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Atmospheric Response to 1988 Drought Conditions and Future Climate Implications[1]

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Plentiful precipitation in the central United States is one of the basic components of the successful agricultural industry in the Corn Belt. A combination of moisture, wind, and topographic factors creates an ideal condition for rainfall over most of the region during the late spring and early summer. In 1988, many ingredients necessary for wet weather were absent. The region experienced a drought unequalled since the 1930's. The drought of 1988 demonstrated that the symptom of drought, namely, dry soils, can exacerbate and even perpetuate drought conditions by decreasing available moisture, altering circulation patterns vital to storm development, and increasing air temperatures.

Models that predict future climate change, forecast that dry conditions, such as those in 1988, will become more prevalent in the future "greenhouse" atmosphere of the central United States. Many of the smaller-scale effects, which were important in perpetuating the drought of 1988, could not be anticipated from these poor-resolution climate models. Therefore, great care should be taken in interpreting these forecast results.

INDEX DESCRIPTORS: climate change, soil moisture, Drought of 1988

The drought of 1988 has brought great attention to the prospects of a changing climate and its effects on midwestern agriculture. Researchers believe it is unlikely that global warming due to increased carbon dioxide concentrations played an important role in the unusually dry and warm conditions in the mid-continent region of North America in 1988 (Trenberth et al. 1989). Nevertheless, many climate models agree that droughts in the Midwest and Great Plains region of the United States will become more frequent in a "greenhouse" atmosphere (Manabe and Wetherald 1986, Meehl and Washington 1988).

These climate models predict weather on a global scale and incorporate large-scale effects in their simulations. However, these models have poor grid resolution and provide little information for smaller scales. In fact, in many of these forecast models the agricultural region of the Corn Belt is represented by only one grid point.

Local and regional circulation patterns that affect precipitation in agricultural regions are highly sensitive to earth-atmosphere interactions due to soil moisture and other surface characteristics that may vary significantly over small regions. Global climate models cannot incorporate the local effects of the unique surface characteristics of the agricultural Midwest. The 1988 soil moisture distribution may have had a significant impact on the atmospheric conditions that perpetuated the hot, dry conditions. This paper will analyze the role of soil moisture in the production of normal springtime rainfall, examine the 1988 atmospheric conditions that prevented normal precipitation, and discuss the implications of these conditions on the interpretation of future climate forecasts in the central United States.

NORMAL CONDITIONS

The agricultural regions of the central United States rely heavily on plentiful late spring and early summer precipitation for adequate crop development throughout the growing season. In most of the Corn Belt, May, June, and July are the wettest months. During this period most areas of the Corn Belt will average 10-11 inches of precipitation. The wet weather is in part due to persistent southerly (blowing from the south) low-level winds, which allow moisture from the Gulf of Mexico to interact with storm fronts as they pass west to east over the region.

Predominant springtime southerly winds in the Great Plains and Mississippi Valley areas are produced by clockwise winds around a strong atmospheric high pressure system over the western Atlantic Ocean and southeastern United States together with counterclockwise winds around a low pressure region over the Rocky Mountains. As shown in Fig. 1, this flow pattern results in the northward advance of warm, moist air from the Gulf of Mexico, creating a boundary or frontal zone with the cooler, dry air to the north. This strong contrast provides the potential for thunderstorms, although other specific ingredients are necessary to trigger significant precipitation.

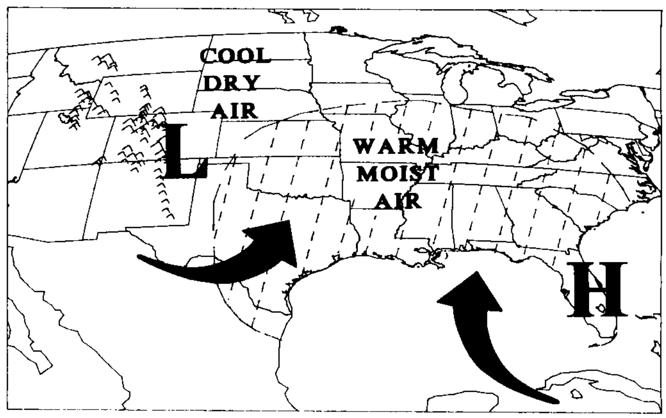

Fig. 1 Normal springtime weather conditions. Bold dashed line denotes air mass boundary, and arrows indicate wind direction. L and H represent low and high surface pressure centers, respectively.

After compiling nearly 100 years of hourly precipitation data, Wallace (1975) reported that the highest summer thunderstorm frequency occurs near local midnight over much of the north-central United States. Riley et al. (1987) also reported that heavy May and June rainfall periods in South Dakota, Nebraska, and Kansas have their highest frequency between 2300 LST (Local Standard Time) and 0500 LST. Bonner (1968) and Astling et al. (1985) attributed this nocturnal precipitation to a wind maximum or jet over the southern and central Great Plains that develops with a southerly wind direction. This phenomenon, known as the Great Plains low-level jet, forces air to the north to rise, producing clouds and precipitation. This event may help trigger precipitation over the Corn Belt even when the larger-scale or synoptic-scale features suggest that rain is not likely. Figure 2 shows the strong correlation between the strength of

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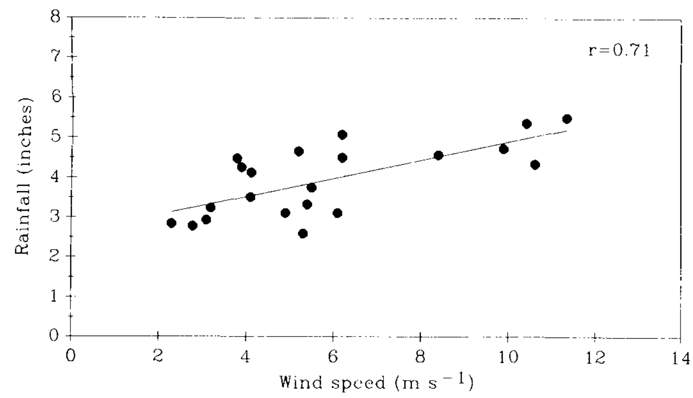

Fig. 2 Average May low-level wind speed maximum at Topeka, KS (observed at 0600 Local Standard Time) versus May rainfall, averaged for 28 stations in the Corn Belt, for the period 1958-1979. The r-value or correlation coefficient is 0.71.

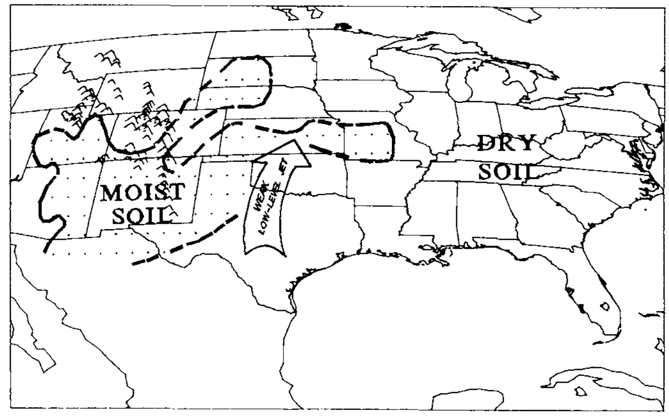

Fig. 4 Estimated soil moisture conditions, based on the Crop Moisture Index for late May, 1988, that are linked to a weaker low-level jet.

the May-averaged nocturnal, low-level jet observed over Topeka, Kansas, and May precipitation amounts at several Corn Belt locations downwind (north) of this upper-level wind station.

The strength and geographic coverage of this wind phenomenon and related storm episodes are linked to the unique structure of the topography in the central United States, and may be influenced by soil moisture patterns that develop south of the Corn Belt during the early spring. McCorcle (1988) demonstrated that the Great Plains jet results from the influence of the gentle east-to-west upward slope of the Great Plains terrain. In addition, it was shown that the distribution of soil moisture over the Great Plains slope and the Lower Mississippi River Valley can affect the location and relative strength of the jet and resulting rainfall distribution. The strong gradient of soil moisture that exists between the dry mountainous regions of the southern Rockies and the relatively moist southern Plains creates an air circulation, similar to a sea breeze, that can greatly magnify the jet and aid the development of convective precipitation. In addition, the evaporation of soil moisture in the south and central Plains can act as a moisture source for developing storm systems. This extensive source of moisture is much like extending the influence of the Gulf of Mexico northward. The typical scenario of soil moisture and jet development is depicted in Fig. 3. If anomalous soil moisture conditions exist this "sea-breeze" or secondary circulation can reduce the strength of the jet or change its location.

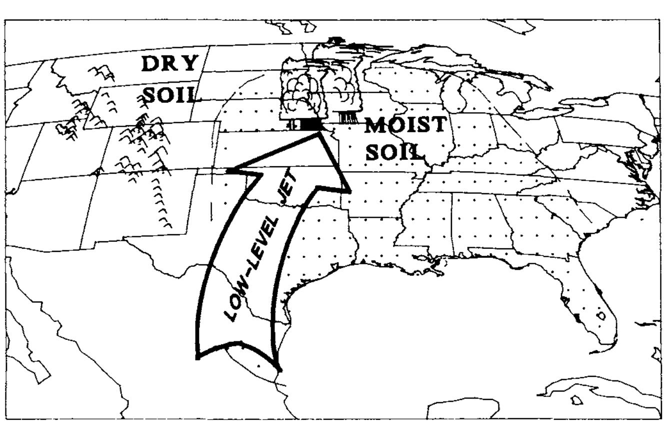

Fig. 3 Normal spring soil moisture conditions that produce strong low-level jets.

THE DROUGHT OF 1988

For many regions of the Corn Belt the spring and summer of 1988 had less than 50% of normal precipitation. Topsoil moisture, which was barely adequate at the beginning of the growing season, was quickly consumed in evapotranspiration processes, and with little additional precipitation, large deficits were common by the end of May. These conditions worsened in June and July as abnormally hot weather dominated the region.

The strong surface high-pressure center, normally located over the eastern Atlantic Ocean during late spring, was positioned over the central Mississippi Valley and rarely allowed appreciable moisture into the Midwest from the Gulf of Mexico. In this position, the Gulf moisture was not transported northward, but instead was advected westward toward the southern and central Rockies. Many parts of western Texas, New Mexico, and Arizona received above-normal rainfall. As shown in Fig. 4., this weather pattern created a much different soil moisture distribution than that shown in Fig. 3, with available moisture increasing from east to west rather than west to east.

The dry surface conditions over the Corn Belt, depicted in Fig. 4, had an obvious effect of reducing the moisture available for developing storms, thus limiting their size and intensity.

McCorcle (1988) showed that with this anomalous type of soil moisture pattern the secondary circulation which develops in response to the resulting temperature gradient may counteract to some degree the low-level jet circulation, thereby reducing jet speeds or confining the jet's influence further to the south. As a result, later in the 1988 growing season, when atmospheric moisture was able to penetrate to the Upper Midwest and the conditions were favorable for precipitation, the surface moisture distribution may have locally suppressed appreciable storm development north in the Corn Belt while in part triggering convective precipitation further south.

The effect of soil moisture distribution on the low-level circulation patterns can be illustrated with a modelling experiment. A detailed three-dimensional model of the lower atmosphere described in McCorcle (1988) has been successful in simulating low-level atmospheric phenomena, including jets in the Great Plains. The forecast model includes a soil layer to simulate the effects of soil moisture on atmospheric circulations.

Two model simulations were initialized with the weather conditions of May 27 through 28, 1988. During this period, the large-scale weather indicators favored precipitation development in the Corn Belt, however, very little rain was observed. Most observed precipitation was confined to the south in southwestern Kansas, Oklahoma, northern Texas, and eastern New Mexico.

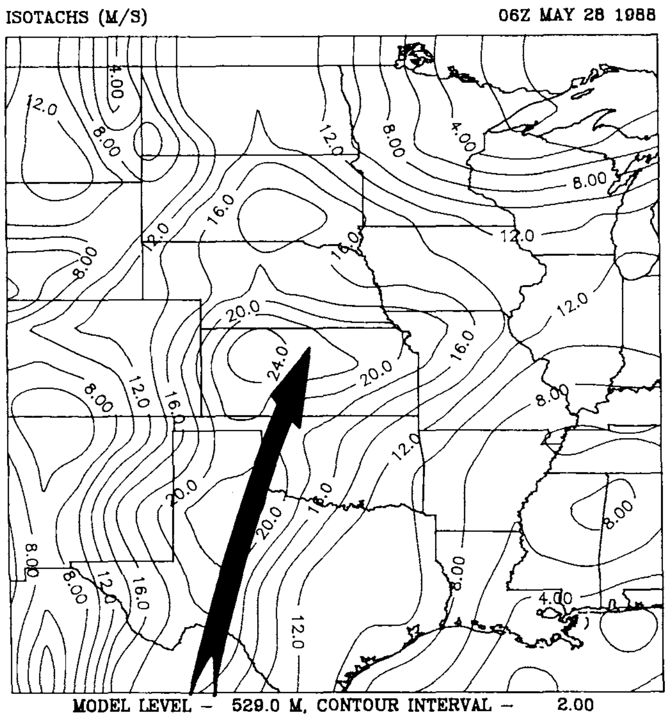

Fig. 5 Model forecast of wind speed at 500 m above the ground for 0000 LST May 28, 1988 for the normal soil moisture conditions shown in Fig. 3. Contour interval is 2 m s^{-1}. The arrow denotes the strength and direction of the low-level jet.

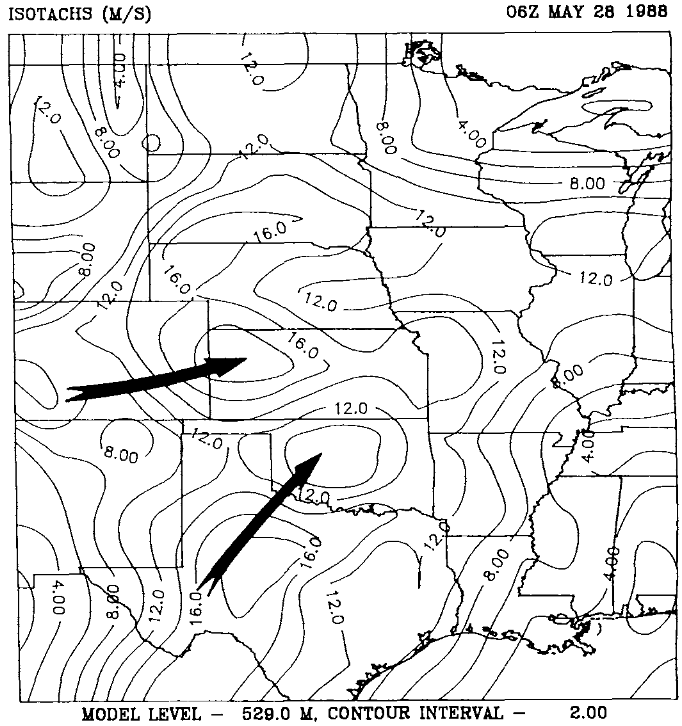

Fig. 6 As in Fig. 5, with soil moisture conditions of 1988 shown in Fig. 4.

The first simulation considered a soil moisture field representing normal May conditions as portrayed in Fig. 3. The model-predicted nocturnal wind speeds at 500 m above the ground are shown in Fig. 5. The model predicted maximum jet speeds of greater than 24 m s^{-1} (meters per second). Observational evidence suggests that the most favorable region for convective precipitation was downwind of the jet maximum, which, in Fig. 5, corresponds to western Nebraska and Iowa.

In a second simulation, actual May 1988 soil moisture conditions, estimated from Crop Moisture Index maps issued by the National Weather Service, were used to initialize model surface moisture. All other model inputs were identical to the first simulation. The predicted jet speeds of 18 m s^{-1}, depicted in Fig. 6, were 25% weaker and much farther south than the case with normal moisture conditions. The weaker jet circulation produced by these soil conditions may have been partly responsible for the suppression of precipitation over the Corn Belt. The more southerly location of the jet may have contributed to the precipitation development over Kansas and Oklahoma.

The soil moisture conditions of 1988 also had an impact on the abnormally hot weather. Under normal, moist soil conditions, the high heat capacity of the water and evaporative cooling can appreciably reduce daytime maximum temperatures. However, in 1988, the dry Corn Belt soils caused greater heating of the air and helped boost the hot daytime temperatures, thus increasing crop stress. Quantitative analysis of the soil moisture influence on temperature is given by McCumber and Pielke (1981).

The drought of 1988 was a result of a persistent anomaly in the North American weather pattern. The unusual soil moisture conditions observed in 1988, depicted in Fig. 4, were certainly an artifact of this unusual large-scale weather pattern. The experiments described above demonstrated that a symptom of drought, namely, dry soils, can augment drought by decreasing available moisture, altering circulation patterns vital to storm development, and increasing air temperatures.

IMPLICATION FOR FUTURE CLIMATE

Many models that predict future climate forecast that hot and dry conditions, as in 1988, will become more prevalent in the future "greenhouse" atmosphere of the central United States. These forecasts are based on interpretations of global-scale features of wind and temperature averaged over long time periods. The inability of these models to incorporate surface-air interactions and regional-scale weather details on short time scales could be a large source of error for future climate.

The magnitude of this climate model uncertainty may be related to the relative roles of the scales of motion in producing springtime precipitation in the Corn Belt. How much of this precipitation can be attributed to local or regional effects and how much is a result of the large-scale atmospheric flow features? Shaw and Waite (1973) reported that dry summers in Iowa are characterized by fewer rain events rather than reduced storm intensities. Therefore, it is necessary to determine whether regional mechanisms produced by topography or surface heterogeneities will result in an increase or decrease in the number of rain events in the future climate of the central United States.

Astling et al. (1985) demonstrated that a regional-scale phenomenon, such as the Great Plains low-level jet, may produce precipitation when the large-scale support for rain is not present. Conversely, the results in Figs. 5 and 6 suggest that regional effects may also be a positive feedback mechanism for dry, hot weather as local soil conditions and atmospheric phenomena enhance drought symptoms by preventing rainfall during favorable conditions.

Using 1988 as a blueprint, one might conclude that reduced low-level jet circulations and drier soils may result in arid conditions more extreme than those forecast by current climate models in certain localized areas. This conclusion is probably premature as many other generalizations of global climate models likely produce the opposite tendency. Nevertheless, to deduce the full impact of regional effects on climate and agriculture, forecast models must resolve the important site-specific topographic, soil, and atmospheric characteristics of the central United States. Furthermore, future research should analyze the role of soil moisture and other local parameters in the development of historical precipitation events.

SUMMARY

Hot and dry conditions in the central United States in 1988 produced drought conditions unequalled since the 1930's. This drought has brought attention to climate forecasts suggesting global warming in future decades will force agriculture to adjust to a warmer, drier Corn Belt. Because these climate models have such poor spatial resolution, they exclude smaller-scale mechanisms shown to be important to springtime precipitation episodes. Using 1988 as an example, a low-level atmospheric model demonstrated that regional variations of soil moisture can have a large impact on circulations that may lead to storm development. Care must be taken in interpreting future climate forecasts that do not incorporate these regional effects.

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