UNIVERSITY OF WISCONSIN

DEPARTMENT OF METEOROLOGY

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ANNUAL REPORT

for

THE STUDY OF DIFFERENTIAL HEATING OF AIR COLUMNS

[redacted]

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1. Introduction

This research under contract No. Cwb-8666 has been directed toward the determination and prognosis of changes in the amount of sensible and latent heat added to columns of air in the lower atmosphere. Such changes can occur from advection or local heating. The differences in the vertical heat budget are caused by differences in terrain, soil properties, and soil cover.

This investigation was designed to study three related problems. These embraced the establishment of relations between tornado occurrence and individual parameters in the heat budget, the analysis of differential heating of air columns, and the feasibility of prognoses of differential low-level heating.

It requires not only the use of available data but also instrumentation to secure currently unavailable data. During the first year heavy stress has been laid upon instrument development. High on the priority list for data accumulation was the development of a simple radiometer to obtain the essentially unavailable net radiation coverage. Almost equally was the development of the beam reflector for airborne albedo measurements.

The analysis of the differential heating of an air column was pursued with the data accumulated during Project Prairie Grass and from data obtained during the Great Plains Project.

A. CLIMATOLOGY:

Considering only sensible heat addition to air columns at this state it has been shown by Sutton (1) and others that the heat budget at the surface of an air column is given by

$$L_o = I_o - I_{ro} - B_o - G_o - E_o \qquad (1)$$

where L_o is the sensible heat
I_o is the insulation
I_{ro} is the surface albedo
B_o is the surface black body radiation
G_o is the subsoil heat transfer
E_o is the interface evaporation.

combining $I_o - I_r - B_o$ into the single net radiation term R_n (1) becomes

$$L_o = R_n - G_o - E_o \qquad (2)$$

The heat added to an air column is given by,

$$L_c = I_o - I_{ro} - B_c - G_o - E_o \qquad (3)$$

where the subscript "c" refers to the top of the column, it is clear that

$$L_c = L_o + \nabla R_a \qquad (4)$$

where ∇R_a is the divergence of radiation between the air-ground interface and the top of the heated column. Thus these four equations serve as the theoretical basis for this research. Much of the data used came from measurements made at O'Neill, Nebraska, during the July and August of 1956. A report of this data will be forwarded at a later time.

TORNADO DIAL

Percent frequency of occurrence of tornadoes in hours before (-) and after (≠) local sunset. This is a six state summary for 1951 through 1955 to include Illinois, Kansas, Missouri, Iowa, Nebraska, and Oklahoma.

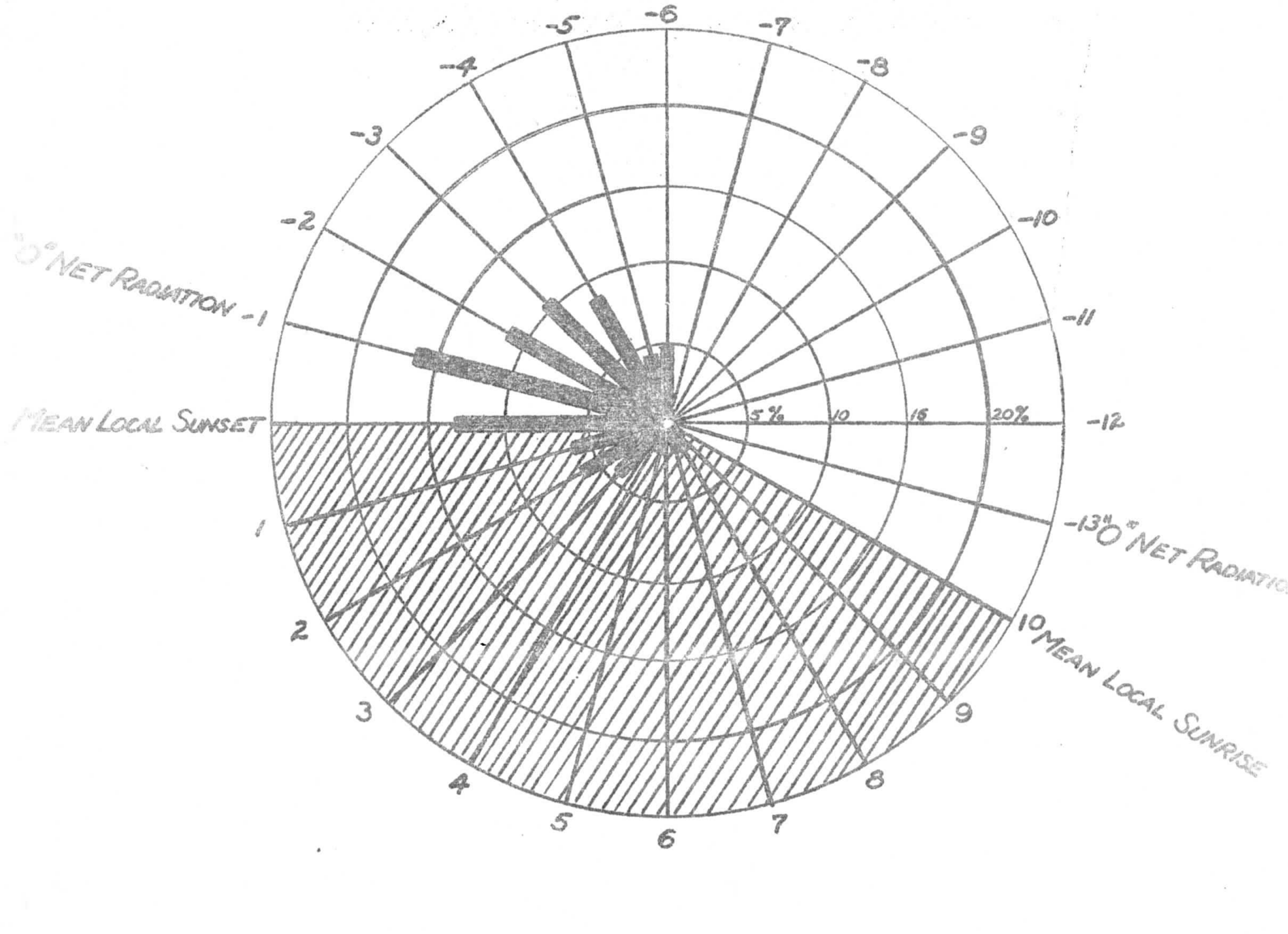


Figure 1

(1) TEMPORAL RELATIONS OF MAXIMUM HEATING TO TORNADO ENVIRONMENT.

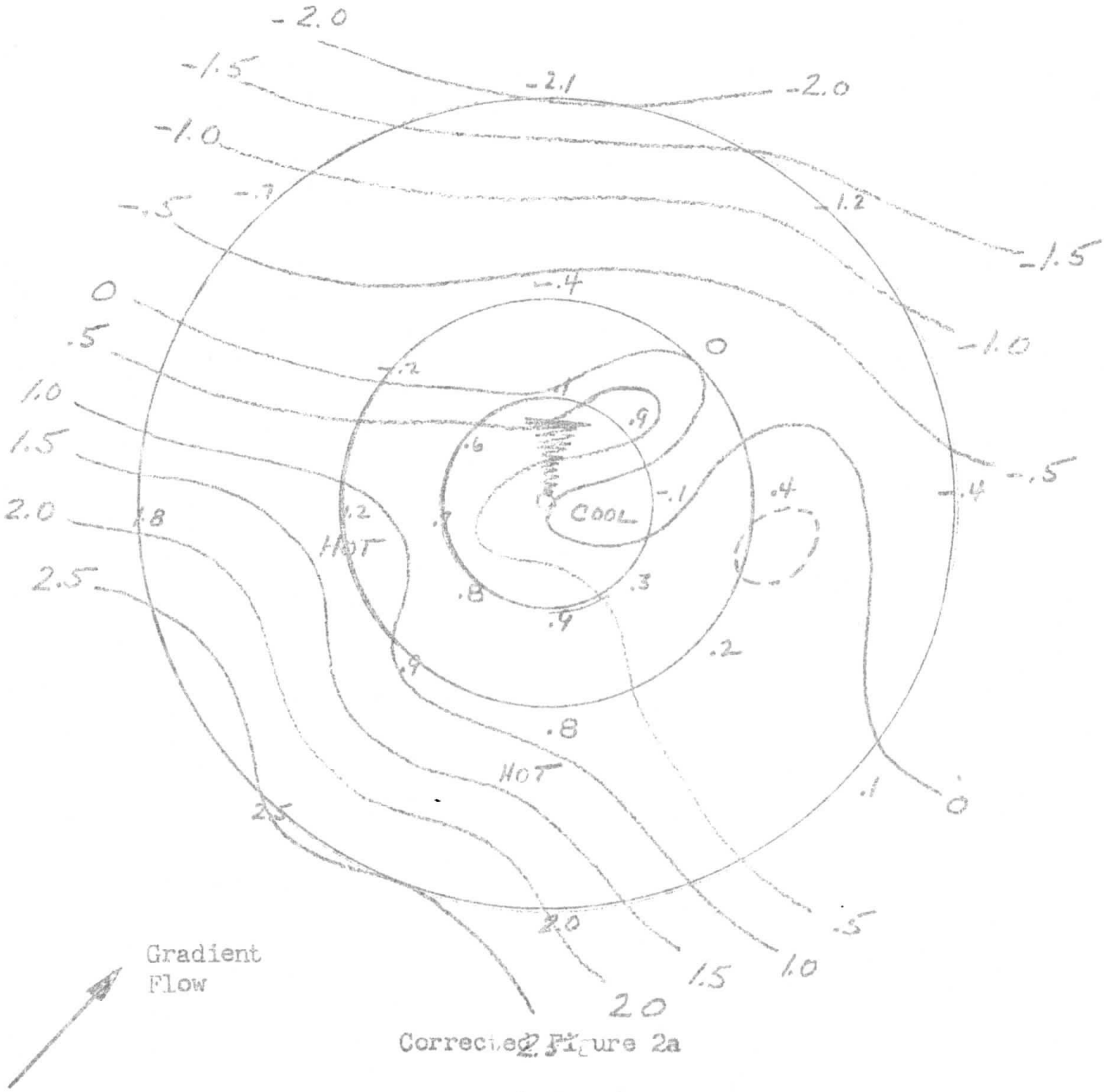
If there is a relation between the amount of heat added and the likelihood of tornado occurrence, one would expect that on a typical day suitable for the development of tornadoes, the maximum heating both sensible and latent would occur just before net radiation sunset. Figure 1 is a plot of the frequency distribution of the occurrence of tornadoes in hours before (-) and after (+) solar sunset. Since time of sunset can vary by as much as an hour for the same latitude and the date, all times were corrected to solar time. This is a six state summary for 1951 through 1955 for Illinois, Kansas, Missouri, Iowa, Nebraska, and Oklahoma for period April 1 through July 31.

The maximum occurrence of tornadoes at radiation sunset indicates that either the time of tornado occurrence is related to the heat added to the air column or to some unknown phenomenon, such as the abrupt changes in stability that were observed to occur between radiation sunset and one to two hours after local sunset during the Great Plains Project at O'Neill, Nebraska, in 1953. This possibility is being investigated further. Of interest is the evident fact that 82% of all tornadoes occur, effectively in the period four hours before and three hours following local sunset. It should be noted that the proximity to radiation sunset for peak time of occurrence of tornadoes that is reported on herein, is quite similar to the peak time of occurrence of all tornadoes reported

Pre-tornado Thermal Environmental Composite Chart

(Correction to analysis of Figure 2a)

Isolines are departures in maximum temperature from the maximum occurring at the tornado location on the afternoon of the day of tornado occurrence/ Maximum temperatures are entered for all U.S.W.B. Climatological Stations. Data is based upon the thermal conditions preceding occurrence of all IOWA-NEBRASKA tornadoes for period 1953-1955.



Corrected Figure 2a

Pre-tornado Thermal Environmental Composite Chart

Isolines are departures in maximum temperature from the maximum occurring at the tornado location on the afternoon of the day of tornado occurrence. Maximum temperatures are entered for all U.S.W.B. Climatological Stations. Data is based upon the thermal conditions preceding occurrence of all OKLAHOMA tornadoes for period 1953-1955.

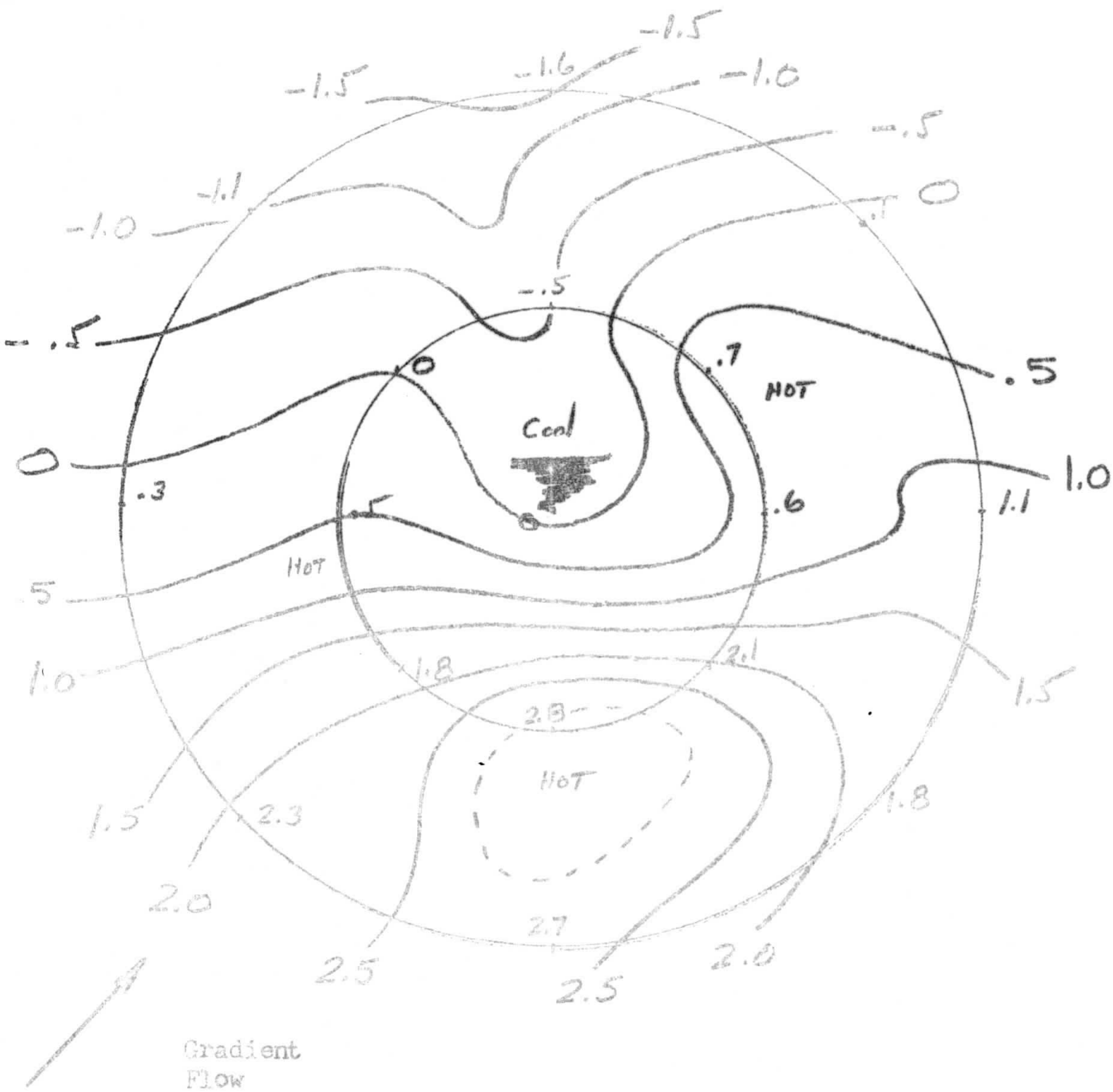
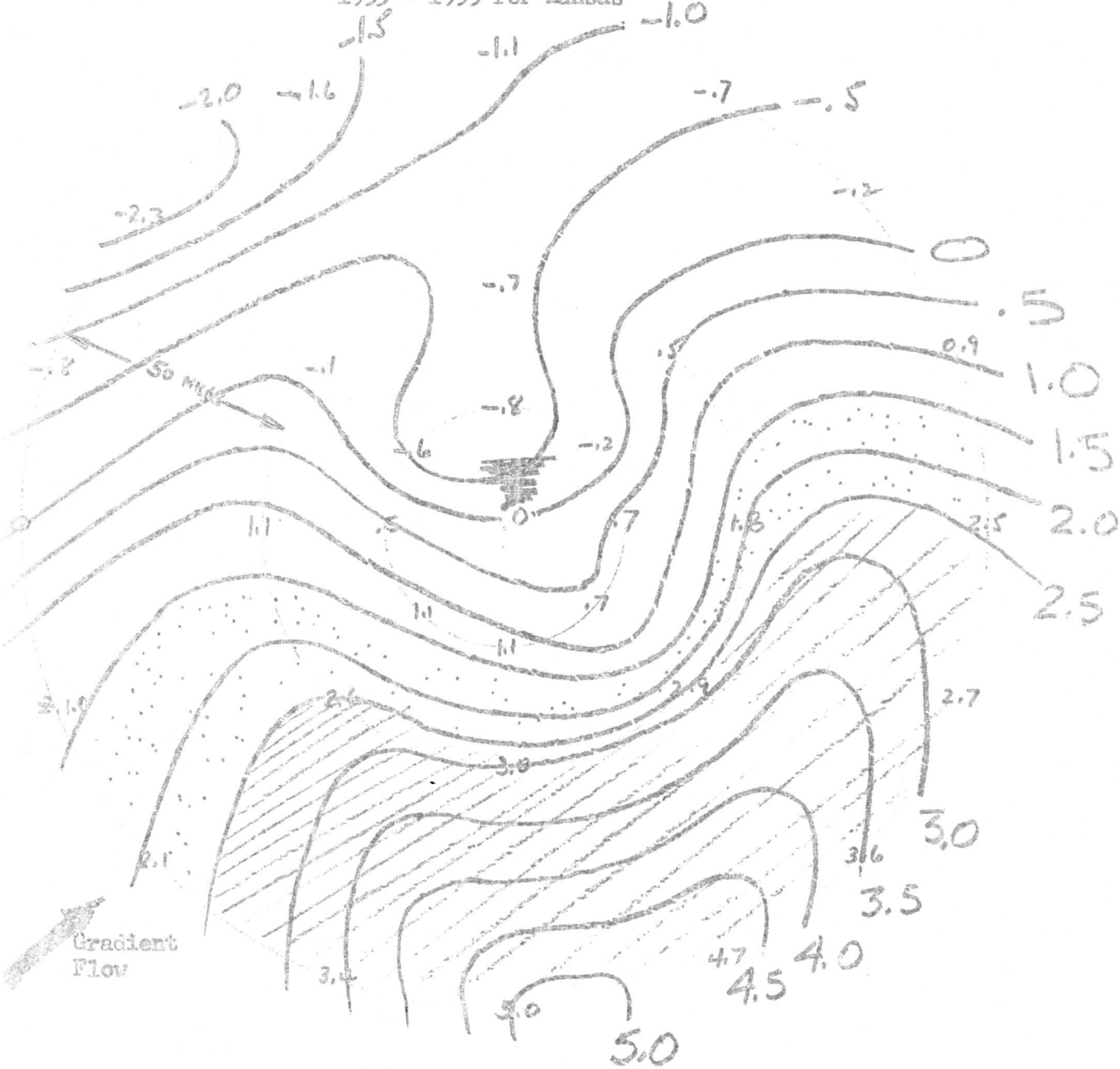


Figure 2c

Pre-Tornado Thermal Environmental Composite Chart

Isolines are departures in maximum temperature from that occurring at tornado location on afternoon prior to occurrence of tornadoes.

Maximum temperatures entered for all U.S.W.B. Climatological Stations. Data based upon all tornadoes recorded by U.S.W.B. for April, May, and June, 1953 - 1955 for Kansas



Note tornado occurrence slightly to left of "hot spot" and downstream. Note also the cool tongue towards tornado and potential thermal lows on either side.

Figure 2b

by S. D. Flora$_2$, "Tornadoes."

(2) HOT SPOT SPATIAL RELATIONS TO TORNADO ENVIRONMENT

Following the temporal link and closely tied in with the heat required to break the plains inversion came the analysis of the thermal field in the tornado environment for the 371 tornado occurrences in the six previously mentioned midwestern states. The analysis covered the period from 1 March through 1 October, 1951 - 1955.

Locations of all tornadoes were plotted and the associated maximum temperature field was analyzed from available U. S. Weather Bureau climatological stations. Since the maximum shelter temperature, occurring about 2 hours before net radiation sunset, is certainly a function of L_o in (1) a composite pre-tornado thermal environmental chart was analyzed. The chart shown in Fig. 2 indicates the link between local heating and downstream tornado occurrence. This analysis was similar to that of Beebe's (3) but on a much more detailed mesoscale and appears to establish the "hot spot - tornado" link. These data are being assembled into a short paper.

(3) NEGATIVE TEMPERATURE SPATIAL RELATIONS TO TORNADO ENVIRONMENT

Assuming local heating to be important in the heat budget of the pre-tornado environment, evidently a large daytime value of E_o, the evaporation, in (1), (2), and (3), should suppress surface heating and subsequent tornado development. This assumption is valid only when we ignore latent heat and consider only the sensible heat addition to the air column.

Since evaporation is the most difficult term to evaluate, let alone prognosticate, we used the available climatological network records of occurrence of rainfall in the preceding twenty-four hours to 7:00 AM LST of the day of tornado occurrence. O'Neill heat budget data indicate a gradual daily decrease in the percent of the total heat budget used in evaporation to 0% by the 15th non-rain day after a soil saturating rain.

An initial study of 371 tornado occurrences in seven states showed that 67% of the tornadoes were first reported at locations having had no precipitation on the preceding day, 85% of the tornadoes occurred at locations with less than .25" precipitation or within 25 miles downstream from such an area.

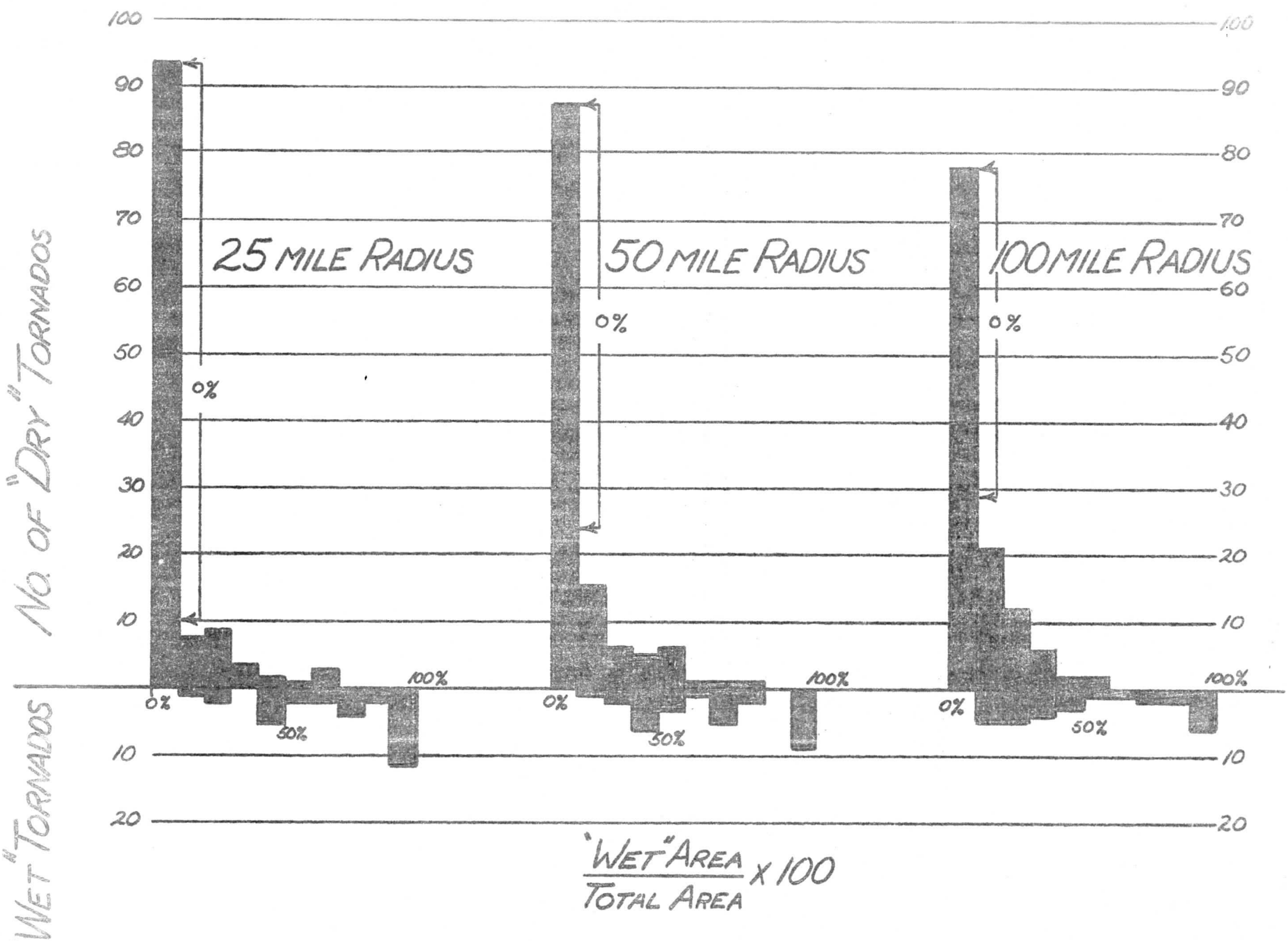
To determine whether tornadoes were showing a selectivity for dry areas it was necessary to determine the ratio of dry to wet areas in cases in which the tornado could indicate selectivity. "Dry areas" were defined as areas reporting .25" or less precipitation for the previous day.

Planimeter measurements were made on 139 cases containing 15% or more "wet area" within a 50 mile radius of the tornado location. In all of this phase of the research, U. S. Weather Bureau climatological stations maximum temperature records were employed. 58% of these tornadoes occurred in "dry" areas representing approximately 50% of the total area. This apparently gives inconclusive evidence of selectivity for dry areas.

To determine whether the area moisture patterns in the immediate vicinity of the tornado differed from those further removed from the tornado location but under the same general synoptic conditions, further planimeter measurements were made. The areas within a 25, 50, and 100 mile radius of 150 tornadoes were planimetered. The 25 mile radius averaged 20% "wet;" the 50 mile radius, 20% "wet;" and the 100 mile circle averaged 18% "wet." Histograms of the distribution of tornado occurrence with respect to percent of total area "wet" for the three circles appear in figure (3). The tornadoes have been classified as either "dry" or "wet," a dry tornado being one first reported at a point of less than .25" precipitation for the previous twenty-four hours ending at 0700 hours LST on the day of tornado occurrence.

Present evaluation of the results of these initial studies of moisture-tornado relationships based on climatological network data show no conclusive evidence of tornado selectivity either for "dry" or "wet" areas. The problem of the realization of the latent heat of evaporation has been purposely omitted pending further evaluation of data on hand.

In any direct evaluation of the Evaporation Term of equation (1), it is necessary to know the amount of moisture at the air-ground interface available for entry into the evaporation process. It is realized that an arbitrarily selected



No. of "Dry" Tornados
"Wet" Tornados
25 MILE RADIUS
50 MILE RADIUS
100 MILE RADIUS
0%
50%
100%
"Wet" Area / Total Area x 100

Figure 3

value of the previous days' precipitation is, at best, a very crude measure of the available moisture. Any exacting study of tornado-surface moisture relationships must be based on considerations of soil types and covers as well as antecedent rainfall from one to four weeks previous.

It was felt that the value of the previous days' rainfall of .25" without regard for soil type and cover might be sufficiently representative of available moisture to permit its use in these initial pilot studies. Investigation of the 30 day antecedent rainfall with consideration for the soil type is in progress. It is believed that a fairly simple empirical formula can be found from with which it will be possible to readily estimate the amount of surface moisture available for evaporation. With the added information it is strongly felt that a marked affinity of tornadoes for dry area can be demonstrated.

(4) MAXIMUM HEATING AND TEMPERATURE FORECAST

Final testing is being completed and a manuscript is being prepared on a forecast technique to prognosticate the differential addition of sensible heat to air columns over various terrain. This technique was suggested by Drs. Wexler and Tepper and is a follow through on research Mr. Kuhn initiated while at the Central Office. This "model" of local heating required extensive testing but shows great promise. Its use will be experimentally carried through during the coming Tornado Season.

B. MEASUREMENT

(1) ECONOMICAL NET RADIOMETER

Equations (1) and (2) again direct attention to a lack of data required not only for analysis but also for prognosis. Since net radiation, R_n, is a key term in the heat budget its measurement is of prime importance in obtaining the addition of sensible heat to air columns and also in an estimate of Evaporation (4). However, there is no data of such nature available in the United States on anything approaching even the synoptic scale. An instrument to accumulate net radiation data was required that would be inexpensive and easily serviced. Appendix A is a copy of the manuscript on this instrument as forwarded to the publication TELLUS. A greatly augumented net radiation measurement program is planned for the coming tornado season.

A simple balloon-borne model of this net radiometer participated in an important flight from Green Bay, Wisconsin, recently. Such a flight points the way to our continued research in evaluations of the divergence of radiation through the tropopause as part of the differential heating of air columns.

(2) Airborne Beam Reflector

Since we may assume a forecast of the isolation, over at least state size areas, it was concluded that true surface albedo measurements, seasonal in nature and in the form of composite charts, were needed to evaluate the effective insolation. Appendix B is a copy of the manuscript on this instrument as forwarded to the publisher.

The varying natureof albedo across the country as well as temporally in passing from fallow to crop to harvest illustrates again the necessity for seasonal albedo measurements as part of the pre-tornado thermal environment.

3. CONCLUSION

The development and testing of the economical radiometer and the beam reflector was completed under point 1 and 2 of the original statement of work. More widespread net radiation and albedo measurements will be undertaken in the continuation of the investigation.

In the main, future work as outlined in the Proposal for Continuation of the study of differential heating of air columns, 29 January 1957, embraces a continuation of tests of the feasibility of calculating and prognosticating the heat added to air columns differentially, and tests of the feasibility of radiation divergence measurements. To this must of course be added the plans for gathering data through field use of the Economical Net Radiometer, both at the surface and aloft.

4. PERSONNEL

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Mr. P. M. Kuhn, Office of Meteorological Research, U.S. Weather Bureau, Assigned meteorologist for U.S. Weather Bureau.
Mr. G. L. Darkow, Research Assistant, University of Wisconsin, Department of Meteorology.

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AN ECONOMICAL NET RADIOMETER

V. E. Suomi[1] and P.M. Kuhn[2,3]

ABSTRACT

A net radiometer of moderate accuracy but of simple construction and very low cost is described. The value of net radiation is obtained from the difference of fourth power temperatures of the upper and lower radiating surfaces. Conduction losses are held to a low value by employing a good insulating material and ventilation losses above and below are kept to a low value by two layers of thin polyethylene film. Field tests, calibration data, and applications are described.

1. Introduction

The net radiation normal to the earth's surface is the difference between the total upward radiation flux and the total downward radiation flux. Net radiation is important to many meteorological problems because it is a measure of the energy available at the earth-atmosphere interface. The energy exchange at the earth's surface

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represents the major input to the giant heat engine which circulates the atmosphere.

A number of instruments which measure net radiation are already available (ALBRECHT, 1933; GIER and DUNKLE, 1951; SUOMI, FRANSILLA, and ISLITZER, 1954). Most of them, however, are fairly expensive. As a result there are only a few stations over the entire earth which make net radiation observations. It is not possible to study the effects of a variable heat input on subsequent weather from these isolated measurements. There are far too few to give anything even approaching a representative sample. The purpose of this paper is to describe a net radiometer of moderate accuracy but very low cost. The low cost and simple construction will make it possible to obtain many more observations of net radiation over land and ocean. The errors due to the performance of the instrument can be more than offset by far better sampling.

2. Simplified theory of the instrument.

The following symbols will be employed:

$R_s\downarrow$ vertical component of sun and sky insolation (short wave).

$R_s\uparrow$ vertical component of insolation reflected from the ground.

L_3 fractional loss in transmission through the polyethylene films due to absorption, scattering, and reflection for short wave radiation

$R_\ell\downarrow$ downward flux of long wave radiation

$R_\ell\uparrow$ upward flux of long wave radiation

L_ℓ fractional loss in transmission through the polyethylene films due to absorption, scattering, and reflection for long wave radiation

ϵ long wave emissivity of polyethylene film

T_p Absolute temperature of polyethylene film

a absorptivity of blackened aluminum foil sensor

K thermal conductivity of insulation

G_1, G_2 effective convective heat transfer of air films, top and bottom

T_t Absolute temperature of top blackened aluminum foil

T_b Absolute temperature of bottom blackened aluminum foil

Fig. 1 shows an "exploded" view of the instrument. The blackened aluminum foil sensing element is supported by a block of light rigid material of low heat capacity and thermal conductivity such as fiberglass insulation. Two sheets of 0.50 or 0.75 mil thick polyethylene film, an insulating guard, and a wooden box framework form a wind screen. The upper and lower surfaces are assembled in reverse order.

When the instrument is oriented above and horizontal to the earth's surface, and equilibrium is reached, the energy balance of the upper surface in sunlight is

$$a\left[R_s\downarrow(1-L_s) + R_\ell\downarrow(1-L_\ell) + \epsilon\sigma T_p^4\right] = a\sigma T_t^4 + G_1(T_t - T_p) + K(T_t - T_b) \qquad (1)$$

The energy balance for the lower surface is

$$a[R_s\uparrow(1-L_s) + R_\ell\uparrow(1-L_\ell) + \epsilon\sigma T_p^4 = a\sigma T_b^4 + G_2(T_b - T_p) - K(T_t - T_b) \qquad (2)$$

In each equation the terms on the left represent the most important heat gains by the blackened surface. The terms on the right are, in order, the losses due to radiation, convection and conduction. When four inches of insulation such as OWENS-CORNING type PF-612, two and one-half pound density, rigid fiberglass is used, the conduction terms comprise only about 1 per cent of the energy exchange, and are therefore ignored. It is possible to evaluate the magnitude of the convection term using the dimensionless numbers of NUSSELT, GRASHOF, and PRANDTL. This was done following the method of de GRAAF and VAN der HELD, 1953. The value of this term should be greatest when the air film is heated from below as the upper blackened surface is in the presence of sunlight. The value varies between 10 and 20 per cent of the total energy exchange. Thus the remaining radiation term is the most important mode of heat loss from the sensor surface.

Fig. 2 shows the per cent transmission of 1.0 mil polyethylene film in the range of from 2 to 15 microns. The polyethylene absorption bands are located in the same region of the spectrum as the water vapor bands, but are much narrower. Polyethylene films of this thickness absorb only about 1 per cent of the incident solar radiation but the scatter due to the milky color of the film is several times this value. The combined effects of fractional transmission of short wave energy, absorption of long wave energy and re-radiation from the polyethylene film was determined experimentally by holding two large sheets of polyethylene film above a ventilated net radiometer (SUOMI, FRANSILLA, and ISLITZER, 1954) and noting the change in observed net radiation. This loss is about 10 per cent of the incident radiation.

The loss due to incomplete transmission is about 10 per cent of the left hand side of (1) and (2), while the convection term is about 10 per cent of the right hand side of these equations. Since these two terms are proportional to the incident radiation they tend to cancel each other. We can rewrite equations (1) and (2), taking these approximations into account, and obtain

$$a[R_s\downarrow + R_\ell\downarrow] = a\sigma T_t^4 + \text{error} \qquad (3)$$

$$a[R_s\uparrow + R_\ell\uparrow] = a\sigma T_b^4 + \text{error} \qquad (4)$$

If (4) is subtracted from (3) the difference in errors is probably smaller than either, since they are likely to have the same sign, and we obtain

$$R_{Net} \approx \sigma\left(T_t^4 - T_b^4\right) \tag{5}$$

Figs. 3 and 4 show a comparison between a ventilated radiometer (SUOMI, FRANSILLA, and ISLITZER, 1954) of good accuracy and the radiometer just described when the temperature of the upper and lower blackened surfaces, measured with mercury thermometers or thermocouples and averaged for one hour are substituted in (5). If a calibration constant were included the agreement between the two sets of observations would be even better.

At low sun angles the flat, milky polyethylene film will cause the cosine response of the instrument to be poor. For example, at zenith angles of 25°, the ratio of the net radiation measured with the ventilated radiometer over that measured with the economical net radiometer is 1.1 whereas at 65° the value is 1.2 and at 80° it averages 1.37. However, at most latitudes the error in the total daily radiation will be small. During the night with diffuse radiation, the cosine error is not as important.

3. Discussion

Equations (3) and (4) contain four unknown radiation currents but the two equations only allow the evaluation of the total downward and total upward radiation flux, and, of course, their sum and difference. If a second radiometer whose sensors are painted <u>white</u> is used in addition to the black surfaced radiometer, and the ratio of the black and white paints' short wave absorptivities and ratio of the black and white paints' long wave absorptivities are known, two more equations with no additional unknowns can be written. This is enough additional information to separate $R_s\downarrow$, $R_\ell\downarrow$, $R_s\uparrow$, and $R_\ell\uparrow$. This application and tests of its validity will be given in another paper.

If one uses thermistors to measure the temperature of the upper and lower blackened surfaces of such a radiometer it is possible to telemeter this information in a manner similar to that used to transmit air temperature in the ordinary radiosonde. By employing very light weight material for insulation and framework, the net radiometer can be made light enough to be carried aloft by a radiosonde balloon. Fig. 5 shows such an instrument which weighs only 125 grams. In order to telemeter air temperature, humidity, and upper and lower surface temperatures it is necessary to add a sequencing switch. The figure illustrates the instrument with such a wind driven switch. This instrument makes it possible to obtain measured values of the vertical profile of net radiation. Tests of this instrument are under way.

It is possible to compute minimum surface temperatures given the net radiation at sunset and the soil thermal properties. Therefore, the economical net radiometer can be useful in frost forecasting.

PENMAN, 1948, and others have shown that evaporation from a growing field crop is highly correlated to net radiation. Irrigation control from net radiation data is thus feasible.

4. Conclusion

We have described a very low cost net radiometer of moderate accuracy. This accuracy is, however, quite sufficient for many meteorological applications.

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Legends for Figures

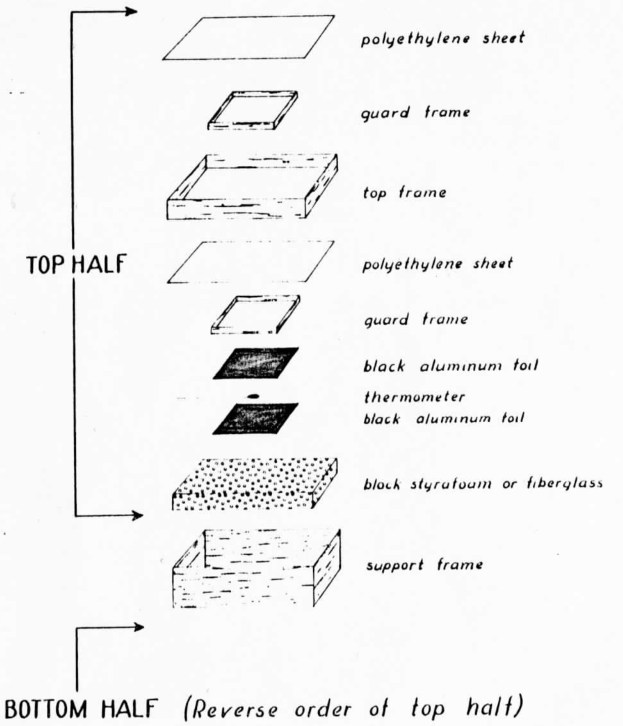
Fig. 1: Exploded view of the Net Radiometer.

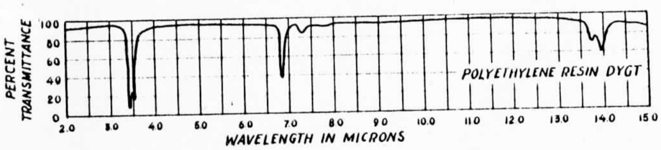
Fig. 2: Per cent transmission of 1.0 mil polyethylene after U. S. DEPARTMENT OF COMMERCE Publication 111438, 1955.

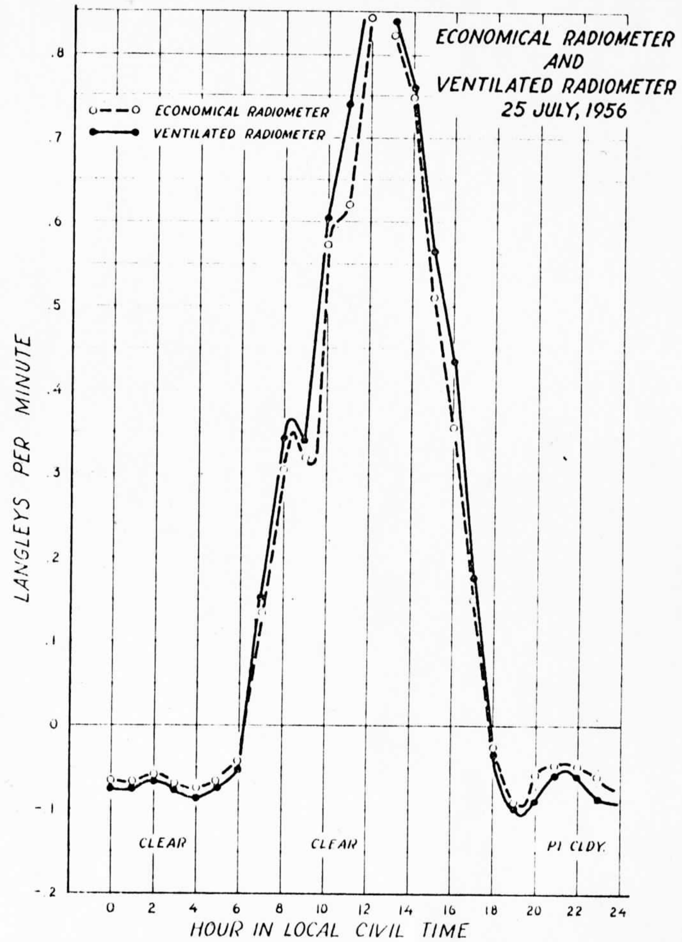
Fig. 3: Hourly net radiation comparison between Economical Net Radiometer and Ventilated Net Radiometer.

Fig. 4: Scattergram of net radiation measurements using economical net radiometer and ventilated net radiometer.

Fig. 5: Balloon-borne economical net radiometer.


polyethylene sheet
guard frame
top frame
TOP HALF
polyethylene sheet
guard frame
black aluminum foil
thermometer
black aluminum foil
block styrofoam or fiberglass
support frame
BOTTOM HALF (Reverse order of top half)


PERCENT TRANSMITTANCE
POLYETHYLENE RESIN DYGT
WAVELENGTH IN MICRONS


ECONOMICAL RADIOMETER
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VENTILATED RADIOMETER
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LANGLEYS PER MINUTE
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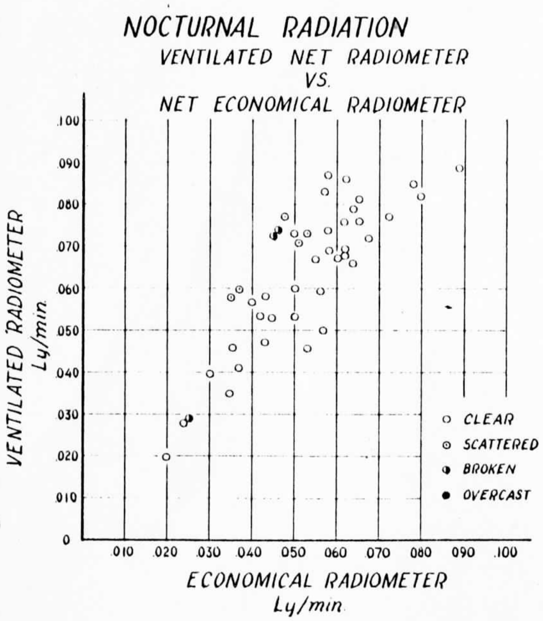
NOCTURNAL RADIATION
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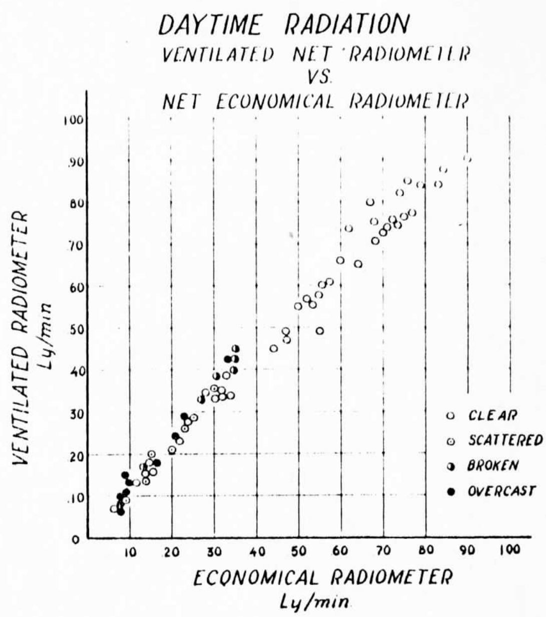
DAYTIME RADIATION
VENTILATED NET RADIOMETER
VS.
NET ECONOMICAL RADIOMETER
VENTILATED RADIOMETER
Ly/min
CLEAR
SCATTERED
BROKEN
OVERCAST
ECONOMICAL RADIOMETER
Ly/min

Balloon-borne Radiometer