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Interactive Initialization of Heat Flux Parameters for Numerical Models Using Satellite Temperature Measurements

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Preface

Besides establishing the use of an interactive system to obtain estimates of soil moisture, the present research demonstrates that there is some justification for attempting to determine patterns of moisture availability on the regional scale. The function of a boundary layer model is to derive the moisture availability parameter from the measured ground temperature response. Although there is some conceptual indeterminancy in the model concerning the real nature of the surface, the moisture availability is probably a purer representation of the surface moisture, and certaily more intrinsic to the ground surface, than is the temperature response itself.

More than conceptual problems stand in the way of deriving meaningful soil moisture values. It is doubtful if any satisfactory representation of the vegetation canopy can be made for general purposes, although it is conceivable that small-scale remote measurements of the blackbody temperature may lend themselves favorably to a more precise parameterization of the surface canopy where the canopy type and height is known. More field measurements are necessary to improve the vegetation parameterization. Another serious impediment to satellite measurement techniques is the interference by cloud and moisture. Cirrus or scattered cumulus can go undetected by conventional analysis but the presence of such obstructions can lead to anomalously cool or irregular temperature patterns. Moisture inhomogeneities can also produce similar, though less drastic, anomalies. Because of clouds, higher resolution satellies, such as HCMM, afford less problems in data interpretation. Indeed, our results seem to demonstrate some superiority of HCMM over GOES in that respect.

The fact that cloud is really more prevalent than one would initially suppose from casual inspection of satellite photos, leads to a problem in continuity of measurement. It is not easy to find two or three clear-sky satellite measurements over the same area on a given day, a necessary arrangement for determining a soil moisture estimate. Since the purpose of this research originally was to derive patterns of moisture availability which are needed in atmospheric models to obtain realistic patterns of surface sensible heating, it may be that an archive of moisture availability patterns can be generated from satellite data for a particular region.

For agricultural use the precise meaning of the moisture availability may be slightly ambiguous except as a rough index of moisture stress, but for numerical atmospheric models the importance of the moisture availability is that it will yield something approximating the correct surface heating patterns, which are so necessary in prediciting the evolution of weather systems. Finally, we suggest that existing HCMM satellite data constitutes a great wealth of information for further model testing and method improvement.

Abstract

An interactive method for obtaining patterns of moisture availability (and net evaporation) from satellite infrared measurements has been developed at The Pennsylvania State University. The method employs the boundary layer model of Carlson (Carlson et al., 1981), and a variety of image processing routines executed with the aid of a minicomputer.

To test the method with regard to regional scale moisture analyses, two case studies were chosen for the availability of HCMM data and because of the presence of a large horizontal gradient in antecedent precipitation and crop moisture index. Results showed some correlation in both cases between antecedent precipitation and derived moisture availability. Apparently, regional-scale moisture avaiability patterns can be determined with some degree of fidelity but the values themselves may be useful only in the relative sense and be significant to within plus or minus one category of dryness over a range of 4 or 5 categories between absolutely dry and field saturation. Interpretation of surface moisture availability patterns undoubtedly must vary according to the nature of the surface (e.g. vegetation type) but our preliminary results suggest that the derived moisture values correlate best with longer-term precipitation totals, suggesting that the infrared temperatures respond more sensitively to a relatively deep substrate layer.

I. Introduction

Drawing on the preliminary but somewhat suggestive results of Kocin (1979) and Cooper (1981), which indicate that some measure of soil moisture can be determined remotely over vegetated canopies using thermal infrared measurements, we attempted to use HCMM infrared measurements to determine regional-scale patterns of moisture availability in two case studies. These case studies were chosen on the basis of available HCMM imagery (a day-night image pair within a 36h interval), absence of clouds and the presence of a large horizontal variation of precipitation and crop moisture index (CMI) across a region. We reasoned that if moisture availability patterns derived from the thermal method described by Carlson et al. (1981; henceforth referred to CD) are to prove meaningful then they should, in some way, reflect the distribution of antecedent precipitation and that the relationship between moisture availability and precipitation should be most obvious over regions containing sharp variations in aridity, as measured by the crop moisture index. Accordingly, we chose one case study for August 1978 (August 22-23) over southern Indiana, Illinois and northern Kentucky and another for July 26-27, 1978 over eastern Kansas. In both of these cases the crop moisture index varied from about - 2 to + 1 across the domain.

The main point of departure between this investigation and those reported by Carlson et al. (1981) or Carlson and DiCristofaro (1981) for urban areas and by Kocin (1979) is the scale. We were specifically interested in the regional scale (a few hundreds of kilometers on a side, sometimes referred to as mesoscale) because we wanted to learn whether the CD could be applied to determine useful patterns of moisture availability and thermal inertia on a scale commensurate with existing mesoscale precipitation networks, so that we would be able to make use of the antecedent precipitation as a kind of ground truth. In addition, we felt that the application of satellite-derived parameters to atmospheric numerical modeling and prediction could more easily be demonstrated if these patterns were constructed over mesoscale regions because of current interest in weather prediction on that scale. A third reason for expanding the scale from that in earlier studies was to compare patterns derived from HCMM measurements, with those from the geostationary satellite (GOES), whose resolution is about 4 km.

Besides, the case study approach an important objective in this research has been to further develop an interactive approach for determining soil moisture patterns with the idea that we will achieve a nearly operational capability using a minicomputer-image processor system available in the Department of Met^orology.

The essence of our work during the past year is summarized by Polansky (1982) in his M.S. thesis, a copy of which is attached as Appendix II for convenience of reference. All figures, unless otherwise noted, will refer to those in Polansky's thesis.

2. Results

2.1 Case studies: Kansas and Indiana

Polansky reworked two case studies initiated by the principal investigator. His research was divided into four general areas: model sensitivity, error analysis, analysis of moisture, and system development; the last was omitted from the thesis. This report will confine itself to a brief account of the results and error analyses discussed by Polansky.

In order to derive patterns from HCMM (resolution 0.5 km) appropriate to the scale of GOES, HCMM pexels were combined to form a larger pixel about

2 km on a side consisting of about 20 original pixels; the 128x128 pixel working area thus contained an area about 250 km on a side.

In the Indiana case, a largely rural, vegetated area (Fig. 4.1), was experiencing a large horizontal variation in crop moisture index and antecedent (3 week total) precipitation with serious drought conditions (crop moisture contour value of - 1 omitted) developing over southern Illinois where less that 0.25 inches of precipitation had fallen in 3 weeks. Despite abundant cloud cover, which largely ruined the impact of the results, it is apparent in Fig. 4.3A that the driest region was also the warmest. In the moisture availability and total daily evaporation patterns derived from CD (Figs. 4.4, 4.6), the lowest values of M (<0.25) appear over the driest region. Thermal inertia (P) values also tended to be a little lower over the rainfall-deficit region (Fig. 4.5).

The Kansas case proved to be better for illustrating a relationship between crop moisture index and satellite-derived moisture patterns because there was less cloud and a greater horizontal variation in crop moisture index (Fig. 4.13B, 4.14) over a region consisting largely of unirrigated crop and grazing land (Fig. 4.12B). Warmest temperatures during the day (Fig. 4.15A) coincided closely with the region of low crop moisture index and light precipitation amounts. However, the temperatures appear somewhat too high, at least as compared with those of GOES (Fig. 4.21B). Moisture availability (Fig. 4.16) and total evaporation (Fig. 4.19) were also relatively low and the heat flux relatively high (Fig. 4.18) over the arid southwestern portion of the image area. GOES moisture heat flux analyses were rather similar to those of HCMM, though differing in detail.

It is evident that in both cases low moisture availability and high surface sensible heat flux tended to coincide with regions where precipitation amounts were less than 0.25 to 0.50 inches (and a crop moisture index of less than - 1) and that relatively high moisture availability and low surface sensible heat fluxes tended to be located where the three-week precipitation totals were in excess of about 1.00 inches (crop moisture index of greater than zero). The correspondence between the aridity indices (antecedent precipitation or crop moisture) is obviously very rough. A more systematic view of such a relationship is presented in Fig. 1 of this report in which the antecedent precipitation, as defined by Blanchard et al. (1981; unpublished manuscript), is plotted against moisture availability. In the figure the data was read from corresponding grid points on both the rainfall and moisture availability charts. Despite considerable scatter the graphs exhibit some systematic behavior, as would be expected from a qualitative examination of the figures. Interestingly, a better relationship was obtained for the antecedent precipitation weighting factor (k) of 0.93 than of 0.78, suggesting that the moisture availability (and hence the surface response measured by satellite) is more sensitive to long-term precipitation trends, and hence, to a relatively deep rooting depth. For comparison, a similar analysis is presented for Kocin's Missouri Watershed analyses (Fig. 2) except that the precipitation in the figure simply refers to a cumulative three-week total. It is to be expected, however, that the relationship between moisture availability and antecedent precipitation will vary with surface type. There is apparently some relationship between precipitation and moisture availability, at least in the June case (Fig. 2a), but the Septemter analysis (Fig. 2b) shows very little correlation between the derived moisture availability and antecedent precipitation. For comparison, Cooper's results of moisture availability versus antecedent precipitation (weighting factor 0.93) is presented in

Fig. 1; the bar length denotes uncertainty due to the range of surface temperatures measured at differing angles over differing crop types using a hand-held radiometer.

The relatively weak correlations evident in Figs. 1-2[1] is not necessarily a cause for discouragement. Antecedent precipitation is not a true measure of soil moisture because the latter can be as easily influenced by the presence of underwater acquifiers, variations in water table level, differences in vegetation type and age, runoff, and artificial watering (e.g. irrigation) as by rainfall itself. Although the crop moisture idex represents an attempt to incorporate runoff and evaporation in determining an effective measure of surface moisture stress, it is determined for averages over relatively large areas. Were the boundary layer model and surface temperature measurements perfect, one would nevertheless anticipate a high degree of scatter between rainfall and moisture availability, even on the scale of a HCMM pixel.

2.2 Errors and limitations

The results of our two case studies, summarized in Figs. 1-2, are siminar to that of Harlan (1981) who plotted antecedent precipitation versus day-night temperature differences and found a systematic inverse relationship, albeit one affected by a considerable scatter of data. There is an unmistakeable relationship between effective soil moisture, vaguely represented by antecedent rainfall, and the derived moisture availablity, although it is not possible to define precisely the surface or substrate (rooting) depth appropriate to the inferred value of moisture availability.

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1 The best correlation between moisture availability and antecedent precipitation ($R^2 = 0.4$) was for the HCMM Kansas data.

Quite probably the measurement is intimately linked in each pixel to the type, height and age of the vegetation canopy and a host of other substrate factors which govern the retention of water. An atmospheric model, such as the one used to obtain Polansky's results, serves only to remove that variability in the satellite measurements which is due to fluctuations in the atmosphere. Although various atmospheric models other than the CM (e.g. models of Price, 1982; Watson and Miller, 1981; Pratt and Ellyett, 1979; Rosema, 1978), would likely yield comparable results, there is probably an irreducible lower limit of error of ± 1-2°C, below which no model is capable of attaining. There are many reasons for this inherent error such as lack of understanding and formulation of the correct boundary layer physics, uncertainty about the nature of surface and substrate, non-advective affects in the atmosphere, errors in input data (i.e. in temperature) due to clouds, instrumentation, and water vapor attenuation. There is also the problem in averaging a semi-infinite number of surface infrared emmitors to produce a single pixel measurement. Thus, errors may be dependent on both model and radiometer. Aside from definable errors there is also a nagging conceptual problem in identifying that particular surface to which a particular moisture availability pertains.

Because of these errors, there are only certain combinations of satellite image times suitable for use. We have investigated three types of image combinations for determining soil moisture: a day-night image pair, a morning-afternoon-night triplet and a morning-afternoon pair. Only one of these combinations, the first one, is appropriate to HCMM orbits but, as it turns out the HCMM overpass times were virtually optimal for day-night image pairs. Nevertheless, even with the superior resolution of HCMM it is likely that the derived moisture availability is subject to an error of ± 0.1-0.2 and, consequently, moisture availability patterns justifiably might be represented without real loss of detail by four or five qualitative categories: e.g. very dry ($M < 0.2$); dry ($M = 0.2-0.4$); marginally wet ($M = 0.4-0.6$); wet ($M = 0.6-0.8$) and very wet ($M = 0.8-1.0$).

3. Conclusions

Regional scale measurements of soil moisture using satellite infrared temperature measurements may be possible but the real validity of the moisture availability values can not be assessed without ground truth measurements. So far such direct measurements are impractical to obtain and the only indirect evidence of a relationship between derived moisture availability and soil moisture is imperfectly reflected in the pattern of antecedent rainfall. A high-degree of scatter in these results may be a consequence of soil moisture fluctuations resulting from factors other than precipitation, such as rooting depth of the vegetation, runoff irrigation, etc.

In two case studies low crop moisture index and small values of antecedent precipitation correlated with low values of moisture availability. Drought conditions were clearly related to higher afternoon surface temperatures, which are equivalent to lower values of moisture availability according to the boundary layer model. The most serious problem, however, is not the model itself but the conceptual framework which is limited in the face of an enormously complex and ground or vegetated surface. Thus, while any reasonable atmospheric model appears to be capable of removing external atmospheric influences on the surface temperature variation and thereby provide a purer measure of soil moisture than does the bulk day-night temperature difference, there remains the question:--what actually does the moisture availability represent? It may be, however, that one must settle in the end for a moisture availability parameter which is able to represent the real soil moisture only indirectly and which itself may be accurate to within plus or minus one category in a range of 4 or 5 categories of soil dryness.

Finally, in comparing GOES with HCMM, patterns of moisture availabilty seem to be more sensitive to surface precipitation with HCMM, suggesting that the finer resolution and generally superior quality of HCMM data is better suited to deriving soil moisture estimates. In any case, we now possess the capability of producing moisture availability maps over a small scale or mesoscale region interactively in a mock operational mode using the Penn State minicomputer system and image processor.

A complete description of the infrared method will be contained in a forthcoming paper by Carlson (198~~3~~4).

Appendix I

List of HCMM scenes for which analyses were performed on the computer compatible tape data.

A118 185801,2	Indiana	day -	August 23, 1978
A117 074803	Indiana	night -	August 22, 1978
A0093 193601,2	Kansas	day -	July 28, 1978
A0092 082303	Kansas	night -	July 27, 1978

Appendix II

A Method for Diagnosing Surface Parameters Using Geostationary Satellite Imagery and a Boundary Layer Model

M.S. Thesis in

Meteorology

by

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(See attachment)

List of Publications and Public Presentations Involving Present Grant

1. Publications in Refereed Journals

Carlson, T.N., 1983. Evapotranspiration and Soil Moisture Estimates Based on Remote Thermal Measurements (to be published in Remote Sensing Reviews)

2. M.S. Thesis

Polansky, A.C. A Method for Diagnosing Surface Parameters Using Geostationary Satellite Imagery and a Boundary Layer Model. Department of Meteorology, The Pennsylvania State University, November 1982, 119 pp.

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Carlson, T.N., J.K. Dodd, S.G. Benjamin and J.N. Cooper, 1981. Satellite Estimation of the Surface Energy Balance Moisture Availability and Thermal Inertia. J. Appl. Meteor., 20, 67-87.

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Figure Captions

Figure 1. Moisture availability versus antecedent precipitation (API in inches; weighting factor k = 0.92) for two case studies using HCMM data for Kansas (July 27-28, 1978; dots) and Indiana August 22-23, 1978; crosses). Values represent corresponding measurements at resampled pixel points. The thin dotted line modifying the linear correlation, suggests an alternate relationship between M and API.

Figure 2a. Same as Fig. 1 but for cumulative three-week precipitation amounts versus moisture availability for Kocin's (1979) June 9-10, 1978 HCMM Missouri Watershed analyses

Figure 2b. Same as Fig. 2a except for September 29, 1978.

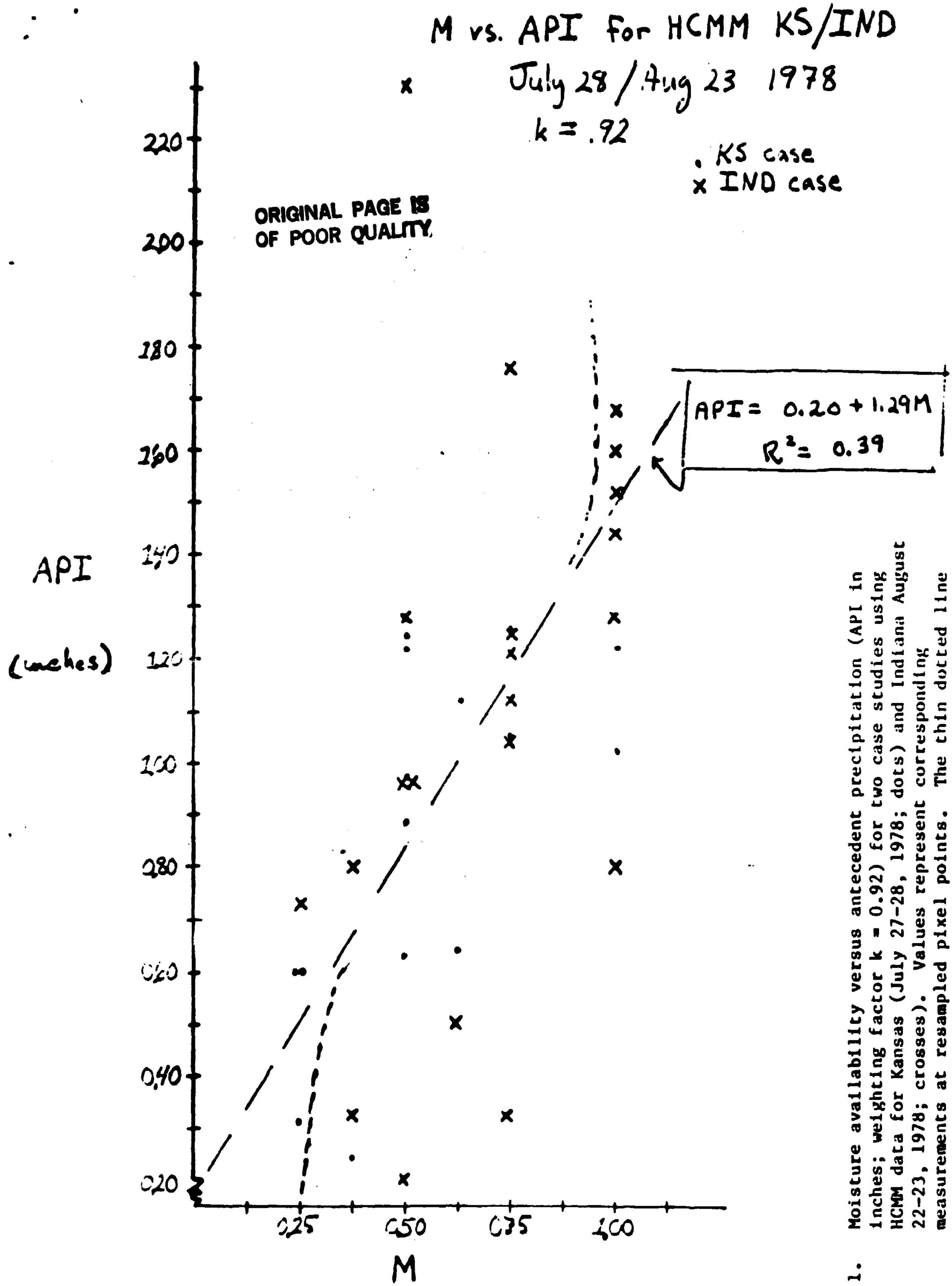

Figure 1. Moisture availability versus antecedent precipitation (API in inches; weighting factor k = 0.92) for two case studies using HCMM data for Kansas (July 27-28, 1978; dots) and Indiana August 22-23, 1978; crosses). Values represent corresponding measurements at resampled pixel points. The thin dotted line modifying the linear correlation, suggests an alternate relationship between M and API.

M vs. API for Missouri
June 9 1978

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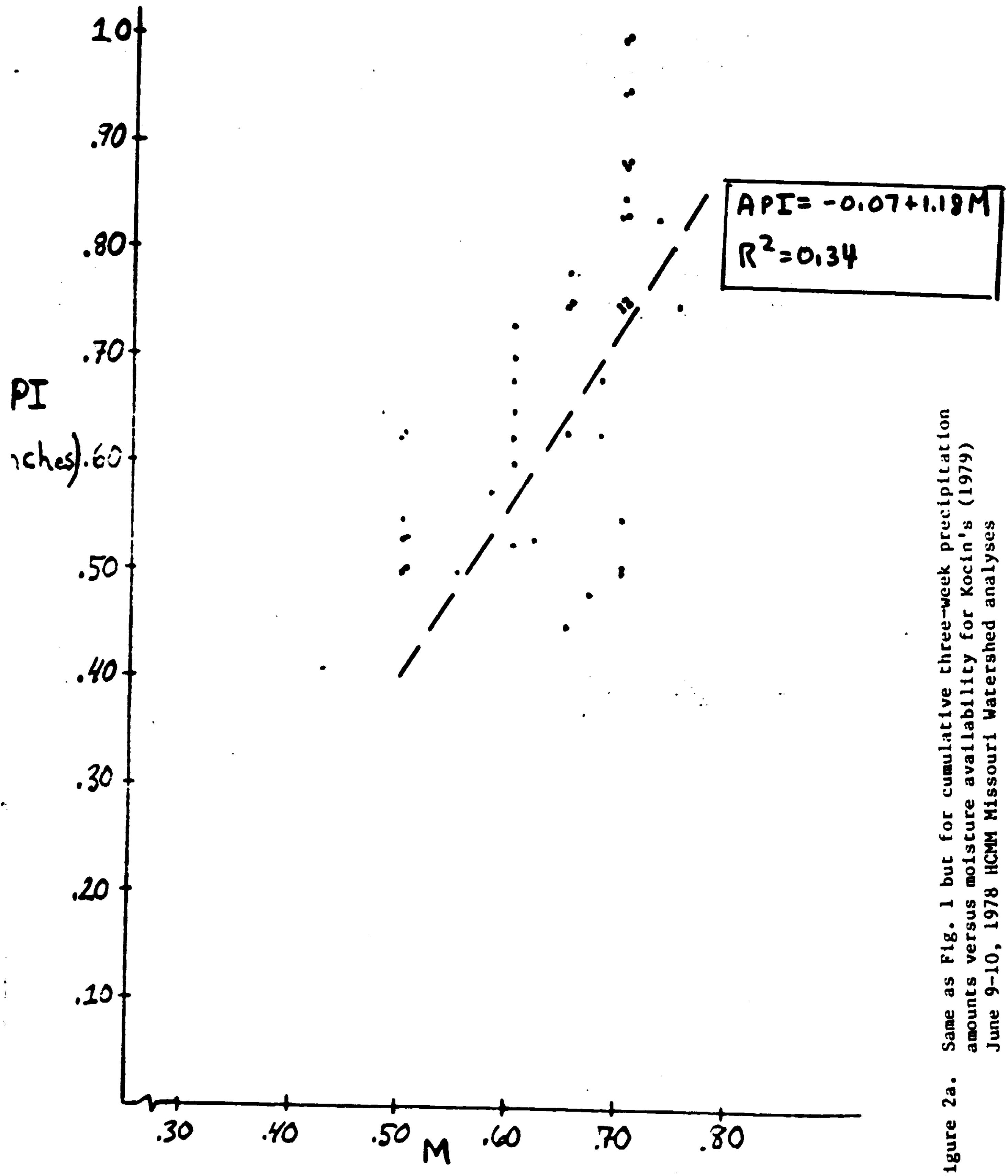

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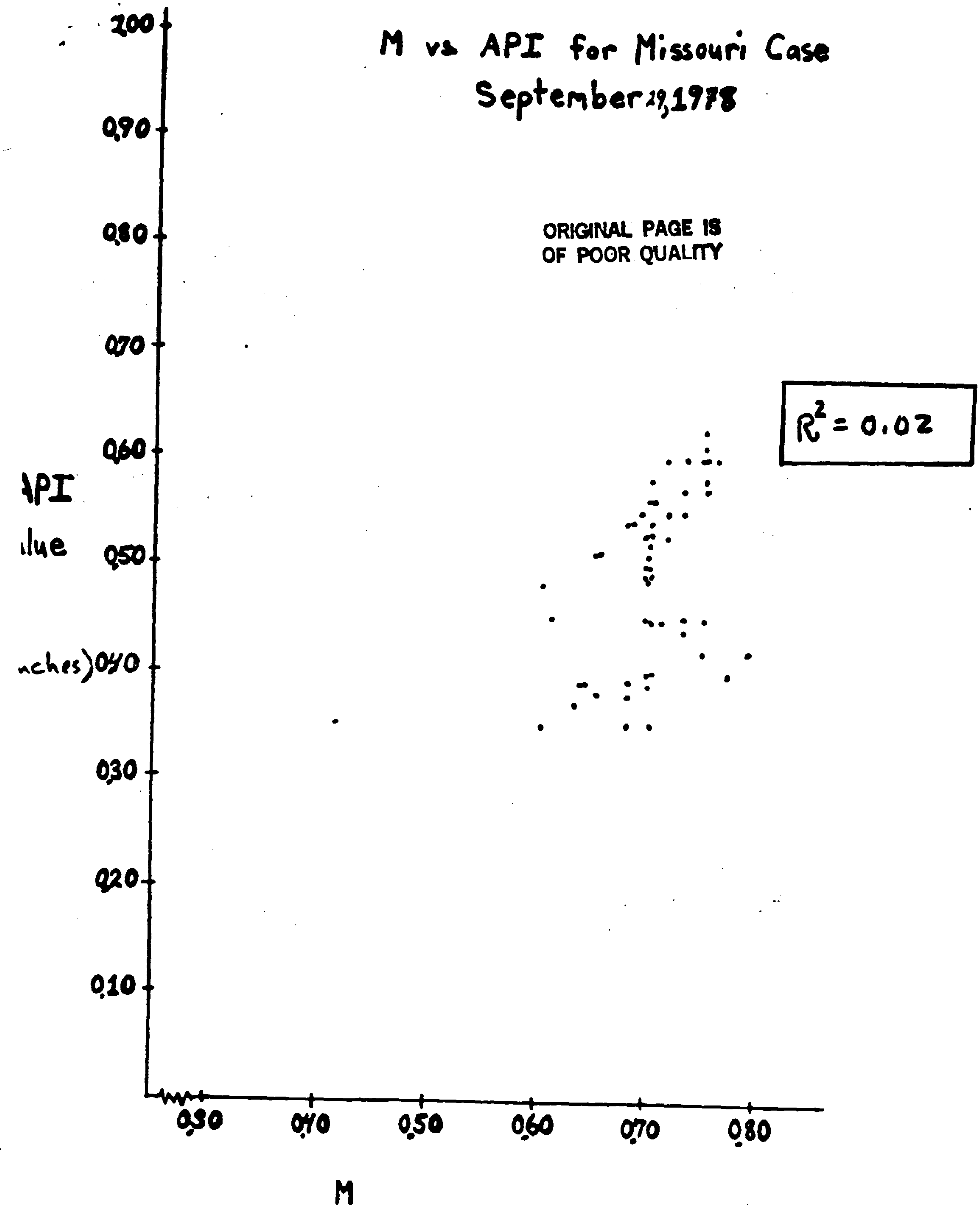

Figure 2b. Same as Fig. 2a except for September 29, 1978.