On the Temporal Decay of the Relationship between Environmental Covariates and Convective Rainfall for the Kansas High Plains

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ABSTRACT

Covariates derived from 1200 GMT tropospheric soundings taken for 13 June at Dodge City, Kansas, were compared with 3 h rainfall within the surrounding area. Correlation magnitudes decreased beginning with the first period for which precipitation lagged the soundings. There were larger decreases thereafter. It is suggested that the correlation magnitudes decrease because the measured environment is not representative of the environment within distant precipitation-producing migratory disturbances. This implies that atmospheric measurements should be taken simultaneously with the initiation of rainfall if maximum correlative power is to be attained.

Spatial analyses are presented as an alternative to frequent observations so that migratory precipitation-producing disturbances can be detected prior to the on-site rainfall. Covariates obtained from spatial fields gave higher correlations with 3 h rainfall than did the covariates obtained from single soundings.

1. Introduction

The dry years of the middle 1970's have stimulated weather modification activities (cloud seeding for the purpose of increasing rainfall from convective clouds) over parts of the Middle West and High Plains agricultural areas. An adequate evaluation of these activities is needed so that the user groups can estimate the productivity of the emerging cloud seeding technology and so that the project operators can utilize proven techniques, materials, timing, etc., to maximize the benefits. However, the proof of even a moderate change in convective rainfall, say, a 25% increase, is very difficult to achieve. This inability to detect such rainfall changes is due, at least in part, to the high variability of natural rainfall.

The noise problem due to natural rainfall variability may be reduced by incorporating covariates into the design and/or evaluation of operational and/or experimental weather modification projects (Neyman and Scott, 1967; Brier, 1974; Simpson and Woodley, 1975; Biondini *et al.*, 1977). Covariates have been used or proposed for cloud seeding experiments for at least 20 years (Spar, 1957). Their effectiveness in reducing the rainfall variance has been demonstrated by Neyman and Scott (1976), Estoque and Partagas (1974), Biondini (1976) and many others.

The design for the High Plains Cooperative Program (HIPLEX)[2] called for careful consideration of covariates for the reduction of the effect of natural rainfall variability in the statistical evaluation.[3]

A pilot study[4] developed covariates (Table 1) from 1200 GMT rawinsondes taken at Dodge City, Kansas, and correlated them with areal average daily rainfall from 22 precipitation stations located within a 175 km square centered over Dodge City (Fig. 1). Since many covariates were calculated for several levels, the actual number was 136. The analysis was based on historical data for Junes 1958–70. No single variable was able to explain more than 10% of the rainfall variance. There was no improvement from a second study that developed covariates from a one-dimensional quasi-time-dependent numerical cloud model (Kreitzberg and Perkey, 1976) despite careful initialization for the boundary layer temperature and moisture at the time of maximum heating.

Some possible explanations for the low correlations are (i) the daily averages were noisy because

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[1] Deceased December 1977.

[2] Bureau of Reclamation, DWARM, 1973: Conceptual plan for a High Plains Cooperative Program. Denver, 52 pp.

[3] Ackerman, B., G. L. Achtemeier, H. S. Appleman, S. A. Changnon, Jr., F. A. Huff, G. M. Morgan, Jr., P. T. Schickedanz, and R. Semonin, 1976: Design of the High Plains Experiment with specific focus on Phase 2, Single-cloud experimentation. Illinois State Water Survey, Final Report, Contract 14-06-D-7197, 231 pp.

[4] Achtemeier, G. L., P. H. Hildebrand, P. T. Schickedanz, B. Ackerman, S. A. Changnon, Jr., and R. Semonin, 1978: Illinois Precipitation Enhancement Program (Phase 1) and design and evaluation techniques for High Plains Cooperative Program. Illinois State Water Survey, Final Report, Contract 14-06-D-7197, 313 pp.

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TABLE 1. List of covariates that use data from single upper air soundings.

1. Layer precipitable water (sfc–900, 900–850, 850–800, 800–700, 700–600, 600–500, 500–400, 400–200 mb)
2. Total precipitable water (sfc–900, 850, 800, 700, 600, 500, 400, 200 mb)
3. Saturation deficit computed at the following levels: surface, 900, 850, 800, 700, 600, 500, 400, 200 mb
4. Height of the convective condensation level
5. Convective temperature
6. Difference between the convective temperature and the 850 mb temperature
7. Height where $T = 0^\circ\mathrm{C}$, $T = -5^\circ\mathrm{C}$, $T = -10^\circ\mathrm{C}$, $T = -15^\circ\mathrm{C}$, $T = -20^\circ\mathrm{C}$.
8. Warm convective depth: the difference between the height where $T = 0^\circ\mathrm{C}$ and the height of the convective condensation level
9. The mean mixing ratio between the surface and the convective condensation level
10. Dewpoint at mandatory levels
11. Mean equivalent potential temperature in the lowest 100 mb
12. Equivalent potential temperature at mandatory levels
13. Height of wet-bulb zero
14. K-index
15. D-index
16. Showalter index
17. Boyden index
18. Cross totals index
19. Vertical totals index
20. Total totals index
21. Potential wet bulb index
22. Energy index
23. Severe storm index
24. Equivalent potential temperature index
25. SWEAT index
26. Temperature at mandatory levels
27. Height at mandatory levels
28. Wind speed at the levels given in (3)
29. Wind direction at the levels given in (3)
30. U component of the wind speed at 850 and 500 mb
31. V component of the wind speed at 850 and 500 mb
32. U component wind shear 500–850 mb
33. V component wind shear 500–850 mb
34. Wind speed shear 500–850 mb
35. Wind direction shear 500–850 mb
36. Difference in wind direction between 300 and 700 mb
37. Wind speed shear between 300 and 500 mb
38. Surface pressure

of the sparcity of the gages (Huff, 1970); (ii) there exists little physical relationship between these covariates and rainfall; and (iii) the rainfall-producing environment was poorly measured. With regard to (iii), Midwest and High Plains shower-producing systems often occur on space scales no larger than 100 km and on time scales of a few hours. Rapid destabilization and deepening of moist layers can occur in advance of these systems and these temperature and moisture lapse rates can differ considerably from the lapse rates found by the morning soundings unless the latter are taken within the convergent zones. Furthermore, it is apparent that the chance of obtaining measurements representative of the precipitation-producing environment decreases as the time interval between observation and precipitation increases.

In the presence of the other factors, the importance of the timing of the environmental data collection can be assessed if a significant percentage of the Kansas June rain falls in association with the migratory disturbances. In this event, the magnitudes of the correlations should decay with increasing time interval between observation and precipitation. Further, the decay rate should give some indication of the rate of transition from the undisturbed to the disturbed environment.

2. Correlations as functions of measurement timing

The hourly precipitation data for stations within the 175 km square surrounding Dodge City were grouped into 3 h periods and the 3 h area average rainfalls were correlated with the covariates listed in Table 1 in the same manner as were the daily rainfall data. Because of the spacing of the hourly rainfall gages (one gage per 6500 km^2 on the average), little confidence could be placed in the correlation magnitudes (Huff, 1970). However, the temporal trends should still be present.

The temporal trends were found by tabulating for each 3 h period the number of correlation coefficients that exceeded a threshold magnitude. Table 2 summarizes these tabulations for four correlation coefficient magnitude thresholds. Highest correlations were found for the first two rainfall periods. Since the sounding launch time was approximately 0500 LST, the relationship between the rainfall and the covariates for these periods was not predictive. The temporal decay is apparent in the smaller number of variables found for the later periods.

Fig. 2 shows the temporal relation for the 0.15 correlation magnitude threshold. The covariates, designed to capture environmental controls, have been stratified into three groups that relate to moisture stratification, the wind field response to the dynamic disturbance that triggers deep convection, and the air mass stability. The first 11 variables of Table 1 address moisture, the next 16 address stability and the remainder relate to the dynamic trigger. We placed little confidence in the period-to-period fluctuations and constructed subjective best-fit straight lines to reveal the trends. The time decay is clearly apparent for all but the stability category for which there were too few covariates to define a trend. After 1500 LST, none of the trigger covariate correlation coefficients exceeded the cut-off magnitude.

Approximately 50% of the covariates retained for the first two periods were moisture variables many of which were related to the depth of the moist layer. This was not unexpected as soundings were more likely to be taken through cloudy areas or areas

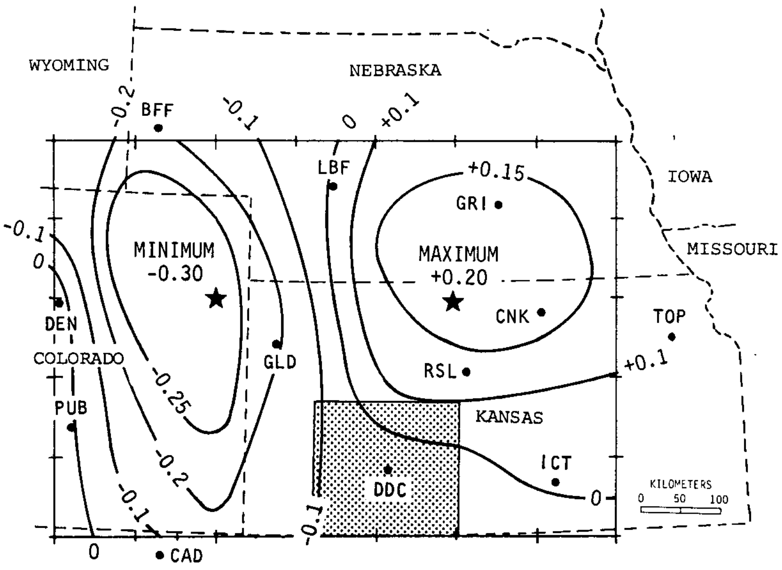

Fig. 1. Map of central High Plains showing the area (shaded) around Dodge City, Kansas (DDC) for which precipitation data were used and contours of correlations between surface moisture convergence (0600 LST) and rainfall for the period 1600–1800 LST.

where the moist layer had been deepened by the migratory disturbances. Covariates retained at longer lags were subsets of the covariates retained at shorter lags. The wind field (trigger) variables were confined mostly to the first three periods. Signs of correlations coefficients from covariates that included low-level winds were consistent with post-frontal or post-squall line conditions. Stability indices, with little continuity, were most prevalent during the early and late afternoon.

The total number of covariates decreased 40% from the non-predictive to the first predictive period. There were larger decreases thereafter. It would appear, therefore, that atmospheric measurements should be taken almost simultaneously with the initiation of rainfall if maximum correlative power is to be achieved. However, this is for the most part, impossible. It would be necessary to make an unreasonable number of rawinsonde observations so as to have a timely one or to have the ability to predict when or where to make the observation.

3. Spatial analysis—an alternative?

As an alternative to the single station approach, we have considered spatial analyses of data from a network of observations as a means of describing migratory disturbances. This approach is attractive, especially if the disturbances are fairly steady with lifetimes of 6–10 h or longer. Since the rainfall frequency for the Kansas High Plains maximizes during a small part of the day (Achtemeier, 1979), it should be possible at one time to determine the preferred spatial location of disturbances that cause much of the convective rainfall over the target area at a later time. Further, the rainfall would be correlated with data collected prior to the operational periods, an approach that eliminates the possibility that changes in storm dynamics brought on by seeding (if changes occur) would modify the mesoscale circulations and bias the observations needed for the evaluation (Neyman and Scott, 1967).

Lacking a dense rawinsonde network with spatial dimensions large enough to detect migratory dis-

Table 2. Number of variables with correlation coefficients exceeding threshold as a function of rainfall period.

Threshold*	01–03	04–06	07–09	10–12	13–15	16–18	19–21	22–24
0.30	2	0	0	1	0	0	0	0
0.25	9	6	0	1	0	0	0	0
0.20	24	19	8	3	3	0	2	0
0.15	39	38	23	12	22	0	13	2

* Absolute magnitude.

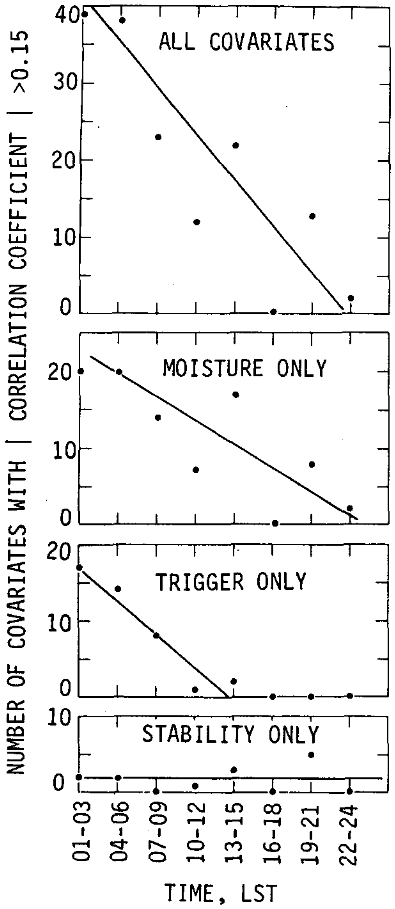

FIG. 2. Time distribution of number of covariates (total, moisture only, trigger only, stability only) with correlation coefficient magnitudes exceeding 0.15.

turbances some distance removed from the target area, we turned to the surface observations which are denser in space and time than those of the current rawinsonde network. While recognizing that some of the parameters important for precipitation cannot be evaluated from surface observations only, we proceeded with the supposition that the vertically integrated effects of subsynoptic and mesoscale phenomena are detectable in the surface observations both in space and time.

Fig. 1 shows the pattern of the correlation coefficient between the moisture divergence at 0600 LST and the Dodge City area rainfall for the period 1600–1800 LST. The divergences have been obtained from horizontal wind components objectively interpolated to an 8 × 6 mesh with a 104 km grid spacing. Table 2 shows that none of the sounding-derived covariates exceeded the minimum correlation magnitude threshold of 0.15 for 1600–1800 LST. It is noteworthy that none of the moisture divergence correlations near the Dodge City rainfall area exceeded this threshold. Yet over eastern Colorado, ~300 km northwest of Dodge City, there is found a center of relatively large negative correlations. This is a reasonable location because, with a propagation speed of 30 km h^{-1}, a disturbance located in this area at 0600 LST would pass over the Dodge City area during 1600–1800 LST.

4. Additional comments

Our spatial analyses of other meteorological fields have also found highest correlations in areas outside of the target area. These correlations, though still small, are larger than the correlations we have been able to obtain from covariates derived from single soundings taken at 1200 GMT.

However, optimism should be tempered by the realization that problems unique to the spatial analysis will limit the correlations. The convective disturbance must be detectable in the surface fields (if the surface fields are to be used). The disturbance must have a history. Differing rates and directions of motion will lead to smaller point correlations.

A factor that enters into project planning is cost of the data collection. If the cost is prohibitive, confirmatory projects may be scrapped or redesigned with a decreased chance for obtaining a prescribed level of statistical significance. One advantage of the spatial analysis is that the relatively inexpensive surface observations may replace the costly rawinsonde as the primary data source for environmental covariates.

These findings point to a potentially useful method to obtain environmental covariates for the evaluation of convective cloud seeding projects, whether experimental or operational. Continuing research into the relationship that couples observation timing with correlative power between covariates and rainfall for sites in the High Plains and in other areas is necessary to determine the full potential of the spatial analysis. Research is continuing in Illinois where accurate rainfall measurements from the Illinois State Water Survey recording raingage networks are available.[5]

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