The Impact of Oklahoma’s Winter Wheat Belt on the Mesoscale Environment

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ABSTRACT

Oklahoma Mesonet data were used to measure the impact of Oklahoma’s winter wheat belt on the mesoscale environment from 1994 to 2001. Statistical analyses of monthly means of near-surface air temperatures demonstrated that 1) a well-defined cool anomaly existed across the wheat belt during November, December, January, February, and April, and 2) a well-defined warm anomaly existed across the wheat belt during June, July, and August. Data from crop year 2000 indicated a slight moist anomaly over the growing wheat from November 1999 through April 2000. In addition, 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.

During the period from 1999 to 2001, about 50 days between 15 March and 1 May showed evidence of heightened values of daily maximum dewpoint over Oklahoma’s winter wheat belt as compared to adjacent grasslands. On more than half of these days, the dewpoint was enhanced only across five or six counties in north-central Oklahoma, where the winter wheat production was the largest. Another 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.

These analyses demonstrate that Oklahoma’s winter wheat belt has a dramatic impact on the near-surface, mesoscale environment during its growth and after its harvest. Consequently, it is imperative that mesoscale forecasts, whether produced objectively or subjectively, account for the vegetation–air interactions that occur across western Oklahoma and, presumably, across other crop regions in the United States and around the globe.

1. Introduction

The earth’s surface, the water that pauses upon or drains over it, and the vegetation that grows from and above it are joined irreversibly to the overlying atmospheric boundary layer through fluxes of energy, momentum, moisture, and gases. The interwoven nature of this demarcation between solid or liquid and the gaseous air above is a topic of heightened interest in the meteorological community (e.g., National Research Council 1998). In particular, the impact of vegetation on the atmosphere—from germination to maturity to senescence to death or dormancy—has been studied across a spectrum of temporal and spatial scales (e.g., Bonan 2001; Freedman 2001; Cihlar et al. 1992; Rabin et al. 1990). The understanding of these vegetation–air interactions is critical to the maturation of atmospheric numerical models (e.g., Emanuel et al. 1995).

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 flux is determined, in part, by the amount of evapotranspiration from plants (Mahfouf et al. 1987; Collins and Avisar 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 indicate 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 Avisser 1994).

Vegetation influences the diurnal range of temperatures, depth of the convective boundary layer, and amount of cloud cover for a region (Segal et al. 1989; Rabin et al. 1990; Bonan 2001; Durre and Wallace 2001; Freedman et al. 2001). Although feedbacks between vegetation and rainfall are not well established, evidence exists that vegetation may enhance or mitigate extreme climatological conditions such as drought (Dirmeyer 1994; Sud et al. 2001).

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). Past numerical studies have modeled highly idealized environments or have lacked an extended set of regional observations for model initialization and verification (e.g., Garrett 1982; Mahfouf et al. 1987; Chen and Avisser 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 the void in adequate measurements by using surface data from the Oklahoma Mesonet.

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 nonirrigated 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. Hence, 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 of mesoscale vegetation breeze circulations—the local Rossby radius of deformation (Anthes 1984; Pielke et al. 1991; Chen and Avisser 1994; Lynn et al. 1995). Thus, Oklahoma is an optimal real-world environment for examination of mesoscale vegetative impacts on the atmosphere.

Section 2 describes the data used in this study, including Oklahoma Mesonet observations, measurements from the Atmospheric Radiation Measurement Program, land-cover information, spectral vegetation index products from satellite, and county production of Oklahoma wheat. Section 3 overviews the development of winter wheat in Oklahoma and presents the results of the observational study, including monthly, daily, and instantaneous anomalies in measured fields. Results are reviewed and summarized in section 4.

2. The study region and observational data used

a. 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 is characterized by either winter wheat or a winter wheat/grassland mix as the land-use type designated by the United States Geological Survey (USGS). Oklahoma’s wheat belt is defined as that subset of the winter wheat belt located solely within Oklahoma.

The boundary of Oklahoma’s winter wheat belt, as defined for this research and as outlined in Fig. 1, is designated using a land-cover database, aerial photographs, and Oklahoma Mesonet field technician reports. The land-cover characterization was from the North America Land Cover Data Base from the USGS. The database was constructed from 1-km Advanced Very High Resolution Radiometer (AVHRR) data spanning April 1992 through March 1993 (Loveland et al. 1999).

b. Description of the study region

The topography of Oklahoma influences the state’s climate, which, in turn, governs the natural vegetation of the region. In general, the land slopes downward west to east, from 1500 m above sea level in the far western Panhandle to 90 m in southeastern Oklahoma. Normal annual rainfall and mean annual air temperature, as well as substantial hydrologic features, greatly influence the type of vegetation that grows naturally across the region. Duck and Fletcher (1943), through mapping of the potential natural vegetation1 of Oklahoma (Fig. 2), indicated that the mixed-grass/eroded plains regime resided predominantly to the west of Oklahoma’s wheat belt and was characterized by a moisture deficiency during all seasons. Most of the land area of the current wheat

1 Potential natural vegetation is a term used in the biological sciences to describe a well-founded estimate of the type and location of natural vegetation across a region.
belt originally was tallgrass prairie. Although the tallgrass prairie was more humid than the mixed-grass/eroded plains, it also featured deficient moisture during all seasons. The post oak/blackjack oak regime was characterized by adequate moisture during all seasons and was located mostly to the east of the current wheat belt.

Significant to the location of today’s wheat belt, Duck and Fletcher (1943) remarked that “climatic peculiarities do not characterize the Tallgrass Prairie Game Type

Fig. 1. Measurement sites of the Oklahoma Mesonet. The shaded region represents Oklahoma’s winter wheat belt as defined for this study. Mesonet sites selected for the statistical analysis are denoted by a square, open circle, or × to represent those sites belonging to regions Wheat, West, and East, respectively. Four-letter identifiers for selected Mesonet sites are displayed near the corresponding site location.

Fig. 2. The potential natural vegetation of Oklahoma, as published by Duck and Fletcher (1943). Note that tallgrass prairie once dominated the landscape that now composes Oklahoma’s winter wheat belt.
insofar as Oklahoma is concerned.” Thus, substantial anomalies in the atmospheric measurements across this region were not expected, and results to the contrary found in this study were considered significant.

c. Observational datasets

The primary source of observational data for this study is the Oklahoma Mesonet (Brock et al. 1995), a statewide surface network comprising more than 110 stations (http://www.mesonet.org). 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 since 1994. All above-ground measurements are recorded every 5 min; soil temperature measurements are recorded every 15 min.

Quality control of the data is accomplished in several steps. First, laboratory personnel calibrate all Mesonet sensors prior to their 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 examines the data and manually “flags” any suspect data or removes automated flags from data deemed to be consistent with atmospheric conditions (e.g., heat burst, thunderstorm outflow). The quality-assured data archive contains 99% of the observations possible.

Monthly averages computed for crop year 2000 in section 3 were based on more than 3000 daily maxima or minima each month. The statistical analyses were founded upon more than two million Mesonet observations over eight distinct years. These observations spanned crop years with annual wheat production ranging from 67 to 140 million bushels, reported from counties that make up the wheat belt.

In addition to data from the Oklahoma Mesonet, this study made use of thermodynamic vertical profiles in the atmosphere from the Atmospheric Radiation Measurement Program (ARM; Ackerman and Stokes 2003). Part of Oklahoma’s winter wheat belt is located within ARM’s Cloud and Radiation Testbed, sponsored by the U.S. Department of Energy.

d. Spectral vegetation observations

The growth and condition of the winter wheat crop was monitored through the use of a spectral vegetation index. Satellite reflectances were used to produce spectral vegetation indices, which described some aspects of the vegetative state. Past studies indicate that an increase in living vegetation coverage across an area increases the albedo for near-infrared wavelengths and decreases the albedo for visible wavelengths (Anthes 1984). For this study, products derived from the normalized difference vegetation index (NDVI), generated from AVHRR data, were employed. NDVI is defined as follows:

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

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 (Tucker 1979).

The primary NDVI-derived product used was visual greenness, as defined by the Forest Service Intermountain Fire Sciences Laboratory of the U.S. Department of Agriculture (Burns and Hartford 1993). Visual greenness depicted the state of greenness of the vegetation compared to a very green reference, such as an alfalfa field. Values ranged from 0% to 100%. To generate this product for each week of crop year 2000, 7 days of NDVI observations were composited at each pixel; the highest value of NDVI during each week was used. This visual greenness product also has been implemented within the Oklahoma Fire Danger Model (Carlson et al. 2002).

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. By visual inspection of Fig. 3, the counties that had the greatest percentage of dark green pixels (representing high vegetative greenness) coincided with the counties that also produced the greatest wheat harvest during crop year 2000 (Oklahoma Agricultural Statistics Service 2001). On the other hand, counties that recorded the greatest wheat production during 2000 did not contain substantial acreages of winter wheat and were associated with lower visual greenness values. This strong, subjective interconnection indicated that maps of visual greenness could be used to define the spatial extent and general health of the Oklahoma wheat belt during crop year 2000.

3. Results

Evidence that Oklahoma’s winter wheat crop modified the surface layer was noted by scientists at the Oklahoma Climatological Survey since 1996. Fiebrich and Crawford (2001) illustrated a swath of anomalously moist, monthly averaged dewpoints across the growing wheat belt during November and April. Quality assurance meteorologists for the Mesonet reported a corresponding swath of anomalously warm, monthly aver-
aged air temperatures during July across the harvested wheat belt. In the current study, observational analyses of the monthly, daily, and instantaneous anomalies in the variable fields measured by the Oklahoma Mesonet were used to quantify the impact of the winter wheat belt on the mesoscale environment.

a. Winter wheat development

To better understand the seasonal cycle of wheat growth across Oklahoma, visual greenness maps from the 1999–2000 winter wheat crop year were examined (Fig. 3). “Green-up” of the winter wheat fields commenced at the end of October 1999 (Fig. 3a) and was followed by rapid crop growth during November (Fig. 3b). Crop dormancy began during December, as the crop’s visual greenness slowly decreased from December 1999 through February 2000 (not shown). Green-up recommenced during early March; visual greenness values steadily increased to a peak during mid-April (Fig. 3c). By early May, wheat became senescent (i.e., golden and with reduced transpiration) and other species of vegetation started to grow across Oklahoma, masking the boundaries of the wheat belt. A minimum in visual greenness values across the wheat belt became noticeable during late May, 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 riverbeds that cross the wheat belt, growing vegetation within the wheat belt remained sparse throughout the summer (Fig. 3d).

b. Monthly anomalies for crop year 2000

To determine whether Oklahoma’s wheat belt significantly altered the mesoscale environment, monthly averages of several variables were calculated at every Mesonet site. For this study, TMAX, TMIN, and TAVG were defined as the maximum, minimum, and average daily air temperatures (°C), respectively. Similarly, DMAX, DMIN, and DAVG were the maximum, minimum, and average daily dewpoints (°C), respectively. All derived variables were applicable at 1.5 m above ground and were calculated for midnight to midnight central standard time (CST). A one-pass Barnes analysis (Barnes 1964) was employed to obtain gridded data for contour maps.

A distinct minimum in the values of monthly averaged TMAX was collocated with the winter wheat belt during November 1999 (Fig. 4a), a month previously noted to be a period of rapid wheat growth. From 1994 through 2001, this 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. 4b) displayed a similar cool bias over the dormant or growing wheat. The most pronounced latitudinal gradient in 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 Coun-
ties. These same counties recorded the highest wheat production during crop year 2000.

During May 2000, TMAX values across Oklahoma no longer exhibited a distinct cool anomaly (Fig. 4c). As demonstrated earlier, May was identified as the month when other vegetative species greened rapidly statewide. By June 2000, the month when the wheat harvest concluded, a warm anomaly had developed and remained evident in the data through July (Fig. 4d) and August 2000, similar to Raymond et al. (1994). 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.

The characteristic patterns indicated by the maps of monthly averaged TMAX also were apparent in maps of monthly averaged TAVG for crop year 2000 (not shown), though the magnitude of all anomalies was reduced for the monthly averages of TAVG. 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.

The monthly averaged values of TMAX for the period November 1999 through April 2000 were consistent with previous studies that disclosed that an increase in living vegetation created cooler maximum temperatures (Anthes 1984). Analogous results indicating that increased foliage was associated with increased minimum temperatures were not apparent in the TMIN data for crop year 2000.

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. 5a–c). During May (Fig. 5d), the statewide pattern began to be characterized by a predominantly east–west gradient, attained by July. This meridional pattern continued through September 2000.

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, as seen in Fig. 5c.


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 (i.e., the largest county in
Oklahoma), encompassing the primary wheat-producing counties of the state. This swath was divided into three regions, and representative 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 6 sites at an average latitude of 36°8′34″N as compared to 11 sites averaging 36°18′18″N for Wheat and 11 sites averaging 36°22′29″N for East. Table 1 lists the Mesonet sites assigned to each region, and Fig. 1 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 (Wilks 1995). This test did not assume that any probability distribution adequately represented the data. The test was executed individually for each month from November through August for nine variables: TMAX, TMIN, TAVG, DMAX, DMIN, and DAVG, as well as the daily average vapor deficit (VDEF), 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 equaled 224 days for February; 240 for April, June, and November; and 248 for January, March, May, July, August, and December.

Results from the significance testing of the total daily solar radiation and total daily rainfall indicated either 1) an east–west gradient that was characteristic of Oklahoma’s climatology or 2) differences between regions that were not statistically significant. Thus, Oklahoma’s wheat belt did not produce an evident signature in the statistical analysis of either total daily solar

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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 patterns.

Table 2 displays the mean values of five variables, by month, for each of the three regions. An anomalous monthly mean is defined for this study as a monthly mean for West 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 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. Results for TAVG and DAVG were similar to those of TMIN and DMIN, respectively.

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 \( \leq p \leq 0.0012 \)). 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°C–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 (\( p = 0.0143 \)),
uary ($p = 0.0001$), 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.

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 ($p = 0.8259$), DAVG ($p = 0.8808$), 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, DMIN, and DAVG 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, DMIN, and DAVG for Wheat averaged 0.49°C, 0.41°C, and 0.42°C higher than the respective values for East. DMAX, DMIN, and DAVG for Wheat also averaged 2.33°C, 2.49°C, and 2.35°C higher than the respective values for West. These results were even more interesting when one considered that during March between 1994 and 2001, ~25 frontal passages occurred, eliminating evidence of mesoscale gradients across the wheat belt boundaries.

Monthly means of the average daily vapor pressure deficit, VDEF, across the three regions mirrored the monthly means of TMAX (Table 2) during the wheat's growing season. With the exception of March, the Wilcoxon test indicated that VDEF differences during the 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.

Given these results, one might expect that the reported anomalies would be amplified during March and April when the wheat crop was bountiful and suppressed during those months when the wheat crop was poor. Year-to-year comparisons were conducted (data not shown) for monthly means of TMAX versus crop year wheat production. No relationship was found, indicating that the anomalies were not enhanced or suppressed based on the condition of the crop. This seemingly negative outcome might result from many factors. For example, when the wheat crop grew well, environmental conditions likely were favorable for other vegetative species to green up earlier and to grow abundantly. Thus, differences between the wheat belt and its adjacent land would not be as distinct as those during an average crop season. Other events could occur just prior to or during harvest that damaged or destroyed otherwise outstanding crop production (e.g., widespread flooding). Hence, crop production statistics might not adequately reflect the differences between cropland and adjacent grasslands during every crop year.

d. Daily impact of the wheat belt: Preharvest

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. Using data from the period 1999–2001, approximately 50 days between 15 March and 1 May revealed evidence of heightened DMAX values over Oklahoma's wheat belt compared to adjacent grasslands. More than half of these cases revealed a DMAX enhancement only across five or six counties in north-central Oklahoma. During more than 80 of the remaining days, either solar forcing was weak (i.e., total daily solar radiation < 15 MJ m$^{-2}$) or a substantial gradient in total incoming solar energy existed across the state (i.e., gradient in total daily solar radiation > 10 MJ m$^{-2}$). It was possible that the advection of moisture from the Gulf of Mexico masked some DMAX signatures from the wheat fields. The evolution of the meteorological features near the surface on 27 March 2000 and 5 April 2000 typified spring days when Oklahoma's wheat crop most influenced its environment.

1) 27 March 2000

Clear skies and weak winds characterized the synoptic conditions across Oklahoma on 27 March 2000 (Fig. 6a). Influenced by a large high pressure system over the western United States, surface winds across Oklahoma backed from light northerly in the morning to light westerly by noon. Statewide, the average wind speed was only 2.6 m s$^{-1}$. Rainfall totals of 5–10 cm had been recorded at many Mesonet sites across western Oklahoma during the week prior to 27 March in association with the passage of several weak frontal boundaries. The most significant events occurred on 22 March, when 1–2 cm of rain fell across the western two-thirds
of the state, and on 23 March, when 2–6 cm fell across
the western third of the state.

Mesonet soil moisture values at depths of 5, 25, and
60 cm on 27 March 2000 indicated that water down to
the root zone was available statewide. In fact, the pattern
of DMAX (Fig. 6a) more closely resembled the asso-
ciated visual greenness map (Fig. 3c) than it did the
rainfall pattern of the previous week (not shown). Out-
side of the wheat belt, the May Ranch (MAYR) Mesonet
site received 8.6 cm of rain during the previous week,
while its maximum dewpoint on 27 March was only 5.0°C.
In contrast, nearby Cherokee (CHER), within the wheat
belt, received 8.7 cm of rain during the previous week,
and its maximum dewpoint on 27 March was 14.2°C.
Similarly, Woodward (WOOD) and its neighbor, Seiling
(SEIL), recorded 7.1 and 6.4 cm of rain, respectively,
during 21, 22, and 23 March. Yet the maximum dew-
point on 27 March at WOOD, outside of the wheat belt,
was 5.0°C; at SEIL, within the wheat belt, DMAX was
9.0°C. Apparently, the cycling of water through the root
zone of the growing winter wheat was more efficient at
returning water to the atmosphere than was direct evap-
oration from either the moist soil or dormant vegetation.

The dewpoint field across the region of interest
evolved considerably from sunrise to sunset (e.g., Haug-
land and Crawford 2002). From midnight to sunrise
(about 0630 CST) on 27 March 2000, dewpoints de-
creased 2°C across Wheat and East and 1°C across West
(Fig. 7). At 0600 CST, about 30 min prior to sunrise,
nearturface air was the most moist (6°–7°C) across the
southwest and the southeast corners of Oklahoma and
the driest (1°–2°C) across the northeast corner and the
Panhandle (Fig. 8a). Dewpoints across the wheat belt
were approximately the same as those observed over
adjacent regions. Within an hour after sunrise, dew-
points increased 1°–2°C statewide as a result of the evap-
oration of dew and transpiration.

The significant increase in low-level moisture after
sunrise was aided by the existence of a nocturnal in-
version. The inversion confined the surface flux of mois-
ture to a shallow layer. At the ARM Central Facility
near Lamont, Oklahoma, the morning sounding (0530
CST) indicated a nocturnal inversion in which the tem-
perature increased by 6.4°C within the first 15 hPa above
the ground (~130 m). An analysis of Mesonet obser-
vations suggests that the inversion existed across a broad
region, as dewpoint temperatures increased rapidly
statewide by 0730 CST. Note the rapid increase of near-
surface moisture between about 0700 and 0800 CST for
West, Wheat, and East (Fig. 7). These composite ob-
servations provided additional evidence that, shortly af-
after sunrise, an inversion confined the influx of moisture
to a shallow atmospheric layer across all three regions.

By 0900 CST, it became evident that transpiration
across the wheat belt supplied substantial moisture into
the lower atmosphere (Fig. 8b), similar to the obser-
vations of Dirmeyer (1994). Dewpoints across the nor-
thern two-thirds of Oklahoma’s wheat belt ranged from
5.5° to 8.5°C; several Mesonet sites across north-central
Oklahoma experienced a 4°C increase during 3 h. While
transpiration influenced the dewpoints of several Me-
sonet sites within the wheat belt (not shown), dry-air
entrainment (i.e., vertical turbulent mixing at the top of
the inversion) appeared to cause a 1°–2°C reduction in
near-surface moisture elsewhere between 0800 and 0900
CST. By 1000 CST, surface heating eroded the inversion
over most, if not all, of the Mesonet sites (Fig. 8c).
Composite dewpoints for West, Wheat, and East iden-
tified 1000 CST as the time when a local minimum in
surface moisture occurred (Fig. 7). At that time, dew-
points ranged from −1° to 4°C adjacent to the wheat
belt and from 3° to 7°C within the wheat belt (not
shown).

Interestingly, the magnitude of the increase of dew-
FIG. 7. Composite 5-min observations of dewpoint for regions West, Wheat, and East between 0000 CST 27 Mar and 0000 CST 28 Mar 2000. The solid black, light gray, and dotted lines denote the composite dewpoints for Wheat, East, and West, respectively. The composite data were constructed from the average of all observed values at a given time for the sites located within each region (Table 1). The time series plot extends from midnight to midnight CST—the interval for computing DMAX.

Dewpoints ranged from 9° to 12°C by 1730 CST across the northern third of the wheat belt (Fig. 8e), including 11°C at Lamont. At this time, the mixed layer over the ARM Central Facility extended to about 700 hPa. A surface-based source of moisture still was evident, as the surface dewpoint of 10.7°C was about 3.5°C higher than the dewpoint just 5 mb aloft (via the Lamont sounding; not shown).

One-half hour after sunset (Fig. 8f), dewpoints across the northern half of Oklahoma ranged from 2° to 7°C greater than those measured 30 min before sunrise. Notably, the winter wheat belt not only altered its local area, but moisture advected downwind from the crop and greatly enhanced the dewpoints across several counties to the east.

On a much smaller scale, a microscale impact of moisture advection was evident in observations from the Freedom Mesonet site (FREE). Relative to FREE, wheat was grown to the immediate southwest of the site. Hence, advection by winds from these highly localized wheat fields probably influenced Freedom’s observations. Five-minute dewpoint and wind direction observations from the Freedom Mesonet site (Fig. 9) capably illustrated the advection of moisture from these local wheat fields. Aside from the evaporation associated with sunrise, when winds were from north of west (between 270° and 360°), dewpoint temperatures tended to decrease or remain steady. In contrast, winds between 180° and 270° were associated with rapid increases in dewpoint. The impact was most evident between 1200 and 1630 CST, when the wind direction repeatedly shifted from just north of due west (>270°) to just south of due west (<270°). Interestingly, the dewpoint temper-
Fig. 8. Near-surface dewpoints at (a) 0600, (b) 0900, (c) 1000, (d) 1500, (e) 1730, and (f) 1915 CST on 27 Mar 2000. A one-pass Barnes technique was used for the objective analysis. The white outline depicts the boundary of Oklahoma’s wheat belt.

Fig. 9. Five-min average measurements of dewpoint (solid line, TDEW) and wind direction (dots, WDIR) at the Freedom Mesonet site between 0600 and 1800 CST on 27 Mar 2000. The axis for wind direction (right axis) is expanded vertically for easier interpretation.
atures repeatedly decreased and increased by 1°–3°C in association with these minor changes in the wind direction.

2) 5 April 2000

Rain totals for the week prior to 5 April were significantly less than those prior to 27 March. 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.

The primary features evident on this day were 1) a region of significantly elevated DMAX values over the wheat belt and 2) an associated intensification (as compared to 27 March) of the DMAX gradient across far western Oklahoma (Fig. 6b). Daily maximum dewpoints within the wheat belt ranged from 11°C to 17°C, whereas those just east of the wheat belt ranged from 9°C to 11°C. DMAX values just west of the wheat belt ranged from 4°C to 10°C, with two notable exceptions: 12.4°C at the Buffalo Mesonet site and 12.0°C at Freedom. As noted earlier, dewpoints at FREE were enhanced by moisture advection from local wheat fields. By the same physical processes, local wheat farms influenced dewpoints at Buffalo given favorable wind directions.

Southwest winds at 1530 central daylight time (CDT) averaged 10 m s\(^{-1}\) across the main body of Oklahoma; westerly surface winds prevailed across far northwest Oklahoma and the Panhandle (Fig. 10). Two regions of enhanced moisture were evident: 1) an area across south-central Oklahoma where dewpoints ranged from 9°C to 12°C and 2) an extended region across the wheat belt where dewpoints ranged from 10°C to 15°C (Fig. 10). An animation of the dewpoint 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, the animation revealed that the moisture maximum was generated locally, probably as a result of surface fluxes.

The daytime evolution of near-surface dewpoints on 5 April 2000 (Fig. 11) differed from those of the previous case (Fig. 7). From sunrise to about 1600 CDT, dewpoints for Wheat and East increased steadily. After 1600 CDT, dewpoints for both regions decreased into the nighttime hours as dew began to form. The observations did not reflect a late-morning maximum of low-level moisture over either Wheat or East, as was apparent on 27 March. Composite data for West indicated that substantial drying of near-surface air occurred from ~1200 CDT to sunset. Unlike the previous case, a dewpoint maximum was not evident during the late morning.

The thermodynamic profile from Lamont (not shown) provided a vital clue as to why dewpoints for Wheat did not decrease during the late morning and exceeded 14°C by late afternoon at eight Mesonet sites within the wheat belt. At 0635 CDT, 40 min prior to sunrise, a substantial inversion, with a temperature increase of 10.7°C between the surface (970 hPa) and 860 hPa, was measured at the ARM Central Facility. Soundings at 1530 and 1830 CDT indicated that the inversion never eroded fully over Lamont on 5 April. Hence, moisture added to the mixed layer by transpiration was confined to a layer about 100 hPa deep, and dry air above the inversion was not entrained significantly into the mixed layer. Surface dewpoints measured at the radiosonde site at 0635, 1530, and 1830 CDT were 2.9°C, 14.4°C, and 13.2°C, respectively. Presumably, the stronger winds on 5 April (as compared to the previous case) also enhanced transpiration from the wheat (Doran et al. 1995), with the resulting atmospheric moisture confined to the mixed layer.
e. Daily impact of the wheat belt: Postharvest

As noted in Section 3b, a warm anomaly commenced during June as wheat growers completed the harvest. The warmer temperatures persisted through July (Fig. 4d) and August. 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.

Strong solar forcing appeared to be the most evident factor related to the existence of a warm anomaly over the wheat belt. Presumably, more incoming energy was partitioned into sensible heat over the harvested wheat belt than over growing grasslands. Using the same grouping of stations noted in Table 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, 4 were marked by significant cloud cover elsewhere in the state, 1 was influenced by the passage of a weak cold front, and 3 exhibited a slight warm anomaly over the wheat belt.

10 July 2000

This day typified those summer days when Oklahoma’s harvested wheat belt (Fig. 3d) most impacted its environment. With the exception of the Tulsa metropolitan area in northeast Oklahoma, trees and grasslands pervade eastern Oklahoma. A high pressure system dominated Oklahoma’s weather from 4 July to 10 July 2000. Consequently, no rainfall was measured during this period, and skies were predominantly clear. Statewide, winds were from the south-southeast, south, or south-southwest at an average speed of 4.8 m s$^{-1}$. Values of TMAX (Fig. 6c) across the northern third of Oklahoma’s wheat belt ranged from 36.9$^\circ$ to 39.4$^\circ$C. Directly east of and adjacent to this region, maximum temperatures varied from 34.9$^\circ$ to 36.3$^\circ$C. Across southwest Oklahoma, southerly winds advected air warmer than 38$^\circ$C northward from north-central Texas. Despite the warm-air advection, daytime temperatures were $\sim$1$^\circ$C warmer across north-central Oklahoma than across southwest Oklahoma.

The relative maximum in air temperatures across north-central Oklahoma extended southwest (Fig. 6c) across the central third of Oklahoma’s wheat belt (divided north to south). The value of TMAX was 37.3$^\circ$C at Watonga (WATO), a site that was centrally located within the wheat belt. In comparison, at the western boundary of the wheat belt, the TMAX value at Cameron (CAMA) was 35.7$^\circ$C. West of the wheat belt, the TMAX value at Arnett (ARNE) was 35.6$^\circ$C. Because cattle ranching was a substantial industry across western and northwestern Oklahoma, grazing by livestock reduced the foliage of western grasslands from June to August. Hence, the vegetation gradient across the western boundary of the wheat belt was not as distinct during the summer as it was during the early spring.

The eastern side of the center portion of the wheat belt did not exhibit a distinct warm anomaly (Fig. 6c),
as was measured directly to the west. Cooler temperatures at several of the Mesonet sites across this swath influenced the one-pass Barnes analysis used to create the contour map. If one compares the TMAX observations (Fig. 6c) with the visual greenness map (Fig. 3d), it is clear that the four coolest sites (white circles on Fig. 6c) within this region were characterized by growing vegetation. Two of these sites resided on protected, government lands. Summer crops of peanuts, hay, watermelon, and corn were grown near the other two sites.

A colorized animation of wind vectors and isotherms (not shown) provided evidence that the warm anomaly across the harvested wheat belt did not result from warm-air advection. Instead, the temperatures increased locally across the wheat belt. The cause of the warming was an increase in the flux of sensible heat. Shortly before sunrise, an extremely weak gradient of air temperature existed across the wheat belt and adjacent lands. Within 75 min after sunrise, a warm anomaly became evident across portions of northern Oklahoma within the harvested wheat belt. Throughout the morning, the temperature maximum intensified and expanded in size outward from the wheat belt. Along an east–west line through central Oklahoma, the temperature gradient remained minimal until about 1315 CDT. By 1500 CDT, a warm anomaly was well-defined across north-central Oklahoma. By 1700 CDT, temperatures began to decrease statewide. Shortly after 0100 CDT on 11 July, the temperature pattern ceased to resemble the vegetation pattern across the state.

Just before sunrise, temperatures across Wheat and West were about 1.5°C cooler than those across East (Fig. 12). By 1600 CDT, when temperatures attained their daily maximum, Wheat was 2.9°C warmer than East and 0.6°C warmer than West. Hence, the diurnal temperature range on 10 July was larger across the harvested wheat region than across adjacent lands with growing vegetation. Although high-resolution satellite imagery was not obtained for this case study, the diurnal temperature cycle for Wheat was consistent with an earlier onset of shallow cumulus clouds over harvested wheat as compared to grasslands (Rabin et al. 1990).

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. 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 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.

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.
Monthly averaged values of DMAX and DMIN 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.

During the period from 1999 to 2001, about 50 days between 15 March and 1 May 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 dewpoints were enhanced only across five or six counties in north-central Oklahoma, where the winter wheat production was the largest. Another 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 spring 2000 indicate that the presence of growing wheat influenced the maximum daily dewpoints and the diurnal cycles of dewpoint on days with both weak and moderate winds, and in both moist and dry air masses. Case studies from the summer of 2000 indicate that the warmer temperatures over the harvested wheat resulted from local heating rather than from warm-air advection. A comparison of the prior week's rainfall and values of dewpoint demonstrate that the growing wheat was more efficient at recirculating water back to the atmosphere than occurred across the adjacent lands.

These analyses demonstrate that Oklahoma's winter wheat belt has a significant impact on the near-surface, mesoscale environment during growth and after harvest. Consequently, it is imperative that mesoscale forecasts, whether produced objectively or subjectively, account for the vegetation–air interactions that occur across western Oklahoma and, presumably, across other crop regions in the United States and around the globe.

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