-1}$ over south-central and eastern Nebraska toward the end of the event as the South Dakota MCS began to overtake it.

The simulated reflectivity results for each of the four models run for this PNCI event (Fig. 16) show that none of the four captured this event. Surprisingly, all four models were remarkably consistent with the rest of the nocturnal convection, including the scattered convection in northeast Oklahoma and the well-organized MCS moving through southern South Dakota. Soundings from all four model runs were generally too dry...
FIG. 15. Simulated reflectivity (dBZ) on 24 Jun for the YSU scheme at (a) 0600, (b) 0700, and (c) 0800 UTC; the QNSE scheme at (d) 0600, (e) 0700, and (f) 0800 UTC; the MYNN scheme at (g) 0600, (h) 0700, and (i) 0800 UTC; and the ACM2 scheme at (j) 0600, (k) 0700, and (l) 0800 UTC.
FIG. 16. Simulated reflectivity (dBZ) on 6 Jul for the YSU scheme at (a) 0200, (b) 0300, and (c) 0400 UTC; the QNSE scheme at (d) 0200, (e) 0300, and (f) 0400 UTC; the MYNN scheme at (g) 0200, (h) 0300, and (i) 0400 UTC; and the ACM2 scheme at (j) 0200, (k) 0300, and (l) 0400 UTC.
above 850 hPa compared to the RAP. Additionally, all of the simulations showed signs of developing at least a subtle inversion at or just above 850 hPa that was not present in the RAP analysis sounding. This inversion may have hampered PNCI.

3) 22 JUNE: TYPE 3

A type 3 CI event occurred on 22 June, beginning as two or three clusters of thunderstorms in northern South Dakota and southern North Dakota. These clusters eventually merged into a poorly organized but weakly linear MCS. At the same time, a smaller and weaker cluster of convection was progressing northeastward through central Iowa, likely driven by thermal advection to the north of a retreating warm front. As the MCS approached far eastern South Dakota and southwest Minnesota, a quasi-linear type 3 event initiated in southern Minnesota and along the Iowa–Minnesota border, connecting the MCS to the pre-existing convection that had continued to move northeast out of central Iowa (Fig. 4).

Even though type 3 CI heavily depends on the linear system with which it is associated, three of the four model runs produced the PNCI despite simulating the MCSs in rather different ways (Fig. 17). As expected, the location of the initiation depended on the actual location of the MCS, but the position of each of the three runs’ PNCI results relative to their respective MCSs was quite consistent. The only outlier for this event was the ACM2 run, which did not produce the observed type 3 PNCI (Figs. 17j–l). It is possible that this failure was related to the location of the MCS produced in this run, which is significantly farther north than what was observed and simulated in the other three WRF runs. The northward shift in the ACM2 PBL run may explain a noticeable inversion present above the layer that approached saturation, which may have inhibited convection. The inversion was not present in the other WRF runs, and was much weaker in the RAP analysis. For initiation elevation, the RAP analysis suggests a level just below 700 hPa, or about 3000 m AGL. As with the 24 June type 1 event, the models that showed PNCI likely initiated convection at a lower level than what was observed in the RAP analysis, at least based on near saturation that developed. The QNSE PBL scheme was especially low, initiating convection near 1500 m AGL.

4) 26 JUNE: TYPE 4

The type 4 case that occurred in extreme western Missouri was a bit unique in that it behaved somewhat like a type 3 event, since the PNCI happened relatively close to an organized MCS. However, linear structure was not present, and the cells were almost evenly spaced ahead of the convection as well as its associated gust front. This event happened in conjunction with an MCS that had formed out of a type 1 PNCI event in northeast Kansas earlier in the night. After that MCS slowly progressed through Kansas City, Missouri, a cluster of very small convective cells began to form just ahead of the MCS’s outflow. This continued for about 2 h, at which point the MCS began to accelerate and overtook the area (Fig. 5).

In this type 4 event, only two of the four PBL schemes, YSU and MYNN, produced the PNCI (Figs. 18a–c and 18g–i). In fact, the ACM2 scheme failed to capture the original type 1 PNCI event that caused the MCS (Figs. 18j–l). Examination of the modeled soundings showed that the main difference between the two PBL schemes that failed to produce the type 4 event and the two that did was a more shallow elevated dry layer just above 700 hPa in the models that did not produce the PNCI event. While all four model runs tended to be a bit shallower with the dry layer than in the RAP analysis sounding, the two that failed to capture the event (the QNSE and ACM2 PBL schemes) were the shallowest of the four. Normally, a shallower dry layer would help convection, so it is interesting that the two runs that failed to produce convection had the shallowest of the four dry layers. Perhaps for this type 4 case the difference in dry layers had no effect on initiation of convection. This then fits with the idea that type 4 convection relies on much subtler changes in conditions, since the depth of the dry layers was the only noticeable difference among all four model runs.

4. Conclusions and discussion

A general climatology of PNCI was completed for 287 initiation events during May–August 2015 to better understand four different types of PNCI with a goal of increasing forecasting skill. The climatology was performed over a large domain, encompassing all of the U.S. Great Plains region from central Texas to the Canadian border. Analyses of the timing of the initiation revealed that one major peak exists, occurring near 0400 UTC, with an additional less prominent peak occurring during the 0700–0800 UTC period. An examination of thermal advection by the geostrophic wind showed that positive thermal advection was present in roughly 75%–80% of all type 1–3 PNCI events, but only in half of type 4 events. Although it is possible that the strengthening of the LLJ during the evening could explain the early peak for type 1–3 PNCI events, as it would also be consistent with the frequent positive thermal advection present in those events, it would not explain the peak for type 4. The secondary peak that showed up primarily for type 1 and 2 events could be related to the veering of the LLJ, which might increase the positive thermal advection when a west–east gradient of temperature exists.
FIG. 17. Simulated reflectivity (dBZ) on 22 Jun for the YSU scheme at (a) 0900, (b) 1000, and (c) 1100 UTC; the QNSE scheme at (d) 0900, (e) 1000, and (f) 1100 UTC; the MYNN scheme at (g) 0900, (h) 1000, and (i) 1100 UTC; and the ACM2 scheme at (j) 0900, (k) 1000, and (l) 1100 UTC.
Fig. 18. Simulated reflectivity (dBZ) on 26 Jun for the YSU scheme at (a) 0630, (b) 0730, and (c) 0830 UTC; the QNSE scheme at (d) 0630, (e) 0730, and (f) 0830 UTC; the MYNN scheme at (g) 0630, (h) 0730, and (i) 0830 UTC; and the ACM2 scheme at (j) 0630, (k) 0730, and (l) 0830 UTC. The small areas of interest for the YSU and MYNN schemes are circled.
Further work should explore the dual-peak structure in PNCI in more detail, especially why an early peak occurs for type 4 events and whether some mechanism might be suppressing PNCI between the two peaks.

High-resolution models used during the PECAN field campaign were analyzed to verify their performance at predicting PNCI. LLJ-driven PNCI types (1 and 2) appeared to be better predicted in location than types 3 and 4. Since type 3 is completely dependent on the location of the parent MCS, correct prediction of type 3 initiation can only occur if the parent MCS is also correctly predicted, which increases the challenge in forecasting. Subsequently, type 4 PNCI is likely to be less predictable because this type occurs without obvious forcing mechanisms.

To further examine the model handling of elevation level of each type of PNCI, four versions of a 4-km WRF-ARW model were run for four cases, one for each PNCI type. While many of the models seemed to initiate convection at a lower elevation than what was observed in the RAP analyses used to represent observations, CI did occur in relatively the correct spot (or, in the case of type 3, relatively the same spot in relation to the parent MCS). As was seen several times in the PECAN model verification, every version of the WRF model run for the type 2 case failed to produce the convection. Perhaps in the case of type 2 events, smaller-scale features or impulses moving through the LLJ are causing the initiation, rather than the broader LLJ itself. If these small-scale features, whether they be gravity waves or moisture fluctuations within the jet, are relatively hard to predict, that could explain why some type 2 events are predicted relatively well while other events are completely missed by the model forecasts.

Overall, all four types of PNCI seem to be heavily dependent on small factors/changes in the atmosphere, as well as the choice of PBL scheme as seen by the failure of the ACM2 model to predict the type 1 case on 24 June and in Johnson et al. (2016). While all other boundary layer parameterizations for that day predicted the event remarkably well, the ACM2 completely failed to produce the PNCI event even though its vertical thermodynamic profile was only marginally different from the other models and the observed RAP analyses. Further research will be needed to determine the extent that this type of CI relies on features smaller than the mesoscale, how sensitive initiation is to the occurrence or absence of these features, as well as if these features play a role in the dual-peak structure seen in the timing of PNCI in some areas of the plains.

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