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An Analysis of Valley Fog Behavior at La Crosse, Wisconsin

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1. Introduction

La Crosse, Wisconsin is located in the Upper Mississippi River Valley, surrounded by 600-foot bluffs to the east and west. Its geographic location favors night-time decoupling of the planetary boundary layer from the free atmosphere, especially on clear nights with high pressure overhead. During the late summer and early fall, these nights with preferred radiational cooling can result in widespread fog development in the river valley – with visibilities of ¼-mile or less. When dense fog forms in the valley, the impact on the aviation community at the La Crosse Regional Airport (KLSE) can be significant.

Fig 1. La Crosse Regional Airport is located on French Island, between the Mississippi River (far left), Lake Onalaska (immediate left), and the Black River (immediate right). Image from Google.

An initial study of dense fog at KLSE investigated the role of evening dewpoint depression as a prognosticator of morning dense fog (Thompson 1993). This study furthers that work, by investigating various atmospheric measures that influence dense fog (¼-mile visibility or less) formation at KLSE.

2. Data

The annual climatological peak for radiational valley fog at KLSE is during the late summer into the fall months. While valley fog can occur outside this period, the occurrence is rare compared to this three-month time period. Therefore, the time period of study was confined from August 1st through October 31st for the years 2000-2010. Eleven percent of all the days within that 11-year period observed dense fog due to radiational cooling.

The 11 years of surface observational data with fog were divided into three visibility categories: ¼ statute miles or less, 1-2 statute miles, and 3-5 statute miles (hereafter referred to as 1/4SM, 1-2SM, and 3-5SM, respectively). The 1-2SM fog category consists of visibilities from ½ mile to 2 miles, while the 3-5SM group contains visibilities ranging from 2½ miles to 5 miles. The 1/4SM group was further divided by the length of time for the event: those lasting 4 or more hours, 1-3 hours, and 1 hour or less (hereafter referred to as 4 hours, 1-3 hours, and

1 hour, respectively). Eliminated from the data were fog events that 1) were not caused by radiational cooling (e.g., rainfall, clouds, or strong winds were observed), 2) where the fog was widespread and extended beyond the river valley(s) in the vicinity of KLSE, 3) that were ongoing during the prior day or evening, and 4) where the observations were not deemed of high quality. Hereafter, all references to fog formation in the text shall be represented by the criteria previously stated. The number of fog events with 5-mile visibility or less in this study totaled 176, with a peak in the 1 hour, 1/4SM category (Table 1). All observations for the August-October time range that did not contain fog were also included for comparison (referred to as "No Fog," ~ 800 observations).

4+ hour ¼ SM	1-3 hour ¼ SM	1 hour ¼ SM	1-2SM	3-5SM
28	34	53	40	21

Table 1. Number of cases in each visibility category (SM= statue miles).

To approximate the low-level wind field at KLSE, BUFR-format sounding information was used from the National Centers for Environmental Prediction's (NCEP) North American Mesoscale (NAM) and Rapid Refresh model (RAP). For all events, the initialization hour (00hr) was used from the model to approximate the state of the atmosphere at KLSE. Further, the NAM was only used when RAP data were not available. The authors acknowledge that the data used from the models could contain initialization errors on the true state of the atmosphere.

3. Methodology

Hourly surface observations were investigated at KLSE at times deemed important to an aviation forecaster, focused around Terminal Aerodrome Forecast (TAF) issuance times: 2300, 0000, 0300, 0500, and 0600 UTC. Dewpoint depression (˚F), wind speed (kt), and wind direction were investigated. The BUFR soundings were used to investigate these variables, as well as the depth of the light wind layer (10 kts or less) above the surface, for each of the 176 events. Composite soundings were also created for each of the fog categories (Appendix A).

4. Results

a. Dewpoint depression

Not surprisingly, as the dewpoint depression decreased, the more likely dense fog became. Further, a subtle 1-2˚F difference in the depression did provide value on whether fog developed and how long it lasted.

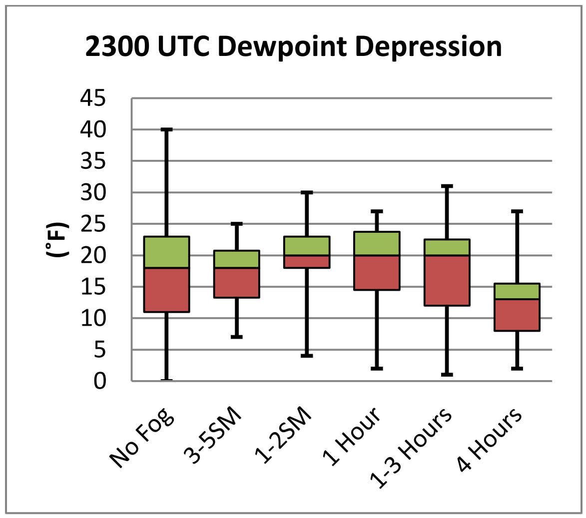


Fig. 2. Box-and-whiskers plot of the difference between the surface temperature and dewpoint (dewpoint depression) for each fog category at 2300 UTC. Each "box" represents the inter-quartile range (25th to 75th percentile) with the horizontal line through each box signifying the median value. The top and bottom of the "whiskers" represent the maximum and minimum dew point depression for each category.

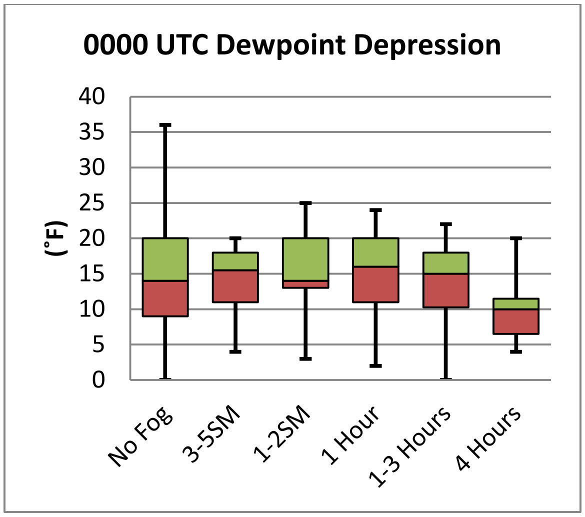


Fig. 3. Same as Fig. 2, except at 0000 UTC.

At 2300 and 0000 UTC (Fig. 2-3, respectively), the visibility categories showed little intra-hour difference, except when compared to the 1/4SM 4+ hour category. An encouraging population offset of 25% (lower) was seen for these higher-impact fog events when compared to all other categories. Dewpoint depression values over 30˚F and 25˚F at 2300 and 0000 UTC, respectively, produced dense fog in only one historical case (out of 228 possible) and should be considered a discriminator for such events. Temperature and dewpoint differences this large proved too much for radiational cooling to overcome for dense fog formation.

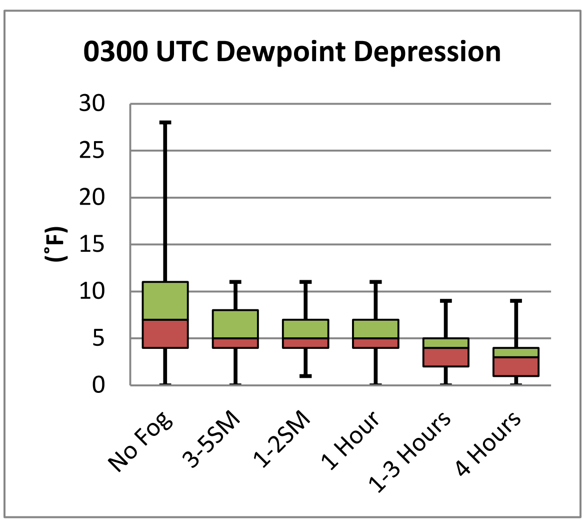


Fig. 4. Same as Fig. 2, except at 0300 UTC.

Thompson (1993) found a 7˚F dewpoint depression at 0300 UTC to be a good indicator of dense fog development overnight due to radiational cooling. In this study, 75% of the depressions were at or below 7˚F at 0300 UTC, for not only the dense fog 1/4SM 1-hour category, but also the 1-2SM category (Fig. 4). This would indicate a lower-impact fog (e.g., 1-2SM) is still possible at 7˚F. However, forecaster confidence should increase for a higher impact dense fog (1/4SM, 1-3 hour and 4+ hour) for observed depressions of 5˚F or less at 0300 UTC, with support from at least 75% of these historical events.

The 0500 UTC and 0600 UTC observations continued the downward trend toward saturation, with 4˚F and 3˚F dewpoint depressions at 0500 and 0600 UTC, respectively, favoring dense fog. When depressions were greater than 5˚F at these times, dense fog was highly unlikely.

Overall, mid-evening or later (e.g., 0300 UTC) dewpoint depression is a good indicator on whether dense fog, especially of higher impact (4+ hours), is probable at the La Crosse Airport. A 5˚F spread by 0300 UTC should provide the aviation forecaster with added confidence in a higher impact (e.g., longer duration), ¼-mile-or-less visibility fog by morning.

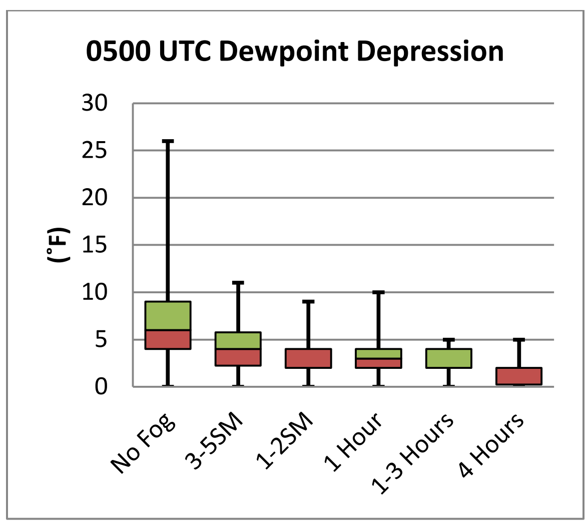


Fig. 5. Same as Fig. 2, except at 0500 UTC.

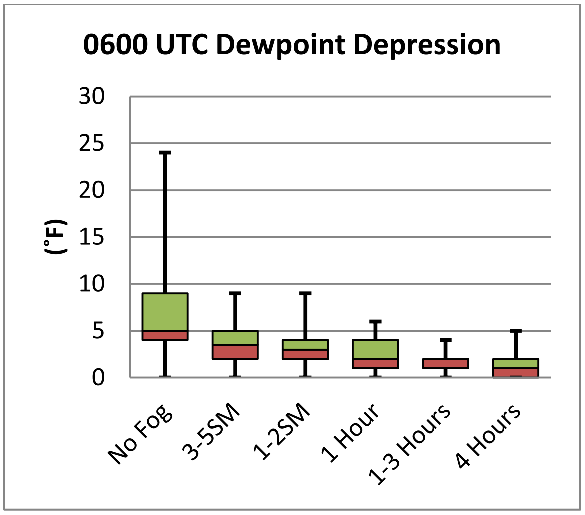


Fig. 6. Same as Fig. 2, except at 0600 UTC.

b. Surface Wind Speed

Very similar general findings to the dewpoint depression were found in the surface wind analysis: the lighter the evening winds, the greater the potential for dense valley fog at KLSE.

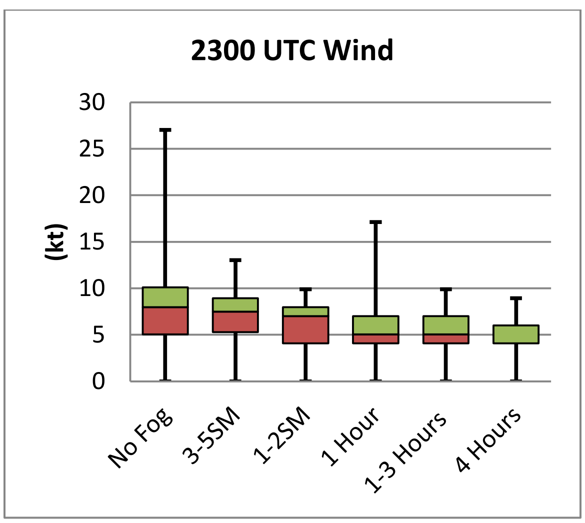


Fig. 7. Box-and-whiskers plot of the surface wind speed in knots for each fog category at 2300 UTC. Each "box" represents the inter-quartile range (25^{th} to 75^{th} percentile) with the horizontal line through each box signifying the median value. The top and bottom of the "whiskers" represent the maximum and minimum wind speed for each category.

The 2300 and 0000 UTC observations (Figs. 7 and 8) highlight 7 kts as a threshold where the probabilities (>75% of the historical events examined) suggest dense fog formation should be strongly considered for the following morning. Wind speeds above 10 kts suggest valley fog is highly unlikely.

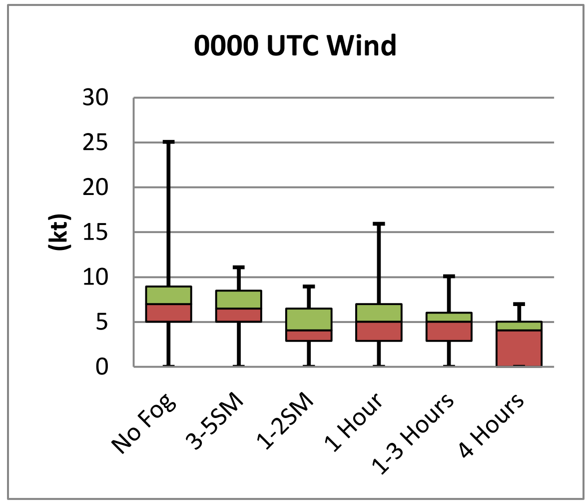


Fig. 8. Same as Fig. 7, except at 0000 UTC.

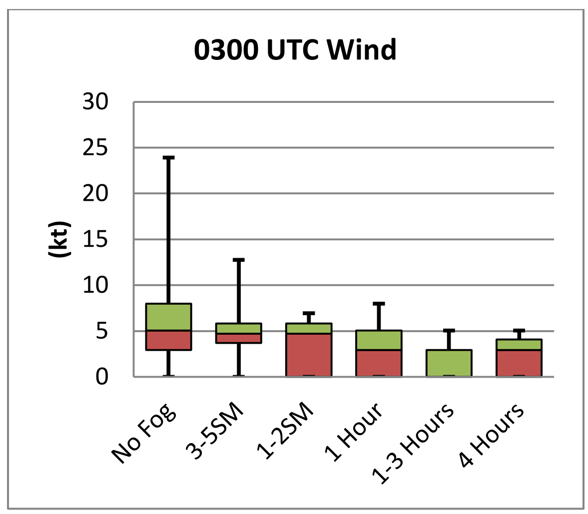


Fig. 9. Same as Fig. 7, except at 0300 UTC.

By 0300 UTC (Fig. 9), the data set showed a distinct, albeit small, decrease in wind speed for favorable valley fog conditions. Dense fog rarely occurred when wind speeds at 0300 UTC were above 5 kts, with dense fog events lasting more than one hour all having surface winds of 5 kts or less. Further, wind speeds over 7 kts are very unlikely to produce Instrument Flight Rule visibility (IFR, visibility < 3 miles) fog events. When only surface wind speed is considered, the populations ranging from 3-5SM to high-impact dense fog had very small differences of only 2 kts.

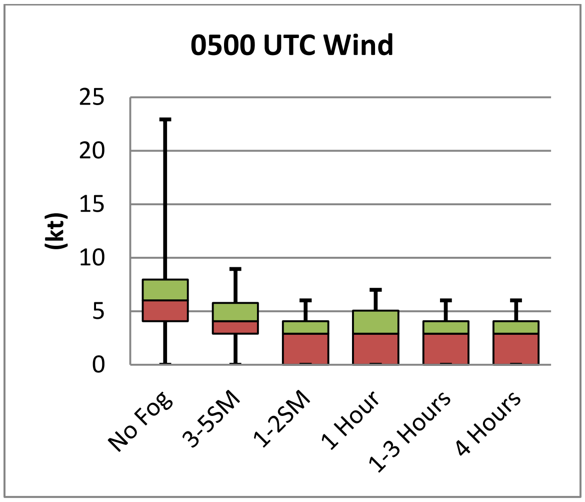


Fig. 10. Same as Fig. 7, except at 0500 UTC.

By 0500 and 0600 UTC (Figs. 10 and 11), there was even less discrimination across the fog visibility classes at or below 1-2SM. Generally, 3 kts or less is a favored speed for fog in these categories, while 5 kts or greater will likely result in no fog. Thus, surface wind speed alone at 0500 and 0600 UTC cannot be used as a dense fog indicator.

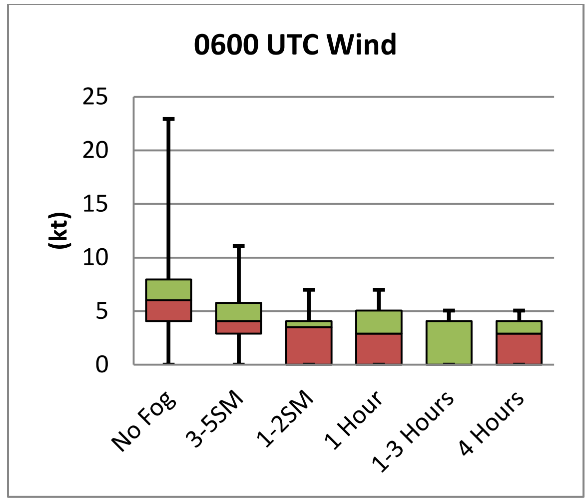


Fig. 11. Same as Fig. 7, except at 0600 UTC.

Overall, surface wind speed is a good indicator for whether fog will develop. However, the subtlety of only a 1-2 knot difference between 1-5SM fog and 1/4SM fog diminishes its utility as a solo predictor of dense fog.

c. Surface Wind Direction

Southeast winds were generally favored for dense fog, with most events occurring in the 110-150˚ range (Fig. 12). Due to the geography of the river valley and airport, this is a preferred wind direction to advect fog from over the Black River, to across the KLSE airfield. This wind direction is a common cold-air drainage flow from surrounding terrain on radiational cooling nights. By 1200 UTC, most winds become calm.

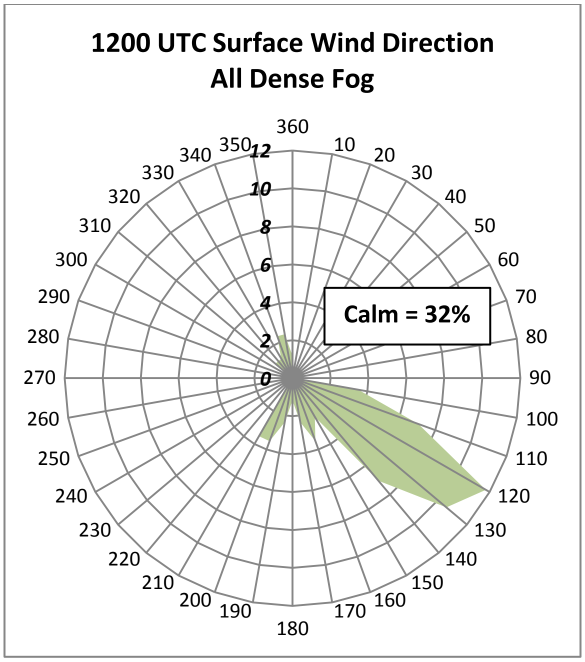


Fig. 12. Surface wind direction frequency (percent) for all 1/4SM category observations at 1200 UTC. Calm winds were the most frequent (e.g., 32% of the observations).

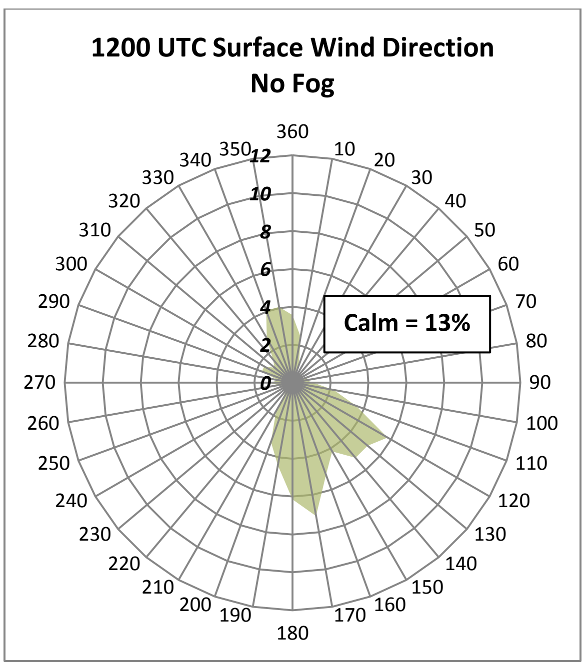


Fig. 13. Same as Fig. 12, except for the "No Fog" cases. Calm winds occurred in 13% of the cases.

Northwest winds were shown to be a deterrent to fog formation in most cases. In several instances where ¼-mile fog was observed at KLSE, the visibility improved (e.g., generally became 1-mile or greater) within an hour of the wind direction becoming northwest. This north signal, as well as less preference for calm or southeast winds is noted in the "No Fog" observations (Fig. 13).

d. Light Wind Layer Depth

While the speed of the surface winds showed predictive skill on dense fog formation, the depth of the light wind layer also showed an influence on fog formation in the river valley. For the purposes of this study, the depth of the light wind layer was defined as the level above the surface at which wind speeds greater than 10 kts were observed at more than two consecutive vertical levels in the model analysis sounding.

At 0000 UTC, the light wind layer depth varied widely across the various categories, and generally, a depth of 600 ft or less does not favor dense fog (Fig. 14). As the depth of the layer increases above 2000 ft, dense fog formation becomes more probable.

By 0600 UTC (Fig. 15), trends become quite evident in the categories. The non-dense fog events continue to support very low depths of light wind (generally 600 ft or less) while the median depth continued to increase as the fog became more dense and longer-lived. For the dense fog categories, a majority of the historical events occurred with depths over 1000 ft.

These trends continue through 1200 UTC (Fig. 16) with the median light wind layer depth increasing above 2000 ft. One notable change is the increase in depth of the 4+ hour dense fog events; the light wind layer increased to over 3000 ft for 75% of these cases. The offset in this category, compared to the 1-2SM, 1/4SM 1-hour and 1–3-hour categories is more than a quartile, suggesting the parameter has more skill in predicting the highest of impact dense fog events.

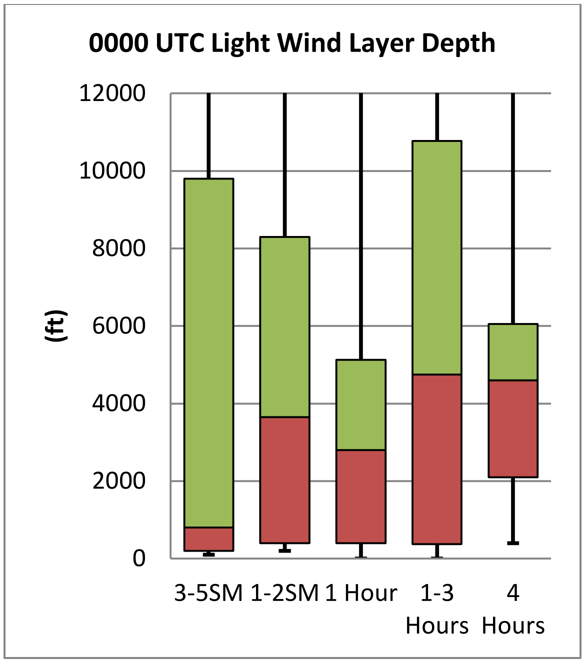


Fig. 14. Box-and-whiskers plot of the light wind layer depth (10 knots or less) for each fog category at 0000 UTC. Each "box" represents the inter-quartile range (25th to 75th percentile) with the horizontal line through each box signifying the median value. The top and bottom of the "whiskers" represent the maximum and minimum depth for each category. For some fog categories, the maximum depth exceeds the top value on the plot.

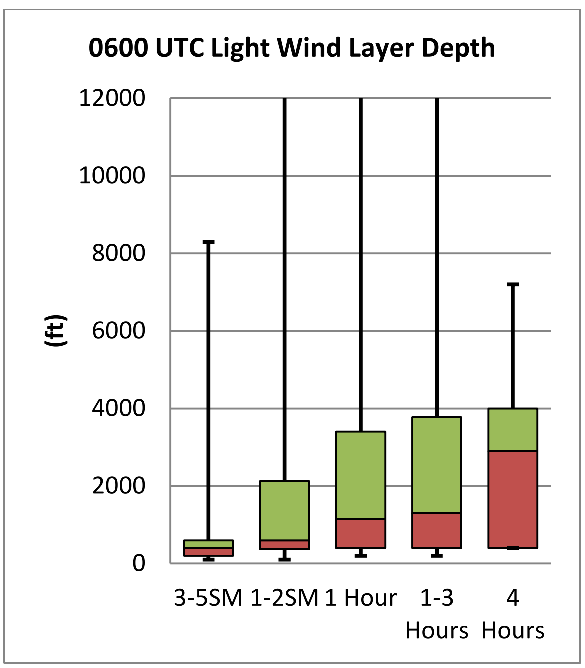


Fig. 15. Same as Fig. 14, except at 0600 UTC.

In summary, at least a 2000-foot depth to the light wind layer provides a good target for dense fog cases, while 600 ft or less generally precludes fog. If a light wind layer depth reaches 3000 ft by 1200 UTC, dense fog appears more likely. The earlier this deep layer sets up in the evening, the more likely that the dense fog event will be long-lived.

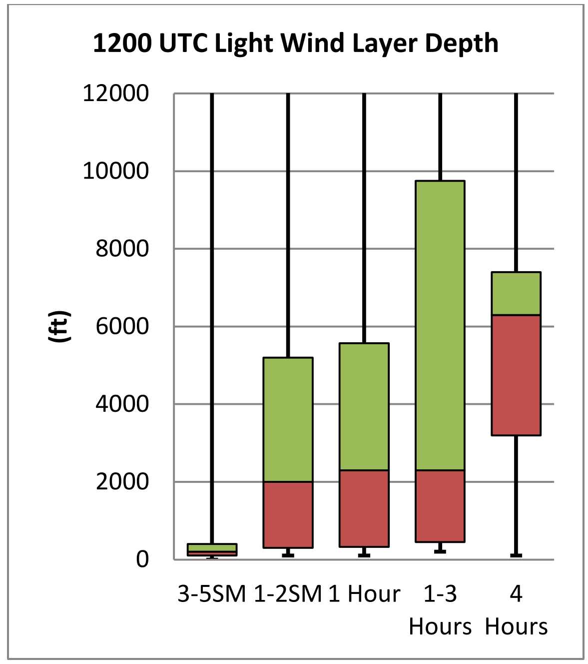


Fig. 16. Same as Fig. 14, except at 1200 UTC.

e. Other Potential Fog Influences

1) RAINFALL

Rainfall can serve as a moisture source to help saturate the boundary layer. So, it would seem to follow that rain would be a supporting factor in fog formation. A comparison of valley fog development and rain the previous day does not support this hypothesis. In the data examined for this study, on mornings with fog, rainfall occurred on the previous day at a lower percentage when compared to non-fog days and climatology (Table 2).

No Fog	Any Fog	Dense Fog	Any Fog: Climatology
32%	23%	26%	30%

Table 2. Percentage of days with/without fog when measurable rainfall occurred the prior day. Also included is the climatology for the number of days when fog was observed. Climatology is from 1872-2014, August-October.

There are likely many synoptic-scale reasons for the differences - frontal passage, abundant cloud cover, stronger winds, etc. While rainfall may assist and enhance fog formation, used alone it is not a good predictor of dense fog formation in radiational-cooling cases.

2) RIVER WATER TEMPERATURES

The temperature difference between the water temperature of the Mississippi River at the nearest point to KLSE (Lock and Dam 7 near La Crescent, Minnesota on the west side of Mississippi River adjacent to the airport), and the KLSE air temperature were compared to the study's valley fog events. The temperature difference showed no correlation between fog, dense fog, and non-fog events. The difference between the water temperature and air temperature varied greatly within each category, not showing any predictive skill for dense fog development (not shown).

3) MODIFIED RICHARDSON NUMBER

The modified Richardson number (MRi) was developed by United Parcel Service (UPS) to quantify boundary layer turbulent mixing (Baker et al. 2002):

$$MRi = (Tb - Tsfc)/u2$$

where Tb is the boundary layer temperature forecast (˚C), Tsfc is the shelter temperature forecast (˚C), and u is the boundary layer wind speed (kts). The MRi is used as a fog forecasting aid and was investigated in this study to quantify boundary layer mixing. The UPS guidelines suggest an MRi of 0.040 or greater for fog.

Using composite soundings for the visibility categories, the MRi showed some skill for indicating conditions favorable for fog development (Table 3 & 4). MRi values near 0.060 were observed for the dense fog category as early as 0600 UTC, while those values for the 1-2SM category appeared later in the night (e.g., closer to 1200 UTC). This trend suggests the duration of higher MRI (e.g., ~0.060) is important to dense fog formation and could help as a predictor. Higher visibility fog MRi values were generally 0.020 or lower.

Dense Fog MRi	**4 Hour**	**1-3 Hour**	**1 Hour**
00 UTC (00h)/ 12 UTC (12h fcst)	.020/ .058	.006/ .059	.005/ .067
06 UTC (00h)/ 12 UTC (6h fcst)	.062/ .060	.083/ .077	.050/ .058
12 UTC (00h)	.066	.061	.078

Table 3. Dense fog MRi from composite soundings. For 0000 and 0600 UTC, the first value is at model initiation, the second is the forecast valid at 1200 UTC.

MRi	**1-2 SM**	**3-5 SM**
00 UTC (00h)/ 12 UTC (12h fcst)	.010/ .049	.024/ .020
06 UTC (00h)/ 12 UTC (6h fcst)	.033/ .044	.018/ .015
12 UTC (00h)	0.64	.018

Table 4. Non-dense fog MRi from composite soundings. For 0000 and 0600 UTC, the first value is at model initiation, the second is the forecast valid at 1200 UTC.

8. Summary

Fog is a common occurrence in parts of the Upper Mississippi River Valley during the late summer-early fall months. When it spreads away from the river's main channel into the larger valley, it can reduce visibilities at the La Crosse Municipal Airport, impacting aviation.

An analysis of historical surface observations and BUFR model soundings for an 11-year period at KLSE showed there was a relationship between dense fog formation, dew point depression, surface winds, and depth of the light wind layer.

Small differences in both the dewpoint depression and surface wind speed have a substantial impact on whether dense fog would form, and how long it would last. In some cases, a change of just 1-2˚F or 1-2 kts was the difference between dense fog or no fog.

The depth of the light wind layer also displayed skill in answering the dense fog question. BUFR model analysis soundings showed that a shallow light wind layer acts to inhibit dense fog formation, while a deep layer of light winds, especially if it exceeds 2000 ft, promotes dense fog. Longer duration, higher impact dense fog becomes more probable if the light wind layer exceeds 3000 ft.

Composite soundings were used to assess the evolution and skill of the MRi in predicting river valley fog at KLSE. Forecasters should key on MRi values approaching .060, with dense fog more probable the earlier these values are achieved in the overnight hours (e.g., 0600 UTC).

While this study found discriminators to aid in forecasting dense fog, other variables were investigated and found to be less useful. Rainfall on the day prior to dense fog, when evaluated independently, did not show any predictive skill, occurring at about the same rate as non-fog days and climatology. The difference between the nearby river water temperature and air temperature also proved to be a non-factor. Also of interest was the disparity in dense fog to non-dense fog cases – nearly 2:1. This suggests that if river valley fog is going to occur due to radiational cooling, ¼-mile visibilities are more likely.

Overall, keying in on the dewpoint depression, surface wind speeds, MRi duration, and depth of the light wind layer will assist the aviation forecaster in predicting dense fog at KLSE. Confidence in forecasting these events should increase, resulting in higher predictability, improved lead times, and better service to the aviation community. A forecaster aid has been included summarizing the study findings for use in operational aviation forecasting for KLSE (Appendix B).

9. Acknowledgements

Thank you to Andrew Just for compiling the composite soundings.

10. References

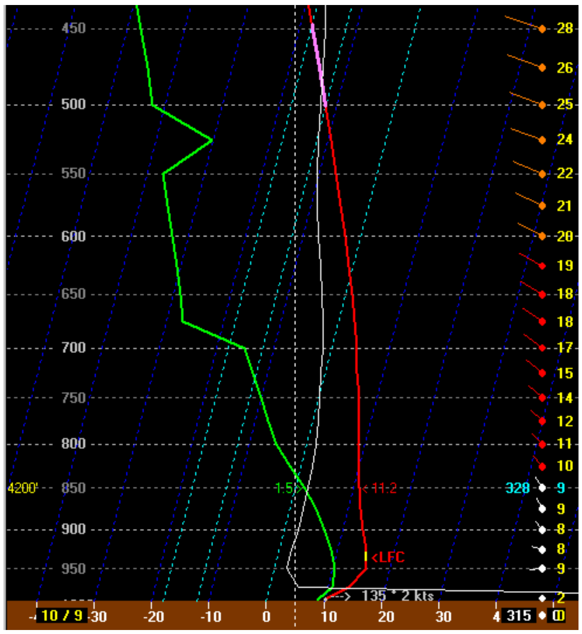
Baker, R., J. Cramer, and J. Peters, 2002: Radiation Fog: UPS Airlines Conceptual Models and Forecast Methods. *10th Conference on Aviation, Range, and Aerospace Meteorology*, Portland, OR, Amer. Meteor. Soc., 5.11. [Available online http://ams.confex.com/ams/pdfpapers/39165.pdf.]

Thompson, S. , 1993: "Forecasting Dense Fog at La Crosse, WI". NOAA/NWS/Central Region Technical Attachment 93-15.

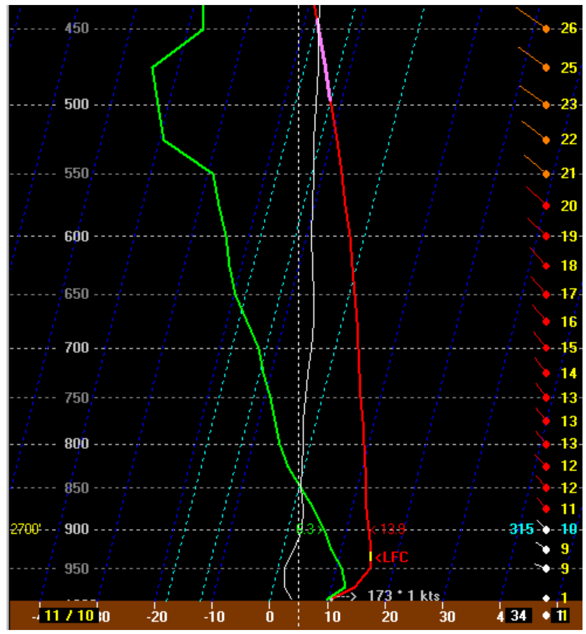
Appendix A

1200 UTC composite BUFR soundings at KLSE utilizing NAM and RAP initialization data for each fog category investigated.

Dense Fog Cases (¼ SM or less)

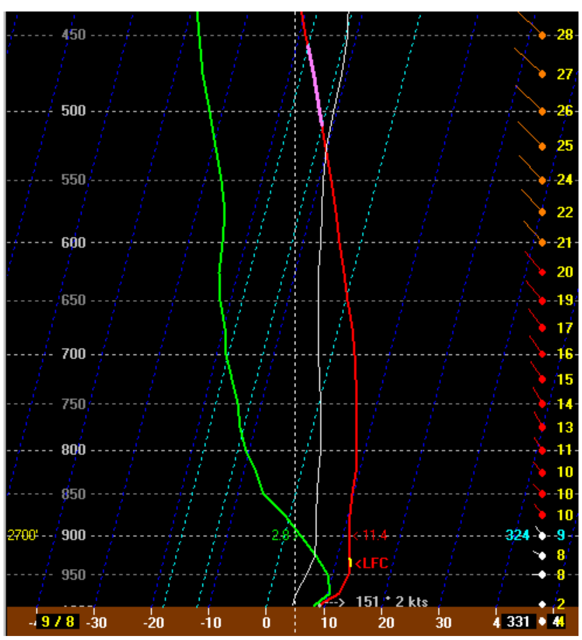


1 Hour

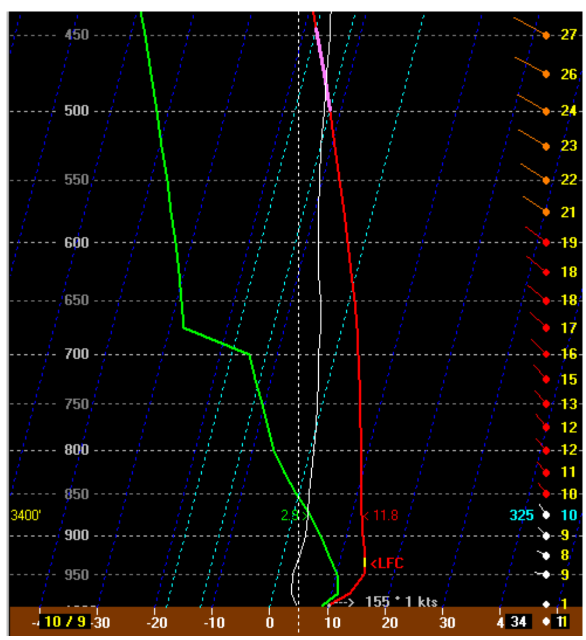


1-3 Hours

Dense Fog Cases (¼ SM or less)

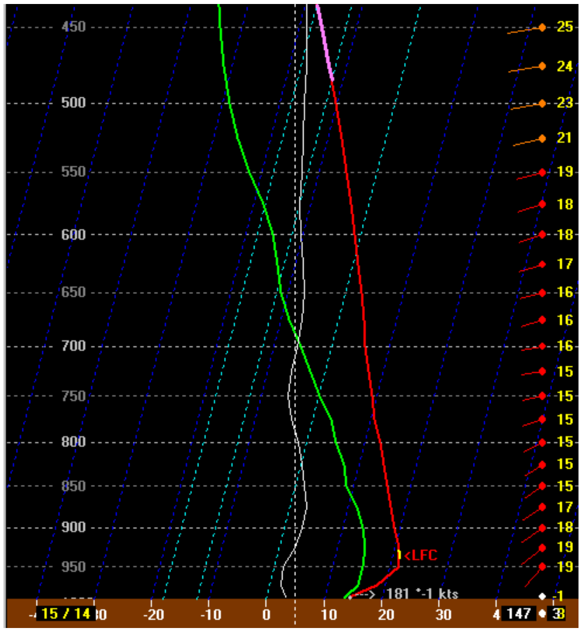


4 Hour

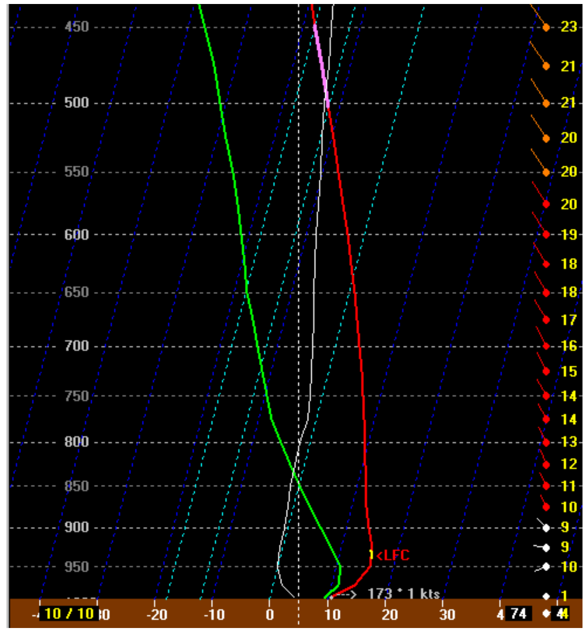


ALL Cases

1-5 SM Fog Cases



3-5 SM



1-2 SM

Appendix B

Decision aid for assessing ¼-mile fog potential at La Crosse, WI (KLSE). "Best for 1/4SM" category would suggest a longer-duration fog.

Hour (UTC)	SFC Dewpoint Depression (˚F)	SFC Wind Speed (kts)	Light Wind Layer Depth (<=10 kts)	MRi	Dense Fog?
2300	< 15F < 25F >= 30F	<= 6kts <= 10 kts >= 18 kts			Best for 1/4SM Better for 1/4SM No 1/4SM
0000	<= 10F <= 20F >= 25F	<= 5 kts <= 10 kts >= 15 kts			Best for 1/4SM Better for 1/4SM No 1/4SM
0300	<= 5F <= 7F >= 12F	<= 3 kts <= 5 kts >= 8 kts			Best for 1/4SM Better for 1/4SM No 1/4SM
0500	<= 3F <= 5F > 10F	<= 3 kts <= 5 kts >= 7 kts			Best for 1/4SM Better for 1/4SM No 1/4SM
0600	<= 2F <= 4F > 6F	<= 3 kts <= 5 kts >= 7 kts		>= 0.060 ~0.050 < ~0.035	Best for 1/4SM Better for 1/4SM No 1/4SM
1200			> 4000 ft > 2000 ft < 600 ft *	>= 0.060 ~0.050	Best for 1/4SM Better for 1/4SM No 1/4SM

*** There are cases when dense fog has occurred with light wind layers this shallow at 1200 UTC. In those cases, the 0000-0600 UTC time frame usually had a deeper light wind layer. These values should be used as guides and in concert with dewpoint depression and other variables.**