J3.7 THE MESOSCALE IMPACT OF OKLAHOMA'S WINTER WHEAT BELT

Renee A. McPherson *
Oklahoma Climatological Survey, Norman, Oklahoma

David J. Stensrud
NOAA/National Severe Storms Laboratory, Norman, Oklahoma

Kenneth C. Crawford
Oklahoma Climatological Survey, Norman, Oklahoma

1. INTRODUCTION

The quantity, type, and condition of vegetation strongly influence the fluxes of energy, momentum, and moisture in the atmospheric boundary layer (Taylor and Lebel 1998). Vegetation affects the surface albedo and, hence, the amount of net radiation entering the surface energy budget. The partitioning of this incoming energy into latent and sensible heat fluxes is determined, in part, by the amount of evapotranspiration from plants (Mahfouf et al. 1987; Collins and Avissar 1994). These fluxes, in turn, influence the temperature and moisture profiles in the lower atmosphere. In addition, evapotranspiration and photosynthesis affect the exchange of water vapor and carbon dioxide near the land surface (Cihlar et al. 1992).

At the mesoscale, the differences in surface fluxes over vegetation and over dry, bare soil can result in differential heating that generates a sea breeze-like circulation, or a "vegetation breeze" (Mahfouf et al. 1987; Segal et al. 1988). Observations indicate that vegetation breezes and other "inland breeze" circulations can have an appreciable effect on the formation of shallow cumulus clouds (Garrett 1982; Cutrim et al. 1995). Numerical simulations denote that these circulations can provide preferred regions for focusing atmospheric instabilities and initiating convective development (Garrett 1982; Mahfouf et al. 1987; Chang and Wetzel 1991; Chen and Avissar 1994).

These studies and others highlight that mesoscale areas of vegetation can alter the mesoscale environment. Nevertheless, many previous studies are limited in their real-world applicability. Past observational studies have focused on specific events or case studies (e.g., Segal et al. 1989), relatively short time periods (e.g., LeMone et al. 2000), or small regions (e.g., Smith et al. 1994). The authors have acknowledged these restrictions and have attributed them to a dearth of long-term, mesoscale observations across a large area. This study helps to fill this void in adequate measurements by using surface data from the Oklahoma Mesonet in observational experiments. Consequently, this research further delineates the magnitude and scale (in both space and time) whereby a crop belt can alter the near-surface environment.

Winter wheat, which accounts for about three-fourths of U.S. wheat production, is sown in the fall and harvested in the late spring or early summer. During early spring, a mature wheat crop forms a swath about 150 km wide that extends from southwest Oklahoma into north-central Oklahoma and southern Kansas (Rabin et al. 1990; Markowski and Stensrud 1998). The density of the wheat fields increases from the Oklahoma-Texas border, where summer crops or grasslands are interspersed with wheat crops, to the Oklahoma-Kansas border, where about 90% of the land is used for growing wheat. On either side of this band of non-irrigated cropland is sparse or dormant vegetation, especially across extreme western Oklahoma and the Panhandle. During the late spring or early summer, after growers harvest the wheat, previously dormant grassland grows. The result is a band of short stubble and bare soil surrounded by mature prairie grasses.

Oklahoma's wheat belt affords scientists the unique opportunity to study the impact of a band of either abundant or sparse vegetation when compared to adjacent lands. Just as important, the width of this band is consistent with the preferred scale for mesoscale vegetation breeze circulations – the local Rossby radius of deformation (Anthes 1984; Pielke et al. 1991; Chen and Avissar 1994). Thus, Oklahoma is an optimal real-world environment for examination of mesoscale vegetative impacts on the atmosphere.

This study examines whether monthly and daily averaged surface temperature and moisture fields are significantly affected by the evolution (e.g., during growth and within one month after harvest) of Oklahoma's winter wheat crop. Section 2 overviews the data used in this study, including Oklahoma Mesonet observations, land cover information, visual greenness, and county yields of Oklahoma wheat. Sections 3, 4, 5, and 6 present results, conclusions, acknowledgments, and references, respectively.

2. DATA

2.1 *Definition of Oklahoma's Wheat Belt*

For the current study, the *winter wheat belt* is defined as the swath of land across Oklahoma and Kansas that was characterized by either winter wheat

*Corresponding author address: Renee A. McPherson, Oklahoma Climatological Survey, Univ. of Oklahoma, Norman, OK 73019-1012; e-mail: renee@ou.edu.

or a winter wheat/grassland mix as the land use type designated by the U.S. Geological Survey (USGS). *Oklahoma's wheat belt* is defined as that subset of the winter wheat belt located solely within Oklahoma. The location and extent of Oklahoma's wheat belt is depicted in Fig. 2.1. Only the impact of Oklahoma's wheat belt was analyzed in this observational study.

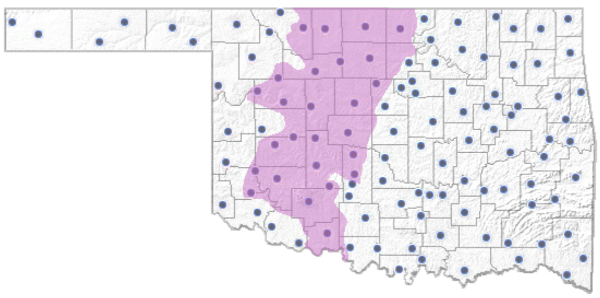

Figure 2.1. Map of the measurement sites of the Oklahoma Mesonet (dots). The shaded region (violet) represents Oklahoma's winter wheat belt, as defined for this study.

Land cover characterized as winter wheat or a mix of grassland and winter wheat was outlined and used as the definition of the border of Oklahoma's wheat belt. The land cover characterization was from the North America Land Cover Data Base from the USGS. The data base was constructed from Advanced Very High-Resolution Radiometer (AVHRR) data spanning April 1992 through March 1993. It has a 1–km nominal spatial resolution and is georeferenced in a Lambert Azimuthal Equal Area projection (Loveland et al. 1999).

2.2 *Observational Data*

This observational study utilizes land and atmospheric surface layer measurements from over 110 automated sites in the statewide Oklahoma Mesonet (http://www.mesonet.ou.edu; Brock et al. 1995). The Mesonet dataset extends from 1994 to the present and includes the following variables at every station: air temperature at 1.5 m, relative humidity at 1.5 m, wind speed and direction at 10 m, rainfall, station pressure, incoming solar radiation, soil temperature at 10 cm under both bare soil and natural sod cover. Additionally, 9-m air temperature, 2-m wind speed, 5-cm soil temperature under both bare soil and sod, and 30-cm soil temperature under sod have been measured by at least half of the Mesonet sites. All above-ground measurements are reported every five minutes; soil temperature measurements are reported every 15 minutes.

Quality control of the data is accomplished in several steps. First, laboratory personnel calibrate all Mesonet sensors prior to deployment in the field. Second, field technicians visit each site at least three times per year to clean equipment, mow vegetation, and conduct sensor intercomparisons. Third, the Mesonet central computer system operates an extensive set of automated quality assurance routines. These routines are detailed by Shafer et al. (2000) and include step, range, persistence, like-sensor, and nearest neighbor tests. Finally, a quality assurance meteorologist manually examines the data.

2.3 *Visual Greenness*

The growth and condition of the winter wheat crop was monitored through the use of a visual greenness product derived from the normalized difference vegetation index (NDVI). NDVI is defined as follows:

$$\text{NDVI} = (NIR - red) / (NIR + red),$$

where *NIR* is the amount of energy measured in the near-infrared spectral band and *red* is the amount of energy measured in the red portion of the spectrum.

Visual greenness depicts the state of greenness of the vegetation compared to a very green reference, such as an alfalfa field. Wet or densely vegetated areas appeared green, and dry or sparsely vegetated areas appeared red to tan. Values ranged from 0 to 100 percent. To generate this product for each week of Crop Year 2000, seven days of NDVI observations were composited at each pixel; the highest value of NDVI during each week was used.

A relationship between visual greenness and the extent and maturity of the winter wheat crop was demonstrated by comparing a visual greenness map from late in the growing season (April) with the winter wheat production from Crop Year 2000.

3. RESULTS

The following observational analyses of monthly, daily, and instantaneous (i.e., during a given five-minute measurement period) anomalies in the variable fields measured at Oklahoma Mesonet sites were used to quantify the impact of the winter wheat belt on the mesoscale environment.

3.1 *Overview of a Wheat Crop Year in Oklahoma*

An overview of the development of Oklahoma winter wheat will aid in the interpretation of all results. Because these results discuss Year 2000 data, the 1999-2000 winter wheat crop year is reviewed.

Figure 3.1 displays a subset of weekly maps of visual greenness from Winter 1999 through Summer 2000. "Green-up" of the winter wheat fields commenced at the end of October 1999 (Figs. 3.1*a*,*b*) and was followed by rapid crop growth during November (Fig. 3.1*c*). Crop dormancy began during December (Fig. 3.1*d*); the crop's visual greenness slowly decreased from December 1999 through February 2000 (Figs. 3.1*d*,*e*,*f*). Green-up rapidly recommenced during early March (Fig. 3.1*g*); visual greenness values steadily increased to a maximum during mid-April (Fig. 3.1*h*). By early May, wheat became senescent and other species of vegetation started to grow (Fig. 3.1*i*), masking the boundaries of the wheat belt. A minimum in visual greenness values across the wheat belt became noticeable during late May (Fig. 3.1*j*), coincident with the onset of the harvest of Oklahoma's winter wheat. By June, the disappearance of growing wheat was manifest by a distinct minimum in visual greenness (not shown). Except for the growth of other species near several river beds that cross the wheat belt, growing vegetation within the wheat belt remained sparse throughout the summer (Figs. 3.1*k*,*l*).

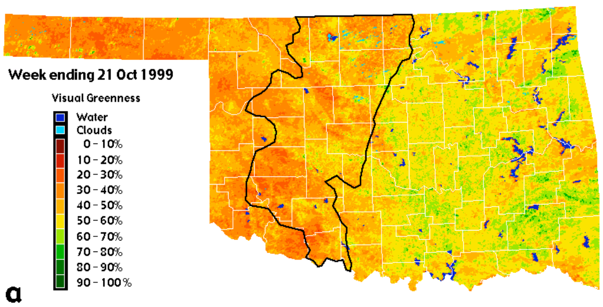

Figure 3.1*a*. Map of visual greenness for the week ending 21 October 1999. Wet or densely vegetated areas appear green, and dry or sparsely vegetated areas appear red to tan. The black outline represents the boundary of Oklahoma's winter wheat belt.

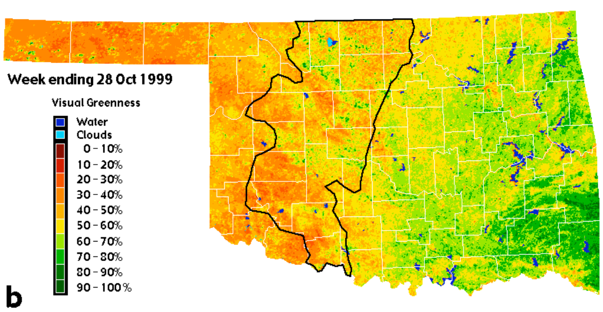

Figure 3.1*b*. Same as Fig. 3.1*a* except for the week ending 28 October 1999.

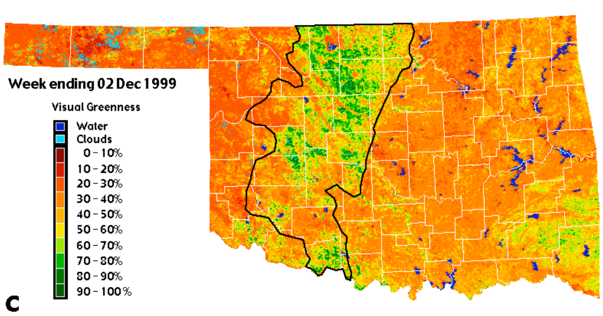

Figure 3.1*c*. Same as Fig. 3.1*a* except for the week ending 2 December 1999.

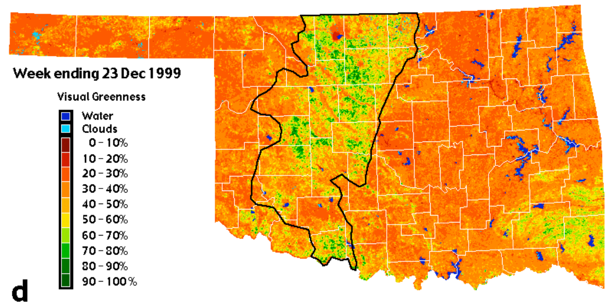

Figure 3.1*d*. Same as Fig. 3.1*a* except for the week ending 23 December 1999.

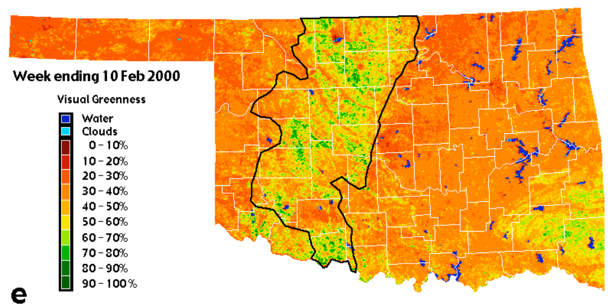

Figure 3.1*e*. Same as Fig. 3.1*a* except for the week ending 10 February 2000.

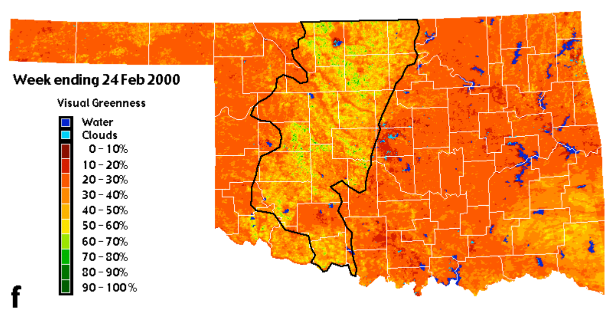

Figure 3.1*f*. Same as Fig. 3.1*a* except for the week ending 24 February 2000.

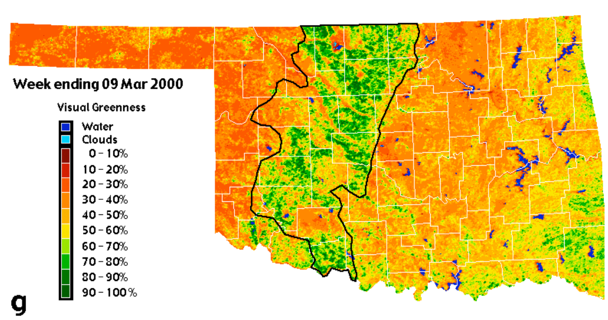

Figure 3.1*g*. Same as Fig. 3.1*a* except for the week ending 9 March 2000.

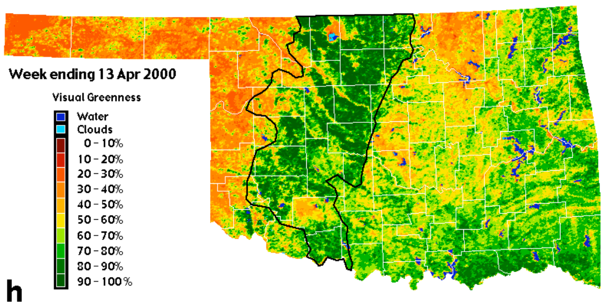

Figure 3.1*h*. Same as Fig. 3.1*a* except for the week ending 13 April 2000.

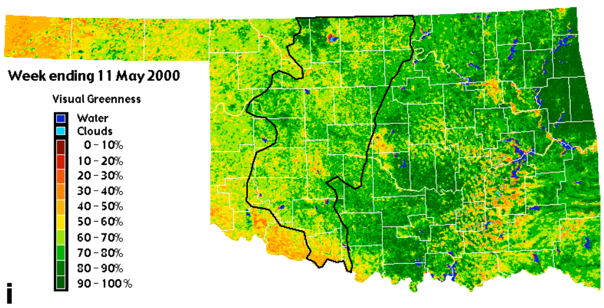

Figure 3.1*i*. Same as Fig. 3.1*a* except for the week ending 11 May 2000.

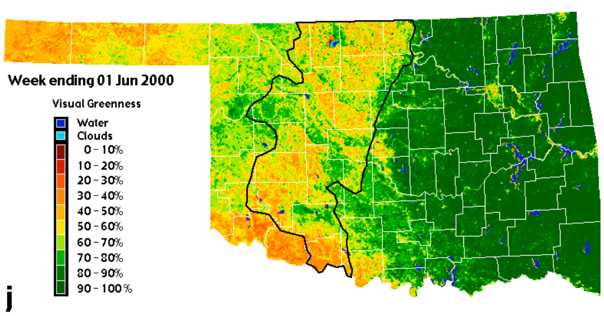

Figure 3.1*j*. Same as Fig. 3.1*a* except for the week ending 1 June 2000.

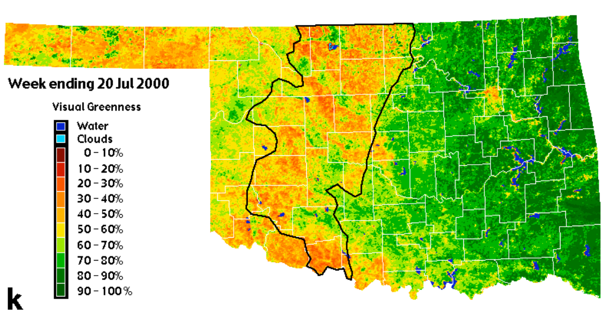

Figure 3.1*k*. Same as Fig. 3.1*a* except for the week ending 20 July 2000.

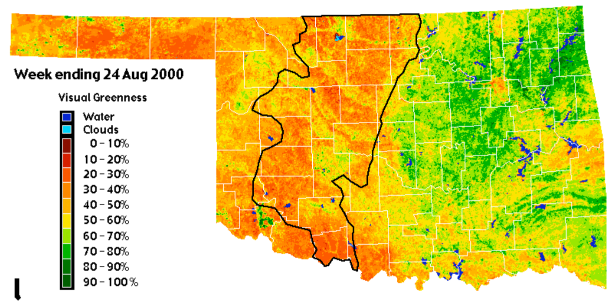

Figure 3.1*l*. Same as Fig. 3.1*a* except for the week ending 24 August 2000.

3.2 *Monthly Anomalies*

To determine whether Oklahoma's wheat belt significantly altered the mesoscale environment, monthly averages of several variables were calculated at every Mesonet site. If the wheat belt's influence occurred rarely (e.g., on days with unusual environmental conditions), then monthly averages should not reveal a distinct pattern of change across the wheat belt. If, however, the wheat belt frequently or continually affected its environment, then its location should be evident in the monthly averaged data.

For this study, TMAX and TMIN were defined as the maximum and minimum daily air temperatures (in ˚C), respectively. Similarly, DMAX and DMIN were the maximum and minimum daily dew points (in ˚C), respectively. In addition, VDEF was the average daily vapor deficit (in mb). All derived variables were applicable at 1.5 m above ground and were calculated for midnight to midnight Central Standard Time (CST; CST = UTC – 6 h). A one-pass Barnes analysis (Barnes 1964) was employed to obtain gridded data for contour maps (e.g., Fig. 3.2).

A distinct minimum (i.e., thermal trough) in the values of monthly averaged TMAX was collocated with the winter wheat belt during November (Fig. 3.2*a*), a month previously noted to be a period of rapid wheat growth. From 1994 through 2001 (not shown), a minimum consistently appeared in maps of monthly averaged TMAX for November. Monthly averaged values of TMAX for the period of December 1999 (not shown) through April 2000 (Fig. 3.2*b*) displayed a similar cool bias over the dormant or growing wheat. The most pronounced latitudinal gradient of TMAX values across the wheat belt (about 1-1.5˚C over 80-100 km) occurred across north-central Oklahoma, including Grant, Garfield, and Alfalfa counties. These same counties recorded the highest wheat production during Crop Year 2000 (Fig. 3.3).

During May 2000, TMAX values across Oklahoma no longer exhibited a distinct cool anomaly (not shown). As demonstrated earlier, May was identified as the month when other vegetative species greened rapidly statewide (Fig. 3.1*i*). By June 2000, the month when the wheat harvest concluded (not shown), a warm anomaly had developed and remained evident in the data through July (Fig. 3.2*c*) and August (Fig. 3.2*d*). Although the July warm anomaly persisted from year to year, the TMAX pattern during August typically was disorganized. During August, vegetation became senescent or was consumed by cattle across the western half of Oklahoma. Monthly averaged values of TMAX during September and October 2000 (not shown) did not reveal any definitive anomaly across the wheat belt.

Monthly averaged values of TMIN (not shown) exhibited the marriage of a latitudinal temperature gradient (i.e., temperature increased as latitude decreased) and an elevation gradient (i.e., temperature increased as elevation decreased). Hence, the warmest monthly averaged values of TMIN occurred across southeast Oklahoma, corresponding to the lowest elevation and the most southern latitude in Oklahoma.

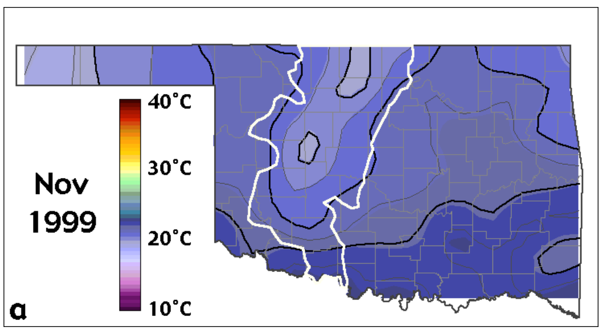

Figure 3.2a. Map of the monthly averaged values of TMAX (maximum daily air temperature) during November 1999. The white outline represents the defined boundary of Oklahoma's winter wheat belt.

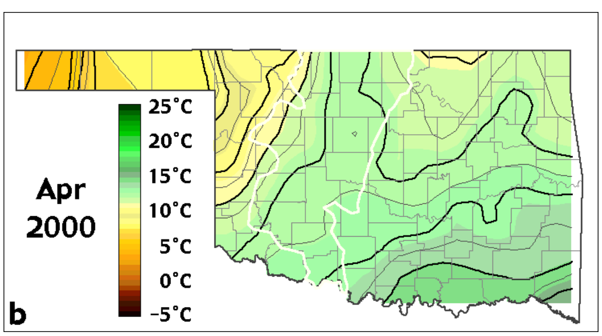

Figure 3.2b. Same as Fig. 3.2a except for April 2000.

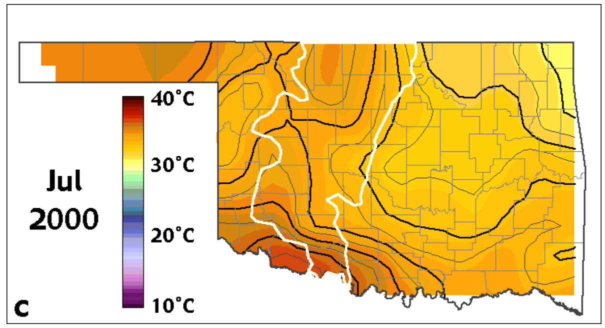

Figure 3.2c. Same as Fig. 3.2a except for July 2000.

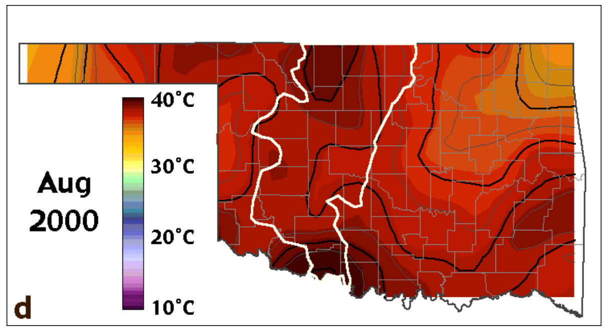

Figure 3.2d. Same as Fig. 3.2a except for August 2000.

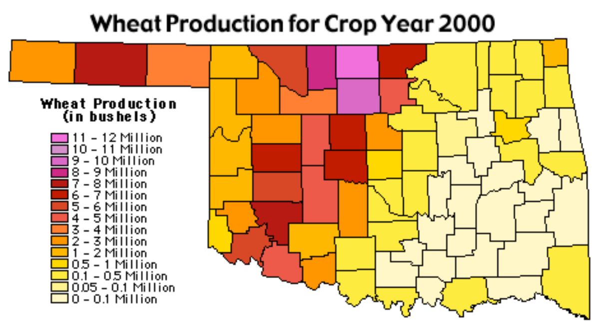

Figure 3.3. Map of Oklahoma Wheat County Estimates for Crop Year 2000, based on data from the Oklahoma Agricultural Statistics Service (2001). Purples and dark reds indicate high wheat production; light yellows denote low wheat production.

The relationship between the surface-level moisture field and the growth of winter wheat was observed using monthly averaged values of DMAX during Crop Year 2000. A slight moist bias existed over Oklahoma's wheat belt between November and April (Figs. 3.4*a*,*b*). During May (Fig. 3.4*c*), the statewide pattern began to be characterized by a predominantly east-west gradient, attained by July (not shown). This meridional pattern continued through September 2000 (not shown).

An enhancement of DMAX values occurred across the wheat belt every year during April from 1995 to 2001 (not shown). Although its intensity varied from year to year, the moist anomaly over the wheat belt was most evident across the northern half of the wheat belt. In addition, a relative minimum of DMAX existed east of the wheat belt along the Oklahoma-Kansas border and enhanced the appearance of the moist anomaly (e.g., Fig. 3.4*b*). Monthly averaged values of VDEF (daily average vapor deficit) for April 2000 (Fig. 3.5) also exhibited a minimum over Oklahoma's winter wheat crop.

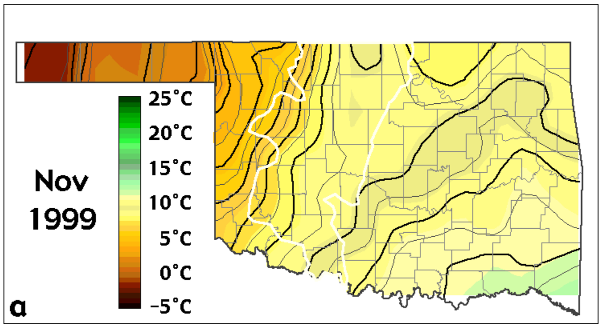

Figure 3.4a. Map of the monthly averaged values of DMAX (maximum daily dew point) during November 1999. The white outline represents the defined boundary of Oklahoma's winter wheat belt.

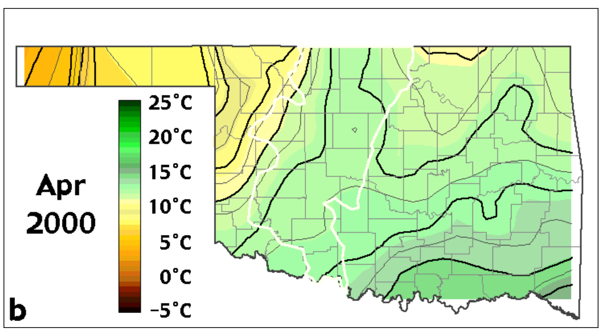

Figure 3.4b. Same as Fig. 3.4a except for April 2000.

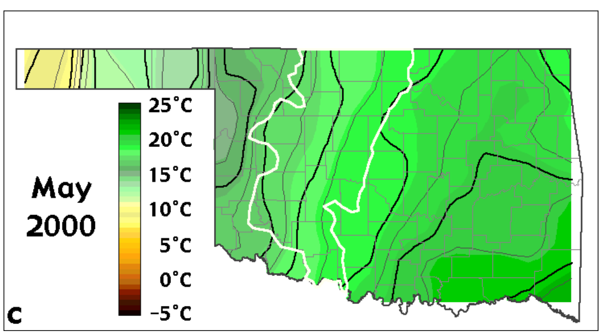

Figure 3.4c. Same as Fig. 3.4a except for May 2000.

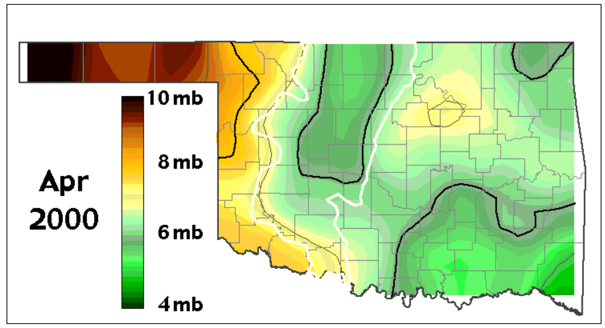

Figure 3.5. Map of the monthly averaged values of VDEF (average vapor deficit) during April 2000. The white outline represents the boundary of Oklahoma's winter wheat belt.

3.3 *Statistical Analysis*

A statistical analysis was used to determine whether the patterns detected in the examination of the statewide maps were statistically significant. For this analysis, a west-to-east swath was defined from the eastern Panhandle to Osage County, encompassing the primary wheat-producing counties of the state. This swath was divided into three regions, and Mesonet stations within the swath were assigned to a region. From west to east, the regions were labeled "West", "Wheat", and "East" and represented Oklahoma's northwestern grasslands, northern wheat belt, and eastern mixture of grasslands and hardwood forest, respectively. Although care was taken to minimize numeric and latitudinal differences between each region, "West" contained only six sites at an average latitude of 36˚ 36' N as compared to 11 sites averaging 36˚ 18' N for "Wheat" and 11 sites averaging 36˚ 22' N for "East". The average elevation was 626 m above sea level for "West", 402 m for "Wheat", and 301 m for "East". Table 3.1 lists the Mesonet sites assigned to each region, and Fig. 3.6 displays their locations.

For this analysis, the null hypothesis stated that the wheat belt did not influence the near-surface conditions and, hence, the three regions represented the same population. To try the null hypothesis, the Wilcoxon signed-rank test was implemented. The Wilcoxon signed-rank test (Wilks 1995) does not assume that any probability distribution adequately represents the data. The test was executed individually for each month from November through August for TMAX, TMIN, DMAX, DMIN, and VDEF, as well as for total daily solar radiation and total daily rainfall. Mesonet data from 1994 through 2001 were used such that any extreme during a specific year (e.g., drought) was tempered by data from seven other years. As a result, the sample size *n* equaled 224 for February, 240 for April, June, and November, and 248 for January, March, May, July, August, and December.

Table 3.1. Mesonet sites assigned to three regions for statistical analysis.

West	***Wheat***	***East***
Arnett (ARNE)	Blackwell (BLAC)	Burbank (BURB)
Buffalo (BUFF)	Breckinridge (BREC)	Foraker (FORA)
Freedom (FREE)	Cherokee (CHER)	Guthrie (GUTH)
May Ranch (MAYR)	Fairview (FAIR)	Marena (MARE)
Slapout (SLAP)	Kingfisher (KING)	Newkirk (NEWK)
Woodward (WOOD)	Lahoma (LAHO)	Oilton (OILT)
	Marshall (MARS)	Pawnee (PAWN)
	Medford (MEDF)	Red Rock (REDR)
	Putnam (PUTN)	Skiatook (SKIA)
	Seiling (SEIL)	Stillwater (STIL)
	Watonga (WATO)	Wynona (WYNO)

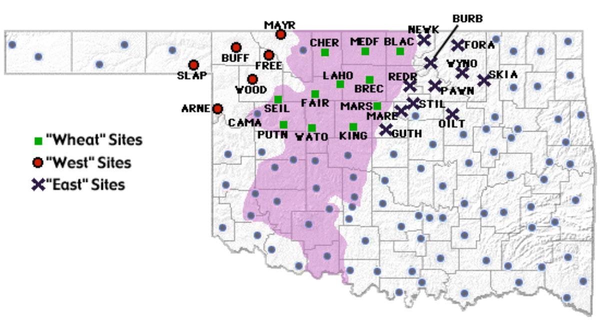

Figure 3.6. Location of Mesonet sites selected for statistical analysis. Sites belonging to "Wheat" are green squares. Those representing "West" and "East" are red circles and dark blue X's, respectively. The shaded region (violet) represents Oklahoma's winter wheat belt. Four-letter identifiers for selected Mesonet sites are displayed near the corresponding site location.

Results from the significance testing of the total daily solar radiation and total daily rainfall indicated either a meridional gradient that was characteristic of Oklahoma's climatology or differences between regions that were not statistically significant. Thus, Oklahoma's wheat belt did not produce an evident signature in the statistical analysis of total daily solar radiation or total daily rainfall. Consequently, differences evident in the analysis of the other variables did not result from differences in incoming solar energy or rainfall.

Table 3.2 displays the mean values of five variables, by month, for each of the three regions. An *anomalous monthly mean* was defined for this study as a monthly mean for "Wheat" that did not have a numerical value between the monthly mean values for "West" and "East". Values shaded in gray denote *anomalous monthly means* that cannot be explained by the climatology of Oklahoma or by synoptic-scale patterns. In addition, observable trends that resulted from changes in elevation across the region were expected to either monotonically increase or monotonically decrease. Hence, neglecting land-air interactions, the monthly mean for "Wheat" was expected to have a numerical value between that for "West" and that for "East".

The anomalies suggested by examining maps of objectively analyzed data also were evident as anomalous monthly means (Table 3.2). First, as vegetation grew across the wheat belt, maximum daily temperatures were cooler than those measured across adjacent regions of dormant grasslands (November – April). Second, as green-up of grasslands occurred and wheat became senescent during May, the cool anomaly over the wheat belt disappeared. Third, after the wheat harvest, maximum and minimum daily temperature data revealed a warm anomaly across the wheat belt. Fourth, DMAX and DMIN mean values indicated a slight moist bias during the early spring across the wheat belt, particularly during March. Fifth, lower VDEF values were computed over the growing wheat as compared to the dormant grasslands that bordered the wheat belt.

Using the 95% confidence level to indicate statistical significance (i.e., p value less than 0.05), the Wilcoxon signed-rank test indicated that all TMAX differences between the three regions were significant during June, July, and August ($0.0001 \le p \le 0.0012$). Based on eight years of daily data from 28 Mesonet sites, the maximum temperatures across the northern portion of Oklahoma's wheat belt averaged 1–2°C higher during the climatological summer than those across grasslands directly to the east and averaged about 0.3°C warmer than those across the grasslands directly to the west. During July and August, the warm bias represented by the TMIN values over the wheat also was statistically significant ($p = 0.0001$).

From November through April, TMAX differences between "West" and "East" were not statistically significant (p values ranged from 0.0735 to 0.984). Variations between "Wheat" and "East", however, were significant during all of these months ($p = 0.0058$ for January; $p = 0.0001$ for remaining months). Statistical significance between "West" and "Wheat" during wheat growth was noted for November ($p = 0.0001$), December ($p = 0.0143$), January ($p = 0.0001$), February ($p = 0.0114$), and April ($p = 0.0032$). The null hypothesis was not rejected for March, though the p value was only 0.0599. In summary, the data confirmed the existence of a significant cool anomaly over growing winter wheat as compared to adjacent, dormant grasslands; thus, the null hypothesis was rejected.

Table 3.2. Mean values of TMAX (˚C), TMIN (˚C), DMAX (˚C), DMIN (˚C), and VDEF (mb) for November through August using Mesonet data from 1994 – 2001. Shaded values are "anomalous monthly means", as defined for this study. The three regions are defined in Table 3.1.

	TMAX			TMIN			DMAX			DMIN			VDEF		
	West	Wheat	East	West	Wheat	East	West	Wheat	East	West	Wheat	East	West	Wheat	East
Nov	15.88	15.33	15.86	1.63	2.84	3.33	4.10	6.74	6.98	-3.41	-0.64	-0.34	5.27	4.03	4.38
Dec	9.44	9.06	9.61	-3.73	-2.51	-1.99	-0.64	1.61	1.78	-7.88	-5.64	-5.34	3.27	2.49	2.79
Jan	8.81	8.03	8.37	-4.54	-3.69	-3.40	-1.72	0.08	0.58	-8.83	-7.07	-6.77	3.24	2.53	2.65
Feb	12.69	12.35	13.03	-1.85	-1.03	-0.53	0.75	2.96	3.00	-7.28	-5.11	-5.11	4.69	3.83	4.30
Mar	15.33	15.02	15.66	1.07	2.06	2.76	3.64	5.97	5.48	-4.27	-1.78	-2.19	5.61	4.47	5.39
Apr	21.23	20.92	21.51	6.27	6.93	8.17	8.03	10.80	10.79	-0.74	2.63	3.11	8.73	6.76	7.62
May	26.76	26.69	26.12	12.99	13.71	14.34	15.38	17.34	17.64	8.13	10.80	11.52	10.16	8.35	7.67
Jun	31.31	31.65	30.05	17.84	18.66	18.68	19.08	20.38	21.42	12.45	14.52	15.98	13.58	12.72	9.46
Jul	35.05	35.36	33.54	20.87	21.75	21.57	20.26	21.63	23.09	14.56	16.31	18.31	18.84	18.09	13.10
Aug	34.52	34.83	33.97	20.44	21.19	20.89	19.27	20.59	21.88	13.89	15.32	16.92	18.50	17.94	14.40

During May, TMAX data populations from "West" and "Wheat" were indistinguishable (p = 0.5353). Although differences between the three regions were statistically significant for TMIN, DMAX, DMIN, and VDEF during May, the means were not anomalous – they exhibited a meridional gradient. These results strengthened the argument that, as green-up commenced across western grasslands, differences between the wheat belt and adjacent lands that were forced by land use were minimized.

A principally uniform gradient of moisture was expected from east to west across the region of interest; hence, it was consequential that mean DMAX values for "Wheat" during March and April were larger than those for "East". Perhaps more interesting was how the values of DMAX and DMIN changed from February to March, when the wheat crop grew rapidly. The February mean values of both DMAX and DMIN for "Wheat" were within 0.05˚C of those for "East". Appropriately, the Wilcoxon signed-rank test indicated that the values of DMAX (p = 0.8259) and DMIN (p = 0.8887) from "Wheat" and "East" were from the same population. Hence, during February, a month with minimal precipitation, the moisture content near the surface was indistinguishable between these two regions.

In contrast, during March, the Wilcoxon test computed *less than a 0.1% chance* that DMAX and DMIN for "West", "Wheat", and "East" represented similar populations. *These results were based on almost 21,000 daily statistics over eight unique years.* In addition, the computations showed that DMAX and DMIN for "Wheat" averaged 0.49˚C and 0.41˚C higher than the respective values for "East". DMAX and DMIN for "Wheat" also averaged 2.33˚C and 2.49˚C higher than the respective values for "West". These results were even more interesting when one considered that ~25 frontal passages occurred during the months of March between 1994 and 2001.

Monthly means of the average daily vapor pressure deficit, VDEF, across the three regions mirrored the monthly means of TMAX (Table 3.2) during the wheat's growing season. With lower TMAX values and, during some months, higher DMAX values, it was not surprising that VDEF was anomalously low over "Wheat" from November through April. Post-harvest values of VDEF were comparable to those of "West", but still within its expected range (i.e., a value between that of "West" and "East"). With the exception of March, the Wilcoxon test indicated that VDEF differences during the wheat's growing season *were* statistically significant (p < 0.0025). During March, VDEF differences between "West" and "East" were not significant (p = 0.3472), although those between "Wheat" and its neighbors were significant at the 99.99% confidence level.

3.4 *Daily Anomalies*

To better interpret how Oklahoma's wheat belt alters its environment, case-study days were examined during three of the eight years of available data. From the period 1999 to 2001, approximately 50 days between 15 March and 1 June revealed evidence of heightened DMAX values over Oklahoma's wheat belt compared to adjacent grasslands. By two-week periods, the number of days classified as showing evidence of these heightened DMAX values was 19 days between 15 March and 31 March, 12 days between 1 April and 15 April, 12 days between 16 April and 30 April, six days between 1 May and 15 May, and two days between 16 May and 1 June. More than half of these cases revealed a DMAX enhancement only across five or six counties in north-central Oklahoma. It was possible that the advection of moisture from the Gulf of Mexico masked some DMAX signatures from the wheat fields.

Figures 3.7 and 3.8 display DMAX for 4 April 2000 and 5 April 2000, respectively. The evolution of the meteorological features near the surface on these days typified spring days when Oklahoma's wheat crop most influenced its environment. The associated visual greenness map is displayed in Fig. 3.9 for the week ending 6 April 2000.

3.4.1 *4 April 2000*

Throughout the day of 4 April 2000, winds across the main body of Oklahoma were light and southerly or southeasterly, with wind speeds strengthening slightly during the afternoon. Winds across the Panhandle were westerly until about 1700 Central Daylight Time (CDT; CDT = UTC – 5 h), when they began to veer to the north. Statewide-averaged wind speeds were 3.6 m s^{-1}. Rainfall events associated with frontal passages occurred on 28 March, 29 March, 31 March, and 1 April, with the most significant rainfall occurring across southwestern Oklahoma.

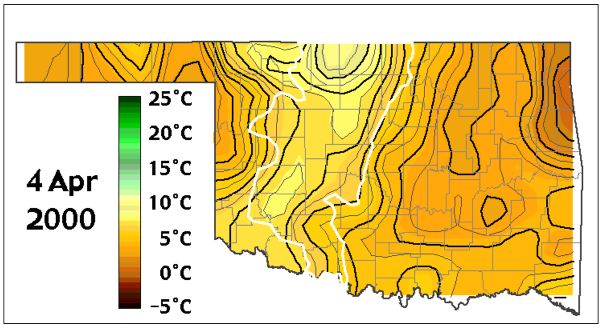

Figure 3.7. Map of the maximum dew points for 4 April 2000. The white outline represents the defined boundary of Oklahoma's winter wheat belt.

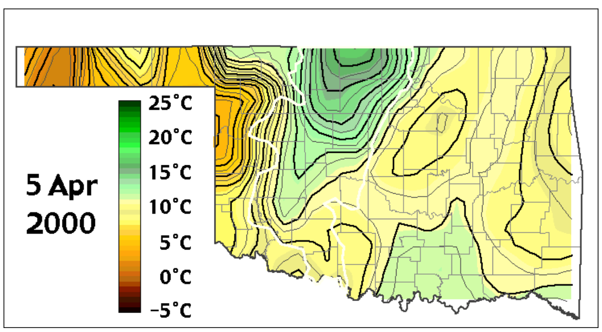

Figure 3.8. Same as Fig. 3.3 except for 5 April 2000.

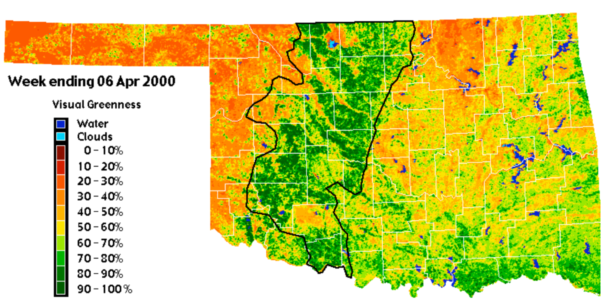

Figure 3.9. Visual greenness map for the week ending 6 April 2000. The black outline represents the boundary of Oklahoma's winter wheat belt.

The pattern in the DMAX field mimicked the pattern in the visual greenness map (Fig. 3.9) moreso than it did the rainfall pattern of the previous week (not shown). Just west of the wheat belt, May Ranch received 3.5 cm of rain from 27 March to 4 April and observed a maximum dew point of 5.5˚C on 4 April; Cherokee, a neighboring site within the wheat belt, recorded 0.8 cm of rain during the same week and observed a maximum dew point of 10.7˚C on the same day. On the east side of the wheat belt, Newkirk received 3.1 cm of rain during the previous week and measured a maximum dew point of 5.2˚C on 4 April. In contrast, Medford (a neighboring site within the wheat belt) recorded 1.7 cm of weekly rainfall and a DMAX of 9.7˚C.

Figure 3.10 depicts the daily maximum dew point (DMAX) measured at Mesonet sites on 4 April. Values of DMAX overlay a visual greenness map for the week ending 6 April 2000. With the exception of Freedom, where moisture advection from its nearby wheat fields increased DMAX to a value of 10.7˚C, the values for DMAX on the wheat side of the wheat belt boundaries were greater than those adjacent to the wheat belt. In most cases, DMAX was about 2˚C higher for sites within the wheat belt than for their neighbors outside of the belt. Skin temperature imagery from NOAA's GOES-8 satellite (Fig. 3.11) confirmed the existence of a corresponding region of cooler temperatures across the wheat belt.

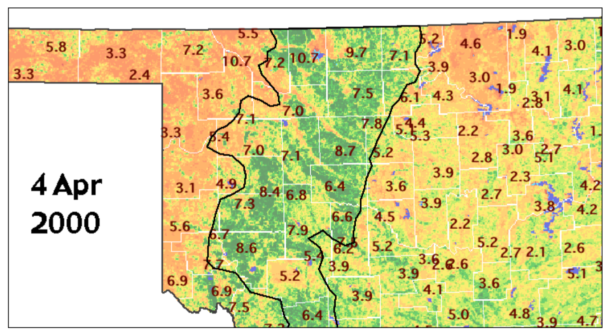

Figure 3.10. Zoomed map of visual greenness for the week ending 6 April 2000 with plotted observations of the daily maximum dew point (DMAX) in degrees Celsius for 4 April 2000. Wet or densely vegetated areas appear green, and dry or sparsely vegetated areas appear red to tan. The solid black line represents the boundary of Oklahoma's winter wheat belt, as defined for this study.

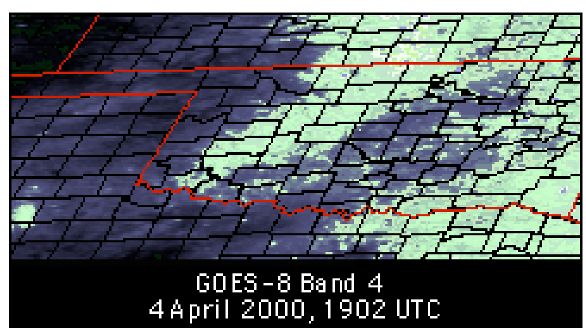

Figure 3.11. Surface temperature image (10.7 mm) at 1402 CDT on 4 April 2000 from the GOES–8 geostationary satellite. Note the relative minimum in skin temperature over the wheat belt of western Oklahoma. Data courtesy of the Space Science and Engineering Center at the University of Wisconsin.

With weak winds and a substantial moisture gradient across the boundary of the wheat belt on 4 April, conditions appeared favorable for detecting a landscape-induced mesoscale circulation (e.g., Chen and Avissar 1994). At 1700 CDT, a 4˚C dew point difference existed between the Cherokee and Alva Mesonet sites (31 km apart), and a 9˚C difference was observed between Cherokee and May Ranch (64 km apart). About 1700 CDT, the weather radar at Vance Air Force Base (KVNX), located near the border of Alfalfa and Grant counties, detected several isolated convective elements within 100 km of the radar. Movement of the convection was toward the east or northeast, corresponding to the 10-m wind directions (not shown). At 1830 CDT, KVNX detected the development of a southwest-to-northeast-oriented thin line in southeastern Woods County. Movement of the thin line was toward the northwest, *perpendicular* to the movement of surrounding echoes, including one echo that moved within 10 km of the thin line. By 1930 CDT, the thin line was undetectable.

The location of the thin line over time was coincident with changes in near-surface winds and dew points at the Alva Mesonet site in eastern Woods County (Fig. 3.12). Between 1700 and 1830 CDT, winds at the Alva site backed from 220˚ to 165˚, reflecting the passage of a surface boundary. During this 90-minute period, dew points increased by 3.3˚C at Alva. The wind shift and subsequent moisture increase were not measured at surrounding Mesonet sites. Hence, it is possible that the thin line represented the boundary of a local vegetation breeze.

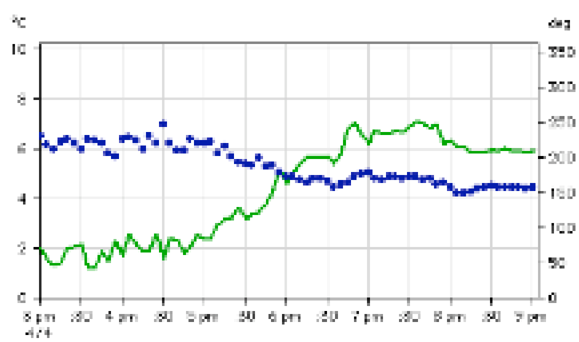

Figure 3.12. Graph of 5-minute measurements of dew point (green line, TDEW) and wind direction (blue dots, WDIR) at the Alva Mesonet site between 1500 and 2100 CDT on 4 April 2000.

3.4.2 *5 April 2000*

No rain fell during the clear days of 4 April and 5 April; however, wind speeds significantly increased from one day to the next in response to an approaching low pressure system. Winds were southerly or southwesterly across the state for most of the day on 5 April, with speeds averaging 6.4 m s^{-1} statewide and gusting to about 15 m s^{-1}. Wind speeds across western Oklahoma were slightly higher than those across the eastern half of the state. Skies on 5 April were clear statewide.

A comparison of the DMAX fields on 4 April (Fig. 3.7) with those on 5 April (Fig. 3.8) demonstrated a considerable increase in near-surface moisture from one day to the next. The primary features evident on 5 April were: (1) a region of significantly elevated DMAX values over the wheat belt and (2) an associated intensification (as compared to 4 April) of the DMAX gradient across far western Oklahoma (Fig. 3.8). Daily maximum dew points within the wheat belt ranged from 11-17˚C, whereas those just east of the wheat belt ranged from 9-11˚C. DMAX values just west of the wheat belt ranged from 4-10˚C, with two notable exceptions: 12.4˚C at Buffalo and 12.0˚C at Freedom. Dew points at Freedom and Buffalo were enhanced by moisture advection from local wheat fields.

Southwest winds at 1530 CDT on 5 April averaged 10 m s^{-1} across the main body of Oklahoma; westerly surface winds prevailed across far northwest Oklahoma and the Panhandle (Fig. 3.13). Two regions of enhanced moisture were evident: (1) an area across south-central Oklahoma where dew points ranged from 9 to 12˚C and (2) an extended region across the wheat belt where dew points ranged from 10 to 15˚C. An animation of the dew point field (not shown) revealed that the former area increased its low-level moisture as a result of positive moisture advection from North Texas and the Gulf of Mexico. Over the latter region, however, surface fluxes generated a local moisture maximum.

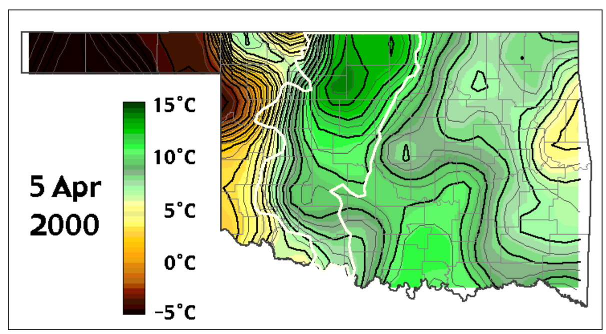

Figure 3.13. Map of near-surface dew points at 1530 CDT on 5 April 2000. A one-pass Barnes technique was used for the objective analysis. The black outline depicts the boundary of Oklahoma's wheat belt. Thick black lines denote isopleths at intervals of 1˚C.

In addition to the moist anomaly, a cool anomaly was evident in the near-surface temperature field across a portion of the wheat belt. Mesonet sites measured air temperatures between 27 and 30˚C within the northern half of the wheat belt at 1530 CDT (Fig. 3.14). To the west of the wheat belt, temperatures ranged from 31 to 34˚C. Along the eastern boundary of the wheat belt, the temperature gradient was less evident. On average, however, temperatures just east of the wheat belt were 1˚C warmer than those measured at their closest neighbor sites within the wheat belt.

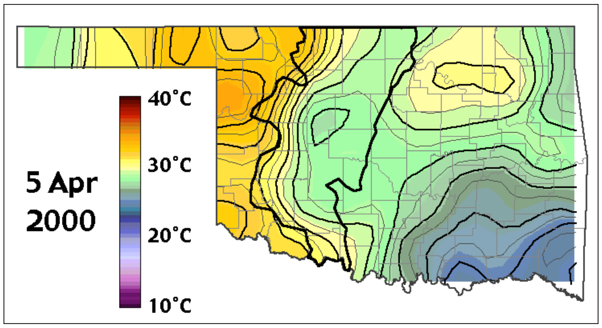

Figure 3.14. Same as Fig. 3.13 except for air temperatures (color contours).

As in the 4 April 2000 case, KVNX detected the development of a thin line that was oriented from southwest to northeast and was located in eastern Woods County (Fig. 3.15). At 1630 CDT on 5 April, the thin line was evident in an image acquired via the radar's precipitation mode. While other nearby echoes progressed toward the east, the thin line remained quasi-stationary until 1830 CDT, when it began to move northwest. As before, the thin line became undetectable by 1930 CDT. Winds at the Alva Mesonet site backed from 253˚ at 1620 CDT to 192˚ at 1625 CDT; a *corresponding dewpoint increase of 7.7˚C was measured during this 5-minute period* (Fig. 3.16). Between 1630 and 1730 CDT, the wind direction at Alva varied between 178˚ and 216˚ and dew points remained greater than 10˚C. From 1735 to 1800 CDT, winds shifted to westerly and the dewpoint values plunged to 1.6˚C. After 1800 CDT, winds returned to southerly or south-southeasterly. The wind direction and dew point changes appeared to coincide with the movement of the thin line. The observations are consistent with the documented attributes of a vegetation breeze (e.g., Doran et al. 1995; Smith et al. 1994).

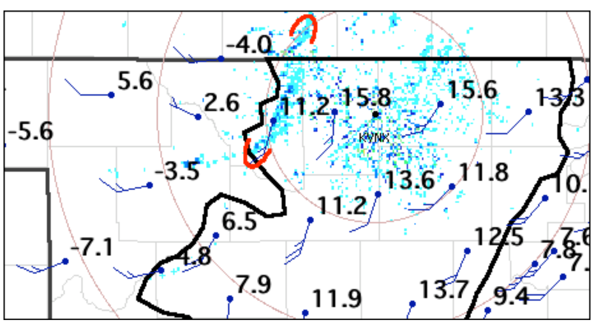

Figure 3.15. Base reflectivity at 1728 CDT on 5 April 2000 from the Vance Air Force radar (KVNX) in north-central Oklahoma. The red horseshoes depict the location of the ends of the thin line. Mesonet winds and dew points at 1725 CDT are identified by barbs and numbers, respectively. A full barb represents 5 m s^{-1}. The black outline portrays the boundary of Oklahoma's wheat belt. Radar data are courtesy of the Oklahoma Climatological Survey.

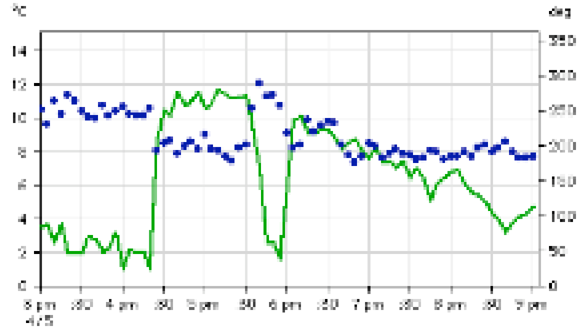

Figure 3.16. Graph of 5-minute measurements of dew point (green line, TDEW) and wind direction (blue dots, WDIR) at the Alva Mesonet site between 1500 and 2100 CDT on 5 April 2000.

3.4.3 *14 July 2000*

As noted previously, a warm anomaly commenced during June as wheat growers completed the harvest. The warmer temperatures persisted through July (Fig. 3.2*c*) and August (Fig. 3.2*d*). In fact, for 92 (out of 183) days from June and July of 1999, 2000, and 2001, a distinct warm anomaly existed in the daily maximum temperature field over the wheat belt, particularly across north-central Oklahoma. It was possible that, during a number of these days, warm air advection from the Mexican Plateau into southwestern Oklahoma masked the TMAX signature from the wheat fields. By two-week periods, the number of days classified as showing evidence of warm anomalies was 19 days between 1 June and 15 June, 13 days between 16 June and 30 June, 30 days between 1 July and 15 July, and 30 days between 16 July and 31 July.

Strong solar forcing appeared to be the most evident factor related to the existence of a warm anomaly over the wheat belt. Using the same grouping of stations noted in Table 3.1, the average of the total daily solar radiation was computed for regions "West", "Wheat", and "East". The computed average for each of the three regions was greater than 26 MJ/m^2 on 72 days during June and July of 1999-2001. On 62 of those days, warm anomalies were evident over north-central Oklahoma. Of the 10 remaining days, four were marked by significant cloud cover elsewhere in the state, one was influenced by the passage of a weak cold front, and three exhibited a slight warm anomaly over the wheat belt.

A weak low pressure system crossed the Central Plains into the Ohio Valley between 11 July and 13 July 2000. The low pressure brought bands of cloud cover across portions of Oklahoma during those three days. By 14 July, high pressure dominated Oklahoma's near-surface atmosphere, and the skies were clear except for sporadic cumulus clouds. Winds were calm statewide prior to sunrise on the 14th and remained so until 1200 CDT, with the exception of the Panhandle, where light south-southwest winds prevailed. Light easterly winds blew across the main body of Oklahoma during early afternoon. By 1600 CDT, the southerly winds across the Panhandle extended eastward across the harvested wheat in north-central Oklahoma. At sunset, winds became calm across the eastern third of Oklahoma, were light southeasterly across the Panhandle and northwestern quarter of Oklahoma, and were light easterly throughout the remainder of the state. Statewide, winds averaged 1.8 m s^{-1} on 14 July.

Patterns in the TMAX field for 14 July (Fig. 3.17) mimicked the pattern in the visual greenness map (Fig. 3.18). The northern third of Oklahoma's wheat belt exhibited the largest TMAX values, which ranged from 36.7˚C at Marshall to 39.3˚C at Cherokee. Directly east of this region and outside the wheat belt, maximum temperatures varied from 35.1˚C at Marena to 36.1˚C at Red Rock. To the west and outside the wheat belt, Woodward (in western Woodward County) measured 35.6˚C as its daily high temperature.

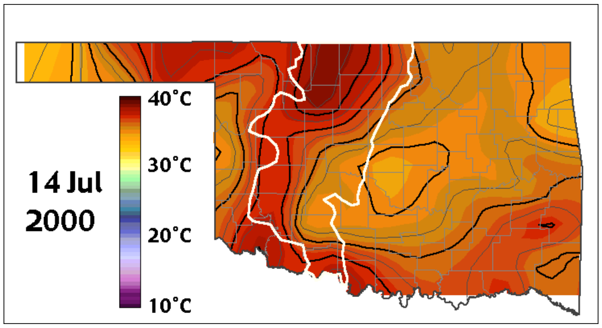

Figure 3.17. Map of the maximum air temperatures for 14 July 2000. A one-pass Barnes technique was used for the objective analysis. The white outline represents the boundary of Oklahoma's winter wheat belt.

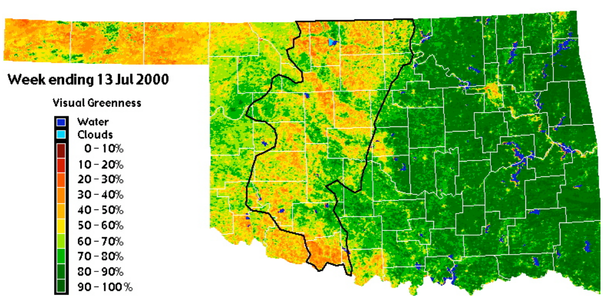

Figure 3.18. Visual greenness map for the week ending 13 July 2000. The black outline represents the boundary of Oklahoma's winter wheat belt.

Stations within the central third of Oklahoma's harvested wheat belt (divided north to south), where the landscape included grassland and summer crops, observed maximum temperatures 1˚-2˚C cooler than those across the northern third of the wheat belt. TMAX values across southwestern Oklahoma were larger than those across the central third of the wheat belt; yet, the maximum temperatures across southwestern Oklahoma were cooler than those across the northern third of the wheat belt.

Just before sunrise, temperatures across "Wheat" and "West" were about 1.5˚C cooler than those across "East" (Fig. 3.19). By 1700 CDT, when temperatures attained their daily maximum, "Wheat" was 2.5˚C warmer than "East" and 1.3˚C warmer than "West". Hence, the diurnal temperature range on 14 July was larger across the harvested wheat than across adjacent lands with growing vegetation.

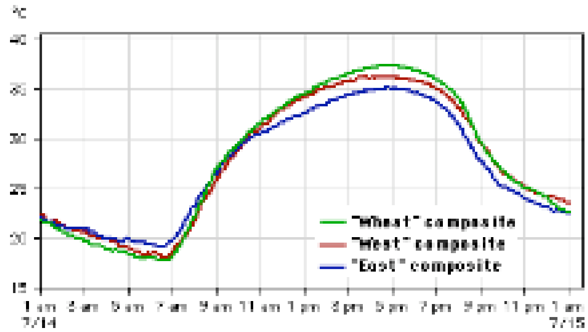

Figure 3.19. Graph of composite 5-minute observations of air temperature for regions "West", "Wheat", and "East" between 0100 CDT on 14 July 2000 and 0100 CDT on 15 July. The green, red, and blue lines denote the composite temperature for "Wheat", "West", and "East", respectively (see Table 3.1). The composite data were constructed from the average of all observed values at a given time for the sites located with each region. The time series plot extends from midnight to midnight CST – the interval for computing TMAX.

4. CONCLUSIONS

Analyses of many related observations demonstrated that Oklahoma's winter wheat belt had a significant impact on the near-surface temperature and moisture fields, both during the period when winter wheat was growing and during the period after harvest. In particular, the following results are noteworthy from this study:

1. As vegetation grew across the wheat belt, maximum daily temperatures were cooler than those measured over adjacent regions of dormant grasslands. Monthly averaged values of TMAX (maximum daily air temperature) for Crop Year 2000 displayed a cool anomaly over the growing wheat from November 1999 through April 2000. Using Mesonet data from 1994 through 2001, the cooler temperatures over the wheat belt were shown to be statistically significant at the 95% confidence level for November, December, January, February, and April.

2. As green-up of grasslands occurred during May, the cool anomaly over the wheat belt disappeared. After the wheat was harvested, maximum and minimum daily temperature data revealed a warm anomaly across the wheat belt during June, July, and August. The warmer temperatures also were shown to be statistically significant for all three months.

3. Monthly averaged values of DMAX and DMIN (maximum and minimum daily dew points) indicated a slight moist bias during the early spring across the wheat belt, particularly during March. DMAX for Crop Year 2000 indicated a

slight moist anomaly over the growing wheat from November 1999 through April 2000. Based upon 21,000 daily statistics over eight unique years, statistical computations indicated *less than a 0.1% chance* that the moist anomaly during March resulted from random chance.

4. During the period from 1999 to 2001, about 50 days between 15 March and 1 June showed evidence of heightened DMAX values over Oklahoma's winter wheat belt as compared to adjacent grasslands. On more than half of these days, the dew points were enhanced across only five or six counties in north-central Oklahoma, where the winter wheat production was the highest.

5. Case studies from the spring of 2000 indicated that the presence of growing wheat influenced the maximum daily dew points and the diurnal cycles of dew point on days with both weak and moderate winds, and in both moist and dry air masses. Days with clear skies were examined so that uneven solar forcing across the state did not mask the results.

6. For the spring case studies, a comparison of the prior week's rainfall with values of dew point demonstrated that the growing wheat was more efficient at recirculating water back to the atmosphere than was dormant grassland in adjacent lands.

7. On two of the case study days (4 April and 5 April), evidence supported the existence of a vegetation breeze in Woods County.

8. During the period from 1999 to 2001, about 90 days between 1 June and 31 July revealed a distinct warm anomaly in daily maximum air temperatures over the wheat belt, particularly across north-central Oklahoma. Case studies from the summer of 2000 indicated that the warmer temperatures over the harvested wheat resulted from local heating rather than from warm air advection.

5. ACKNOWLEDGMENTS

Many thanks to all employees of the Oklahoma Mesonet whose countless hours of dedication have made this research possible. This material is based upon work supported by the National Science Foundation under Grant No. NSF-0074852.

6. REFERENCES

Anthes, R. A., 1984: Enhancement of convective precipitation by mesoscale variations in vegetative covering in semiarid regions. *J. Clim. Appl. Meteor.*, **23**, 541-554.

Barnes, S. L., 1964: A technique for maximizing details in numerical weather map analysis. *J. Appl. Meteor.*, **3**, 396-409.

Brock, F. V., K. C. Crawford, R. L. Elliott, G. W. Cuperus, S. J. Stadler, H. L. Johnson and M. D. Eilts, 1995: The Oklahoma Mesonet: a technical overview. *J. Atmos. Oceanic Tech.*, **12**, 5-19.

Burgan, R. E., and R. A. Hartford, 1993: Monitoring vegetation greenness with satellite data. Gen. Tech. Rep. INT-297. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 13 p.

Chang, J. T., and P. J. Wetzel, 1991: Effects of spatial variations of soil moisture and vegetation on the evolution of a prestorm environment: a numerical case study. *Mon. Wea. Rev.*, **119**, 1368-1390.

Chen, F., and R. Avissar, 1994: Impact of land-surface moisture variability on local shallow convective cumulus and precipitation in large-scale models. *J. Appl. Meteor.*, **33**, 1382-1401.

Cihlar, J., P. H. Caramori, P. H. Schuepp, R. L. Desjardins, and J. I. MacPherson, 1992: Relationship between satellite-derived vegetation indices and aircraft-based CO_2 measurements. *J. Geophys. Res.*, **97** (D17), 18,515–18,521.

Collins, D., and R. Avissar, 1994: An evaluation with the Fourier amplitude sensitivity test (FAST) of which land-surface parameters are of greatest importance for atmospheric modelling. *J. Climate*, **7**, 681-703.

Cutrim, E., D. W. Martin, and R. Rabin, 1995: Enhancement of cumulus clouds over deforested lands in Amazonia. *Bull. Amer. Meteor. Soc.*, **76**, 1801-1805.

Deering, D. W., E. M. Middleton, J. R. Irons, B. L. Blad, E. A. Walter-Shea, C. J. Hays, C. Walthall, T. F. Eck, S. P. Ahmad, and B. P. Banerjee, 1992: Prairie grassland bidirectional reflectances measured by different instruments at the FIFE site. *J. Geophys. Res.*, **97** (D17), 18,887–18,903.

Doran, J. C., W. J. Shaw, and J. M. Hubbe, 1995: Boundary layer characteristics over areas of inhomogeneous surface fluxes. *J. Appl. Meteor.*, **34**, 559-571.

Garrett, A. J., 1982: A parameter study of interactions between convective clouds, the convective boundary layer, and forested surface. *Mon. Wea. Rev.*, **110**, 1041-1059.

LeMone, M. A., R. L. Grossman, R. L. Coulter, M. L. Wesley, G. E. Klazura, G. S. Poulos, W. Blumen, J. K. Lundquist, R. H. Cuenca, S. F. Kelly, E. A. Brandes, S. P. Oncley, R. T. McMillen, B. B. Hicks, 2000: Land–atmosphere interaction research, early results, and opportunities in the Walnut River Watershed in Southeast Kansas: CASES and ABLE. *Bull. Amer. Meteor. Soc.*, **81**, 757–780.

Loveland, T. R., Z. Zhu, D. O. Ohlen, J. F. Brown, B. C. Reed, and L. Yang, 1999: An analysis of the IGBP global land-cover characterization process. *Photogrammetric Engineering and Remote Sensing*, **65**, 1021-1032.

Mahfouf, J.-F., E. Richard, and P. Mascart, 1987: The influence of soil and vegetation on the development of mesoscale circulations. *J. Clim. Appl. Meteor.*, **26**, 1483-1495.

Markowski, P. M., and D. J. Stensrud, 1998: Mean monthly diurnal cycles observed with PRE-STORM surface data. *J. Climate*, **11**, 2995-3009.

Oklahoma Agricultural Statistics Service 2000: Oklahoma Irrigated Wheat County Estimates for Crop Year 2000. http://www.nass.usda.gov/ok/wheat00.htm, Okla. Dept. of Agriculture, November 9, 2000.

Pielke, R. A., G. A. Dalu, J. S. Snook, T. J. Lee, and T. G. F Kittel, 1991: Nonlinear influence of mesoscale land use on weather and climate. *J. Climate*, **4**, 1053-1069.

Rabin, R. M., S. Stadler, P. J. Wetzel, D. J. Stensrud, and M. Gregory, 1990: Observed effects of landscape variability on convective clouds. *Bull. Amer. Meteor. Soc.*, **71**, 272–280.

Segal, M., R. Avissar, M.C. McCumber, R.A. Pielke, 1988: Evaluation of vegetation effects on the generation and modification of mesoscale circulations. *J. Atmos. Sci.*, **45**, 2268–2292.

Segal, M., W. E. Schreiber, G. Kallos, J. R. Garratt, A. Rodi, J. Weaver, and R. A. Pielke, 1989: The impact of crop areas in northeast Colorado on midsummer mesoscale thermal circulations. *Mon. Wea. Rev.*, **117**, 809-825.

Shafer, M. A., C. A. Fiebrich, D. Arndt, S. E. Fredrickson, and T. W. Hughes, 2000: Quality assurance procedures in the Oklahoma Mesonetwork. *J. Atmos. Ocean. Tech.*, **17**, 474–494.

Smith, E. A., M. M.-K. Wai, H. J. Cooper, and M. T. Rubes, 1994: Linking boundary-layer circulations and surface processes during FIFE 89. Part I: observational analysis. *J. Atmos. Sci.*, **51**, 1497-1529.

Taylor, C. M., and T. Lebel, 1998: Observational evidence of persistent convective-scale rainfall patterns. *Mon. Wea. Rev.*, **126**, 1597-1607.

Wilks, D. S., 1995: *Statistical Methods in the Atmospheric Sciences.* Academic Press, 467 pp.