**J1.9** LAND-ATMOSPHERE FEEDBACK ACROSS EASTERN OKLAHOMA FOLLOWING THE MCS EVENTS OF AUGUST 1994

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## 1. OVERVIEW

During a 60-hour period in August 1994, two mesoscale convective systems (MCS) deposited 50+ mm of rainfall in a footprint across central and eastern Oklahoma. No significant rainfall occurred across the region during the week before and the week after these events. The region was dominated by a single air mass through the period. Oklahoma Mesonetwork (Mesonet) data indicated a pronounced diurnal oscillation of moisture over the footprint during each of the six days following the event. Afternoon dewpoint temperatures were greater, and air temperatures less, than nearby areas that received no rainfall. This suggests a larger latent heating component in the heat flux over the footprint, relative to those areas that did not receive rainfall.

## 2. BACKGROUND

The planetary system is made up of many complex and interactive components, all of which determine how incoming solar energy at the Earth's surface is used and distributed within the system. These components (e.g., atmosphere, biosphere, and hydrosphere) translate this diurnal forcing into all scales of motion and interaction (Entekhabi, 1995). One critical coupling of these components occurs at the land-atmosphere interface. This coupling plays a dominant role in surface energy balance and in modulating the hydrosphere.

At the surface, net radiation can be partitioned into latent heat flux, sensible heat flux, or a combination of both. This energy balance is modulated by several surface characteristics. Among these, typical soil moisture variations have a larger impact on the characteristics and evolution of the planetary boundary layer than typical variations in albedo, roughness or soil thermal capacity (Zhang and Anthes, 1982).

When soils are sufficiently moist, latent heat flux is energy-limited, i.e., atmospheric conditions and the amount of energy reaching the surface limit the rate of evaporation. As available soil moisture is exhausted, latent heat flux becomes soil-limited, i.e., evaporative flux is limited by the rate at which the soil can provide water vapor to the atmosphere. When latent heat flux is small, diabatic heating is dominated by the flux of sensible heat.

Studies suggest that the impact of spatial contrast in soil wetness is greatest when the following four conditions exist:

*Highly continental regions.* In the interior of continents, moisture recycling can account up to 40% of regional precipitation over long time periods (Brubaker et al., 1993). In these regions, soil moisture availability often is bimodal, tending toward either the wet and dry ends of the spectrum, rather than toward the center of the distribution (Entekhabi, 1995).

*Warm season.* During the summer, more incoming energy is available to be partitioned between latent and sensible heating processes. Many studies, from the mesoscale (e.g., Burman et al., 1975) to the scale of continents (e.g., Zhao and Khalil, 1993), reveal that land-surface interaction is most effective during the warm season.

*Minimal large-scale forcing.* Modeling studies (e.g., Yan and Anthes, 1988) have stressed the importance of minimal large-scale forcing to the emergence of smaller-scale detail related to surface forcing.

*Ideal scale.* Yan and Anthes (1988) and Lynn et al. (1998) modeled solenoidal circulations related to contrasting wet-dry bands of surface moisture content. These circulations were strongest when the bands were ~100-200 km.

### *2.1 The Oklahoma Mesonet*

The Oklahoma Mesonet resulted from cooperative efforts by scientific leaders from Oklahoma's two major research universities

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and from several other meteorological and agricultural disciplines (Brock et al., 1994). In 1994, the average distance between a Mesonet station and its six closest neighbors was 37 km, compared to 130 km for the region's federal surface observation network. The Mesonet was commissioned as operational on 10 March 1994.

## 3. A UNIQUE OPPORTUNITY

On 5 August and 7 August of 1994, two MCS propagated across the heart of the densely-instrumented Oklahoma Mesonet (Fig. 1). Thus, these rainfall footprints were centered in a densely observed (both spatially and temporally) region with quality mesoscale observations of atmospheric conditions. During the two-week period spanning these MCS events, synoptic scale

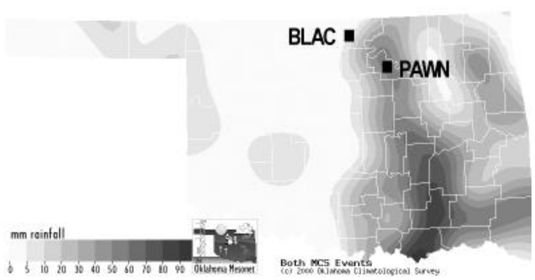


**Figure 1.** Combined rainfall from the MCS events of 5 August and 7 August 1994. The Blackwell (BLAC, 0 mm rainfall) and Pawnee (PAWN, 53 mm) Mesonet stations are noted.

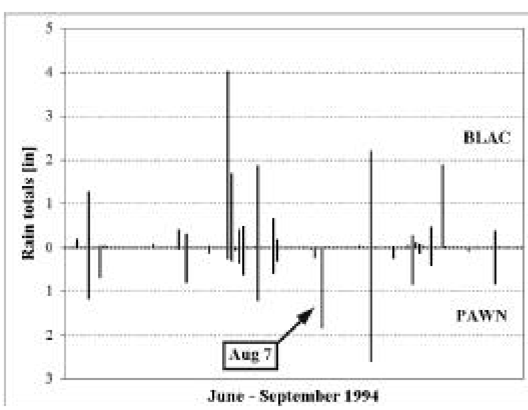


**Figure 2.** Daily Mesonet rainfall during June-Sept 1994. Each bar represents a 24-hour period ending at 0000 UTC. Values at BLAC appear above the zero line; those at PAWN appear below. The 7 August event is noted.

features were weak across the southern Great Plains. During 8-13 August 1994, a strong mid-tropospheric ridge developed across the region. The remarkable absence of synoptic-scale forcing across the southern Great Plains created an "incubator" for the evolution of mesoscale forcing. The well-defined rainfall footprint, mature operation of instruments in the Mesonet, and very favorable atmospheric conditions created a unique opportunity to study the evolution of mesoscale patterns forced by the footprint.

## 4. RESULTS FROM TWO CLOSELY-LOCATED MESONET STATIONS

Observations from the Blackwell (BLAC) and Pawnee (PAWN) Mesonet stations were chosen because they were only 60 km apart (Fig. 1). Neither station received rain for several weeks prior to the MCS events (Fig. 2). PAWN, in the heart of the rainfall footprint, recorded 53 mm during the two MCS events. BLAC, located just west of the footprint, did not record any rainfall. Based on these facts, diurnal trends of the near-surface mixing ratio were determined on a week-versus-week and a site-versus-site basis to contrast the differences in data between these two stations.

### *4.1 Week 1: 1-6 August*

During the week before the major MCS event, the average mixing ratio at BLAC and PAWN were similar throughout the diurnal cycle (Fig. 3a). The average mixing ratio at each site gradually declined from sunset until sunrise. However, the average mixing ratio at PAWN was slightly greater than that observed at BLAC during the nighttime hours. With sunrise, the surface layer at both stations revealed a rapid increase in moisture. By late morning, the rate of increase dminished to near zero and, during the afternoon hours, the average values of mixing ratio declined as convective mixing and dry air entrainment became dominant.

### *4.2 Week 2: 8-13 August*

The average nighttime mixing ratio at BLAC decreased in a manner similar to that observed at the site during the previous week. However, the values were ~1 g/kg less than those of the previous week (Fig. 3b). At PAWN, the nighttime average mixing ratio was ~1 g/kg greater than during Week 1. The decreasing trend during these hours was more pronounced at PAWN during Week 2 than during Week 1, which suggested more transfer of moisture from the atmosphere to the surface as dew. During daytime hours of the second week, the average mixing ratio at BLAC was markedly less than the values observed during Week 1. In contrast, the average daytime mixing ratio at PAWN was clearly greater than its value during Week 1.

Both stations observed a rapid increase of surface moisture following sunrise. This moisture surge at PAWN was of larger magnitude and of longer duration than at BLAC. In addition, dry air entrainment from convective mixing became evident during the afternoon hours in the weekly average at BLAC. At PAWN, ET was able to overcome the negative effects of dry air entrainment. As a result, the mixing ratio held constant through the afternoon.

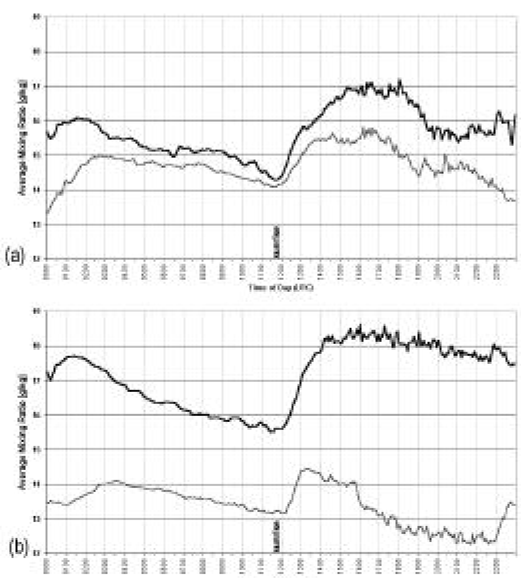


**Figure 3.** The diurnal cycle of the average mixing ratio (g/kg) at the Pawnee (thick trace) and Blackwell (thin trace) Mesonet stations during (a) 1-6 August 1994 and (b) 8-13 August 1994. Abscissa is time of day (0000-2355 UTC). Ordinate is mixing ratio (12-19 g/kg).

### *4.3 Discussion*

The increase in surface moisture at PAWN coupled with its decrease at BLAC during the second week occurred even though both stations remained within the same air mass. Because the large-scale setting did not change during this two-week period, the contrasting evolution of moisture conditions at the two stations suggests differences in local forcing, i.e., land-atmosphere interaction. This disparity of trends represents evidence of different evaporative regimes at the two stations. At BLAC, the atmospheric demand for moisture exceeded the ability of the earth's surface to provide a supply (soil-limited). At PAWN during Week 2, the flow of moisture into the atmosphere was energy-limited (i.e., the ability of the earth's surface to provide moisture through ET processes exceeded the demand of the atmosphere).

At PAWN, the largest increases in the average mixing ratio from Week 1 to Week 2 occurred in the late afternoon. During these hours of Week 1, convective mixing and dry air entrainment became dominant at PAWN. However, during Week 2, entrainment processes did not dominate at PAWN as more moisture moved from the earth's surface into the atmosphere. At BLAC, large *decreases* occurred between 1600 UTC and sunset, because entrainment processes at BLAC became dominant *earlier* in the day during the second week than occurred during the first.

Even though it had not rained at BLAC since 25 July 1994, the diurnal trace there featured a brief increase in atmospheric moisture shortly after sunrise during both weeks. Dickinson (1984) describes this as a real phenomenon that has not been accurately captured by the parameterization of subsurface moisture into conventional climate models. Overnight, in the absence of incoming solar energy, near-surface soil moisture recharges even during very dry conditions. After sunrise, the atmospheric demand for moisture increases, soil water is surrendered until the supply is exhausted, and a supply-limited ET regime emerges.

At PAWN during the second week, the increase of near-surface moisture following sunrise was larger and lasted longer than the same feature in the other three scenarios (PAWN Week 1, BLAC Weeks 1 and 2). Heavy rainfall at PAWN during the two MCS events had saturated the soil. This enabled an energy-limited evaporative regime to persist long into the day. In other words, during Week 2, the soil at PAWN was sufficiently moist to meet the evaporative demand of the atmosphere long into the day before coming into equilibrium with entrainment processes.

## 5. STATEWIDE OBSERVATIONS FROM THE OKLAHOMA MESONET

Mesonet station plots across Oklahoma represent a detailed look at weather conditions at 15-minute intervals throughout the period of 8-13 August 1994. Color-filled analyses and animations of Mesonet air temperature and dew point values helped isolate important features in these fields.

### *5.1 Diurnal Rhythm in Air Temperature and Dew Point Temperature*

A consistent diurnal pattern emerged in the Mesonet air temperature and dew point fields throughout the second week (Fig. 4). Each night, spatial gradients in air and dew point temperatures relaxed to near uniform values by sunrise. Soon after sunrise, the air temperature and dew point fields gained a strong east-versus-west gradient. Air temperatures across western Oklahoma increased more rapidly than did those across eastern Oklahoma. Dew point values in eastern Oklahoma increased rapidly after sunrise, while those in western Oklahoma remained near their overnight values. During early afternoon, this broad contrast sharpened so that the dew point field across eastern Oklahoma closely resembled the pattern of the MCS rainfall footprint. A double-lobed pattern of lesser air temperatures and greater dew point temperatures was co-located with the rainfall maxima. This pattern persisted until early evening. The broad east-versus-west contrast lasted until sunset, when the spatial gradients began to relax. At night, the spatial contrast dissolved into a near-uniform pattern. This diurnal cycle of developing then weakening spatial gradients occurred on the six days of the second week. The diurnal oscillations ended on 14 August when a cold front crossed the state.

### *5.2 Other Meteorological Features*

Mesonet station plots displayed a different pattern in the wind field during the second week than occurred during the first week. During the afternoon hours, winds were stronger and gustier across western Oklahoma than across eastern Oklahoma.

Solar radiation observations during the afternoons of 9-11 August showed a chaotic pattern that suggested the presence of cumulus clouds across eastern Oklahoma. Visible satellite imagery from the afternoons of 9-10 August confirmed the presence of cumulus clouds. The pattern of cumulus development bore a striking resemblance to the double-lobed pattern of the combined rainfall footprint.

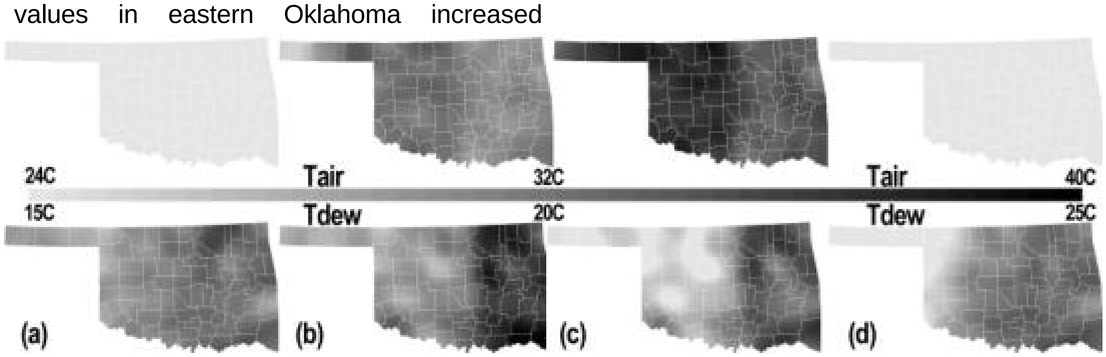


**Figure 4.** Mesonet air temperature (top) and dew point temperature (bottom) at (a) 1200 UTC on 11 August 1994; (b) 1600 UTC on 11 August 1994; (c) 2100 UTC on 11 August 1994; and (d) 1200 UTC.

### *5.3 Discussion*

The station and contour plots illustrated two important features within the data set:

1. A noticeable difference existed in the partitioning of incoming energy between those areas that received significant rainfall during the MCS events versus those that did not.
2. Differences in the character of heat flux followed a distinct diurnal rhythm across Oklahoma. Strong contrast existed during the daylight hours, but near-uniform conditions returned by sunrise each day.

In areas that received no rainfall, the evaporative regime was supply-limited and the sensible heat component dominated the energy flux into the atmosphere. Because incoming energy was partitioned almost exclusively into heating the surface, air temperatures increased rapidly with the rising sun. The flux of sensible heat induced convective mixing and a rapid assault on the convective temperature. As a result, lapse rates across western Oklahoma became dry adiabatic. In turn, this feature contributed to gusty winds by early afternoon. During the post-sunrise morning hours of the second week, conditions across areas that received minimal rainfall resembled those over areas that received the greatest precipitation. In other words, across the *entire* rainfall footprint, dew points were greater (and air temperatures less) than those observed across western Oklahoma. However, by early afternoon, atmospheric conditions over the areas that received minimal rainfall revealed less of a contrast with conditions across western Oklahoma; atmospheric conditions over the axes of greatest rainfall continued to contrast sharply with those from western Oklahoma.

These patterns strongly suggest a demand-limited evaporative regime with a significant latent heat flux component across the maximum rainfall footprint. In areas that received maximum rainfall, more energy was partitioned to the evaporation of soil water, and less was partitioned into increasing the surface temperature. In these areas, soil moisture did not become depleted during the day, and a demand-limited evaporative regime dominated. The areas with lesser rainfall apparently switched to a more supply-limited ET regime when the soil moisture became exhausted during the day. In these areas, soil moisture at the surface recharged during the low-demand overnight conditions, but the supply was exhausted by late morning.

## 6. NETWORK INTERCOMPARISON

Observations from the federal surface observation network and the Oklahoma Mesonet were objectively analyzed to a 12-km by 12-km mesh. The change in average mixing ratio (Week 2 average minus Week 1 average) was calculated at each grid point. Spatial correlation products (the change in average mixing ratio versus observed rainfall) for both networks were created on two subsets of this grid. These values were used to compare how the two networks captured the atmospheric response to the MCS events on a statewide scale and on the mesoscale.

The larger domain extended across most of Oklahoma, excluding the panhandle. It was chosen to capture broad differences between meteorological conditions across eastern Oklahoma and those across western Oklahoma. Roughly one-half of the analysis points in the larger domain were not within the rainfall footprint of either MCS event. Nearly all of the zero-rainfall analysis points were located in western Oklahoma.

The smaller domain was limited to the eastern half of Oklahoma. It was designed to capture details in the spatial structure of atmospheric responses within the area of rainfall. Nearly every grid point across the domain witnessed rainfall from the MCS events. In this regard, spatial correlation values with the rainfall footprints were more related to the detail in the *magnitude of rainfall in eastern Oklahoma* than the broader contrast across the larger domain.

### *6.1 Results and Discussion*

The mesoscale and synoptic scale networks both captured a broad east-versus-west contrast that developed across the state during the daylight hours. In fact, calculations based on data from the two networks produced quite similar results across the larger domain. However, only the Mesonet captured detail within the area dominated by the rainfall footprint. The details that emerged from using the Mesonet data across the smaller domain were essentially invisible to the federal network.

Across the smaller domain, greater correlation values observed by the Mesonet late in the morning are the manifestation of a developing "focus" in the change fields over the axes of greatest precipitation. This feature suggests that the ability to maintain a demand-limited ET regime varied across eastern Oklahoma. Areas that received the most rainfall met the atmospheric evaporative demand longer into the day than did those that received minimal rainfall.

The maximum change in the average Mesonet mixing ratio across the smaller domain occurred at 1500 UTC, while the maximum spatial correlation occurred three hours later. Mesonet change maps at 1500 and 1800 UTC (Fig. 5) illustrate this temporal lag. At 1500 UTC, increases of 2.5g/kg or more are evident throughout eastern Oklahoma. At this map time (shortly after sunrise), all locations within the rainfall footprint met the evaporative demand during the second week but were beginning not to do so during the first week. Hence, positive changes in the average mixing ratio were observed throughout the rainfall footprint. Three hours later, the magnitude of the increase had diminished across most of the region. The areas still providing an increase >2.5-g/kg were focused over areas of maximum precipitation. Over these areas, evaporation of copious moisture into the atmosphere continued longer into the day, whereas the supply became exhausted in areas that received little rainfall.

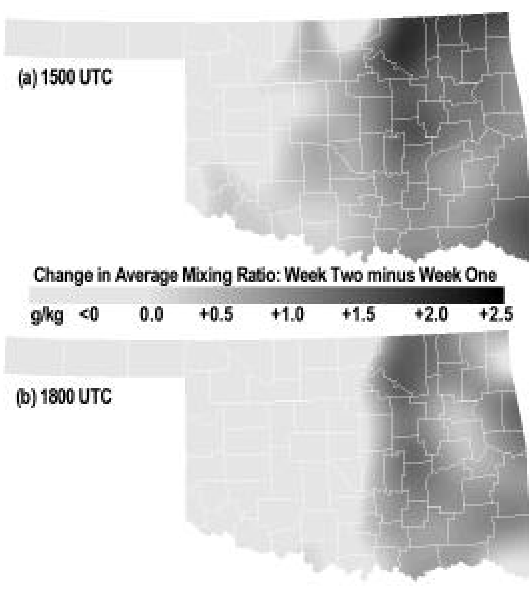


**Figure 5.** Using Mesonet data, change of the average mixing ratio at (a) 1500 UTC, and (b) 1800 UTC, between the week of 1-6 August 1994 and the week of 8-13 August 1994.

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