NOAA TECHNICAL MEMORANDUM NWS CR-74

On the Observation and Modeling of the Slope Winds Of the Upper Current River Valley of Southeast Missouri and Their Relationship to Air-Mass Thunderstorm Formation

Bartlett C. Hagemeyer
Weather Service Office
Columbia, Missouri

June 1985

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

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John V. Byrne, Administrator

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1. Introduction

During the summer of 1983 the Upper Current River Valley (UCRV) of southeast Missouri (Fig. 1) was discovered to be a preferred area for thunderstorm development when weak synoptic scale conditions and a tropical air mass prevailed over the area (Hagemeyer, 1984). The initial investigation led to the theory that thunderstorm development was caused by differential heating in conjunction with orographic lifting and an additional local moisture source (transpiration from the dense forest covering the Valley). This theory was based on a small but very encouraging data sample which appeared to show a striking relationship between the location of thunderstorm formation and the UCRV and led to the development of a forecast scheme to predict thunderstorm formation (Fig. 2). Thus, the initial theory was based largely on climatology and was written up because of its immediate benefit to operational forecasters.

The investigation could have stopped after 1983 but it was felt that there was more of a physical basis for the observed climatological relationship than was originally presented. Indeed, the conclusions resulting from the initial investigation were necessarily not precise. It was therefore desirable to continue to study the UCRV and obtain proof of the physical processes taking place there that lead to preferred thunderstorm development. It was toward this end that a study of the UCRV was undertaken during the 100-day period from 1 June 1984 to 8 September 1984 in which first echo and thunderstorm distributions were documented and a large amount of synoptic data were collected. In addition, a field trip was made to the UCRV to observe and photograph its effect on the atmosphere.

This paper will present models of the slope winds of the UCRV and thunderstorm formation based on a simplified geometry of the Valley and solar radiation input. Results of the field trip and the summer 1984 radar study will be discussed and additional evidence from which inferences can be made on the UCRV effect will also be presented.

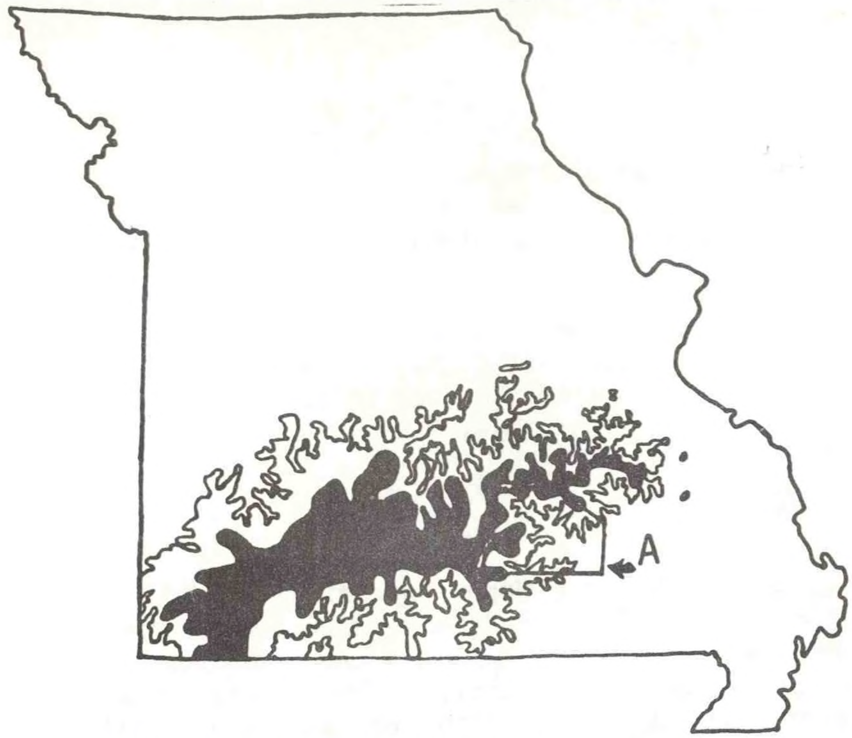


Fig. 1a The Ozark Mountains of Missouri. The UCRV is enclosed by the line at "A". The first contour is 1000 ft (305 m) MSL and the solid area is 1200 ft (366 m) and above.

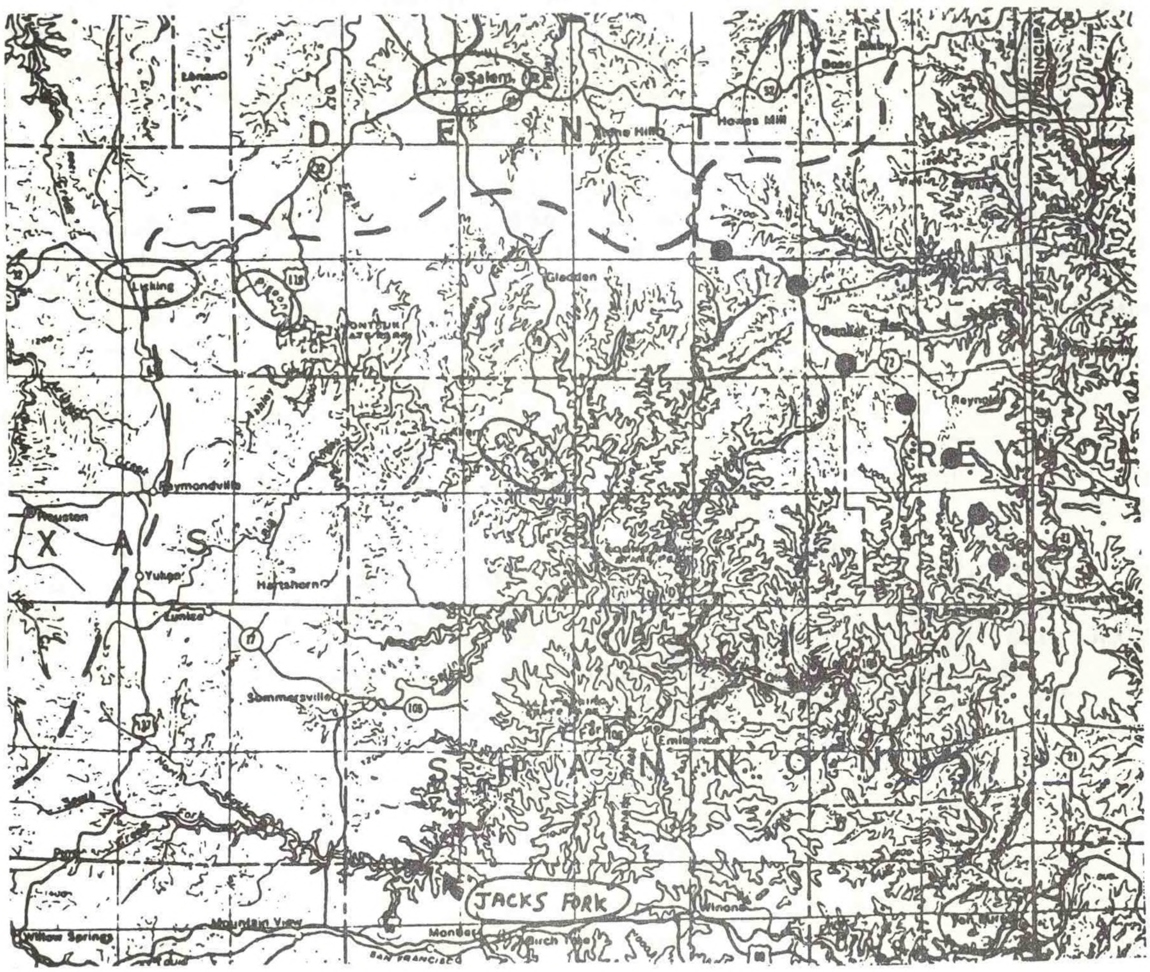


Fig. 1b Detailed map of the UCRV (all maps from USGS).

FORECAST DECISION TABLE FOR THUNDERSTORMS FORMING
OVER THE UPPER CURRENT RIVER VALLEY DURING THE AFTERNOON

(Based on observed or forecast 12Z conditions over the UCRV)

PARAMETER	VALUE	YES	NO	REMARKS AND DATA SOURCES
Low level wind Sfc. Geostrophic	$120° \leq \omega \leq 240°$ 5 kts or calm			(9AM), LFM progs (L2M etc.)
Sfc. Dew Points	$\geq$ 65°F 18°C			12Z SFC observations for PØ2, TBN and CGI. (Under these conditions dew points will generally rise during the day.)
Strong Surface Heating				Generally clear skies or thin cirrus over area before onset of convection (100% sunshine is ideal.) Satellite data is best source.
Stability Indices	Only one of the Showalter or lifted indices need to be checked.			
Showalter	≤ 0			UMN and SLO RAOB Plots; LFM (12L, 14L, etc.), FRH65, FTJ56, interpolation of UMN and SLO RAOBS is best method.
Lifted Index	≤ -4			
K-Index	> 25			
850 mb wind	[1] $120° \leq \omega \leq 240°$ calm or light and variable			1. No wind speed criteria is given for a favorable direction! 8ØA
700 mb wind	[1] $120° \leq \omega \leq 250°$ calm or light and variable			7ØA
500 mb wind	[1] NE-S-W or $<$15 kts			5ØA
THUNDERSTORMS FORECAST				
THUNDERSTORMS OBSERVED OVER THE U.C.R.V.				

Fig. 2 Forecast decision table (Hagemeyer, 1984).

2. Overview of the field trip to the UCRV on 13 July 1984

Before proceeding to the modeling of the effect of the UCRV, it is necessary to review the conditions and methods of the field study since the results were used in the model development and will be referred to often in the next section. The field trip was the most important goal of the summer 1984 study. No instruments other than camera, compass, field glasses, and a keen eye were used on the trip.

Considering the topography of the UCRV, it would seem reasonable to believe that if a local effect did indeed exist it would be observable from the ground. There are several state-owned fire towers around the area that offer spectacular views of the Valley and the tower used for the field study is indicated by the arrow in Fig. 3. The tower is 38 m tall (Fig. 4) and sits right on the edge of the northern valley ridge off of State Highway 32 east of Licking. Down-valley from the tower is some of the most rugged terrain in the UCRV. The tower afforded an excellent view of the northwest corner of the Valley where the two main ridges come together at nearly right angles. The Valley is most symmetric here and it is in this area that radar data indicated thunderstorm formation most often during the summer of 1983. Permission to use the tower was obtained from Jack Lamar, Missouri State Forester for Dent and Phelps counties, and his help is greatly appreciated.

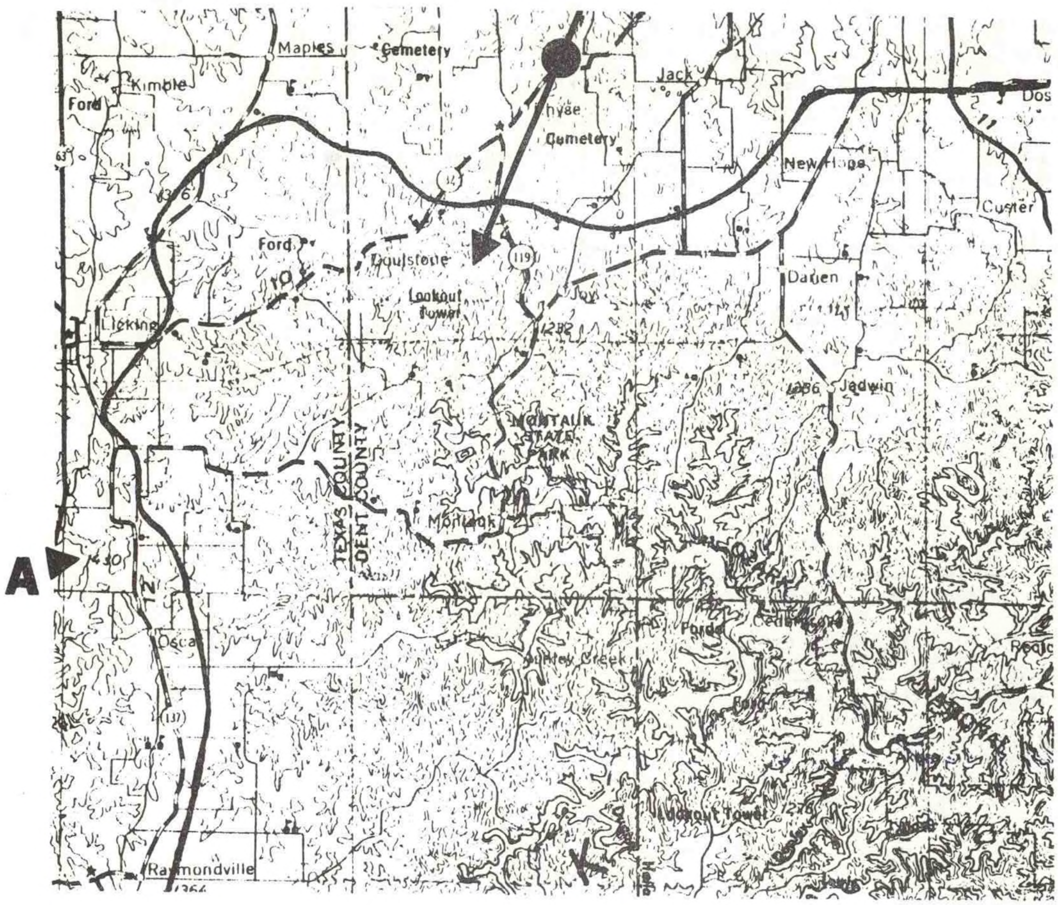


Fig. 3 Detailed map of field trip site (NW corner of the UCRV).

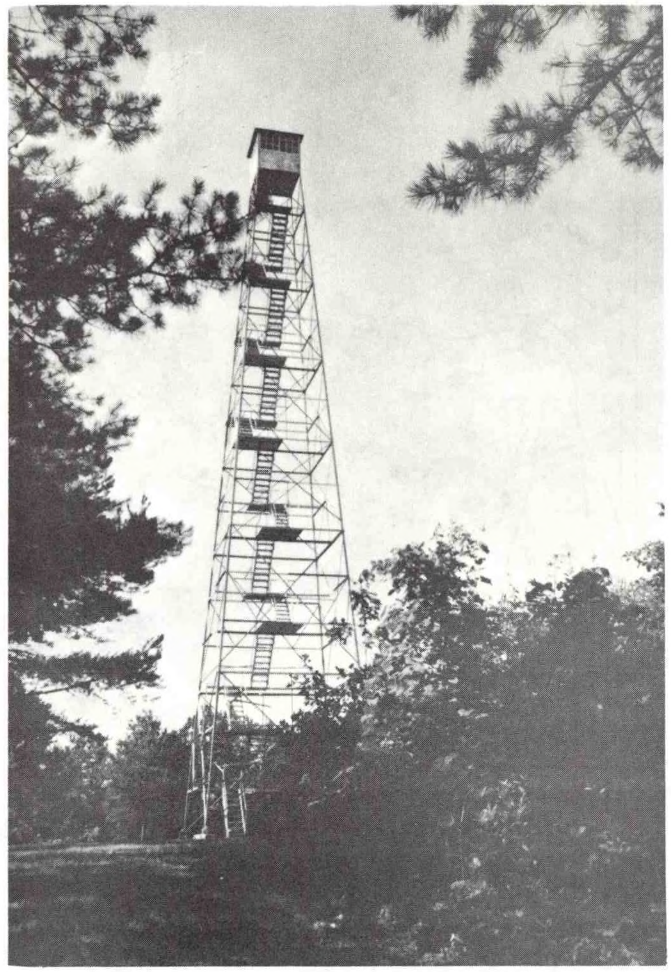


Fig. 4 Montauk State Fire Tower

The primary goal of the field study was to observe thunderstorm development over the Valley on a day when all the parameters on the forecast checklist were favorable. Barring that, it was desirable to at least observe the Valley on a day when local effects could be expected to develop (clear skies and very light surface winds) since an effect should exist whether thunderstorms developed or not. Clouds would be necessary, however, to observe the resulting air currents.

Because of time constraints, 13 July 1984 was selected as the day of study. On that morning a stationary front extending from central Oklahoma to northern Georgia blocked off the tropical air mass from southeast Missouri (Fig. 5). Weak southeast surface flow had returned to southeast Missouri and very dry northerly flow was present above 700 mb. Skies were clear and the surface geostrophic winds were southeast at 5 kts (Fig. 6). The essential ingredients for local wind development were therefore present. The 1200 GMT Monett, Missouri, sounding is shown in Fig. 7; however, neither the Monett (210 km WSW) or Salem, Illinois (265 km NE) soundings were considered representative of the stability and low-level moisture over the UCRV (later satellite pictures will bear this out). The 1200 GMT surface dew point over the UCRV was approximately 59°F (15°C) while Monett and Salem reported dew points of 66°F and 64°F (19°C and 18°C), respectively. The atmosphere over the UCRV on the day of study was therefore relatively dry and stable with pronounced subsidence warming in the mid-troposphere -- clearly unfavorable conditions for air-mass thunderstorm development.

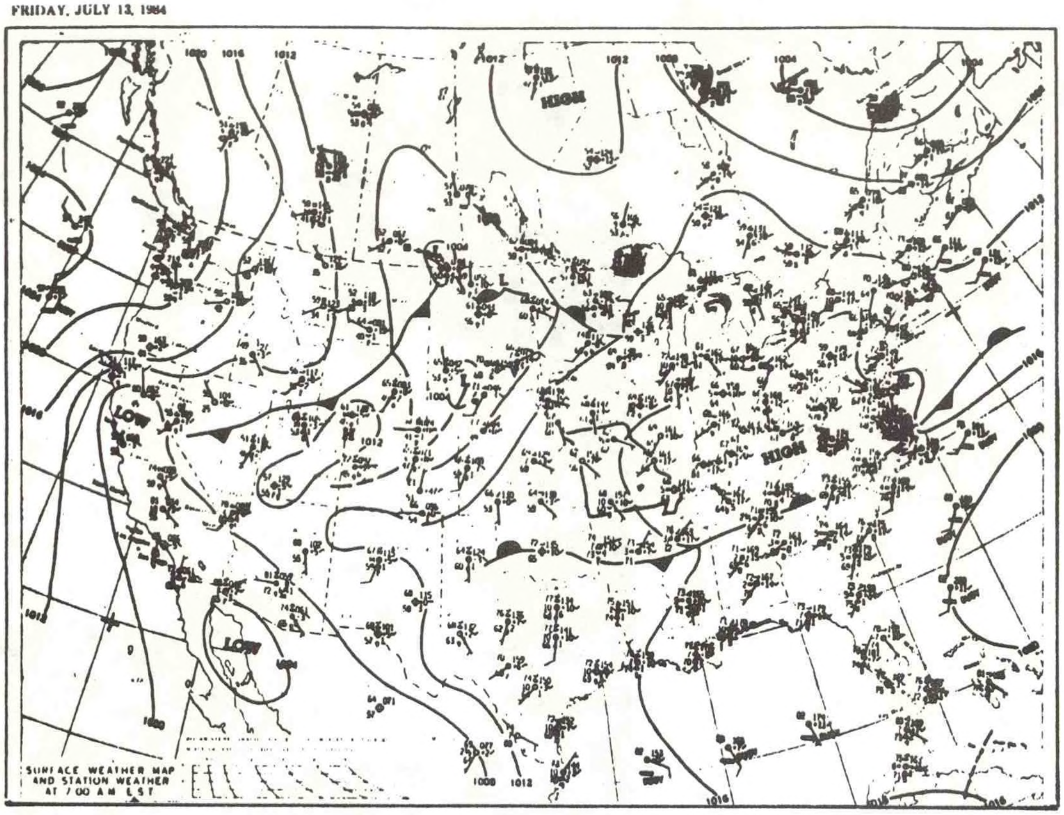


Fig. 5 Daily weather map for 13 July 1984.

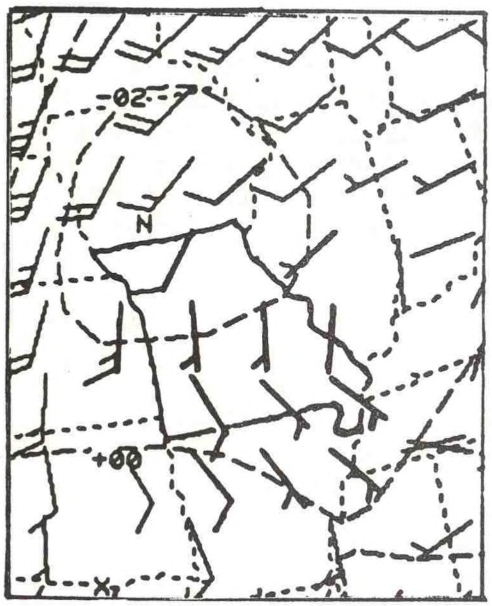


Fig. 6 Surface geostrophic chart for 1200 GMT 13 July 1984.

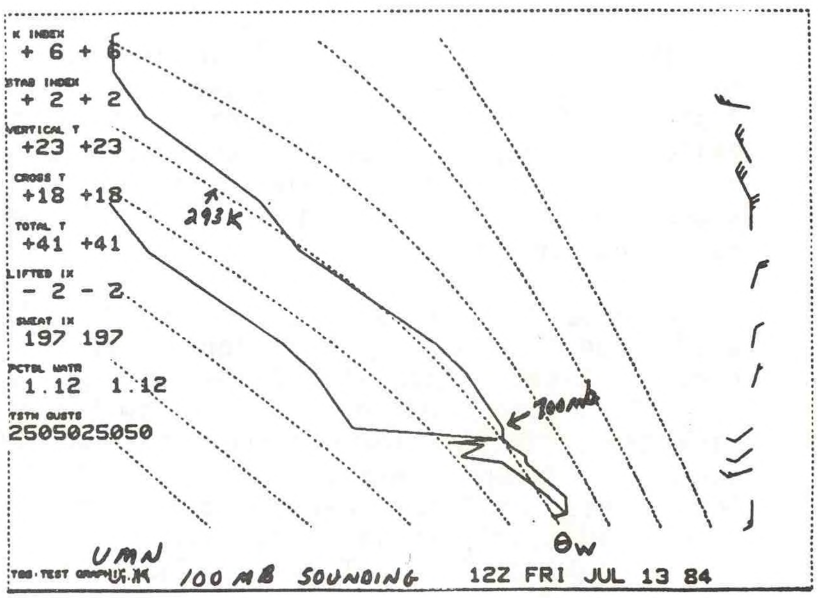


Fig. 7 1200 GMT Monett, Missouri sounding, output from AFOS RAOB program.

Reference photographs were taken of the tower and the surrounding area shortly after arrival at 0915 CDT (1415 GMT) and the study lasted until 2000 CDT (14/0100 GMT). The key observations will be presented and interpreted in the next section.

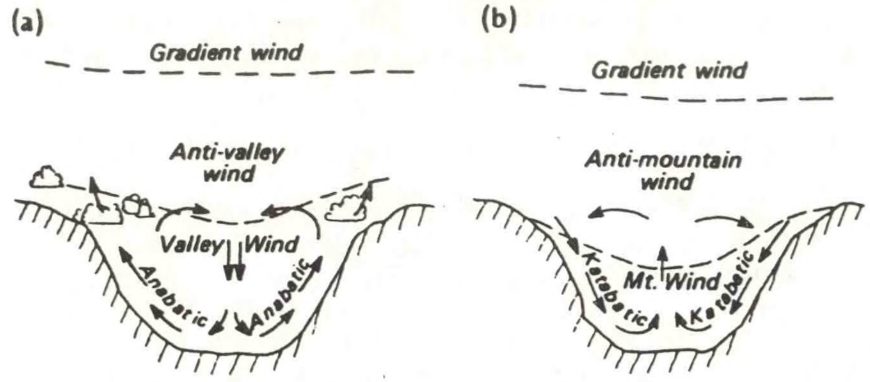
3. Modeling of the UCRV effect: local winds and thunderstorm development

In attempting to understand the local effects taking place over the UCRV, we are first and foremost dealing with the thermal differences caused by solar heating of the landscape. It is appropriate then to begin by looking at the traditional concepts of a valley wind system which is a thermally direct, reversible circulation in the vertical (Figs. 8a and 8b). We soon run into difficulty, however, because the theory is best developed for deep valleys such as those found in the American West and European Alps and does not in itself account for thunderstorm development. In addition, the depth of the entire valley wind system is generally limited to twice the depth of the valley (Atkinson, 1981), and the UCRV is broad and relatively shallow. One should not feel forced to fit the UCRV system to the strict concepts of valley circulations since different factors come into play for any given valley and little work has been done on valleys the size of the UCRV. Indeed, since we are concerned mainly with the ability of the local winds of the valley to influence precipitation distribution, we should not get bogged down by dealing with the entire valley wind system for which complete observations are not currently possible. Rather, we should key in on the most important component of the system, the slope wind circulation. As long as continuity of mass and the circulation theorem are respected in a basic sense, a simple model can be attempted. It is now believed that enough evidence has been gathered over parts of three summers to develop a simple qualitative model of the UCRV's effect. Three models (all variations of a basic model) will be presented: 1) slope winds in a stable atmosphere; 2) slope wind-aided thunderstorm or shower development in a marginally unstable/stable atmosphere; and 3) thunderstorm development in a moist, unstable atmosphere.

a. Initial model conditions and simplifying assumptions

The model is intended to be valid during the months of June, July and August (the months of maximum solar radiation and most frequent presence of tropical air masses), and is applicable only under weak synoptic conditions (surface geostrophic winds $\leq$ 5 kts). Initial atmospheric conditions at sunrise are assumed to consist of a motionless lower troposphere with zero horizontal pressure gradient, clear skies, and a stable stratification of the air in the Valley and boundary layer. Figs. 9a and 9b show that for very weak synoptic conditions like those of the field trip day, the above assumptions can be reasonably approximated in the real atmosphere.

The simplified geographic model of the UCRV is illustrated in Fig. 10. The rugged topography of the Valley has been simulated by straight lines and plane surfaces with the Current River represented by line AB in the Valley bottom. The ridge tops are assumed to be horizontal and at a uniform elevation of 425 m above MSL. The slope of the Valley walls is not specified except in the qualitative sense that the slopes that can receive sunshine on the northeast side of the Valley (northeast slopes) are predominantly SE-SW-W-facing, and the slopes of the southwest side of the Valley (southwest slopes) that can receive sunshine are predominantly NE-E-SE-facing. The northeast slopes are steeper and more uniform than the southwest slopes.



Mountain and valley wind system viewed at a valley cross-section with the reader looking up-valley. (a) By day slope winds are anabatic, and the valley wind fills the valley and moves upstream (into the page away from the reader), with the anti-valley wind coming downstream (out of the page). (b) At night the slope winds are katabatic and reinforce the mountain wind which flows downstream, with the anti-mountain wind flowing in the opposite direction above.

Fig. 8a Simple sketch of mountain and valley wind system (Oke, 1978).

Table 27 Nomenclature of slope and valley wind circulation

Term	Meaning
Slope/valley wind	Thermally induced day-time upslope/-valley wind in the lower layers
Downslope/down-valley (mountain) wind	Thermally induced night-time downslope/-valley wind in the lower layers
Anti-slope/-valley wind	Compensation wind to slope/valley wind of opposite direction, flowing just above top of the slope/valley wind
Anti-downslope/-down-valley (mountain) wind	Compensation wind to the downslope/down-valley (mountain) wind of roughly opposite direction, flowing just above the downslope/down-valley (mountain) wind
Valley wind system	The system of the above-named four winds in *valleys* as opposed to *slopes*
Anti-wind	Anti-slope/valley wind or anti-downslope/-down-valley (mountain) wind

Source: Buettner and Thyer (1959).

Fig. 8b Table of accepted names for the various components of slope and valley wind circulations (Atkinson, 1981).

Fig. 9a The Maries River Valley at sunrise, taken enroute to the UCRV on the field trip day. It is not uncommon for valleys south of the Missouri River to fill up with fog (i.e., cold air) from ridge to ridge on clear and calm summer nights.

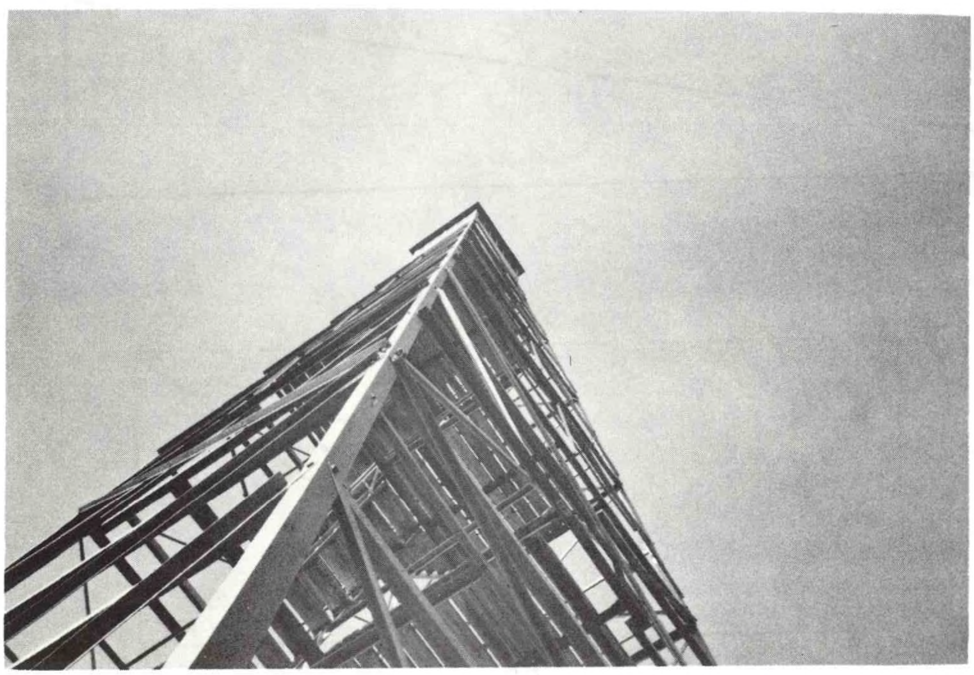


Fig. 9b Reference photo of the Montauk Fire Tower taken at 0915 CDT. Skies were perfectly clear and the fog had burned off over the Valley.

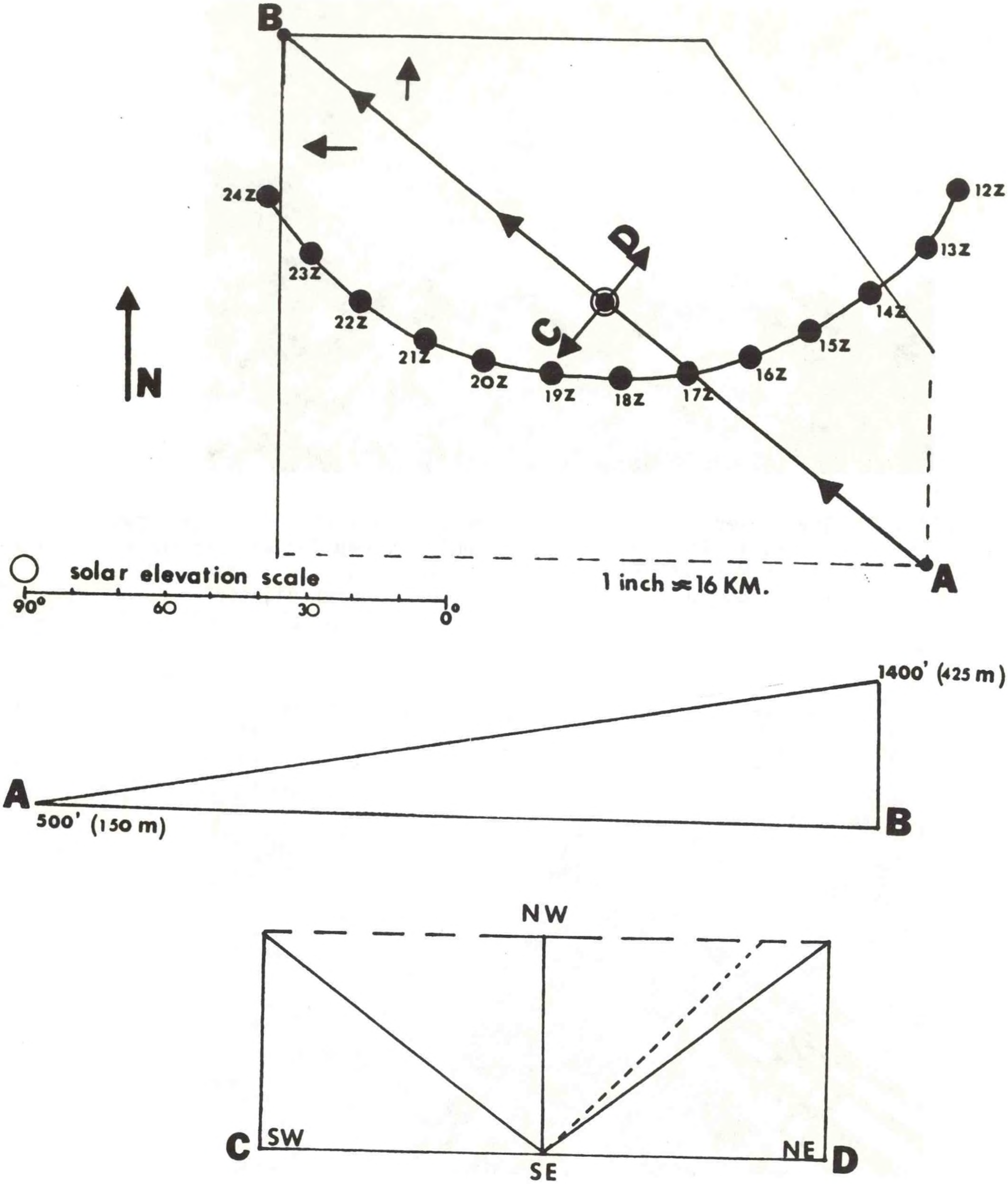


Fig. 10 Geometric model of the UCRV and the track of the sun around point O, the approximate Valley center. The general slope of the terrain is indicated by arrows ▲ ; the vertical scale is greatly exaggerated.

The only input to the model is direct beam solar radiation which is governed by the relationship:

$$S_{sfc} = S\ (\sin \Theta) \qquad (3.1)$$

(a variation on the Cosine Law of Illumination, Huschke, 1959) where S_{sfc}, the direct solar energy incident on a given unit surface, is equal to the solar energy that would be received by a hypothetical surface normal to the direct beam of solar energy (S) times the sine of the angle formed by the direct beam and the given surface (Fig. 11).

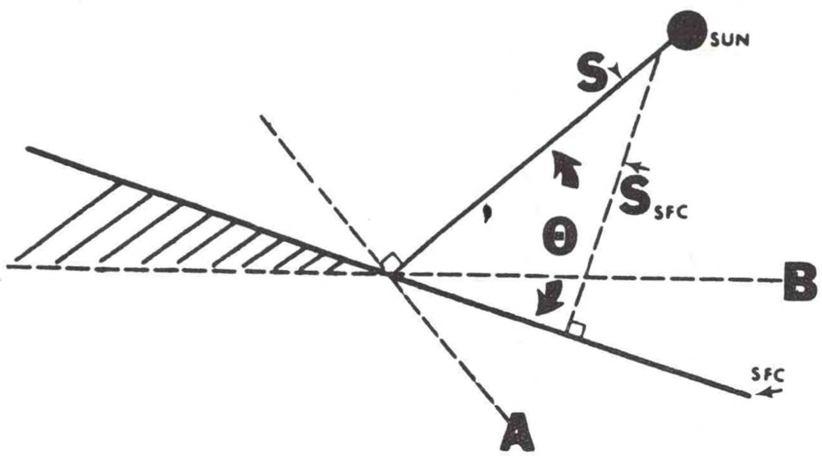


Fig. 11 Variation on the Cosine Law of Illumination. Line B is a hypothetical horizontal reference from which solar elevation and surface slope are measured and line A is a hypothetical normal to the direct solar beam.

Clearly, a surface facing the sun and normal to its direct beam will receive the maximum possible radiation per unit area. The solar radiation incident on a given surface is therefore specified by its slope and the elevation and azimuth angles of the sun. Computer printouts of solar elevation and azimuth for three summer days are given in Fig. 12. The data for Julian day 195 (the day of the field trip) was used in the model. The solar data was computed for the approximate valley center and the path of the sun is plotted on Fig. 10. There are no significant differences in the solar values for June and July but by late August, solar elevation and azimuth differ considerably from early summer values.

In this model, the flux of sensible heat and water vapor from the surface is assumed to lag solar energy receipt by only a short time (Gay, 1974, and Wallace, 1977). The Valley slopes are nearly 100 percent forest-covered and are assumed to be a local source of water vapor through transpiration. Stomatal resistance is neglected as is the partitioning of solar energy between sensible and latent heat flux. The effect of the Coriolis force can be neglected (Atkinson, 1981), but frictional forces, although left unspecified, are very important because of the rugged and heavily forested terrain. Indeed, frictionally-induced turbulence in the surface layer should result in very efficient transport of sensible heat and water vapor from the slopes into the boundary layer.

ENTER LATITUDE IN DEGREES 37
ENTER LATITUDE IN MINUTES 20
ENTER LATITUDE IN SECONDS 0

ENTER LONGITUDE IN DEGREES 91
ENTER LONGITUDE IN MINUTES 30
ENTER LONGITUDE IN SECONDS 0

ENTER JULIAN DATE 165 6/14

TIME	EL	AZ
1200	12.71	70.35
1300	24.19	78.41
1400	36.00	86.64
1500	47.91	96.01
1600	59.56	108.62
1700	70.00	130.25
1800	75.83	174.37
1900	71.73	223.20
2000	61.79	248.10
2100	50.27	261.83
2200	38.30	271.63
2300	26.52	279.99
2400	14.96	288.02

NEXT? 1=DAY 2=STN 3=TIME 4=END 5=PRINT SOLAR NOON 5

TRUE SOLAR NOON = 1066 LST

ENTER BEGINNING TIME OF TABLE (IN Z TIME) 1200
ENTER ENDING TIME FOR TABLE (IN Z TIME) 2400
ENTER INTERVAL IN MINUTES 60

ENTER JULIAN DATE 241 8/29

TIME	EL	AZ
1200	4.48	81.22
1300	16.36	90.18
1400	28.23	99.74
1500	39.73	111.00
1600	50.23	125.82
1700	58.50	147.06
1800	62.32	176.28
1900	59.89	206.76
2000	52.43	229.91
2100	42.30	245.94
2200	30.97	257.84
2300	19.15	267.67
2400	7.25	276.69

NEXT? 1=DAY 2=STN 3=TIME 4=END 5=PRINT SOLAR NOON 5

ENTER LATITUDE IN DEGREES 37
ENTER LATITUDE IN MINUTES 20
ENTER LATITUDE IN SECONDS 0

ENTER LONGITUDE IN DEGREES 91
ENTER LONGITUDE IN MINUTES 30
ENTER LONGITUDE IN SECONDS 0

ENTER JULIAN DATE 195 7/13

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ENTER ENDING TIME FOR TABLE (IN Z TIME) 2400
ENTER INTERVAL IN MINUTES 60

TIME	EL	AZ
1200	10.82	70.72
1300	22.32	78.92
1400	34.15	87.27
1500	46.06	96.76
1600	57.67	109.32
1700	68.09	130.04
1800	74.29	169.92
1900	71.31	217.30
2000	61.97	244.04
2100	50.66	258.88
2200	38.81	269.23
2300	26.91	272.88
2400	15.26	286.06

NEXT? 1=DAY 2=STN 3=TIME 4=END 5=PRINT SOLAR NOON 5

TRUE SOLAR NOON = 1112 LST

Fig. 12 Solar data for the center of the UCRV. Output from AFOS "SUN" program.

b. Slope winds in a stable atmosphere

Experience has indicated and theory suggests that environmental stability has a strong influence on local wind development (Atkinson, 1981). Beginning with a stable, subsiding atmosphere, we will look at two key phases of the UCRV slope wind circulation. The stable case is felt to be the "pure" example of the UCRV effect.

From Fig. 10, it is apparent that while the UCRV is relatively shallow (305 m maximum depth), the slopes are immense. The smoothed southwest slopes have an area of roughly 2100 km^2 and the northeast slopes 1300 km^2. The actual surface area of the slopes is, of course, much greater and the slope of the terrain varies widely. The closest analogy to the UCRV effect in the literature is found in Scorer (1958), where he discusses thermals in a shallow valley and heating a stable layer (Fig. 13). The process begins as the southwest slopes of the UCRV are heated by the morning sun with the resulting fluxes of heat raising the temperature of the air near the slopes (strictly speaking, we are dealing with potential temperature). This "slope" air is warmer than "free" air at the same level in the Valley and the resulting horizontal pressure gradient force (PGF) from free air to slope and buoyant force cause an upslope wind (Fig. 14). Initially, we can imagine the slope thermals quickly losing their buoyancy in the stably-stratified atmosphere until the Valley air begins to become well-mixed and warmed. This process will eventually result in a slope circulation where the slope winds feed into a vertical branch over the ridges. A counterflow from the ridges, returning to Valley center above the slopes and descending, completes the circulation. In this way the air over the slopes can be well-mixed and warmed without penetrative convection occurring. The slope circulation will result in a PGF from plain to valley and thus, a valley breeze and reverse flow aloft as required by theory will develop. However, we can reasonably assume the up and down valley components of motion, resulting from such a PGF, to be small in such a shallow valley. The end result of the valley breeze (up-valley component) is that every point up-valley is warmer than a point down-valley at the same level (Defant, 1951). We should then expect the warmest temperatures over the vertex or northwest corner of the Valley due to the up-valley component of motion and the convergence of airflow due to topography.

It has been found that temperature differences between "slope" and "free" air of only fractions of a degree are sufficient to initiate the slope wind process (Atkinson, 1981):

> Wenger (1923) calculated that the velocity around a closed vertical circulation near a slope would be $9\Delta T$ ms^{-1} (where ΔT is the temperature difference between near-slope and free air) only 3 h after initiation. Despite the approximations made in his analysis, his (Wenger) results clearly illustrated the remarkable effectiveness of the baroclinic overturning required by the Bjerknes circulation theorem.

The time of three hours (no doubt variable for any given slope) is all there is to go on when considering a qualitative model for the UCRV, but as we shall see, it agrees remarkably well with observations.

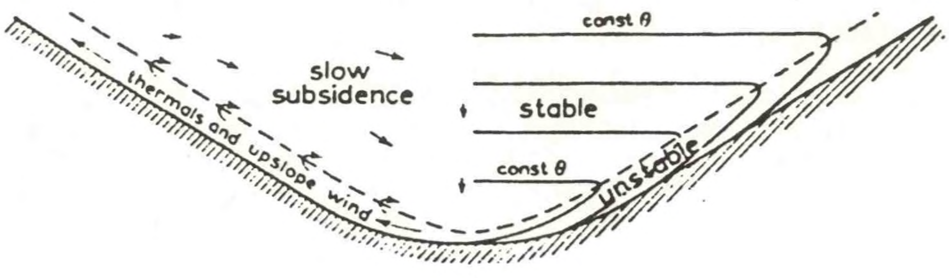


Fig. 13 The slope wind process in a stably-stratified atmosphere (const θ are lines of constant potential temperature) (Scorer, 1958).

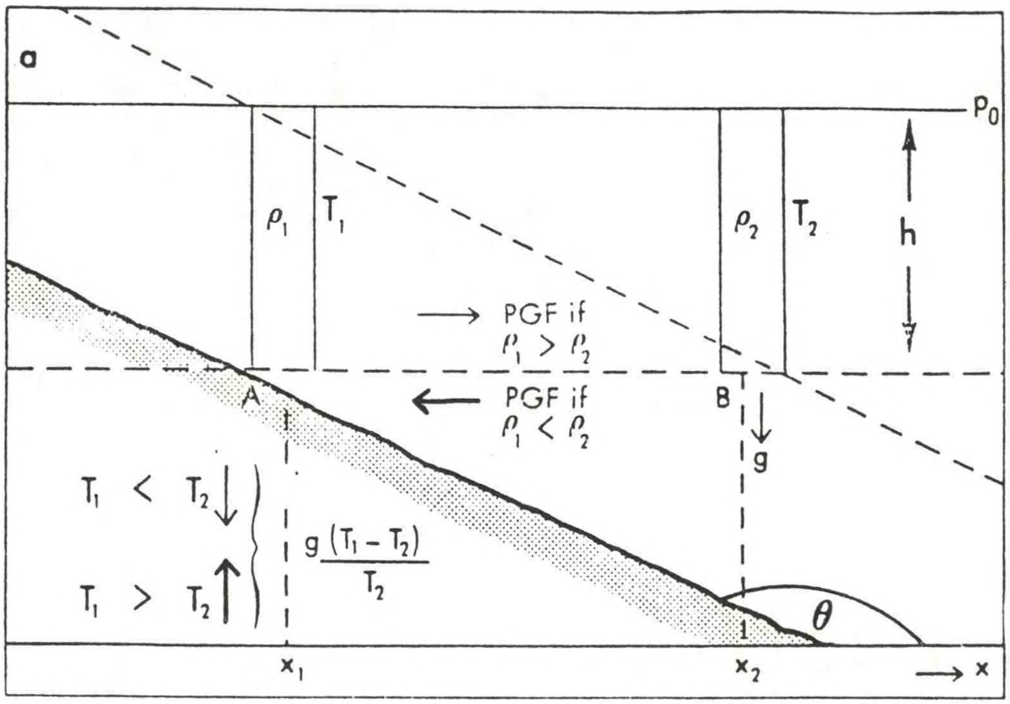


Fig. 14 Force diagram for slope wind mechanism (Atkinson, 1981). During the daytime, $T_1 > T_2$ and $\rho_1 < \rho_2$ so the horizontal PGF is toward the slope and the buoyant force is positive (upward). The layer "h" is assumed to be initially in hydrostatic equilibrium.

In considering the path of the sun over the UCRV, it is reasonable to assume that the initiation of the slope wind process begins between 1300 and 1400 GMT so the southwest slope circulation should be well developed between 1600 and 1700 GMT. Figure 15 shows the modeled late morning slope wind circulation. The slope winds transport heat and water vapor to the Valley ridges where they ascend in vertical air currents resulting in cumulus clouds. A Landsat 4 picture with a resolution of around 30 m (Fig. 16) shows well developed southwest slope winds over the UCRV at 1610 GMT in excellent agreement with available theory. As the sun tracks westward and increases in elevation, strong insolation begins on the northeast slopes between 1600 and 1700 GMT and insolation is roughly even over both sides of the Valley at 1700 GMT. After 1700 GMT, heating continues to increase on the northeast slopes and decreases on the southwest slopes. A well-developed slope circulation should then be present over the northeast side of the Valley between 1900 and 2000 GMT. Figure 17 shows the modeled mid-afternoon slope wind circulation.

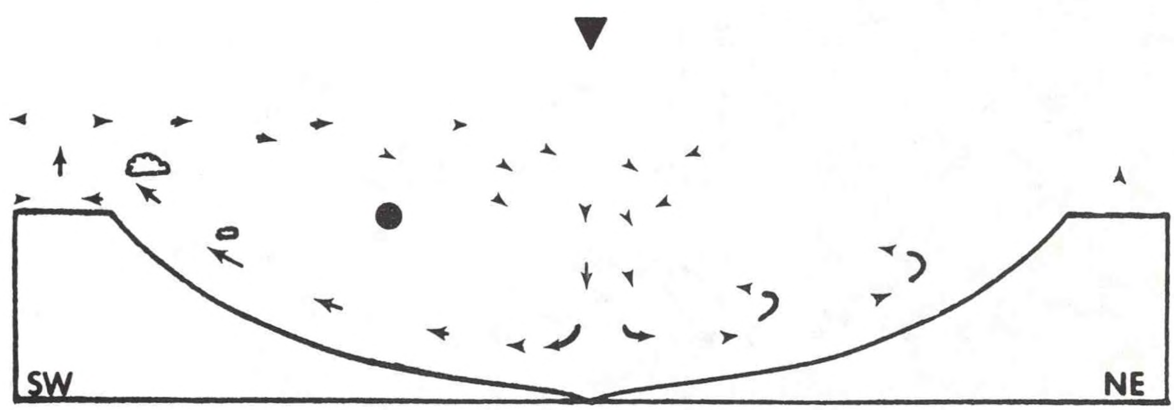


Fig. 15 Idealized late morning (1600-1700 GMT) slope wind circulation in a stably-subsiding atmosphere. The valley cross section is normal to the valley centerline (circulation is not drawn to scale). The large scale vertical motion is downward ▼, and the circulation has a component of motion into the paper ●. The southwest slope wind circulation is fully developed with small cumulus forming along the ridgeline while the slope wind process is beginning on the northeast side of the valley.

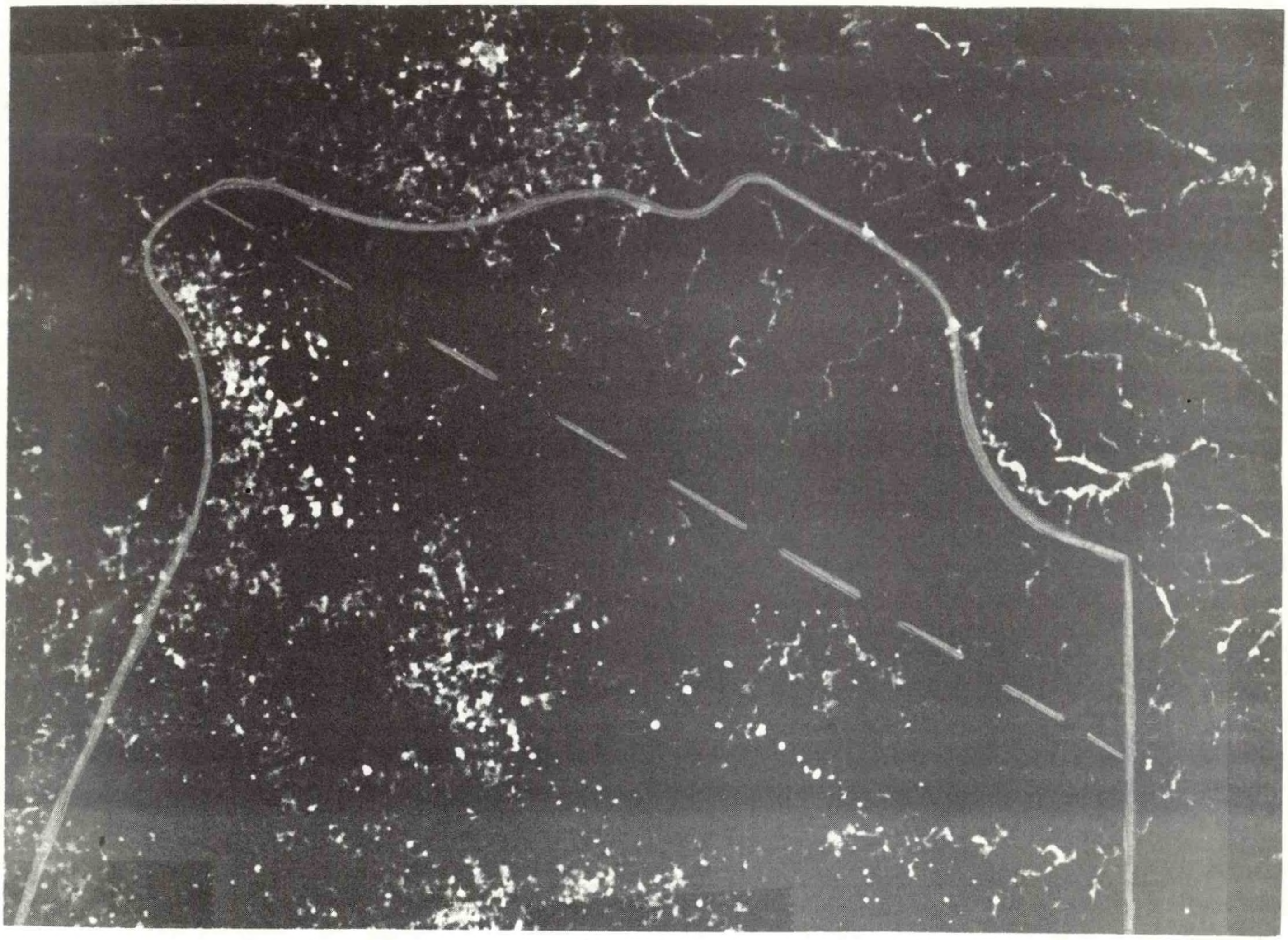


Fig. 16 Landsat 4, Thematic Mapper picture taken on 29 August 1982. The solar elevation and azimuth were 51° and 129°, respectively, so the picture was taken at 1610 GMT. The UCRV is outlined in white and the Valley centerline is marked by a dashed line. Slope wind cumulus are indicated by the bright white dots southwest of the Valley centerline. The Current River cannot be seen because of the steep bluffs and dense forest cover. Anticyclonic weather and a stable atmosphere prevailed on this day. The best developed and most organized cumulus are along the western ridgeline in the northwest corner of the Valley.

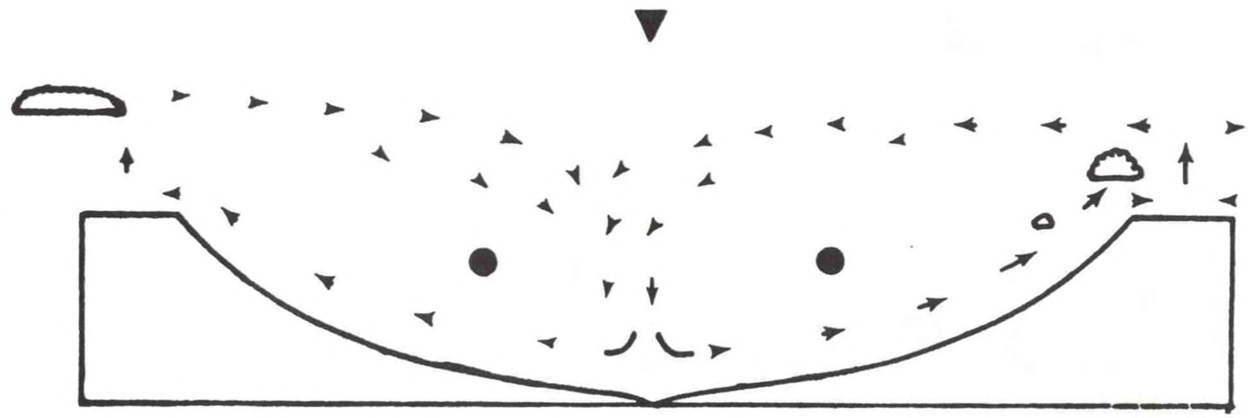


Fig. 17 Idealized mid-afternoon slope wind circulation in a stably-subsiding atmosphere. The northeast slope wind circulation is fully developed with cumulus forming along the ridgeline while the southwest slope circulation is diminishing with stratocumulus clouds remaining over and downwind of the ridge due to the deepening and moistening of the mixed layer during the day.

On the day of the field study, the tower location was ideal to observe the northeast slope circulation. The key observations will now be discussed in some detail:

A few small cumulus began forming along the ridgeline near the tower at 1830 GMT. This apparently signaled the onset of strong slope winds because the wind at tower level at first died to near calm, then came back up in gusts, and continued stronger but quite gusty afterward. By 1900 GMT, a distinct line of scattered small cumulus extended along the ridgeline a considerable distance down-valley (Fig. 18). No clouds were observed anywhere else at this time. The time and location of the slope wind cumulus development agrees very well with the model.

Slope winds are commonly observed to be relatively shallow (Atkinson, 1981) but due to the large area and relative shallowness of the UCRV, the slope winds might be expected to reach a depth of around 300 m. The first cumulus to form along the ridgeline were clearly, and surprisingly, quite low with bases estimated at no more than 300 m above ground level. Evident in Fig. 18 is the fact that the UCRV is a veritable sea of trees. It is believed that the slope winds transport considerable amounts of sensible heat and water vapor to the ridges and decelerate to feed the rising branch of the slope circulation. It is expected then that the mixed layer would rise over the ridges once the slope wind circulation is well underway. The rising branch of the circulation is really a combination of slope wind deceleration and added heat and moisture in addition to the normal thermals which would be present over the relatively flat ridges. This combined vertical transport undoubtedly takes place in large thermals and this process could actually be seen from the tower. Fig. 19 shows a very thin and extensive layer of condensate which developed over the tower and surrounding ridge at 1945 GMT (compare with Fig. 9b). It is believed that this layer marked the rising inversion at the top of the mixed layer. In fact, a thermal can be seen collapsing back into this layer practically over the tower cab. This whole layer could be seen to be swirling with small eddies marked by fleeting strings of cloudy material. Occasionally, much larger globs of cloudy material would form and then dissipate. At times one could actually "feel" the thermals rising around the tower.

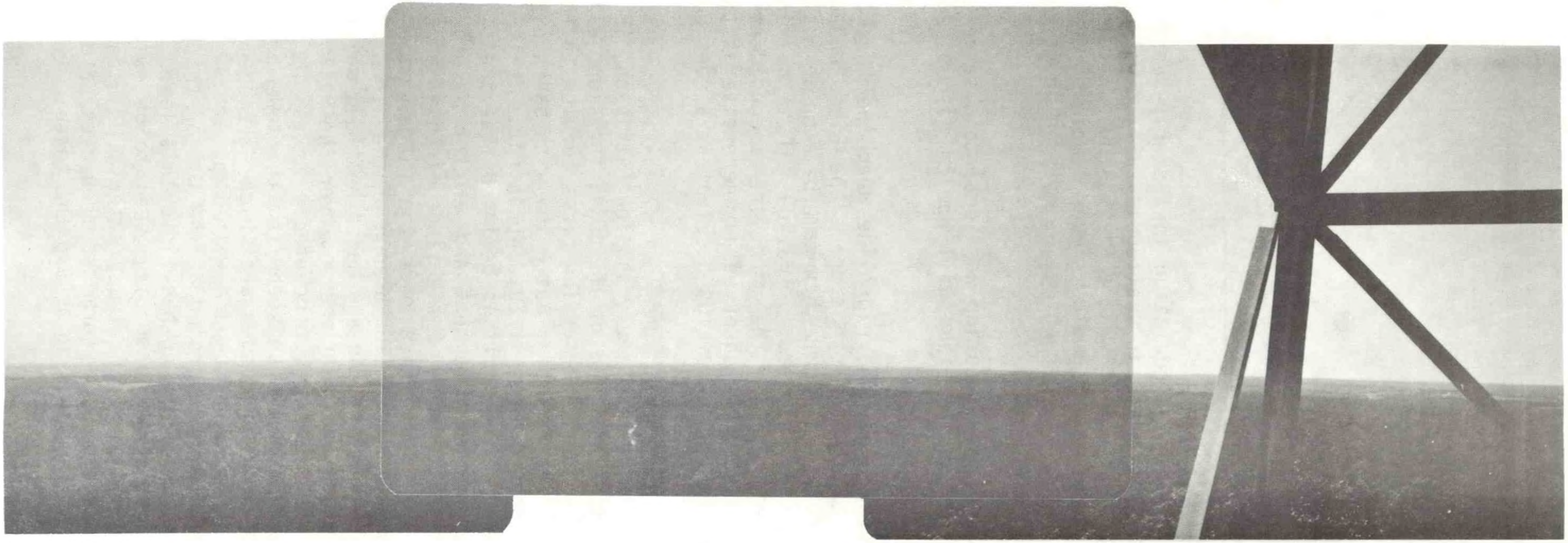


Fig. 18 Panorama of slope wind cumulus over the northeast slopes of the UCRV, taken at 1900 GMT on 13 July 1984, looking south through west. The near ridgeline shows up as a distinct deep-green line, the high ground on the far horizon is the opposite side of the Valley (a distance of about 14 km). High ground in the center of the picture is indicated by "A" in Fig. 3. The small cumulus associated with the southwest slope winds could not be seen from the tower but a high resolution satellite picture confirmed their existence.

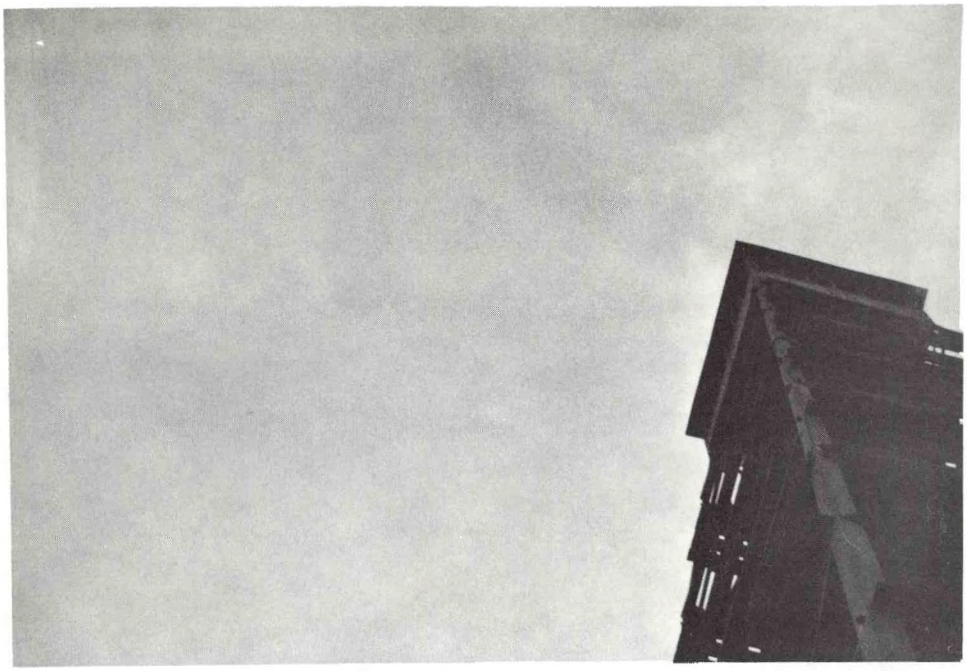


Fig. 19 Extensive layer of condensate and cloudy material over the tower site and surrounding ridge at 1945 GMT 13 July 1984. This layer did not develop until after the onset of strong slope winds.

By 2055 GMT cumulus clouds had become firmly established over the ridge and the bases of the clouds had risen considerably. The small clouds over the UCRV were generally not resolved by the GOES East satellite but a NOAA 7 picture (Fig. 20) shows the lines of cumulus over the ridges at 2044 GMT. It was evident from the tower site that the largest cumulus were located over the flat ridge tops downwind of the slopes because the mixed layer rises downwind. It is felt that in reality there is a "plume" of heat and moisture overspilling the ridges and extending over the plateau downwind from the valley.

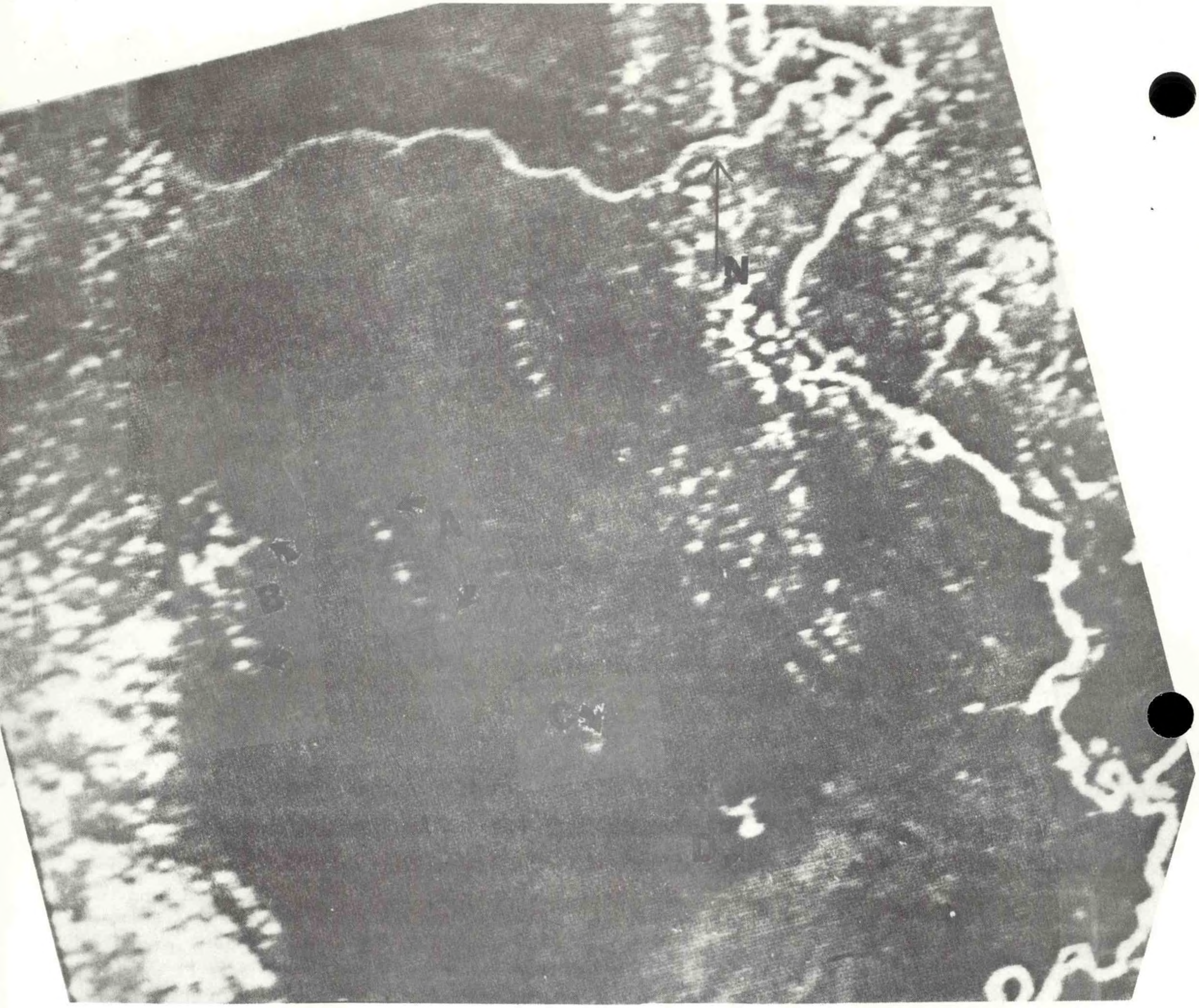


Fig. 20 Maximum enlargement of a NOAA 7 high resolution pass taken at 2044 GMT on 13 July 1984. The cumulus over the northeast ridges of the UCRV (visible from the tower) are shown at "A" and the cumulus over the western UCRV ridges are at "B". No clouds are over the Valley. The very small slope wind cumulus are not resolved by the NOAA 7. Widespread cumulus fields are present over southwest Missouri and southern Illinois. The presence of relatively dry air over southeast Missouri allowed the UCRV effect to be shown in isolation on the day of the field trip. The Missouri and Mississippi Rivers are clearly visible; Clearwater Lake is the white area at "C" (southeast of "A") and the much larger Wappepello Reservoir is at "D".

At 2205 GMT a layer of stratocumulus had formed over the ridge east and west of the tower. Until this time the clouds were not extensive enough to block much sunshine. At 2245 GMT all clouds were rapidly dissolving; only a few small stratified clouds remained over the ridge. At 2300 GMT all clouds had dissipated and at the same level a distinct hazy layer, accentuated by the lowering sun in the western sky, was left over the area. Solar radiation input to the surface had virtually ceased by this time.

In a stable atmosphere it has been reasoned that the overlying stability acts as a dampening mechanism on local circulations, thereby limiting their vertical extent (Atkinson, 1981), and this should be the case with the UCRV. In a most basic way, the heat picked up in the near surface branch of the slope circulation is released as latent heat in the vertical branch over the ridges. Now, while the actual process is not nearly so simple, the UCRV system is clearly working to modify the atmosphere by physically increasing the depth of, and pumping heat and water vapor into, the mixed layer. On the day of the field trip, strong subsidence warming (Fig. 21) and inversion above the mixed layer, in addition to very dry air in the mid-troposphere, halted any prospect of penetrative air-mass convection under normal circumstances; however, we can gain an understanding of the power of the local circulation by looking at two events that happened late in the day of the field trip:

1) Shortly after 2300 GMT stratocumulus billow clouds, indicative of the onset of shear instability, formed rapidly over the Valley ridges north and west of the tower location (Fig. 22). One reasonable explanation for this occurrence is that, given an inversion at the top of the mixed layer and the existence of vertical wind shear across this discontinuity, the lapse rate of the inversion layer was finally modified to a critical value for the spontaneous growth of small-scale waves in a stably-stratified environment. The stability criteria for growth of small-scale waves is given by the dimensionless Richardson Number (Ri) (Atkinson, 1981, and Wallace, 1977).

$$Ri \equiv (g/T)(\Gamma_d - \Gamma)\Big/(dV/dz)^2 \qquad (3.2)$$

where g is the force of gravity, T the mean temperature of the layer, and the critical vertical wind shear for the onset of shear instability (dv/dz) depends on the static stability ($\Gamma_d - \Gamma$) of the layer in question. Γ_d is the dry adiabatic lapse rate and Γ is the environmental lapse rate (ELR). The sign of Ri depends on the ELR with Ri = 0 for a neutral ELR, Ri $<$ 0 for an unstable ELR and Ri $>$ 0 for a stable ELR. It is commonly accepted that Ri must decrease to below about 0.25 for shear instability to begin (Atkinson, et al., 1981) so small wind shear requires small static stability in the layer; alternatively, large static stability requires large wind shear. If we take the shear through a thin layer encompassing the top of the mixed layer as constant, (3.2) reduces to:

$$Ri \equiv \frac{C(\Gamma_d - \Gamma)}{T} \qquad (3.3)$$

and as the ELR approaches Γ_d and T changes very slowly, Ri will decrease to below 0.25 and shear instability will result. Because the top of the mixed layer is relatively moist, billow clouds are formed.

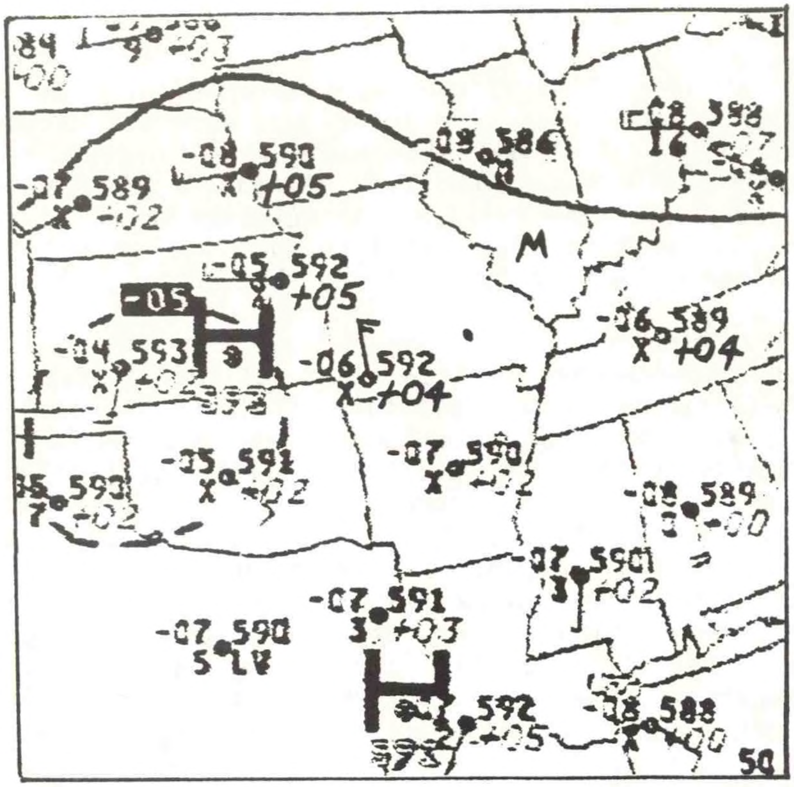


Fig. 21 500 mb chart for 0000 GMT 14 July 1984, showing strong subsidence (40 to 50 m height rises during the day) over the UCRV (indicated by the small dot).

Fig. 22 Billow clouds over the UCRV (looking nearly overhead and northwest of the tower). The tower site was so close to these clouds that it was difficult to get very many of them in one shot.

The slope wind circulation modified and almost destroyed the strong inversion at the top of the mixed layer in a combination of ways. The inversion was being slowly eroded away from the bottom during the day by dissipation of thermals and their added heat and moisture, while at the same time the inversion layer was actually rising. In rising, the dry air immediately above the inversion cools at the dry adiabatic rate while the moist air in the mixed layer (with partly cloudy conditions) cools at a lesser rate, and by late afternoon the inversion layer may be only a few tens of meters thick. If at 2300 GMT we are left with a very thin discontinuity above the mixed layer over the ridges and solar input ceases and scattered clouds dissipate, we can imagine that the lapse rate through the discontinuity finally reached the critical value for shear instability (and clearly it did). The evaporation of the scattered thin clouds and increased radiational cooling at the top of the inversion were the final inputs needed.

It is felt that the formation of the billow clouds over the ridges signaled the end of the daytime slope wind process and the beginning of a gradual reversal to the nighttime circulation which is characterized by negative buoyancy over the slopes and ridges.

2) At approximately 0010 GMT (1910 CDT), a long line of cumulus and cumulus congestus, indicative of penetrative convection, occurred over roughly the middle of the UCRV (Fig. 23). This observation contains interesting implications on the slope/valley system because this roughly symmetrical line occurred in the most symmetrical part of the Valley and extended over the vertex. It is believed that the line of clouds was caused by converging gravity waves coming from both sides of the valley and colliding near the Valley center (Fig. 24). This would destroy the inversion by rapid lifting and thus release the store of warm moist air contained, up until this point, in the Valley system. The stair-stepped appearance of the cloud line, with the highest tops over the vertex of the Valley (not shown in Fig. 23 because of sun glare), and decreasing cloud size down-valley agrees well with the theory that the temperature must increase up-valley at a given level; thus the warmest air and highest tops should be over the vertex area.

In a way we can think of the energy involved in the formation of this line of clouds as indicative of the difference between the "energy" generated by the UCRV and surrounding areas.

I have gone into considerable detail in describing the stable ("pure") case of the UCRV effect because, in essence, nothing is changed in the other cases but the ambient conditions. The stable case is relatively benign from an operational standpoint, yet fascinating because it shows the UCRV system working in isolation. If the Valley's influence is proved in a stably-subsiding atmosphere, it is not hard to extrapolate the influence to more unstable conditions.

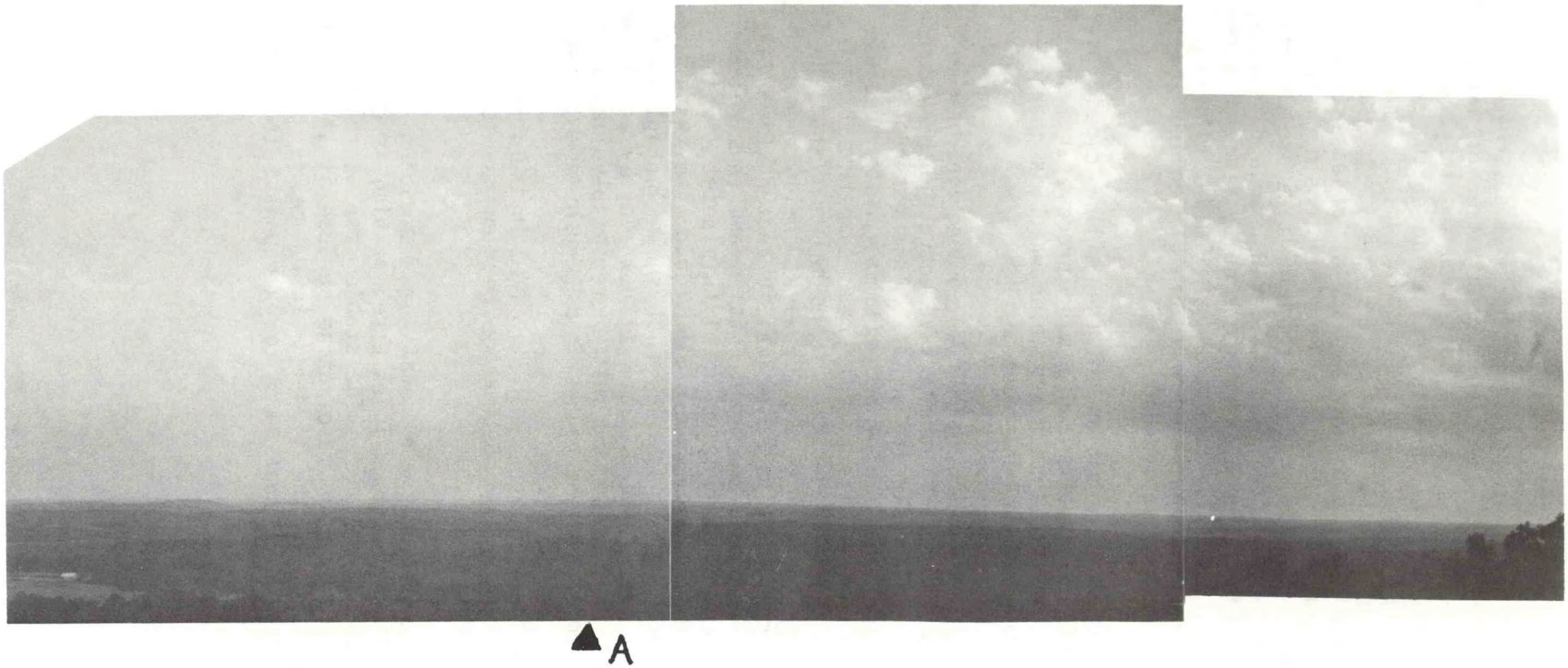


Fig. 23 Panoramic view (SSE-WNW) of cumulus over the UCRV at 0015 GMT on 14 July 1984. The line is clearly over and roughly parallel to, the Valley and extends to the vertex. The near ridgeline is indicated by the dark treeline in the foreground and the far horizon is the opposite ridge as in Fig. 18. Note: There is a gap at "A" which makes the line appear to turn away from the viewer.

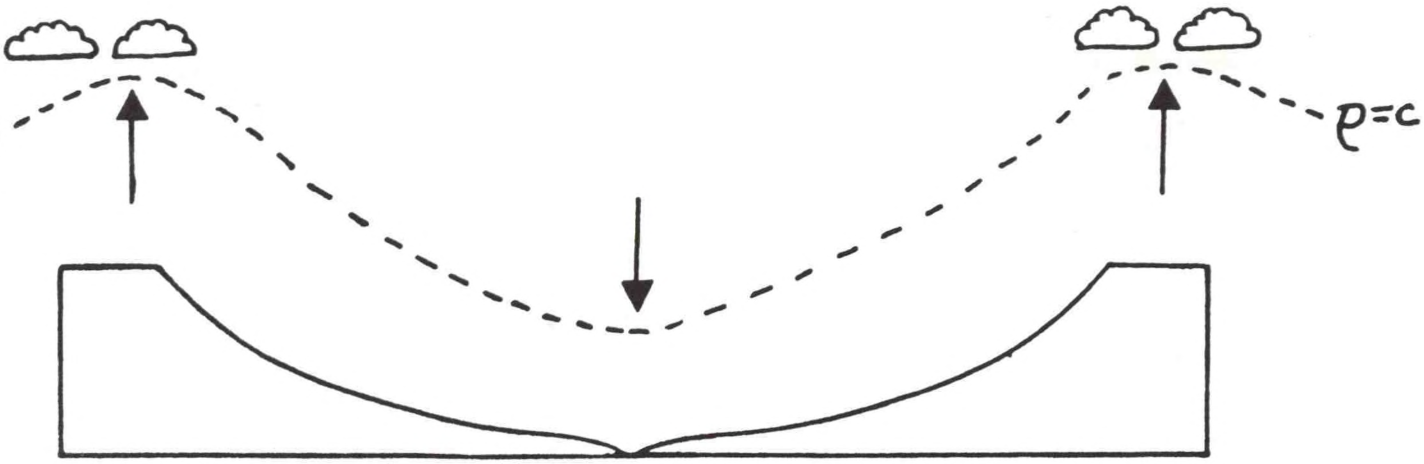


Fig. 24a During the day, the slope wind circulations cause upward motion over the ridges resulting in cloud formation over the ridges and compensating subsidence over the valley center.

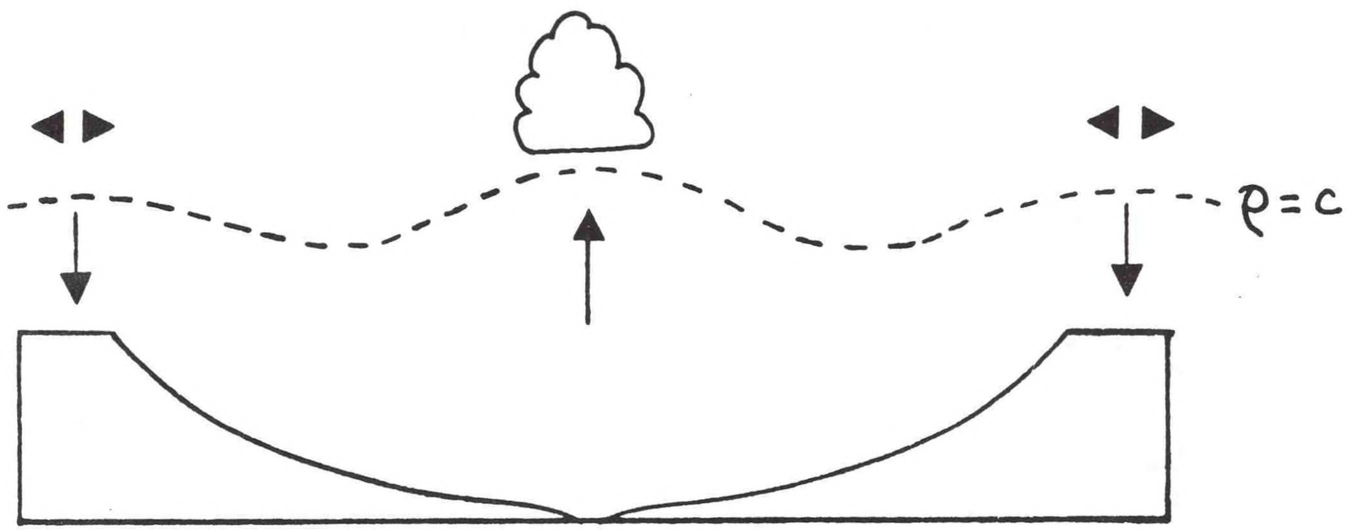


Fig. 24b In the early evening, solar input to the slopes stops. The slope winds will cease and the billow or stratocumulus clouds over the ridges will evaporate, resulting in sinking motion over both ridges and subsequent lifting of the air over the valley center. This destroys the mixed layer inversion and allows short-lived convection.

Fig. 24 Gravity wave schematic: the cross section is normal to the valley centerline; dashed lines are surfaces of constant density and the scale is greatly exaggerated.

c. Slope wind aided convective development model

The slope wind circulations of the UCRV do not cause shower or thunderstorm development directly, and it is now felt that any orographic lifting that results makes a very minor contribution to convective development. Rather, the slope wind circulations are an important contributing factor in convective development when they are capable of destabilizing the atmosphere over the ridges. We have seen in the stable case that after a whole day's work, the circulation came very close to breaking the inversion and allowing convective development, but ambient conditions were too unfavorable. The slope wind aided case is simply the case where the overlying atmospheric conditions are marginal or below for shower development and the rising branch of the circulation, fed by warm, moist slope winds, is able to destabilize the atmosphere over the ridges.

Intuitively, this destabilization must take place some time after the slope winds are well developed (1600-1700 GMT for the southwest slopes and 1900-2000 GMT for the northeast slopes). Clearly, the time and location of convective development over the Valley is related to atmospheric stability and moisture values. It is expected that if the atmosphere is marginally unstable, development should occur over the southwest valley ridges or valley vertex after 1700 GMT, and if the atmosphere is somewhat more stable, convection should occur over the northeast valley ridges or valley vertex after 2000 GMT. The slope wind aided convective development model is shown in Fig. 25.

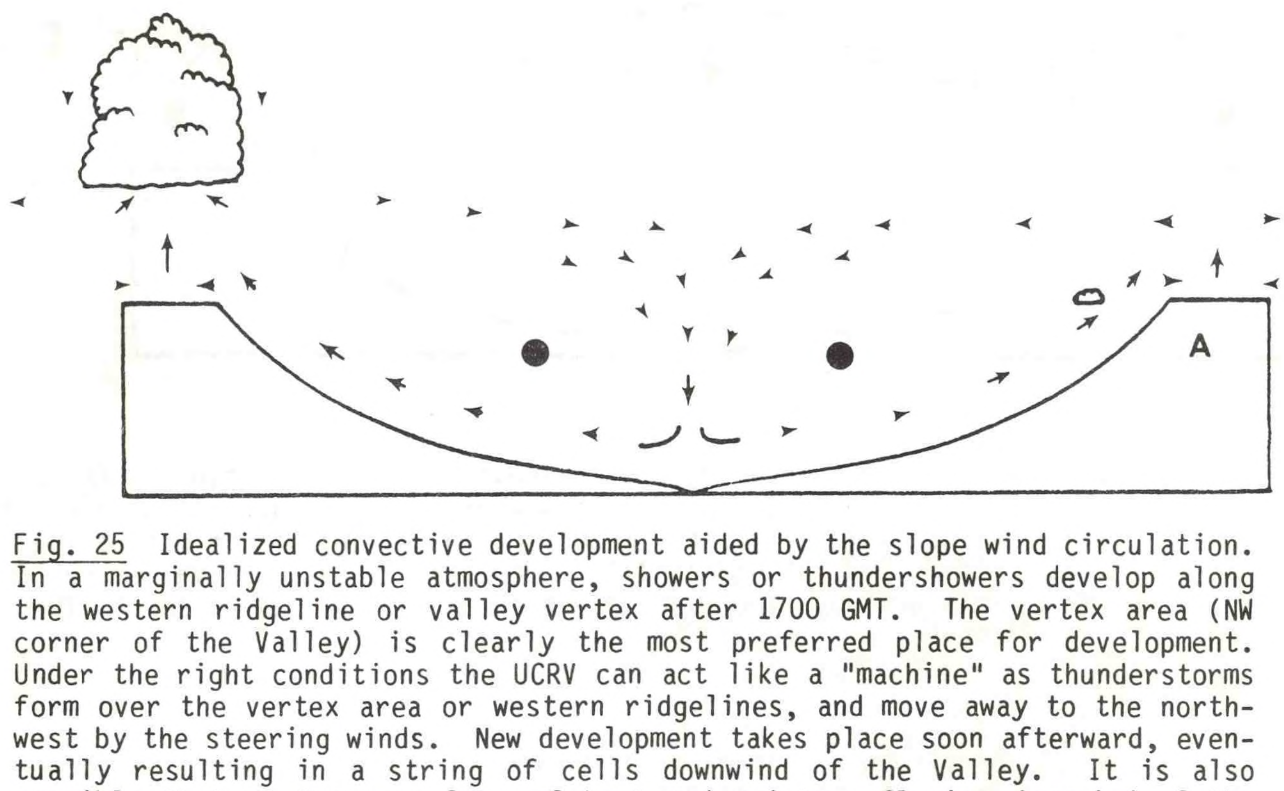


Fig. 25 Idealized convective development aided by the slope wind circulation. In a marginally unstable atmosphere, showers or thundershowers develop along the western ridgeline or valley vertex after 1700 GMT. The vertex area (NW corner of the Valley) is clearly the most preferred place for development. Under the right conditions the UCRV can act like a "machine" as thunderstorms form over the vertex area or western ridgelines, and move away to the northwest by the steering winds. New development takes place soon afterward, eventually resulting in a string of cells downwind of the Valley. It is also possible that an "unseen plume of heat and moisture flowing downwind of the valley vertex may cause convective development a considerable distance away from the Valley under stable conditions. This may well be the case in Fig. 26b, where first development has taken place over the northeast ridges at "A" and at the same time, a cell has developed downwind of the vertex at "B", late in the afternoon. The timing of these events fits with the intuitive concept of delayed development on stable days.

Figs. 26a and 26b show two cases of slope wind aided development, one for each side of the Valley. Fig. 26a shows showers developing over the western ridgeline and just downwind of the Valley vertex at 1835 GMT, while Fig. 26b shows shower development over the northeast ridges at 2235 GMT under more stable conditions. Both the time and location of development agree well with the model. Generally, the slope wind aided convection occurs when showers and thunderstorms are normally not expected to form. Indeed, it was in this situation that the UCRV's influence on thunderstorm development was first discovered. Whenever isolated showers/thunderstorms consistently form over a specific area under weak synoptic conditions, one should wonder why. Clearly, there must be a wide range of moisture and stability values for which the slope wind aided model would apply, but because there is no upper air station reasonably near the Valley, only approximations based on synoptic values can be applied. The minimum values for more than isolated and weak convection are implicit in Fig. 2.

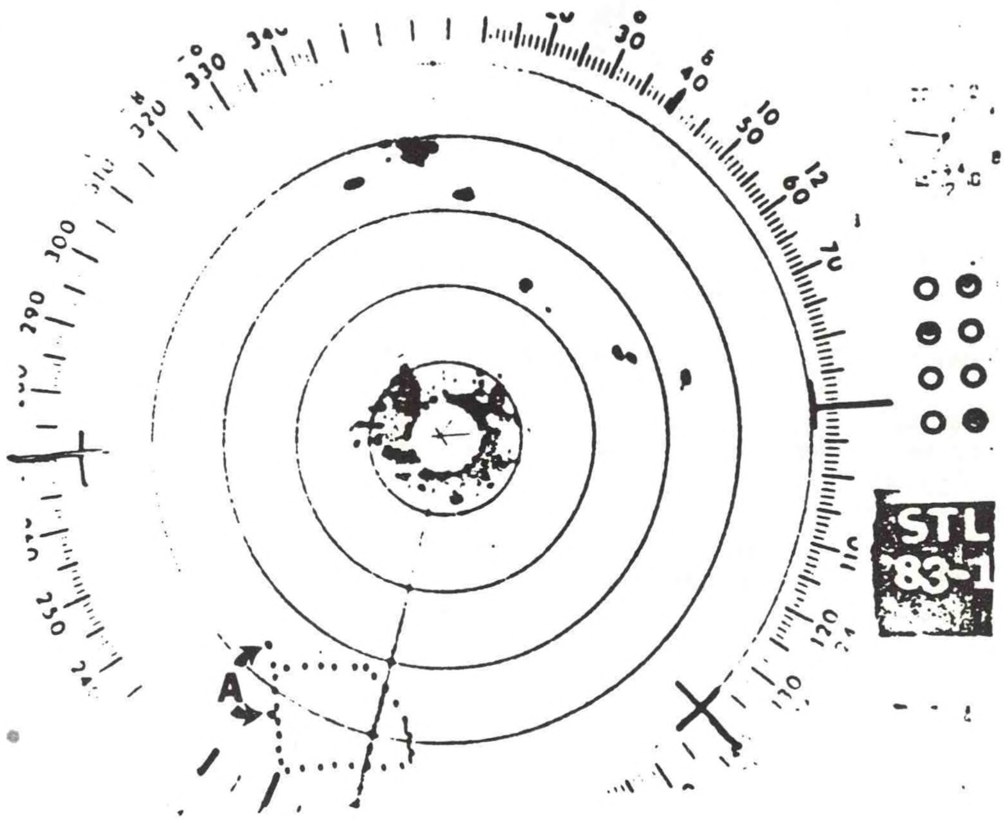


Fig. 26a First echoes over the UCRV (dotted line) at 1835 GMT on 13 July 1983. Newly formed echoes are at "A".

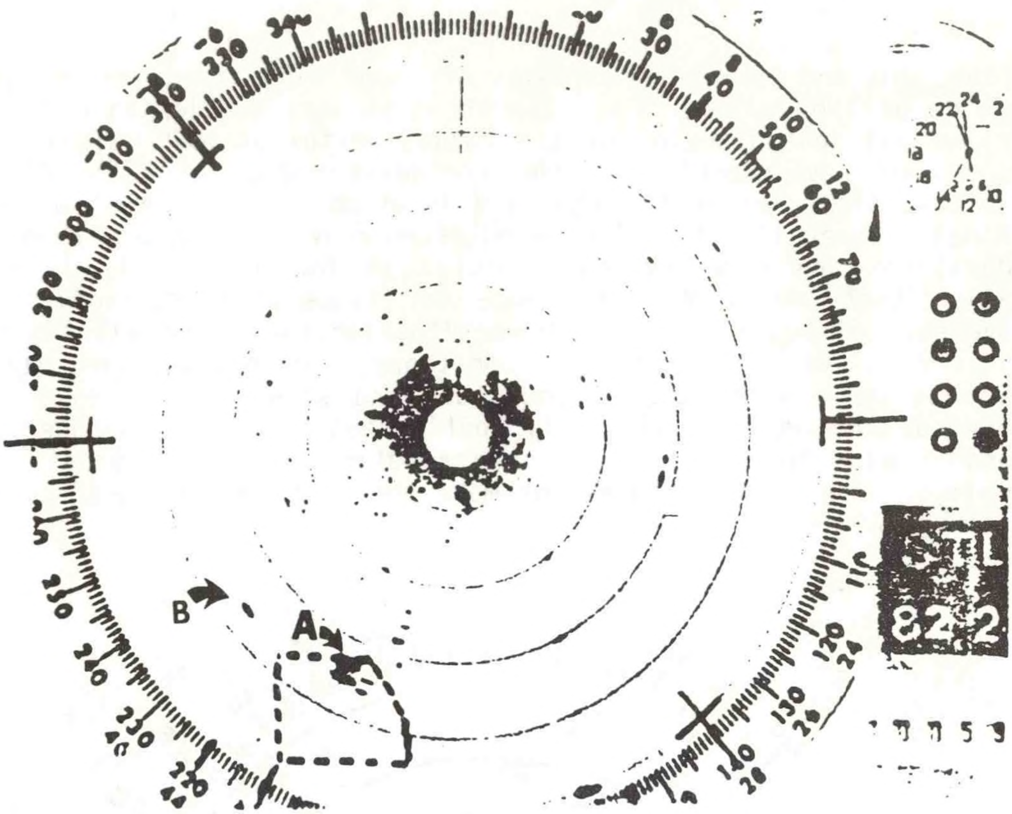


Fig. 26b First echoes over the northeast ridges of the UCRV at 2235 GMT on 25 July 1982.

d. Thunderstorm development in a moist-unstable atmosphere

In a moist-unstable atmosphere, the southwest slope wind circulation is probably never completed before penetrative convection begins. In a stably-stratified atmosphere the circulation is dampened, yet in a sense enhanced, while no such constraint exists in the moist-unstable case. Indeed, in a moist-unstable atmosphere, the vertical (buoyant) component of acceleration can easily exceed the horizontal PGF toward the slope (Fig. 14) resulting in air rising away from the slope (Atkinson, 1981). This will either deepen and weaken the slope winds or destroy the process entirely. The modeling of thunderstorm formation is therefore relatively simple.

Since it is proven that the slope winds exist, it is also proven that the UCRV's slopes are fixed thermal sources due to increased solar radiation receipt (Scorer, 1958). Thunderstorm formation is only possible when low level winds are very weak and the thermals can rise continuously into the same area, resulting in rapid growth of the thermals and penetrative convection. The simple model of thunderstorm formation is given in Fig. 27. Intuitively, thunderstorms should begin to develop over the southwest slopes of the Valley before the slope wind circulation reaches full development under stable conditions (1600-1700 GMT). This is clearly the case for the moist-unstable thunderstorm days documented so far, in which development occurred as early as 1500 GMT, and the average time of development was approximately 1600 GMT (discussed in more detail in the next section).

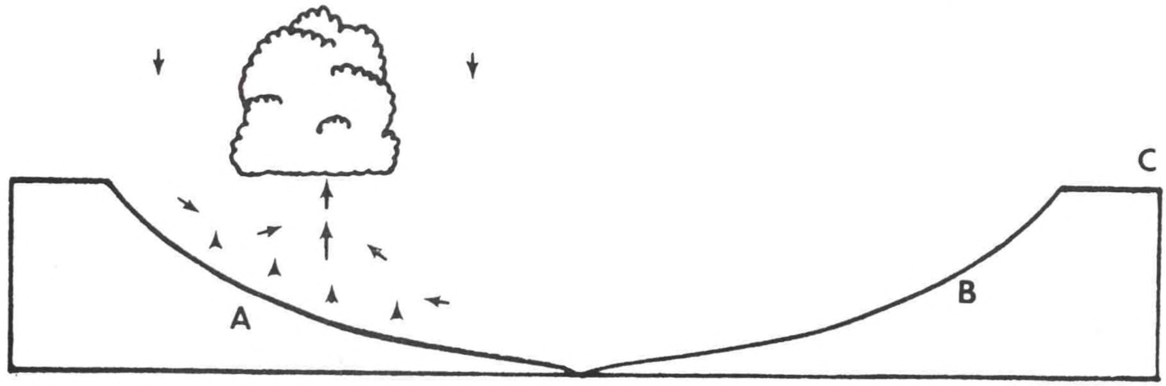


Fig. 27 Idealized thunderstorm formation in a moist-unstable air mass. The air rises away from the southwest slopes (A) into the same area without drifting about, resulting in rapid growth of thermals and subsequent first echo (shower) development by around 1600 GMT. The thunderstorm stage will follow rapidly and once underway, thunderstorm formation will generally continue over or near the Valley all day. Because of the very weak vertical wind shear, the high-level outflow from these thunderstorms generally does not form an extensive anvil cloud and insolation is not blocked over a large area. Indeed, thunderstorms have been observed to develop over the northeast side of the Valley (B) due to preferential afternoon surface heating, after the late morning convection over the southwest slopes has dissipated or moved away. In an extremely unstable atmosphere, first development may occur almost simultaneously at "A" and "C". The development at "C" results from the influence of an adjacent small valley on the other side of the northeast ridge which faces the morning sun.

The occurrence of strong air-mass thunderstorms over the UCRV is clearly the most important case from an operational standpoint, and surprisingly, the easiest case to predict because it is based simply on surface heating and the ability of the resulting thermals to destabilize the lower troposphere. Fig. 28 shows the 1200 GMT Monett, Missouri, sounding for a day of strong thunderstorm development over the UCRV during the summer 1984. The sounding is characterized by very weak winds and virtually no vertical wind shear to the top of the troposphere -- excellent conditions for fixed thermal sources to be effective in causing air-mass thunderstorms. In addition, there is a deep moist layer and the level of free convection is low. Once thermals have destroyed the low-level inversion and condensation takes place, thunderstorms will grow rapidly. There may be those who would say that thunderstorms could develop anywhere under these conditions, but this kind of thinking should be discouraged because it is both unscientific and misguided. Because these thunderstorms almost always occur in anticyclonic weather, there is subsidence taking place and the first thunderstorms to develop will tend to suppress development in the surrounding areas. In addition, the eventual outflow from these thunderstorms may create further development, and generally the first thunderstorms formed over an area will have an influence on the weather over a much larger area during the course of the day.

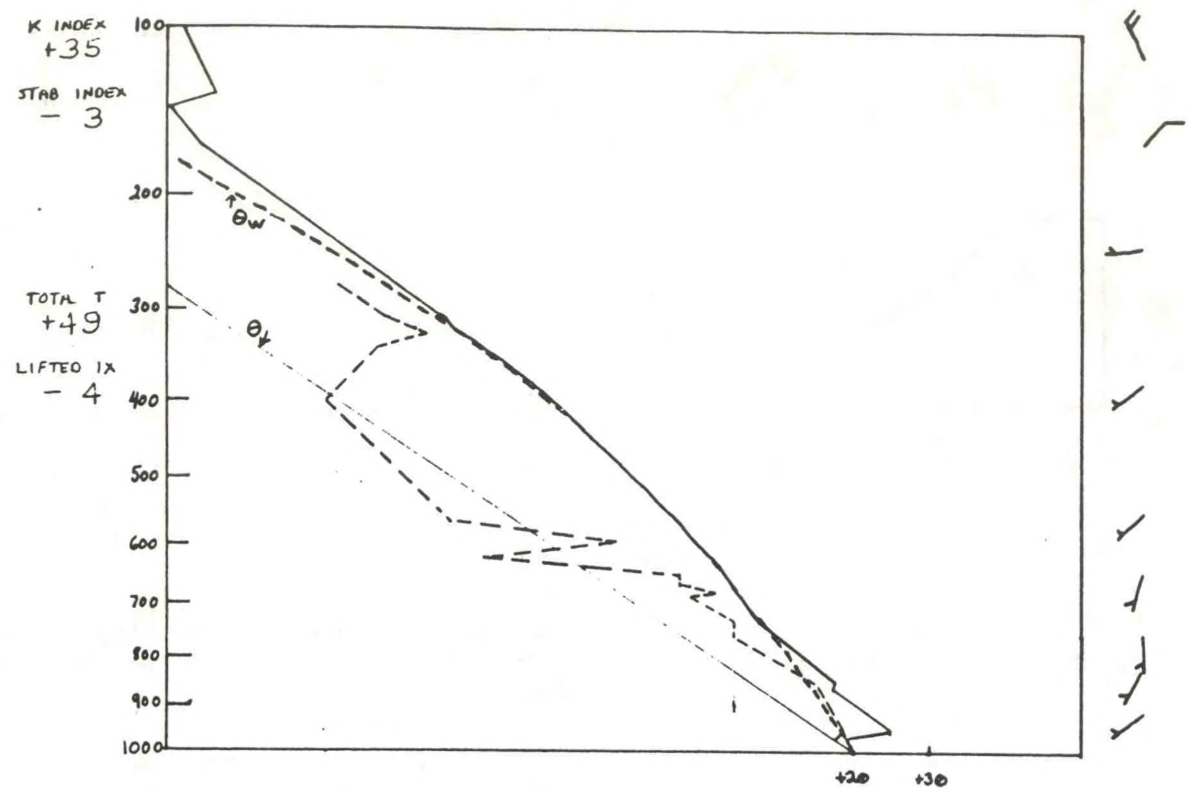


Fig. 28 1200 GMT 14 June 1984 sounding, Monett, Missouri. Output from AFOS RAOB program.

4. Air-mass thunderstorm occurrences and first echo distributions over the UCRV during the summer of 1984

All thunderstorms that developed over or moved into the UCRV during daylight hours were documented during the summer 1984 study. Air-mass thunderstorms developed within the boundaries of the UCRV on only five of the 100 days of study, and four of these five days were correctly predicted by the forecast checklist developed during the initial investigation. The 1200 GMT surface geostrophic wind charts for each of the five days are shown in Fig. 29. Clearly, in each case the wind was either southeast at 5 kts or less than 5 kts which is a strong argument for the existence of a local effect and against random development. It should be stressed that no air-mass thunderstorms were observed to develop over the UCRV on any other day during the study. Of course, there were days when frontal squall lines developed over or moved across the UCRV or thunderstorm complexes moved over the area. If air-mass thunderstorms had formed over the UCRV on days with stronger low-level winds, the local effect of the Valley would be suspect. Clearly, the thunderstorms observed thus far have formed only under conditions of very light winds, in perfect agreement with the theory of local influence. It should be noted that larger mesoscale or synoptic scale influences may take over after initial convective development over the UCRV.

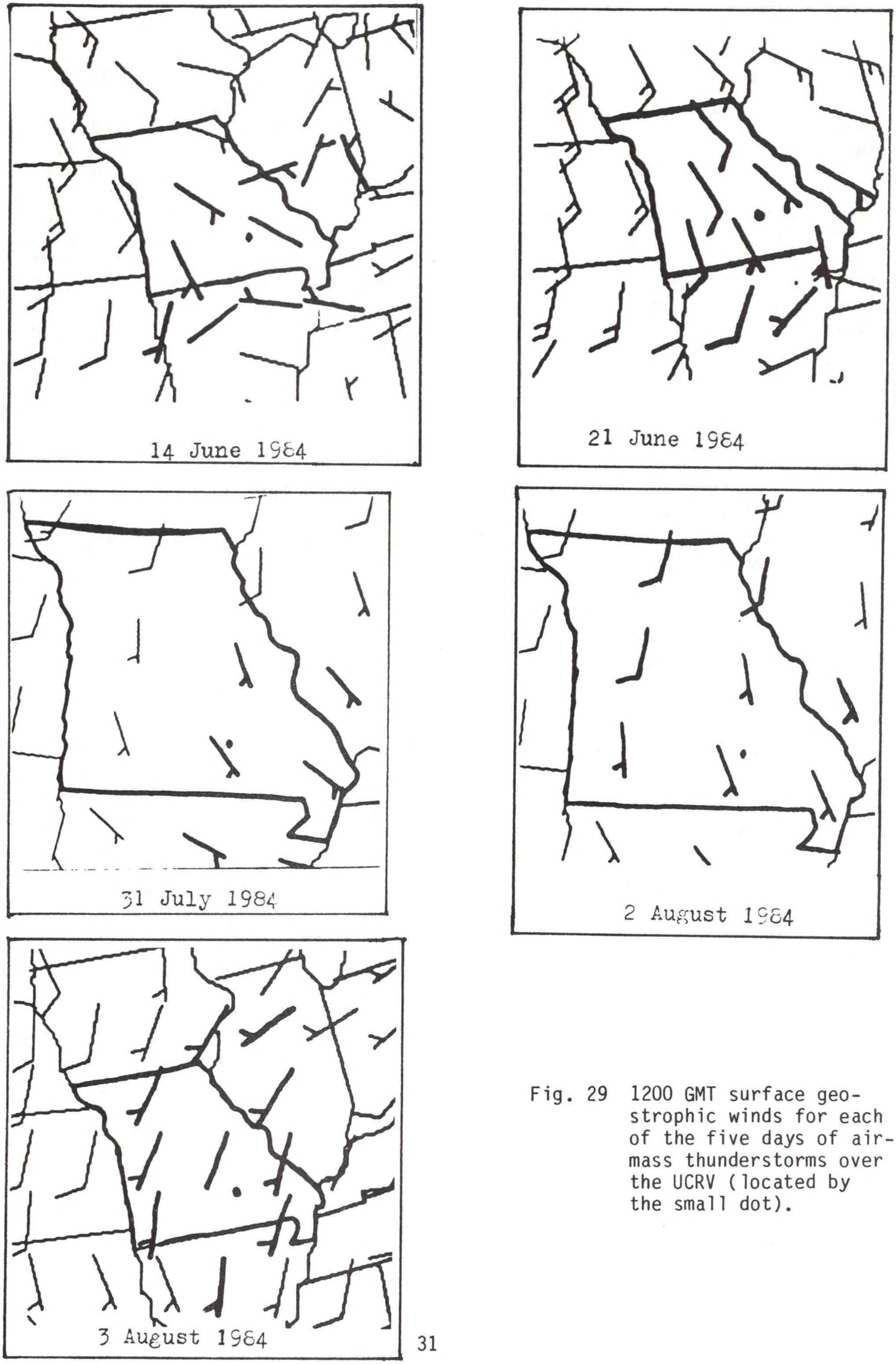


Fig. 29 1200 GMT surface geostrophic winds for each of the five days of air-mass thunderstorms over the UCRV (located by the small dot).

Another important part of the summer 1984 study was to document first echo distributions and times of occurrences over the UCRV and surrounding area. The unrestricted first echoes are shown in Fig. 30. The sample consists of 36 echoes collected on 12 days. In order to isolate those echoes resulting from local effects, the sample was reduced to only those days with mostly clear skies in the morning and no fronts nearby. The resulting sample of 18 echoes on 7 days is shown in Fig. 31. The maximum occurrences are over the southwest slopes of the UCRV, especially in the northwest corner of the Valley, where theory predicts that they should be. This sample was further reduced to those days in which a single first echo was logged since first echoes on days 6 and 10 were probably not logged soon enough. The resulting distribution is shown in Fig. 32.

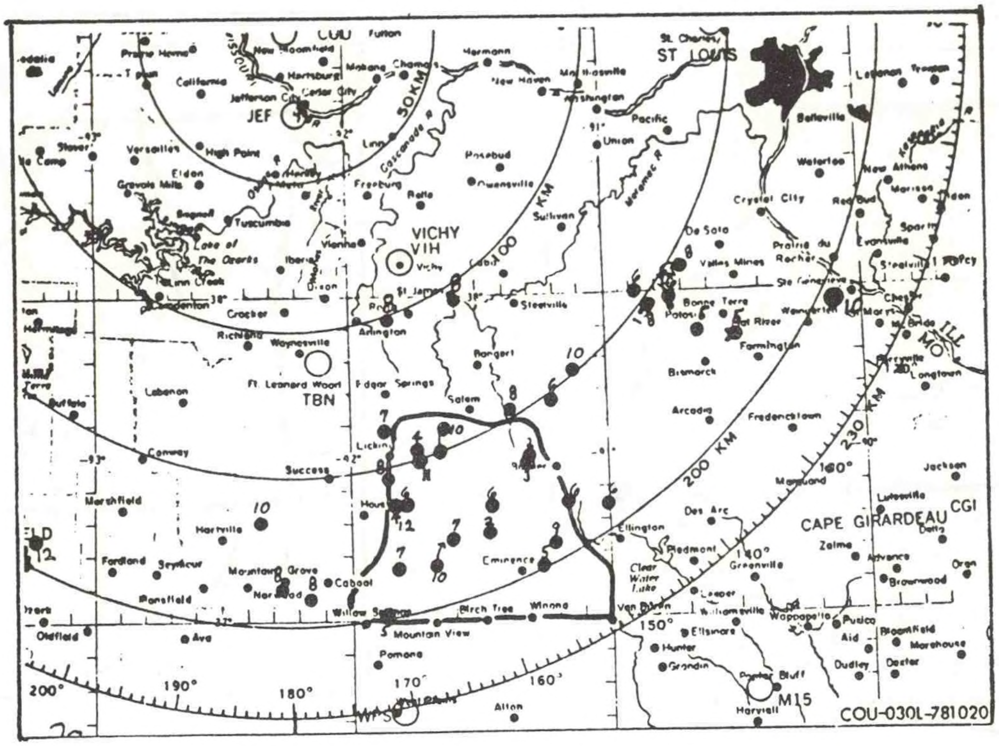


Fig. 30 Unrestricted first echoes of summer 1984. Black dots mark echo centroids, and are numbered from one to twelve so echoes can be identified with a particular day.

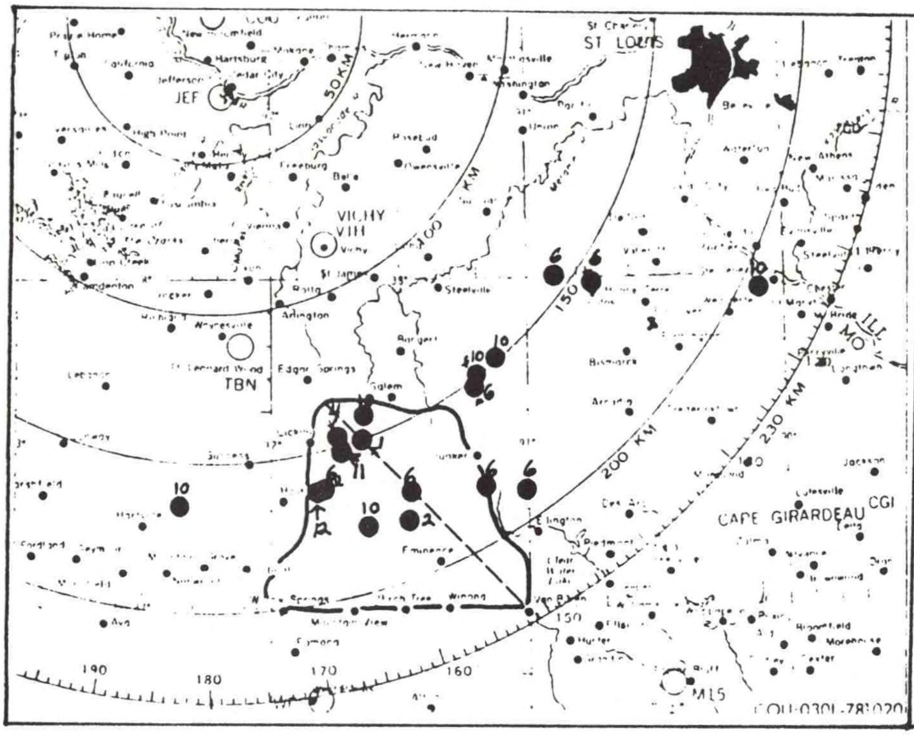


Fig. 31 Clear sky, non-frontal first echoes. Dashed line marks the approximate center of the UCRV.

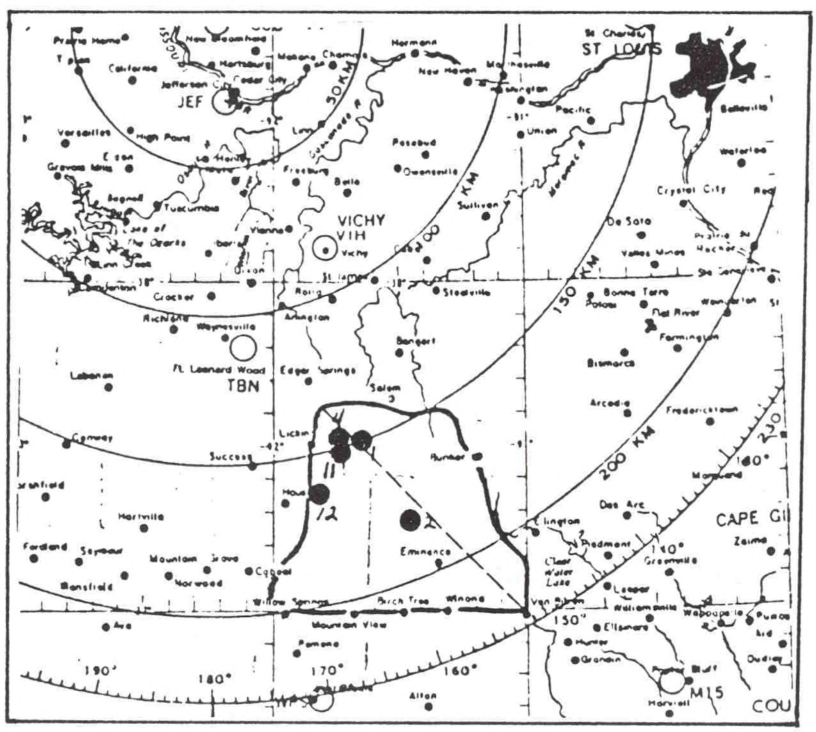


Fig. 32 Single first echoes during summer 1984.

The average time of first echo occurrence, on four of the five days of thunderstorm development with mostly clear morning skies, was 1602 GMT and the times ranged from 1530 GMT to 1655 GMT. The average time of first echo occurrence on the remaining three clear sky shower days was 1838 GMT with a range of 1814 GMT to 1858 GMT. The time and location of echo formation agrees well with the model which predicts maximum heating on the southwest slopes of the UCRV in the late morning hours (1600-1700 GMT) or slope wind aided shower/thunderstorm development a few hours later.

The summer 1984 study confirmed that the influence of the UCRV is most pronounced under light southeast synoptic scale flow. It is now believed that the UCRV can ideally produce thunderstorms in an initially motionless lower troposphere. Since this condition is seldom approximated in the real atmosphere we should expect the influence of the UCRV to be most noticeable when the large scale flow perturbs it the least. Therefore, the light southeast flow ($\leq$ 5 kts) does not augment upslope flow as much as originally thought. Rather, this weak flow, parallel to the Valley centerline and completely filling the Valley, disturbs the local air currents the least (Fig. 33). The UCRV centerline is roughly parallel to a 315° radial drawn from A in Fig. 10, so it is understandable that the most spectacular Valley thunderstorms occur when the surface geostrophic wind is either nearly calm or between 120° and 150° inclusive.

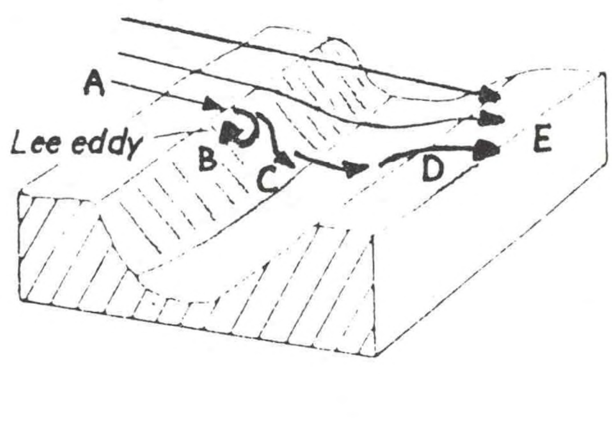
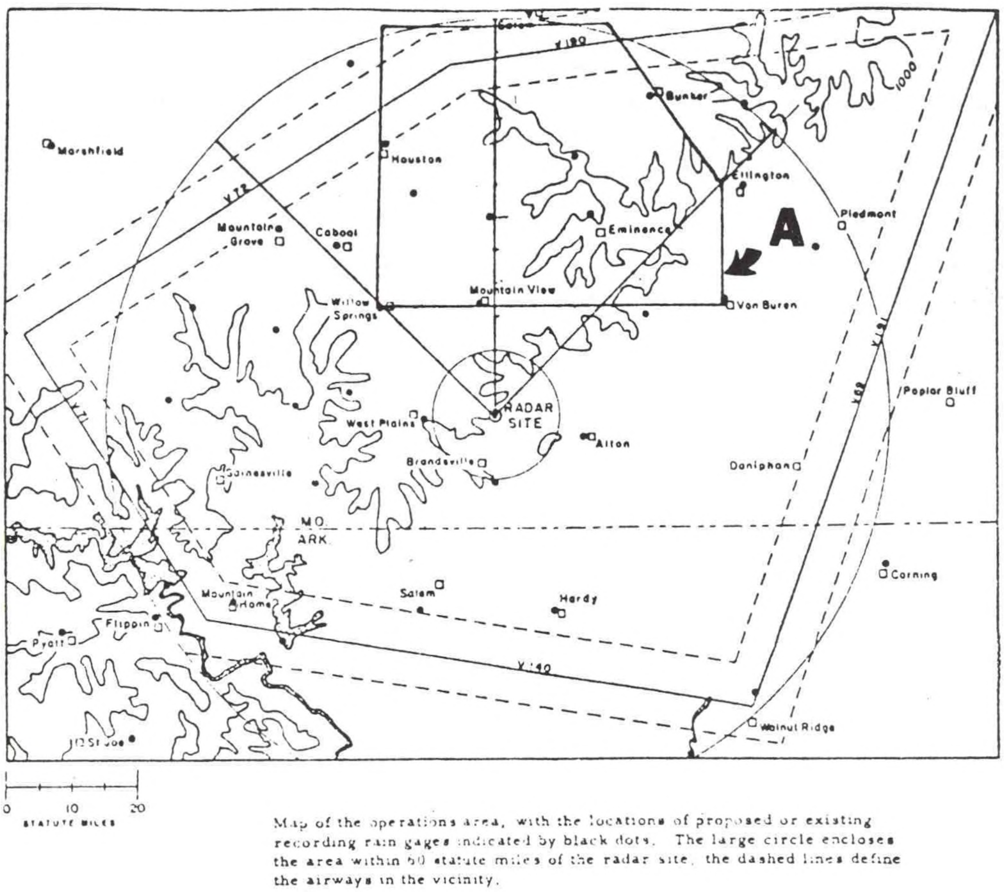


Fig. 33 Modification of airflow due to a valley (Oke, 1978). Any regional wind not parallel to the valley centerline will cause a lee eddy circulation at "B", decreased winds at "C", and increased winds at "D". The modification reaches a maximum for winds normal to the valley centerline (shown above). The locally generated winds are least disturbed by regional winds parallel to the valley centerline.

5. Analysis of first echo distributions over the UCRV from "Project Whitetop" data

During the summer of 1960, the University of Chicago's Department of Meteorology studied the physics of precipitation in summer convective clouds of southeast Missouri and how they were affected by cloud seeding (Braham, 1960, 1962). An AN/TPS-10 3 cm ground radar was used during the study to obtain a 100% time-space coverage of precipitating clouds in the research area. The radar was located east of West Plains, Missouri, and its 60-mile range included all of the UCRV. A map of the research area with the UCRV outlined is shown in Fig. 34.



Map of the operations area, with the locations of proposed or existing recording rain gages indicated by black dots. The large circle encloses the area within 60 statute miles of the radar site, the dashed lines define the airways in the vicinity.

Fig. 34 Map of Project Whitetop operations area. The UCRV is outlined at "A". The Current River is clearly marked by the 1000 ft (305 m) contour (Braham, 1960).

Part of the study was the documentation of the geographic distributions of first echoes on all operational days:

"In this study, days providing fewer than six First Echoes were deleted, leaving a sample of two thousand six hundred eighty-four First Echoes on twenty-one days.

The procedure used was to divide the sixty-mile radius circle into eighty cells by means of forty-five degree radials and five-mile wide annular rings. The number of echoes expected in each of the eighty cells, under the assumption of a uniform distribution, is dependent only upon the size of the cell and the total number of echoes. The 2,684 echo sample permits a minimum of more than five expected echoes in the smallest cell, a number sufficient to insure the reliability of the chi-square test." (Braham, 1960)

Fig. 35 shows the first echo data for each annular ring as a ratio of echoes observed to echoes expected under the uniform distribution assumption. The data were analyzed further to remove synoptic influences and to isolate the geographic influence by using statistical procedures. For this the 60-mile circle was divided into 16 cells bounded by two large annular rings and 45° radials. The large numbers in Fig. 35 represent to what degree each of the 16 cells had an excess or deficit of first echoes considering geographic influence. In the outer ring, values less than 0.34 indicate a cell with a deficit of echoes, and values below 0.46 in the inner ring are indicative of a cell with a deficit of echoes.

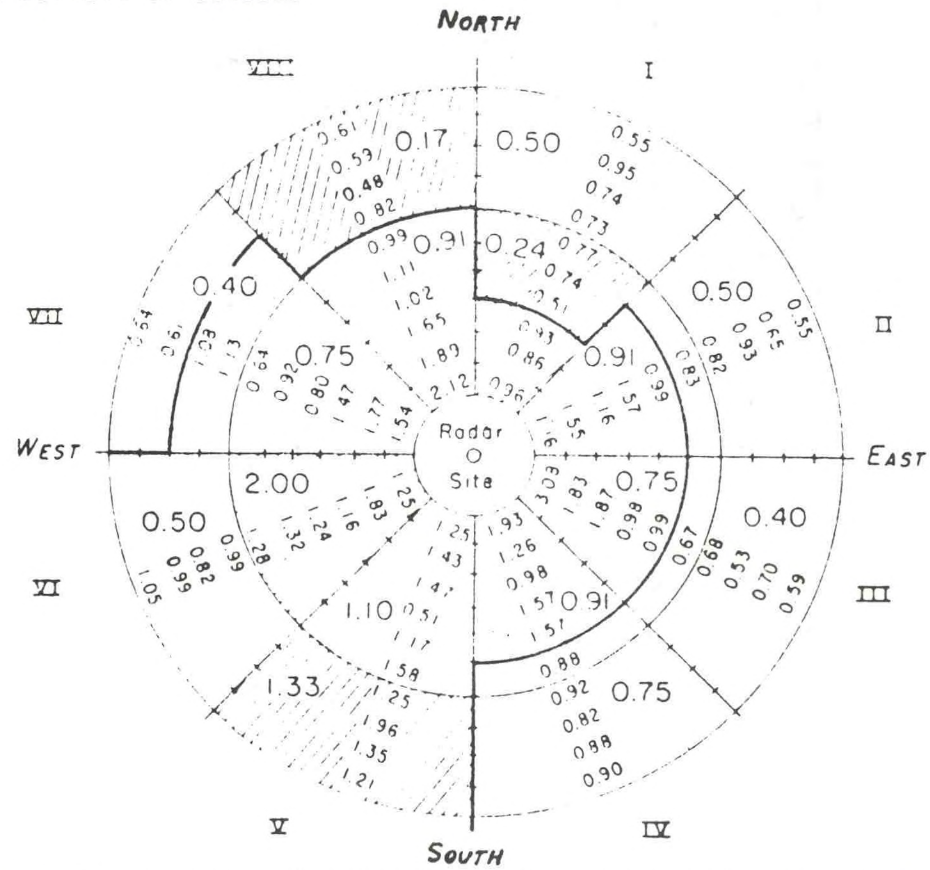


Fig. 35 Raw first echo ratios for five-mile wide annular rings and P-bar values for the 16 cells tested for geographic influences.

Before proceeding further in relating the radar data to the UCRV, it is important to present the conditions under which the radar data was collected. Radar data was collected only on operational days which were picked objectively by the following parameters: precipitable water at Little Rock, Arkansas, and Columbia, Missouri, must equal or exceed 1.30" and 1.05" respectively, based on 0600 CST soundings; and the wind direction at 4,000 feet above MSL over West Plains, Missouri, must be between 170° and 340° inclusive on the morning of the day in question. No wind speed criterion was mentioned in the study.

Unfortunately, the study wind direction criteria excludes the bulk of the wind directions (and probably wind speeds) found to be favorable for airmass thunderstorm formation over the UCRV. South through west winds are increasingly normal to the UCRV centerline and the northwest winds would blow down-valley. In all cases, local winds over the UCRV would be disrupted. Of course, calm winds or nearly calm winds from the above directions could allow local winds to develop, but in general, we can assume that winds from the directions specified in Project Whitetop would be stronger than southeast winds in the summer. Southeast surface flow over southeast Missouri is generally the result of an anticyclone east of the Mississippi River while southwest winds are generally the result of a trough over the central Plains and its associated stronger pressure gradient.

With the above thoughts in mind, an analysis of the radar data with respect to the UCRV can be attempted. Fig. 36 shows the analyzed raw echo ratios over the valley. Rings with a ratio of $\geq .90$ are shaded. A minimum of first echoes is clearly evident right over the UCRV with the greatest deficit (.50) over the northwest corner of the Valley. This is the same area where a maximum of first echoes was observed under very light or light southeasterly low level flow. The relative maximum of first echoes along the northeast UCRV ridgeline running from just south of Salem to Bunker to Ellington (A in Fig. 36) is interesting because the tight first echo gradient on either side of this high ground and the ridgeline is largely normal to the wind directions specified in Project Whitetop.

Fig. 37 shows the two cells with the greatest deficit of first echoes when adjusted for geographic influence. The values of these two cells are 50 percent lower than the next lower cell values. These cells are located over the northwest corner and southwest slopes of the UCRV. Clearly, there is a non-random distribution of first echoes, a conclusion the original investigators also reached. They attributed the excess of first echoes over the terrain which is roughly normal to southwesterly winds, to surface roughness and to a lesser extent, orographic influence and the effect of two large lakes in the western part of the study area. This tends to confirm that they were dealing with higher winds speeds than normally observed when the UCRV is producing thunderstorms or showers.

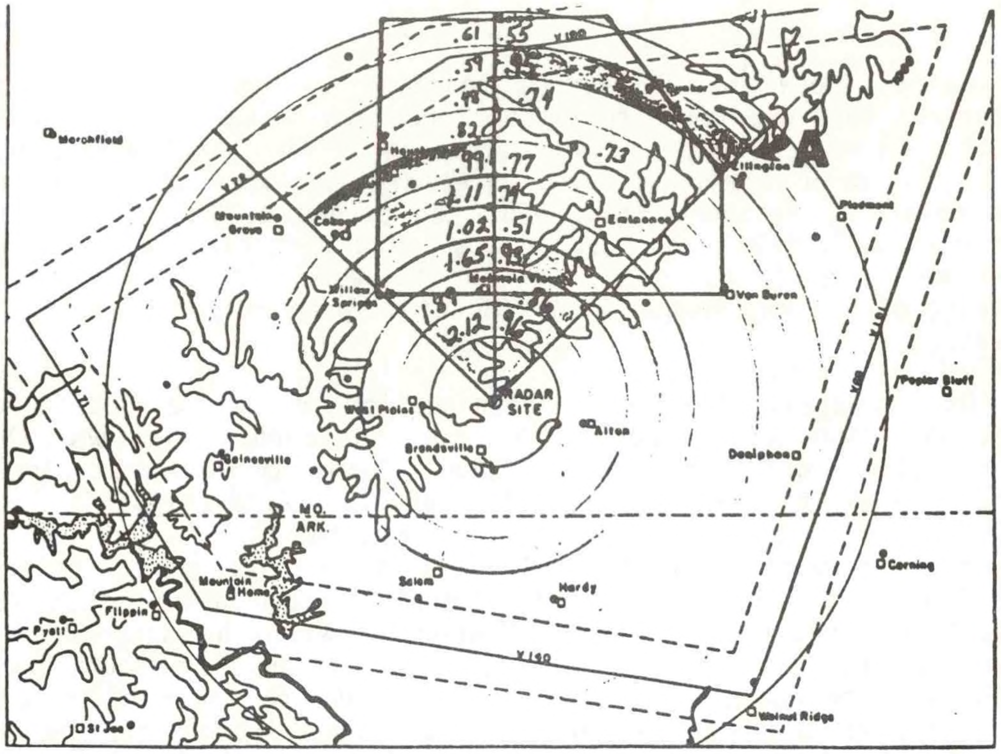


Fig. 36 Analyzed first echo ratios showing a minimum over the UCRV. Ratios greater than 0.90 are shaded.

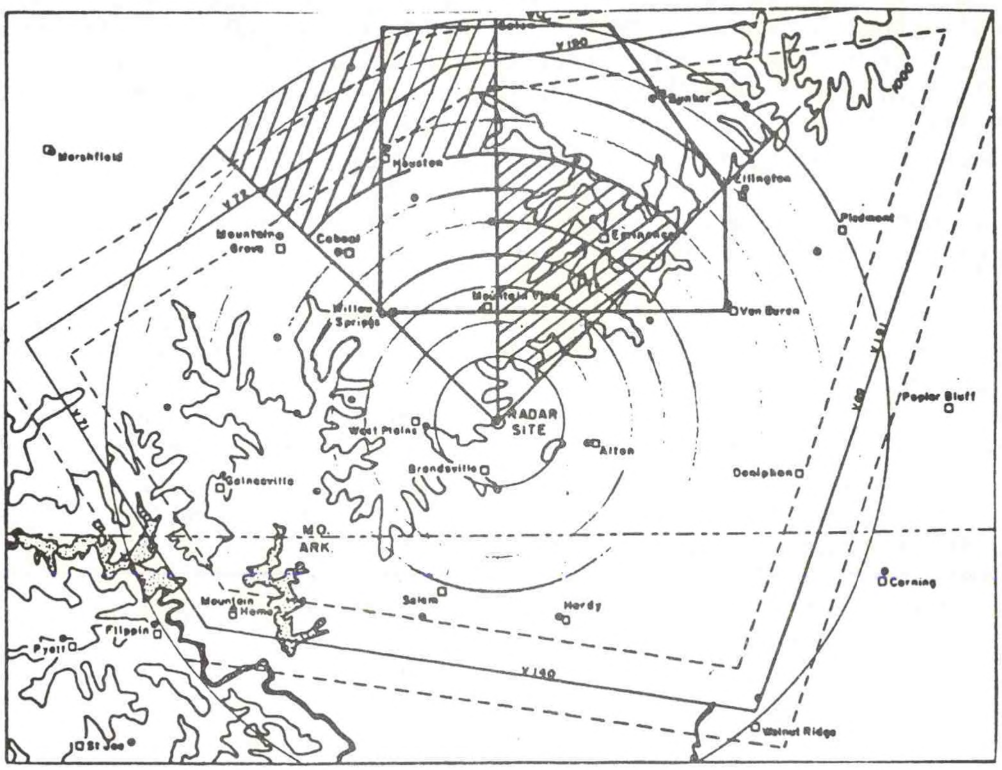


Fig. 37 The two geographic influence cells with extreme first echo deficits (hatched cells).

The fact that the UCRV stands out so strikingly in the analysis when the wind direction is restricted to south through northwest is certainly implicit evidence of its influence under very light or light southeast flow. It may be that if the resolution of the data was greater, the minimum of echoes over the UCRV would be even better defined. For example, some of the annular rings over the southwest slopes of the Valley extend westward for some distance onto southwest facing slopes and it is not known how many echoes were in the east or west portion of the ring. In any case, had the data not shown an obvious pattern of echo distributions over and around the UCRV, doubt would be cast on the Valley's influence. However, nothing in the Project Whitetop data serves to disprove the local effect of the UCRV.

6. Concluding remarks

The summer 1984 study confirmed that the UCRV is a preferred area for thunderstorm development and that mesoscale circulations are indeed generated by the Valley. We can now think of the UCRV system as playing two roles: 1) a theoretical or "pure" role where the physical processes and energy exchanges of the system generally go on below the resolution of our commonly available observational tools; and 2) an operational role where under the right conditions, some of nature's most violent phenomena are produced over the Valley. It is this second role that catches our attention, and rightly so, because over one million people visit the UCRV each summer (Kohler, 1984). On a typical summer weekend, a population equal to a medium-sized Missouri city inhabits the area and most of them are involved in outdoor activities. But we should not forget that, until summer 1983, it was not generally believed (or at least not demonstrated) that a valley like the Current could have such a distinctive influence on the weather. It is one thing to say there is a 20% chance of afternoon thunderstorms over a 50,000 square-mile area and quite another to predict when thunderstorms will form over a specific geographic entity.

It is hoped that the investigation of the Upper Current River Valley's effect will introduce or reinforce a belief in meteorologists that in the seemingly homogeneous atmosphere of summer, consideration of the energy balance of the surface and the boundary layer processes are of the utmost importance in accurately predicting the weather. My method could be both instructive and inspiring to those who have a belief in local effects but have failed to follow up on their intuitions. How many times has a particular radar or satellite presentation momentarily piqued our interest or clicked in our memory of past experiences only to be filed or perhaps thrown away and forgotten? R. S. Scorer puts it clearly: "Our task is to select from the complexity of Nature problems which we can solve. Generally the procedure is not to pose problems, but to construct an ever-growing edifice of theory and knowledge which we call science, and as it grows we find that phenomena we have observed begin to fall into place."

A questioning attitude is necessary if anything significant is to be discovered and this will become even more important in the future as the sophistication of our observing tools (notably Doppler radar) increases. In the distant future numerical models with sensitive inputs from the surface and boundary layer will routinely solve problems which are now too often ascribed to wild and random acts of nature.

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