A Continental Dense Fog Event Associated with Precipitation and Low Clouds

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1. Introduction

In the Midwestern United States, fog greatly impacts surface transportation and can be a significant safety hazard (Goodwin 2002; Westcott 2007). Continental fogs are generally thought to occur when air is cooled to the point of saturation by radiation under clear sky conditions, or when moist air is advected over a cold surface, such as snow (Roach 1995). In fact, much of the current understanding of continental fogs is based on field studies of radiation fogs under clear sky conditions (e.g. Roach, et al. 1976; Justio and Lala 1980; Mason 1982, Turton and Brown 1987, Meyer and Lala 1990). Based on observations taken in the October to March cold seasons from 1970 to 1994, Westcott (2005) found that precipitation often is present at the onset of dense fog. Tardif and Rasmussen (2007) likewise found for the northeastern US that fog often occurs with precipitation or low cloud bases. Continental fogs have been observed to form in association with or between low pressure systems or nearby fronts (e.g. George 1951; Byers 1959; Westcott 2005; Croft and Burton 2006, Tardif and Rasmussen 2007). While forecasters are aware that continental fogs can be associated with low clouds and precipitation (George 1940; Byres 1959; Croft et al. 1997), only a few detailed case studies examining the processes leading to the development of such fog events (e.g. Tardif 2007) have been reported.

Here, a case study is presented of a dense fog event that developed in association with the passage of a low pressure system. This study strives to identify the physical processes important for the development of dense fog under low cloud conditions. This case study is discussed within the context of a climatology of fog events associated with low pressure systems and with low cloud bases.

2. Methods

2.1 Case study

Operational observations taken by National Oceanic and Atmospheric Administration (NOAA) facilities and local field experiment observations in central Illinois were examined to obtain as complete a description as possible of the 6-7 November 2006 dense fog event (Fig 1). Surface observations from National Weather Service (NWS) Automated Surface Observing System (ASOS) and Federal Aviation Administration Automated Weather Observing System (AWOS) taken at time intervals of 20-min to 1-hr, were obtained from the NOAA Midwestern Regional Climate Center (http://mrcc.sws.uiuc.edu) at the Illinois Sate Water Survey. Hourly averaged data from the Illinois Climate Network (ICN) gave valuable additional information on standard meteorological variables, precipitation, net radiation, and soil temperature and moisture at 19 sites throughout Illinois. In addition, data from an AmeriFlux site (Billesbach et al. 2004) were combined with the Champaign, IL, AWOS (KCMI) to give detailed information on the evolution of the fog. In addition to standard meteorological information, the AmeriFlux system provides 30-minute surface observations of momentum, sensible, latent and ground heat fluxes, soil temperature and soil moisture profiles, and net, longwave, and shortwave radiation. The atmospheric flux measurement height was 10 m. In addition to surface observations, high-resolution rawinsonde observations and WSR-88D radar observations taken at Lincoln, IL, (KILX), obtained from the National Climatic Data Center (NCDC) (http://hurricane.ncdc.noaa.gov/pls/plhas/has.dsselect), and GOES-8 Visible and infrared imagery, obtained from the NASA Langley Cloud and Radiation Research Group web page (http://www-angler.larc.nasa.gov/) provided valuable information.

Surface, Radar, Upper Air Sites

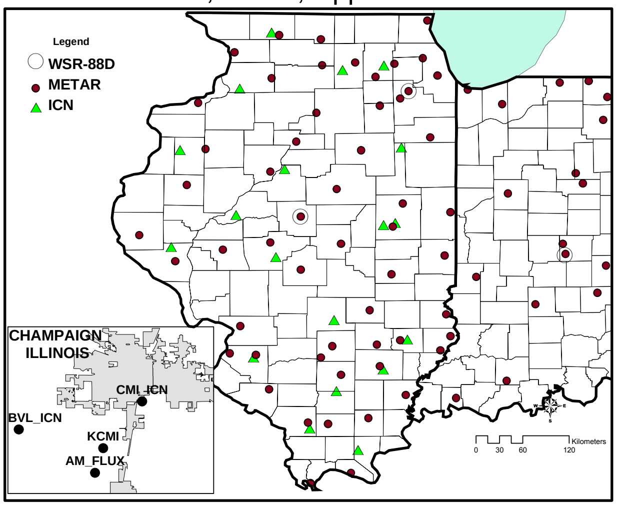

Figure 1. Location of ASOS/AWOS and ICN surface data sites and the Lincoln, Illinois (ILX) radar and sounding site. Insert indicates location of AmeriFlux, AWOS and ICN sties in Champaign area.

2.1 Climatology

A climatology of conditions before and at the time of dense fog formation associated with precipitation, nearby fronts, and low pressure areas was based on a climatology developed for the October-March cold season for the period 1970-1994 at Peoria, IL. The primary data source is Surface Airways Hourly data (Westcott 2005, 2007). Dense fog events were defined as having at least one hour of visibility ≤ 400 m when fog was reported. Peoria, located in central Illinois, was found to be representative of the Midwest (Westcott 2007). The Champaign, IL, area, about 110 km southeast of Peoria, and the location of some of the detailed surface observations in the current case study, is similar to Peoria in that topographic features and urban influences do not greatly affect the surface observations.

For the 1970-1994 period, 302 dense fog events were found. They were classified by synoptic type based on 3-hour surface weather maps. Ten synoptic types were considered in Westcott (2005). The most notable feature was that precipitation often occurred at the onset of dense fog events associated with low pressure systems and approaching or nearby fronts. Because of the similarity in distribution of surface conditions and prevailing weather at dense fog onset and for simplicity of analysis, the 10 original classifications were combined into 5 synoptic types. The classification was made with respect to Peoria, IL at the time of dense fog onset: high pressure, post-frontal, low pressure, between fronts or low pressure areas, and frontal.

Precipitation data for 302 dense fog events at Peoria were obtained from 3 sources: daily precipitation totals at Peoria, IL, ending at midnight, the NOAA Daily Map Series daily precipitation analyses for the surrounding region, ending at 12 UTC (06 LT), and hourly observations of prevailing weather (precipitation type) at Peoria IL. The midnight observation at Peoria and the Daily Weather Map Series data provided an indication of availability of moisture for fog development at Peoria and in the general region.

3. Case study – 6 to 7 November 2006

3.1 Atmospheric preconditioning

During the 18-hour time period proceeding the development of widespread dense fog, the atmosphere was initially preconditioned by horizontal advection and vertical redistribution of moisture into the region by processes associated with an approaching cyclone. As a weakening area of surface low pressure moved from Oklahoma to northern Kentucky from 6 to 7 November 2006, a deep layer of moisture was transported northward and northwestward into the relatively dry region. Precipitation developed to the south and east of the study region. As the cyclone departed, marked drying was evident at higher levels, allowing for radiational cooling at the top of the low cloud layer. Rawinsonde observations taken at Lincoln IL (Fig. 2) shows changes in the atmospheric column that occurred as a result of these processes. Large increases in atmospheric moisture from 12 UTC 6 November to 00 UTC 7 November (06 to 18 LT) were found between about 3 and 10 km height (Fig. 2). Somewhat smaller increases were observed below about 1.5 km. Despite the increase in moisture at higher altitudes, relative humidities below about 850 hPa were unsaturated at 00 UTC (18 LT).

During the nighttime hours of 6 – 7 November, an important redistribution of moisture in the atmosphere took place. Observations from the Lincoln, IL, WSR-88D site (not shown here), indicated that precipitation moved northward into the region at altitudes below 10 km. Widespread precipitation was observed between about 3 and 10 km over much of central Illinois, which evaporated as it fell into the sub-saturated air below. During the period leading to the onset of precipitation, ceilometer observations at many central IL ASOS/AWOS sites indicated a lowering cloud base that was accompanied by falling surface temperatures and rising dew point temperatures and relative humidities (Fig 3).

As the precipitation and deep cloudiness moved northeastward and away from the region, considerable drying of the atmosphere above ~2 km took place (Fig. 2). Moistening of the low-levels by precipitation processes, combined with drying at higher altitudes, both played key roles in allowing for saturation near the surface and ultimately fog formation (see section 3.2).

3.2 Evolution of surface conditions and dense fog development

Fog formed in the early morning of 7 November 2006 in an area of overcast skies. Figure 3 provides an example of surface observations taken at KCMI and the AmerFlux sites, representative of the central Illinois area. Figure 4 shows the area where visibilities of 400 m (¼ mile) or less were observed during the early morning hours of 7 November, overlaid on an IR satellite image from 0445 UTC (2245 LT). It can be seen that the area of eventual dense fog development was located in the wake of, and was closely oriented with, a departing widespread area of deep clouds associated with the low pressure system.

Fog began to develop in south-central Illinois between 08 and 09 UTC (02 and 03 LT) and developed to the north and east throughout Illinois between 11 and 14 UTC (05 and 08 LT). Most dense fog dissipated between 14 and 1530 UTC (08 and 0930 LT), except at sites close to Lake Michigan. During the pre-fog hours, little or no precipitation occurred in the northern and western portion of the state, but light precipitation was observed in central Illinois until about 10 UTC (04 LT). Precipitation was not reported during the fog event at any sites that experienced fog.

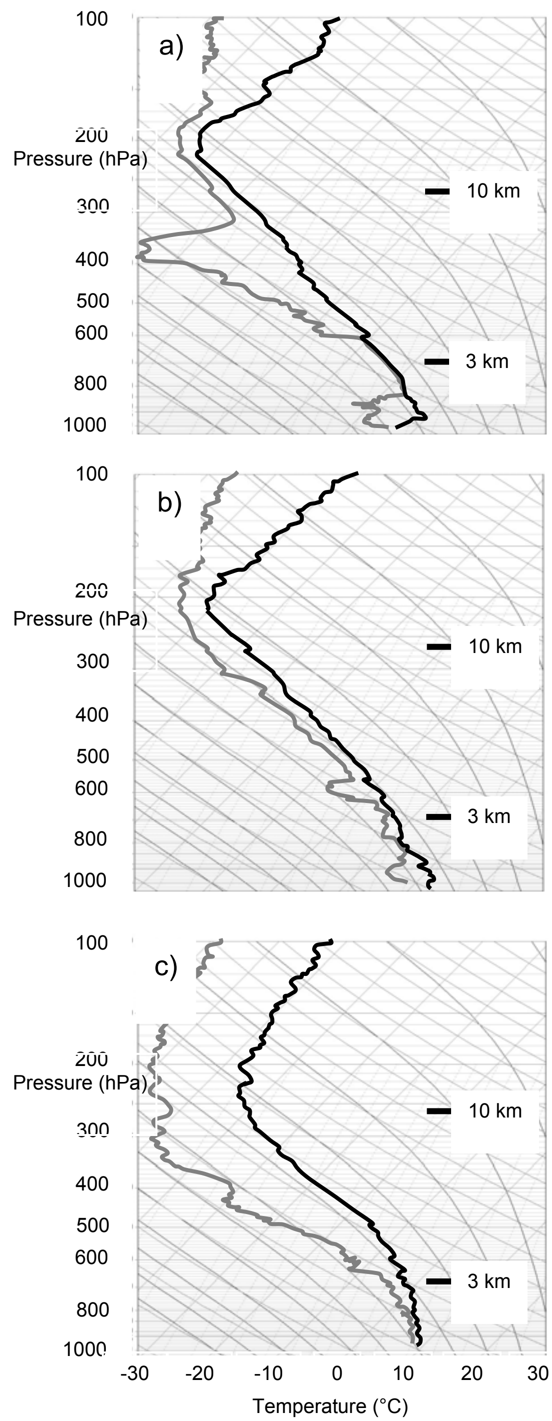

Figure 2. High-resolution soundings taken at Lincoln, Illinois on a) 6 November 2006, 12 UTC, b) 7 November 2006, 00 UTC, and c) 7 November 2006, 12 UTC.

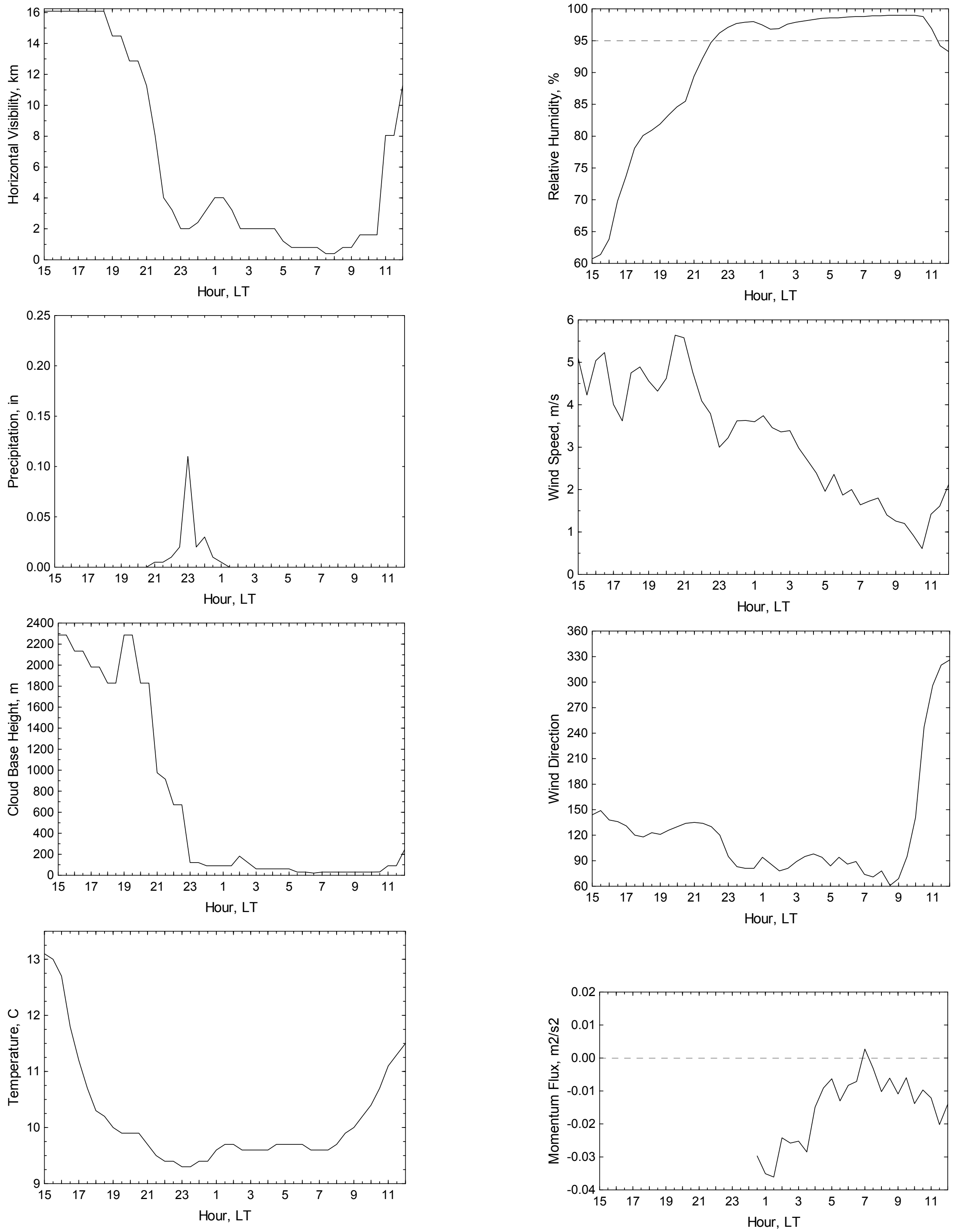

Figure 3. Horizontal visibility, cloud base height, precipitation from the AWOS site at KCMI. Temperature, winds, momemtum flux and relative humidity from the AmeriFlux site for 6-7 November 2006. See Figure 1 for locations.

During the late night-early morning period, a NW-SE gradient in surface temperature was apparent in both the ASOS/AWOS and ICN data, with colder temperatures to the northwest (clear) and warmer temperatures to the southeast (cloudy). The gradient in temperature was oriented in a fashion similar to the 24-hour precipitation and departing deep clouds (Fig. 4), and the relative humidity fields. Wind speeds remained less than 2 ms^{-1} throughout the morning. With easterly winds and a NW/SE temperature gradient, weak warm air advection was found to occur throughout the nighttime hours at the surface. At about 17 UTC (11 LT), northerly winds began to dominate much of Illinois as the low passed to the NE and the remaining fog dissipated.

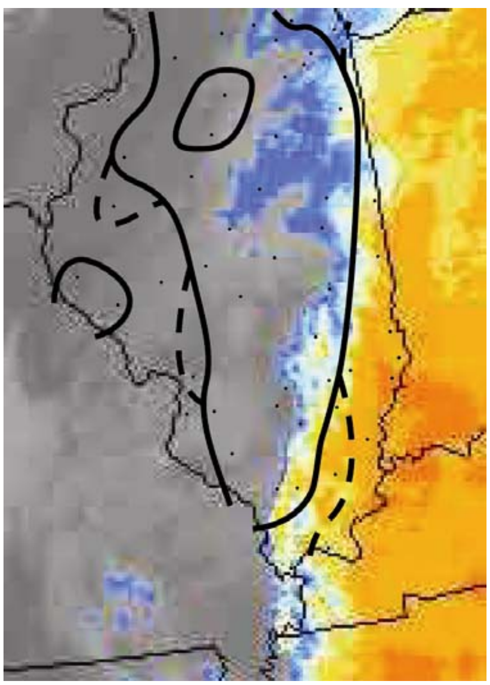

Figure 4. Satellite Image, Goes 8, Color enhanced channel 4, 10.7 µ cloud top temperature K. 0445 UTC (2245 LT), with location of dense fog (400 m visibility) and less dense fog (800 m visibility; dashed) indicated.

4. Climatology

Cloud base height was examined for the 5 synoptic weather types (Table 1). Of the 302 dense fog events, 23% occurred when weather in Illinois was dominated by a low pressure system centered in Illinois or one of the surrounding states at the time dense fog formed, as was the case for 7 November 2006, and 35% with approaching or nearby fronts. The remaining fog cases occurred with high pressure systems (26%), followed frontal passage (7%), or were between synoptic features (9%).

Low cloud bases are common during dense fog events when low pressure centers or fronts dominate Illinois weather. Cases where the sky was clear or where cloud bases were higher than 1000m in the 6 hours prior to dense fog onset made up only 34% of the events, and were usually associated with high pressure or followed the passage of a warm or cold front. When Peoria was located between major synoptic features, low or changing cloud bases were common. Employing the 1 km threshold used by Tardif and Rasmussen (2007), the majority of all dense fog events (57%) were associated with low cloud bases in the 6 hours prior to the onset of dense fog.

4.1 Cloud base height with surface temperature and moisture changes

Typically under clear sky conditions during nighttime hours, the atmosphere cools the lowest region of the atmosphere. On 7 November 2006 at KCMI, the lowest cloud base was below 250 m during the 6 hours prior to dense fog onset. During this period, little or no change in temperature was observed (< 0.5 C) according to AmeriFlux and AWOS data (Fig 3). Surface cooling already had taken place in the hours prior to precipitation and when the cloud base lowered. The relative humidity at the surface (2 m), though nearly saturation (≥ 95%), slowly increased 6 hours prior to dense fog formation. With such small changes in surface parameters in the pre-fog hours, whether cooling, moistening, or mixing lead to widespread fog development is not obvious without the knowledge of processes occurring above the surface.

The Peoria climatology revealed that for October to March 1970 – 1994 dense fog events, for low cloud base cases, small or positive changes in temperature, dewpoint temperature and relative humidity are common 6 hours (Fig 5a) and 3 hours prior to dense fog onset (Fig 5b). For low cloud base cases with or without precipitation at dense fog onset, the atmosphere was nearly saturated, with only 15% of the cases increasing in humidity by more than 5% in the 3 hours prior to dense fog onset, and only 30% increasing more than 5% in the 6 hours prior to dense fog onset.

Table 1. Percentage of dense fog events at Peoria IL with cloud base heights > 1 km, variable cloud bases, or cloud base < 1 km in 6 hours prior to dense fog onset, for the October - March period of 1970 – 1994.

Synoptic Category			Cloud Base Height within -6 hour		
	Sample	Percent of Sample	> 1 km	Variable	<1 km
High pressure	78	26	62 %	12 %	27 %
Post-frontal	22	7	50 %	9 %	41 %
Between features	27	9	22 %	26 %	52 %
Low pressure	68	23	10 %	6 %	84 %
Frontal	107	35	28 %	6 %	66 %
TOTAL Sample	302	100 %	34 %	9 %	57 %

When no precipitation was observed near dense fog onset and cloud bases were lower than 1 km, in the majority of cases no temperature change or a warming of ≥ 0.6°C occurred over the 3 and 6 hours prior to dense fog onset, as occurred in the 7 November 2006 case. If precipitation was present at or near dense fog onset, warming was most common. Note, hourly temperature was recorded in whole degrees Fahrenheit (0.6°C), so subtle changes in temperature may have gone undetected.

A similar examination of dew point temperature by cloud base height indicated that under low cloud conditions with and without precipitation at fog onset, the dew point temperature often increased by ≥ 0.6 °C in the 3 and 6 hours prior to dense fog onset for low cloud events. This occurred with more frequency than temperature increasing, suggesting the addition of moisture into the surface layer.

Under low cloud base conditions, cooling often is not observed at the surface in the near saturated environment, while an increase in dew point temperature often is found. However, under low cloud base conditions, surface measurements cannot address the relative importance of the addition of moisture, and radiational cooling at the top of the cloud layer in dense fog formation.

4.2 Precipitation

Approximately 1 – 5 mm (0.05 – 0.20 inches) of precipitation fell in the Champaign area from 03 – 07 UTC (-01 LT) on 6-7 November 2006, 6 hours prior to the onset of dense fog. No precipitation was observed at KCMI near the time of dense fog onset (Fig 3).

The Peoria climatology indicated that some 70% of all dense fog events were found to occur where precipitation had been observed within the previous 24 hours. When low pressure systems or fronts were moving though the area, precipitation was common before dense fog (~95% and 81%, respectively) and often at the time of dense fog onset (~66% and 53%, respectively.

Precipitation also was almost always observed within the 24-hours prior to fog occurring under low cloud base conditions. In most (76%) cases 24-hour precipitation totals were small (<0.63 cm, <0.25 inch), and in only four cases more than one inch, 25.4 cm. When precipitation was observed at or near dense fog onset, it was almost always light (97%), and usually unfrozen (86%).

The presence of regional precipitation suggests that it may be moistening the overlying atmosphere, helping precondition the low levels of the atmosphere for fog development. It is possible that precipitation at or near dense fog onset is a result of settling within a shallow fog layer rather than from deep clouds, but the depth of the cloud could not be determined for this climatology.

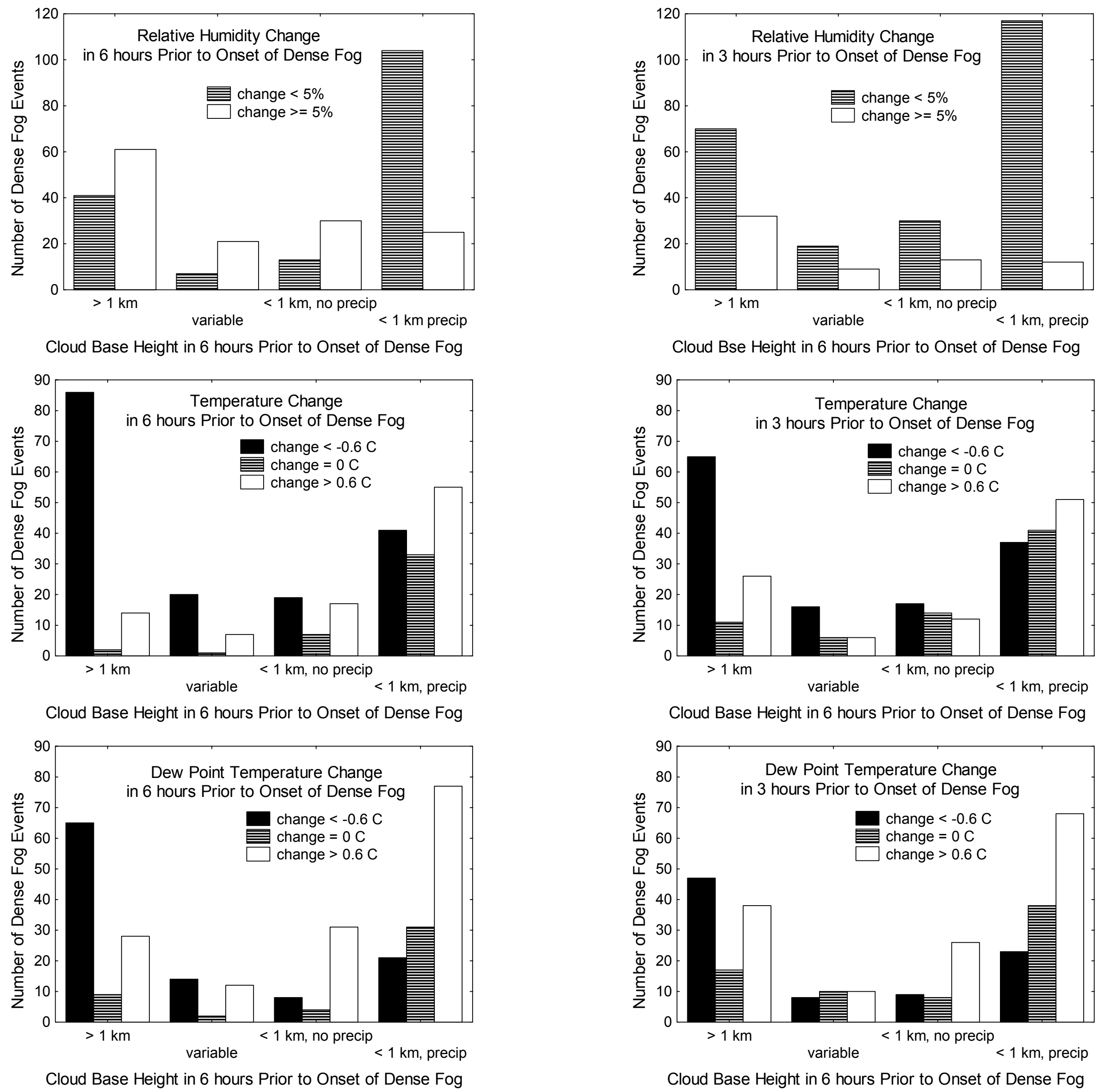

Figure 5. Frequency of relative humidity, temperature, and dew point temperature change in the 6 hours and 3-hours prior to dense fog onset for fog events for: cloud base heights >1 km, variable cloud base heights, and for cloud base heights < 1 km by precipitation occurrence at fog onset for Peoria IL, October – March 1970 - 1994.

5. Discussion and Conclusions

The majority of fog events in the Midwestern United States form when precipitation has occurred in the region and sometimes when it is still occurring and when cloud bases in the 6 hours prior to dense fog formation were less than 1000 m. Despite the frequency of these pre-fog conditions, as shown by the Peoria climatology, little quantitative work has been reported on these types of events.

For the 6-7 November 2006 dense fog event, precipitation played a critical role in the moistening of the lower atmosphere. Precipitation developed above about 3 km over a wide region of central Illinois, but based on ceilometer, radar and surface observations, evaporated before reaching the surface. This precipitation and associated moisture advection associated with a nearby cyclone led to moistening of the lowest layers of the atmosphere and lowering of the cloud base. This process pre-conditioned the atmosphere for eventual fog formation.

After precipitation ended, surface temperature remained nearly constant and the relative humidity was nearly saturated but rose slightly. The net heat flux was negligible, ~1 W/m2 in the 3 hours prior to dense fog onset. This is consistent with the near constant 2-m air temperature. The ground surface temperature also was nearly constant. There was less than a 1°C difference between the temperature at 2 m, the surface temperature, and the soil temperature at 2 cm. These observations suggest that processes at the surface likely played a minimal role in fog development. With such small differences between the ground and the 2-m air temperature and with such low wind speeds, this would not be considered to be an advection fog.

Negative net radiation fluxes of -25 to -50 Wm^{-2} at the surface are not uncommon preceding radiation fogs (e.g. Turton and Brown 1987; Fitzjarrald and Lala 1989; and Duynkerke 1991). As a fog layer forms, the level of maximum radiation flux divergence migrates to the top of the fog layer e.g. Jiusto and Lala 1980; Brown 1987; Fitzjarrald and Lala 1989. Similarly, a maximum in net radiation flux divergence has been found at the top of stratiform cloud layer (e.g. Caughey et al. 1982; Frish et al. 1995; and Nakanishi 2000). Thus, it is not unexpected that on the case study day, the net radiation flux measured at the AmeriFlux site was negligible (~0 W m^{-2}) in the three hours prior to and at dense fog onset on 7 November 2006.

Drying of the atmosphere above about 800 hPa took place (Fig. 2) as evidenced by the 7 November 2006 12 UTC (06 LT) sounding. This would allow for radiational cooling at the top of a fog (e.g. Jiusto and Lala 1980; Brown 1987; Fitzjarrald and Lala 1989) or low cloud layer (Slingo et al. 1982; Caughey, et al. 1982; Frish, et al. 1995; and Nakanishi 2000). We hypothesize that with vertical mixing, radiational cooling at fog or cloud top generates supersaturated conditions (Jiusto and Lala 1980), as radiationally cooled air from above sinks and is replaced by warmer air from below (e.g. Caughey et al. 1982; Frish et al. 1995; Nakanishi 2000). Fluctuations in wind speed and direction and momentum flux were noted in the surface data (Fig. 4), but their exact cause could not be determined.

Clearly in the pre-rain hours, cooling of the lower atmosphere resulted from the evaporation of precipitation and was evidenced by lowing of cloud bases prior to onset of rain at the surface. Without additional measurements above the surface, however, the exact cause of the dense fog is unclear. Intervening nighttime soundings would be invaluable in documenting the transition of the temperature, moisture and cloud fields aloft, as would upper air observations of net radiation.

The Peoria climatology indicates that cases where fog forms in the presence of low cloud base cases are prevalent and that fogs forming with no change in air temperature or a positive change are also common. The source of cooling in these cases is unclear, but at least for the case study day, the drying and clearing of the upper level cloudiness indicates that radiational cooling may be important. The case study observations fit well within the Peoria climatology of surface changes grouped for low cloud base heights. However, the climatology suggest that there may be varying conditions under which fog forms. Clearly further case studies that include upper air observations of cloud structure, as well as surface measurement at finer time steps would be invaluable in determining the source of cooling in the layer.

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