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SURFACE ENERGY FLUXES IN COMPLEX TERRAIN

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A. INTRODUCTION

The emphasis of our 1985 NASA project activity was on field measurements. Initiatives included a 19 station mountaintop monitoring program, testing and refining the surface flux monitoring systems and packing and shipping equipment to the People's Republic of China in preparation for the 1986 Tibet Experiment. Other work included more extensive analyses of the 1984 Gobi Desert and Rocky Mountain observations plus some preliminary analyses of the 1985 mountaintop network data. Details of our field efforts are summarized in Section B and results of our data analyses are in Section C. For convenience and to avoid lengthy and redundant descriptions of our monitoring systems and prior work, we refer you to our First Annual Progress Report (Reiter, et al., 1985)

B. FIELD WORK

1. Rocky Mountain Peaks Experiment (ROMPEX)

In April 1985 we were informed by Chinese officials that logistical problems would require a one-year postponement of our planned 1985 monitoring program on the Tibetan Plateau. We immediately began work on an alternative study of the Rocky Mountains, which was designed to examine both the plateau heat balance over a broad area and an apparent low-level jet phenomenon observed at mountaintop in our 1984 observations at Mt. Werner (Reiter et al., 1985).

Wind data collected at Mt. Werner in August 1984 revealed a distinct diurnal cycle with very strong and persistent nocturnal winds. These winds tended to flow away from the core of the dominant highland area, (Continental Divide) which was approximately 100 km to the southeast of our station. We noted that these winds were most pronounced when: (a) broad high-pressure systems in the mid-troposphere encompassed the western plateau region and;

(b) an active monsoon was present with strong and widespread afternoon thunderstorms over the highland areas.

The persistent nighttime winds at Mt. Werner often exceeded 20 m/s when higher level winds inferred from nearby soundings were comparatively weak. It was concluded that a strong regional scale circulation was being generated by the diurnal heating cycle over the plateau. Hence, we decided to use the time and equipment available to us because of the Tibet program postponement to obtain more information on these winds while, at the same time, doing a broad-scale surface heat balance study.

After extensive negotiations with several agencies, including the U.S. Forest Service, the Bureau of Land Management and the National Parks Service, and then subsequently with the operators of various ski resorts, we obtained access to 19 mountaintop sites. These sites, as shown in Fig. 1, were scattered over the central Rockies from southern Wyoming to north-central New Mexico. The approximate dimensions of the overall data network were 600 (N-S) by 300 (E-W) km and 200 by 100 km for the inner, heat balance network. Our preference for ski resorts in these studies was based on ease of access to mountaintop locations which were, at the same time, comparatively secure from vandalism.

Because of a shortage of time and staff for planning and preparing for the field program, we were unable to inspect most of the sites prior to actual deployment of the instruments. Consequently several of the monitoring sites were less than ideal. The most notable case was site C5 (Crested Butte) where a dense stand of 15 meter spruce trees covered the true peak of the mountain. We were obliged to place this radiation flux monitoring station in a relatively small, 50 by 50 meter clearing, which was 30 meters below and 200 meters west of the true peak. The problem was subsequently overcome by placing a 20 meter

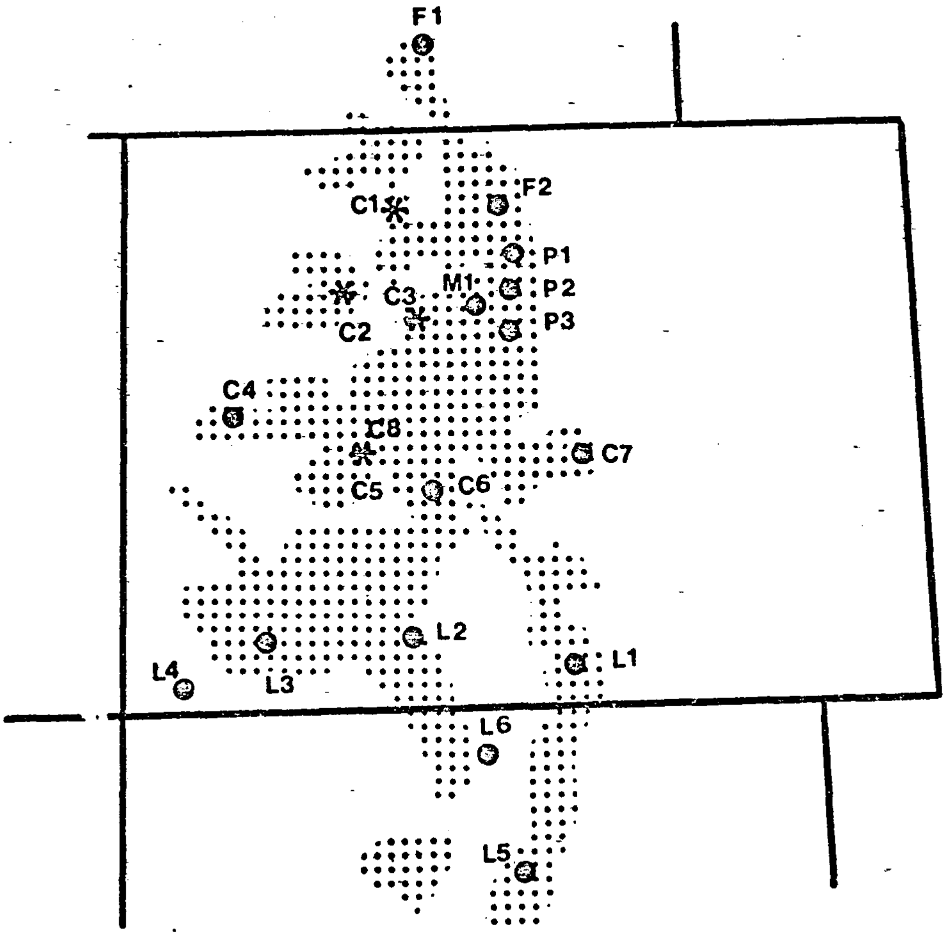


Fig. 1. Locations of the ROMPEX-85 monitoring stations. The stations are keyed to descriptive data in Table 1. Shading indicates elevations greater than 2700 meters (9000 feet). The four locations indicated by stars were sites for surface energy balance measurements.

tower on the true peak. This tower was instrumented at three levels (5, 10 and 20 meters) for UVW winds and at four levels (0.1, 5, 10, 20 meters) for temperature and humidity. Site C4 was also relatively far removed from the true peak. However, a catastrophic failure occurred at this site when stray cattle toppled the 5 meter tower and destroyed the instruments. Although all other sites enjoyed good exposure, some data loss occurred due to wind damage to the UVW anemometers (stations C6 and C7) and due to occasional failure of the CSU satellite ground station for satellite telemetered sites (F1, F2 and M1).

Specific information concerning the location, elevation and measurements made at each monitoring station are given in Table 1. As noted, stations P1, P2, P3 and M1 were already in place as part of other ongoing studies. Stations L1 through L6 were installed and operated by personnel from Los Alamos National Laboratory under the direction of Dr. William Clements. This collaborative aspect of the study was motivated by Dr. Clements' involvement in the ASCOT program which is assessing the potential for transport and diffusion of pollutants in the complex terrain of the Rocky Mountain Plateau region.

Deployment of instrumentation began on June 24, 1985 and the last of the instruments were removed on October 3, 1985. The principal network observation period wherein all stations were in place was from July 24 through September 9, a total of 47 days. Data from the network of heat flux monitoring stations were obtained from July 10 through September 11, a total of 62 days.

In addition to the surface observations, two intensive pibal sounding experiments were conducted to examine the variation with height of the wind speed and direction over the mountain peaks. The first of these efforts was coordinated with personnel at Los Alamos. During the afternoon and evening (1500 to 2400 mst) of August 12, 13 and 14 piball soundings were made hourly

TABLE 1. Station Data.

Station[1]	Name	Elevation (Meters, msl)	Parameters[2] Observed
C1	Mt. Werner	3250	A
C2	Flat Tops	3441	A
C3	Vail	3350	A
C4	Powder Horn	2987	B
C5	Crested Butte	3352	A
C6	Monarch Pass	3597	B
C7	Pikes Peak	4297	B
C8	Crested Butte Tower	3382	D
F1	Elk Mountain	3383	B
F2	Rocky Mountain National Park	3660	B
L1	Cuchara	3290	C
L2	Wolf Creek Pass	3590	C
L3	Mesa Verde	2610	C
L4	Purgatory	3200	C
L5	Santa Fe Mt.	3660	C
L6	Mt. San Antonio	3320	C
M1	Mines Peak	3650	B
P1	Ward	3048	B
P2	Rollinsville	2749	B
P3	Squaw Mt.	3505	B

(1) Station Designations
- C: Operated by E.R. Reiter and Staff, CSU
- F: U.S. Forest Service equipment made available by D. Fox, Ft. Collins, CO
- L: Operated by W. Clements and Staff, Los Alamos National Laboratory, NM
- M: Operated by T. VonderHaar, CSU
- P: Operated by NOAA, Environmental Research Laboratory, Boulder, CO

(2) Index of parameters
- A: Radiation station, WS, WD., Radiation, Air and soil temp. and humidity (see Reiter et al., 1985)
- B: WS, WD, Humidity and Temperature
- C: WS, WD, Temperature
- D: Flux tower: UVW at three levels; Temperature and humidity at four levels. (see Reiter et al., 1985)

at both Los Alamos and on top of Mt. Werner, A similar experiment was conducted on August 28 and 29 at Mt. Werner only.

We are obtaining a large amount of additional data for the analysis portion of our work. These data include digital tapes of routine NWS surface observations and soundings, weather and radar analyses, lightning strike data, and observation from remote station networks operated by the Forest Service and the Bureau of Land Management. Personnel at the NOAA Environmental Research Laboratory in Boulder, CO have agreed to loan us high quality satellite imagery for the period. Also, we are preparing final data tapes of our 1984 and 1985 radiation observations for transmittal to NASA, Langley. We are establishing a working relationship with that laboratory (Dr. Tom Charlock) through which we will be able to obtain AHVRR data for use in our studies.

2. Tests and Modification of Flux Monitoring Systems

Certain deficiencies in the tower portion of our flux monitoring systems were described in our first annual report (Reiter et al., 1985). Specifically the turbulent fluxes of sensible and latent heat estimated by eddy correlation statistics were often an order of magnitude smaller than anticipated values for various conditions. A series of field tests were conducted between March and June 1985 to systematically examine a number of instrument configurations that were suspected of contributing to the problem.

These tests quickly demonstrated that the primary source of error was strong damping and thermal inertia of the thermistor/hygristor shelters. This problem was corrected by developing a remarkably durable "hat" of fiberglass and styrofoam. This hat permitted good, unbiased exposure of the sensors and was small enough to allow us to locate them adjacent to the UVW anemometers with effectively no mechanical interference. However, even with this modification the observed turbulent fluxes were still as much as 50 percent low under strong wind conditions.

Next we examined the effect of increasing the tower height and the height above ground of the sensors and, thereby, decreasing the proportion of turbulent energy in the high frequency portion of the spectrum beyond the measurement capabilities of the system. In this regard we were fortunate to acquire two 20 meter towers from the Los Alamos National Laboratory. With this change we now obtained turbulent fluxes which were approximately 80 percent of what is required for closure of the energy budget for most conditions.

Prior to our Tibet-86 program we plan to conduct several additional tests of the turbulent flux system. These will include adjustments to the wind data for response variations with the angle of attack (cosine corrections) and stability dependent estimates of the high frequency turbulent component beyond the range of the UVW anemometers. We hope to employ borrowed sonic anemometers and fast response thermistors for this work to perform an effective calibration test of the entire system.

In addition to the surface flux stations and radiosonde systems, we have acquired a multiwaveband solar photometer for use in our Tibet-86 program. We hope to supplement our soundings and other data by making extensive measurements of atmospheric extinction due to particulates, water vapor and ozone for premonsoon, monsoon and break monsoon conditions. These measurements should be quite useful in the interpretation of our surface-based measurements of solar fluxes and atmospheric emittance. Moreover, because few high elevation measurements have ever been made with this sort of instrument, the data will provide basic information on pressure effects in atmospheric water vapor determinations. Because of the potential importance of these data and also because of a few minor mechanical flaws, this instrument was returned to the manufacturer in November 1985 for repairs and careful calibration against local (Tucson, AZ) radiosonde data. This calibration will be completed in March 1986, at which time we will also obtain thorough instruction in its proper use.

C. DATA ANALYSIS

In this section we briefly summarize ongoing work with our 1984 data sets and preliminary analyses of our 1985 ROMPEX data. While the emphasis of this work is on the analysis of components of surface energy budgets in remote and complex terrain, we are also looking at periodic oscillations in the heat balance and the role of moist processes in forcing an apparent low-level jet phenomenon over the Rocky Mountains.

1. The Energy Balance of a Shallow Mountain Snowpack

Our first annual report (Reiter et al., 1985) contains a detailed description of an energy balance monitoring program in a mountain valley area called Pingree Park. Briefly, this site was in a clear-cut area near the edge of a largely forested mountain valley at 2800 meters a.m.s.l. The experiment, which ran for 130 days, experienced heavy snow cover at the site during the first 60 days (March 14 till May 9).

The data from the radiation station (see Reiter et al., 1985) have been carefully analyzed for three portions of the spring period (Table 2) when fairly heavy and uniform snow cover was observed below the flux monitors. Detailed results of this study, summarized below, will be the subject of a forthcoming journal article (Sheaffer and Reiter, 1986). The results include: 1) Analyses of short-term variations of the heat balance and integrated effects of melting and evaporation of the snowpack; 2) Observations of strong infrared divergence from a very shallow layer of moist air just above the melting snow surface; and 3) Analyses of the appropriate

TABLE 2. Summary of mean values for key energy flux parameters, Pingree Park snow pack, Spring 1984.

	Study Periods		
	March 23-28	April 4-15	April 23-May 6
Parameter[1]			
Q* (w/m^2)	8.6	-16.6	-23.3
K* "	-37.6	-77.6	-67.0
L* "	44.6	58.5	42.8
V* "	-8.2	-19.5	-17.0
N* "	-29.4	-57.9	-53.3
H_S "	-7.3	-10.0	-14.7
H_L "	9.8	20.1	22.9
Evap. (total, cm)	0.2	0.8	0.7
Thaw "	-1.5 (net freeze)	0.5	3.5
Air T. (°C)	-4.5	-0.5	-1.4
Rel. Hum (%)	63.9	46.3	62.6
WS (m/s)	2.7	3.6	3.9
Ri[2]	.05	.10	.08

(1) See Table 3 ana text for explanation of symbols.

(2) Bulk Richardson number; positive value indicates stable conditions, negative for unstable.

roughness factors for scaling mechanical turbulence in the lower boundary layer in mountainous terrain. The study also includes observations of the radiative components, winds, air temperature and humidity, and soil heat and moisture.

Components of the surface heat balance at the site are given in equation 1.

$$H_g + H_{sn} + H_T = Q^* + H_L - H_s \tag{1}$$

$Q^* = H_g + H_{sn} + H_T - H_L + H_s$

where

H_g = soil heat flux

H_{sn} = snow heat flux

H_T = heat flux for thawing or freezing snow

Q^* = net radiation

H_L = latent heat

H_s = sensible heat

During this experiment the soil temperatures (down to 40 cm.) never varied from 0^oC, indicating little or no heat flux to or from the soil beneath the snow (hence $H_g = 0$). Also, H_{sn} was determined to be comparatively small in most cases and was effectively zero for most 24 hour periods. Therefore, in the present results we treat H_{sn} as part of H_T, or $H_T = H_T + H_{sn}$. Sensible and latent heat were computed using the bulk formulations:

$$H_L = \rho L\, C_d\, (q_s - q_a) \tag{2}$$

$$H_s = \rho\, C_p\, C_d\, U_a\, (T_s - T_a)\, \phi_i \tag{3}$$

where ρ = air density

L = latent heat of vaporization

U_a = wind speed

C_d = drag coefficient

C_p = specific heat of air at constant pressure

T_a = air temperature

T_g = snow surface temperature

ϕ_i = stability dependent scaling term

q_s = saturation mixing ratio of snow surface

q_a = mixing ratio of air

The values for C_d are scaled for variations in stability, using terms suggested by Oke (1978),

$$\phi_s = (1 - 5\ Ri)^2$$

$$\phi_u = (1 - 16\ Ri)^{3/4}$$

where s and u designate stable and unstable conditions respectively, and Ri is a local Richardson number obtained by assuming that the wind speed is zero at the surface.

The mixing ratio at the snow surface was diagnosed from the Effective Black Body Temperature (EBBT) of the surface. The procedure involves first applying the Stefan-Boltzmann law to the upward infrared emittance and then applying empirical formulae by Lowe and Fricke (1974). Allowing that snow is not a perfect emitter, the EBBT at which the snow surface was assumed to take on the characteristics of liquid water was lowered to 271.8°K, corresponding to an actual emissivity of 0.98.

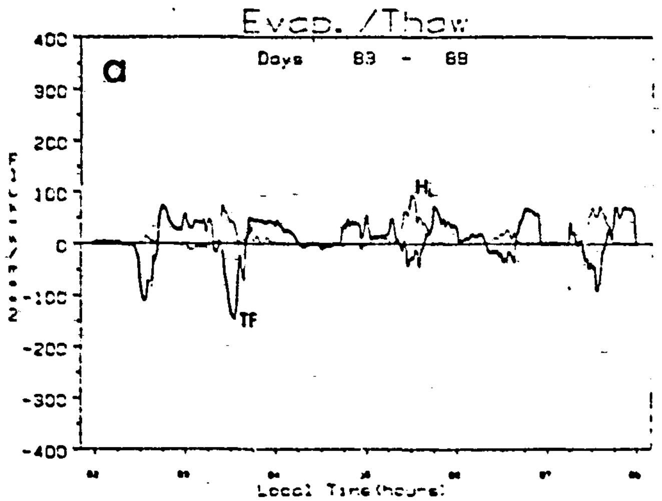
It should be noted that the snow surface EBBT often exceeded the presumed maximum value of 273.15°K by as much as 3 degrees or more. It is unlikely that the thin film of liquid water on the snow surface can assume these values. Various studies have shown a sharp increase in the air temperature near melting snow surfaces, typically reaching a maximum within one meter above the snow. Halberstam and Schieldge (1981) have observed this effect and demonstrated that strong absorption of radiation in a shallow moisture-rich layer just above the surface is the probable cause of the warming.

This layer must be associated with a strong infrared divergence just above the surface which probably accounts for our anomalous surface EBBT values. In addition, the enhancement of the snow EBBT is observed to be generally diminished for increased wind speed. We hope to gather more data on this effect using collocated radiometers at several levels above the surface in a series of tests scheduled for Spring 1986.

Whereas the snow temperature was restricted to a value no greater than 273.15^{o}K for calculation of the surface mixing ratio, the vertical gradients of temperature and virtual temperature (for diagnosing the Richardson number) are based on the observed EBBT value.

Time series estimates of H_L, H_S and thaw for the three experimental periods are shown in Figs. 2, 3 and 4. Figures 5, 6 and 7 show time series for the cumulative melt/freeze and evaporation of the snow pack for these same periods. The effects of occasional systematic errors in net radiation (Q*) are entered as modifications to the net thaw (TF) in Figs. 6 and 7. These effects are due to the formation of frost on the upward looking long-wave radiometers resulting in an upward bias in the estimated net cooling. (Synoptic data and other site parameters did not indicate the presence of heavy cloud cover or snow during these periods, hence the presence of frost is assumed.) The cumulative effect of these errors is indicated by an asterisk at the end of each time series. Average diurnal values for all heat parameters for all three periods are given in Table 2.

Although significant thawing and refreezing of the snow occurred through the period, little net thaw occurred prior to May 1 (Day 122). The final, complete thaw of the snow pack occurred rapidly when a fairly moist air mass arrived and lingered over the area for several weeks. The moist air tended to increase the net atmospheric infrared emittance which, in turn,



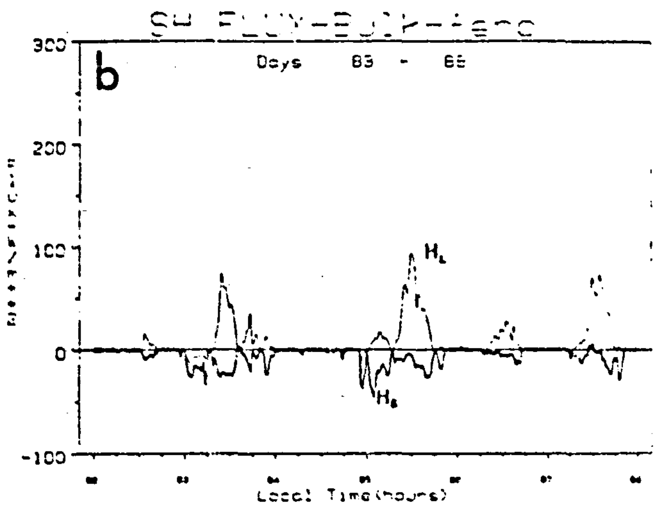


Fig. 2(a). Time series of energy consumed for evaporation/sublimation (H_L) and thaw-freeze (TF) of the snow pack at Pingree Park between March 23 and March 28, 1984. The sign convention for this and other plots is positive for fluxes directed upward from the snow and negative for fluxes into the snow; hence negative values of FT correspond to heating and melting of the snow pack.

Fig. 2(b). As in Fig. 2a, but for latent (H_L) and sensible heat fluxes (H_S).

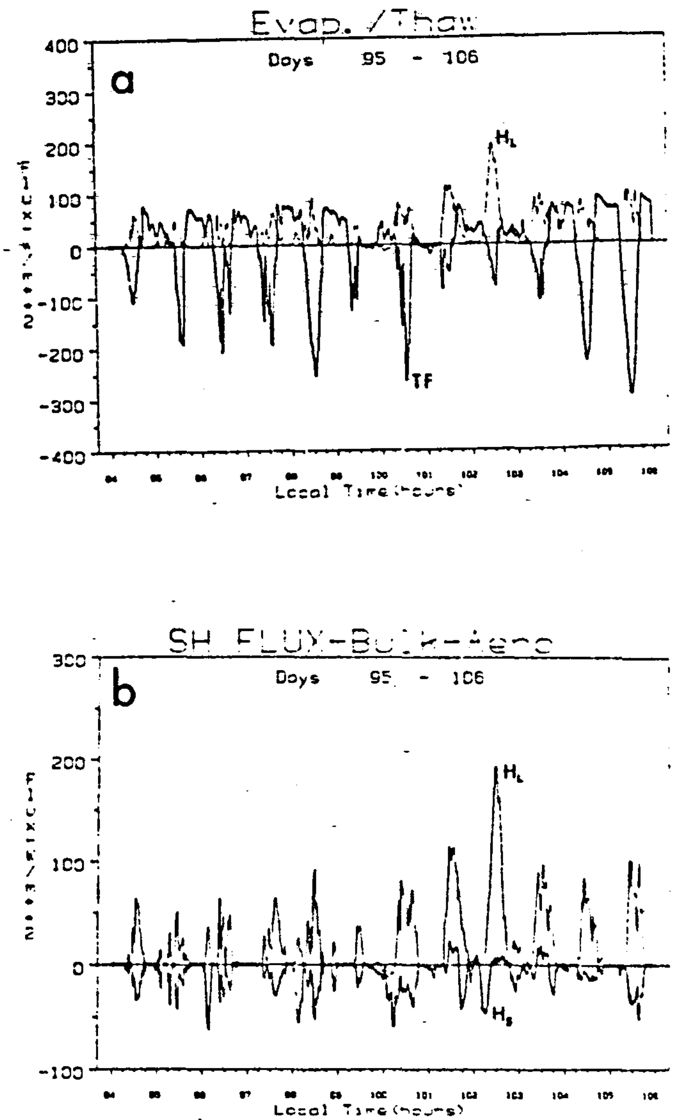
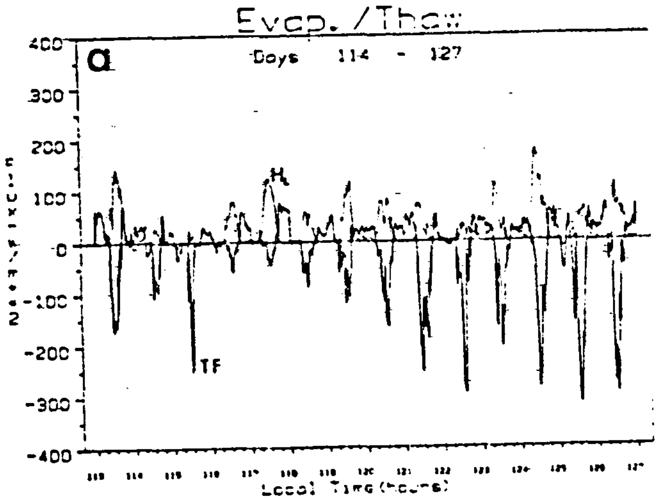


Fig. 3. As in Fig. 2 except for April 4 to April 15, 1984.



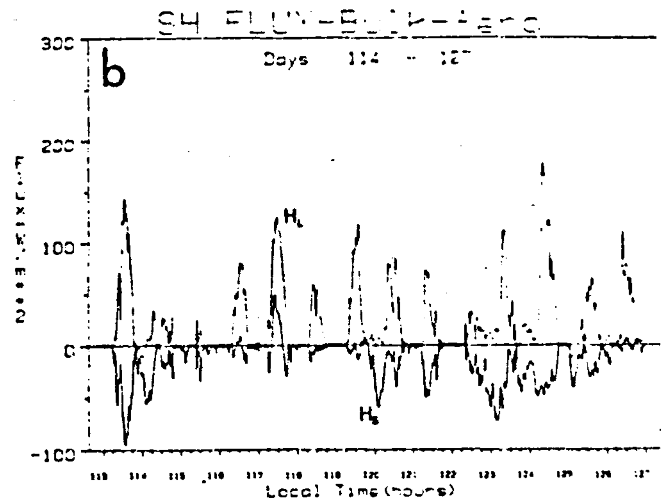


Fig. 4. As in Fig. 2 except for April 23 to May 6, 1984.

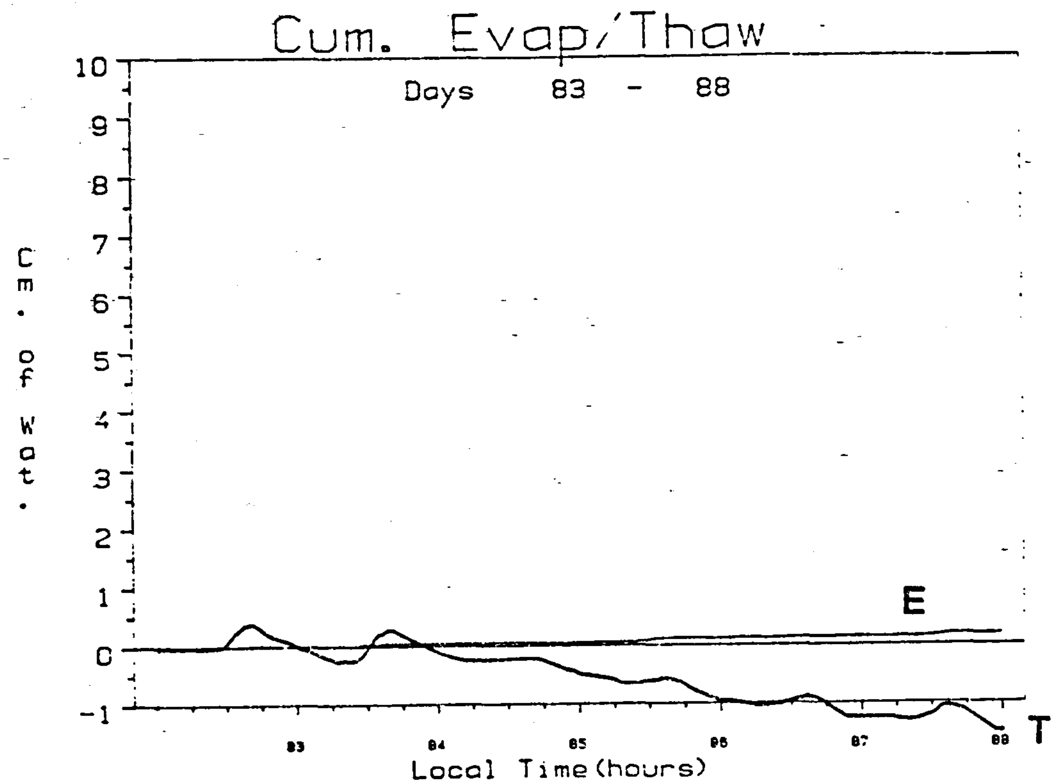


Fig. 5 Cumulative evaporation (E) and thaw (T) of the snow pack at Pingree Park between March 23 and March 28, 1984, expressed as cm. of water. A negative trend in the thaw curve in this figure corresponds to a net freezing of melt water in the snow.

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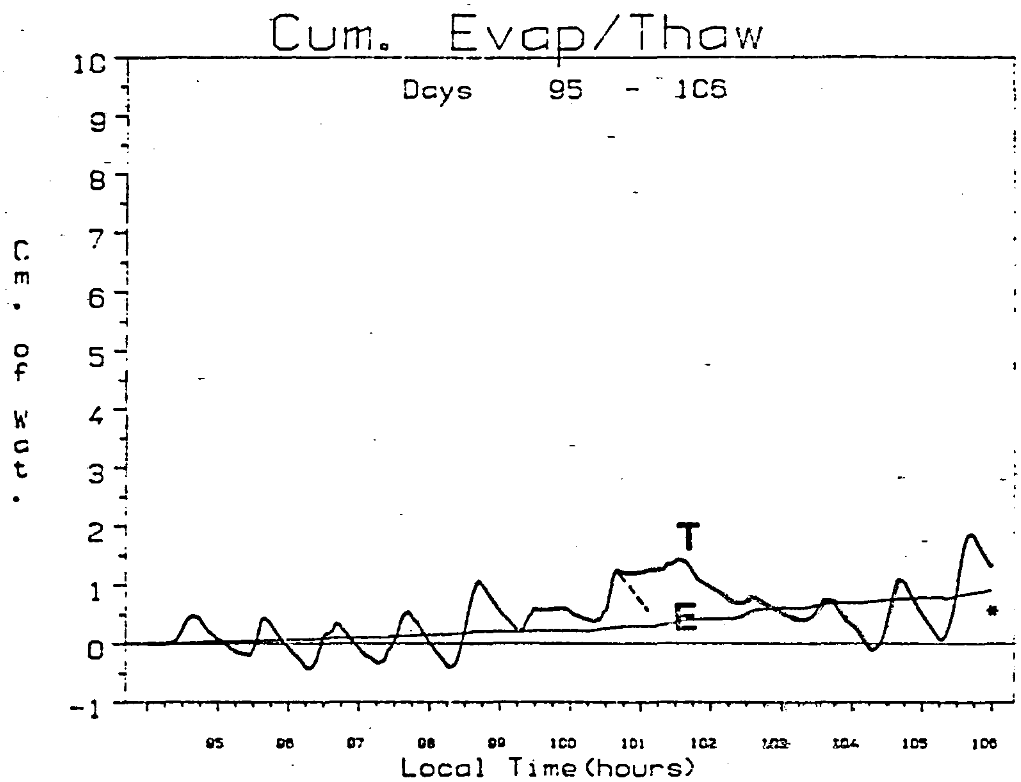

Fig. 6. As in Fig. 5 but for April 4 to April 15, 1984. The dashed corrections to the T curve represent estimated actual cooling of the snow where L↓ values were biased by frost or snow on the radiometers. The astrisk at the end of the T curve shows the estimated cumulative correction due to this problem.

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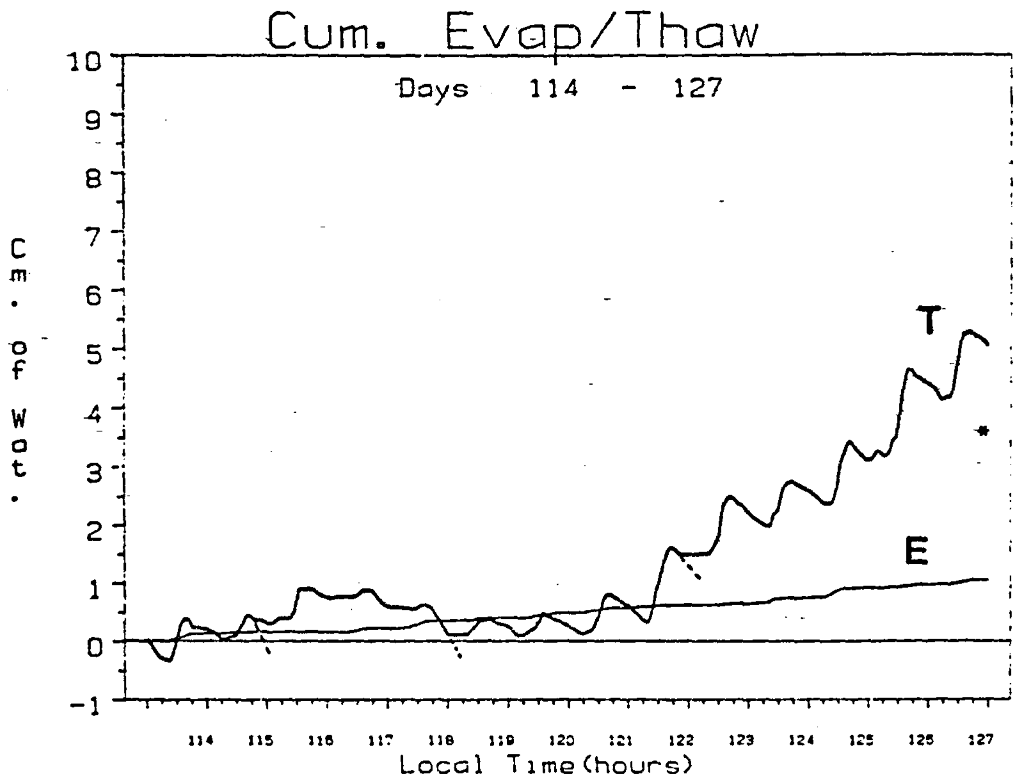

Fig. 7. As in Figs. 5 and 6 but for April 23 to May 6, 1984.

inhibited cooling and refreezing of the snow pack at night after May 1. By May 9 (day 130) the snow under the station was completely gone.

Nearly 35 percent of the moisture present in the snow beneath the station was computed to have evaporated, with the remainder melting and seeping into the soil or nearby deeper snow cover. Peak rates of evaporation occurred on Chinook days when warm, dry winds swept down from higher elevations to the west. Energy consumed for evaporation of snow occasionally exceeded 150 watts per square meter on these days, a rather strong rate of transfer over a smooth surface under slightly stable conditions.

It is significant that a drag coefficient value of 2.5×10^{-3}, typical of values cited for smooth snow, provides what appear to be fairly accurate results for this mountain environment. Our claim of accuracy in this case is based on the reasonable values obtained for specific situations and for the cumulative computed thawing of the snow pack. On days 117 and 118 (Fig. 2) for example, rather cold air temperatures and strong winds suggested that little heating and probably no thawing of the snow pack occurred. Based on the thermal properties of the snow and also on data for similar conditions (Brazel and Marcus, 1979) we estimated that the total daytime snow heat flux is well approximated by the values shown for days 117 and 118 in Fig. 2. Furthermore, measurements of the depth and observations of the condition of the snow pack on day 114 indicated the presence of approximately eight to ten cm. of water equivalent. Although protrucing rocks and twigs precluded accurate flux computations after day 127, extension of the calculations through day 130 suggest a total melt and evaporation of just over 8 cm. of moisture. Varying the estimated drag coefficient between values of 2.0×10^{-3} to 3.5×10^{-3} leadsto either unrealistically low or high estimates of the short-term fluxes and significant differences from the estimated total evaporation and thaw for the period.

We noted in our original proposal that the normal procedure for dealing with large-scale roughness effects of mountainous terrain in numerical models is to use a large drag coefficient to characterize forced mechanical turbulence in the lower boundary layer (see Zhang and Anthes, 1982). The present flux data were obtained using a comparatively small drag coefficient in persistently damped mechanical turbulence (i.e. stable conditions). Therefore, a realistic treatment of surfaces in mountainous terrain would appear to require the use of a smaller roughness scale appropriate to local surface cover in the lower boundary layer. Mountain scale roughness effects such as large mechanical wakes and thermal plumes would then require a separate stability-dependent treatment for fluxes in the outer boundary layer. We hope to further investigate these findings in newly acquired data for several additional mountain settings described in Section C4.

2. Analyses of the 1984 Gobi Desert Heat Balance Observations

An in-depth analysis of our measurements of the surface energy budget in the Gobi Desert during the spring and summer of 1984 has recently been completed. The objective of this study was to observe the heat balance components of the arid Gobi landscape for different seasons and hence for different solar heating rates. Ultimately this work will provide baseline information for diagnosing broad-scale desertification processes by remote means.

In contrast to the dry spring period, the summer observation period was marked by considerable atmospheric moisture, cloud and rainfall. The wet summer conditions strongly influenced the absorption and partitioning of radiant energy into latent and sensible fluxes and precluded simple quantification of the response of the surface system to increased solar radiation. Moreover, the effects of deep atmospheric moisture reduced and redistributed the solar flux such that the net heating at the surface in summer was equivalent to that for early spring. A separate report (Smith et al., 1986) which presents details of this study has been submitted to the Journal of Climate and Applied Meteorology.

Additional work with the Gobi data is being performed by Mr. Lu Longhua of the Academy of Meteorological Science, Shanghai, PRC. Expanding on prior Chinese studies, Mr. Lu is performing extensive auto- and cross-spectral analyses of the Gobi radiation station data (see Reiter et al., 1985). Although this work is still rather preliminary some interesting results have been obtained. In addition to what is assumed to be a synoptic scale periodicity of 7.5 days, a very strong 3.2 day periodicity has been observed in a number of parameters including nearly all of the radiative flux terms and the sensible heat flux. The significance of this apparent 3.2 day oscillation lies in the fact that a similar periodicity has been reported for the development and eastward propagation of mesoscale vortices over the Tibetan Plateau. The latter observation is based on an intensive 90-day upper air study performed by the Chinese during the summer of 1979 (Shen and Huang, 1984). Hopefully, the same analyses can be performed with our two-year, multistation data set for the Rocky Mountain Plateau. Possibly a related, though presumable different, characteristic frequency can be identified and linked to the interaction between the atmosphere and the heat balance of the elevated terrain areas.

Higher frequency spectra of the Gobi data reveal strong periodicities at approximately 30, 80 and 150 minutes. We assume that the 30-minute spectral peak is related to the time scale of larger turbulent (thermal) eddies but implications of the longer period oscillations is not immediately clear.

3. The 1984 Rocky Mountain Low-Level Jet

Observations of strong nocturnal winds at mountaintop were described by Reiter et al. (1985) and also in sections B-1 and C-4 of this report. We have recently begun a study to examine the possible role of moist thermodynamic processes in the forcing of these winds. This work involves the analysis of time variations of equivalent potential temperature and saturation point at mountaintop in relation to the onset of strong winds. The analysis is based on concepts outlined by Betts (1982a, b) for identifying the thermodynamic signatures of specific atmospheric heating processes. Preliminary results tend to confirm our belief that outflow from organized regional scale convection is, at least in part, responsible for the strong and persistent mountaintop wind events (see also Section C-4 below). More extensive work with our 1984 data sets should further clarify this issue.

C-4 Preliminary Results of ROMPEX-85

Final processing and assimilation of the ROMPEX-85 data into several data base archives has not yet been completed. Nevertheless we feel that we have once again obtained a great deal of unique and high quality data from our remote area monitoring work. Several preliminary studies of both the wind field and energy balance data have yielded some very promising results.

1. Wind Analyses

Results of initial work with the ROMPEX wind data tend to confirm our prior conclusions concerning the nature of the mountaintop low-level jet phenomenon, described in Section B1 and in Reiter et al. (1985). In ROMPEX, as in 1984, we find that a fairly strong plateau monsoon in conjunction with a stationary regional anticyclone appear to be necessary conditions for pro-mounced occurrences of the low-level jet. Our selection of August as the principal ROMPEX study period was based, in part, on the fact that the plateau monsoon typically reaches its maximum during this month (Tang and Reiter, 1984). Unfortunately, in August 1985 the monsoon was nearly nonexistent. Several intermittent but fairly intense monsoon periods did occur in July 1985, however, which allowed us to collect some useful regional-scale observations.

Average diurnal cycles of wind direction at Mt. Werner (Station C1) for August 1984 and 1985 are shown in Fig. 8. The time series of Mt. Werner winds in Fig. 9 show details of typical 1984 nocturnal wind events, most notably on days 225, 227, 228 and 231 (August 12, 14, 15 and 18, 1984). Although there is a modest direction cycle in the averaged data in Fig. 8b, both the strength and frequency of the wind reversal events in August 1985

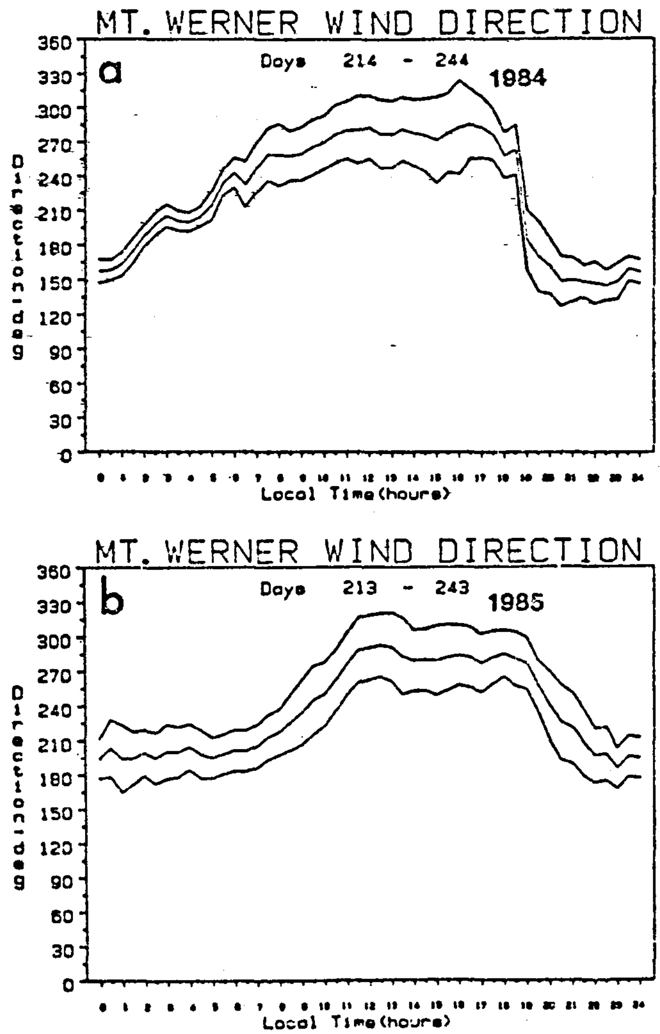

Fig. 8(a) Mean diurnal cycle of wind direction at Mt. Werner (Site C1) for August 1984. The outer pair of curves represent ± one standard deviation of the daily mean values.

Fig. 8(b) As in Fig. 8(a) but for August 1985.

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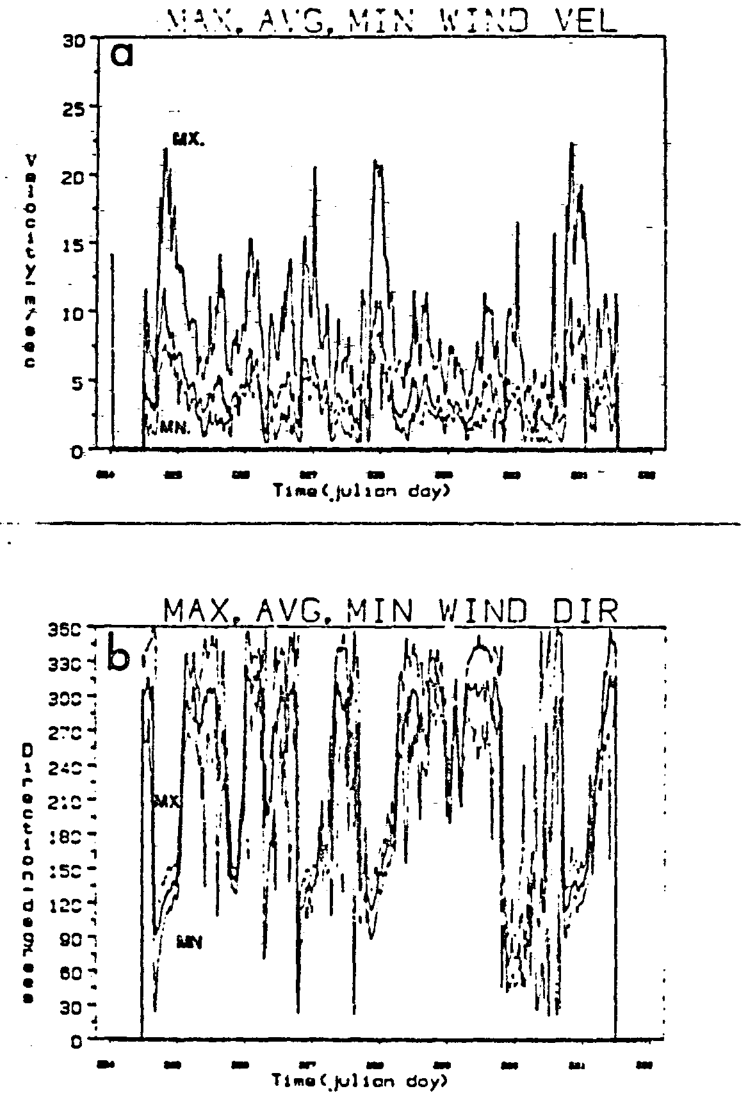


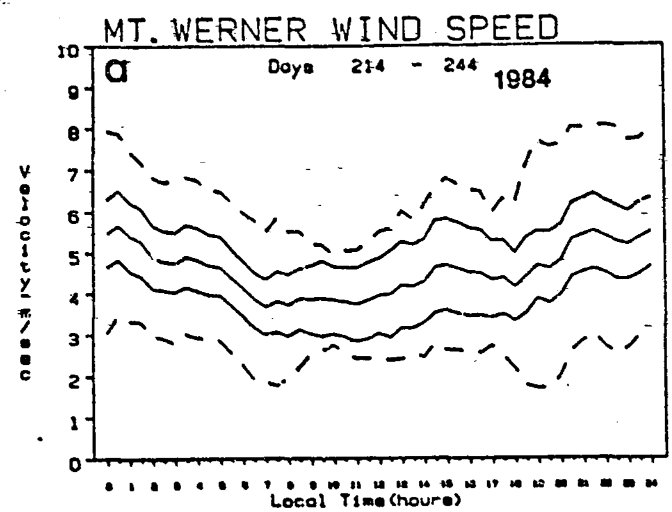
Fig. 9(a) Time series of mean, maximum and minimum wind speed for 15 min. time periods (5 sec. scans) at Mt. Werner for August 12 to August 19, 1984. The large tic marks on the abscissa correspond to local midnight.

Fig. 9(b). As in Fig. 9(a) but for wind direction were greatly diminished. The averaged August wind speeds in Fig. 10 also show this same tendency wherein 1985 daytime (westerly) winds are strongest in contrast to the 1984 nighttime (easterly) maximum. Results for two stations (C1, Mt. Werner and C3, Vail Mountain) for portions of July 1985 are shown in Fig. 11. These data, as noted previously, represent a more active monsoon period and show a much more pronounced diurnal cycle. Mean nocturnal wind speeds for the July 1985 period were also stronger than the afternoon values.

Analyses of regional data for several time periods on the 14th of July 1985 are shown in Fig. 12. At 1200 MST (Fig. 12a) strong regional inflow toward the highlands can be observed at the stations for which data are presently available. This inflow had continued through the afternoon but, by 1900, strong convection over the eastern portion of the network had begun to collapse. At 0100 MST on July 15, a strong and fairly well organized outflow pattern can be observed. The outflow persisted for several hours and gradually relaxed to a weak anticyclonic circulation by the following morning.

As stated previously, we are still expanding and refining our data base to include additional stations (the "P" and "L" sites in Fig. 1). We hope to generate animated analyses (computer movies) of the wind field for the entire experiment. Hopefully, more and better cases similar to that shown in Fig. 12 will be observed when detailed analyses are complete.

One additional analysis has been done for the period during which pibal soundings were made at Mt. Werner and Los Alamos, New Mexico. These results, shown in Fig. 13, reveal an interesting and unexpected effect. An apparent mesoscale wave can be observed moving through the northern portion of the network on the evening of August 14, 1985. Rather strong west-south-



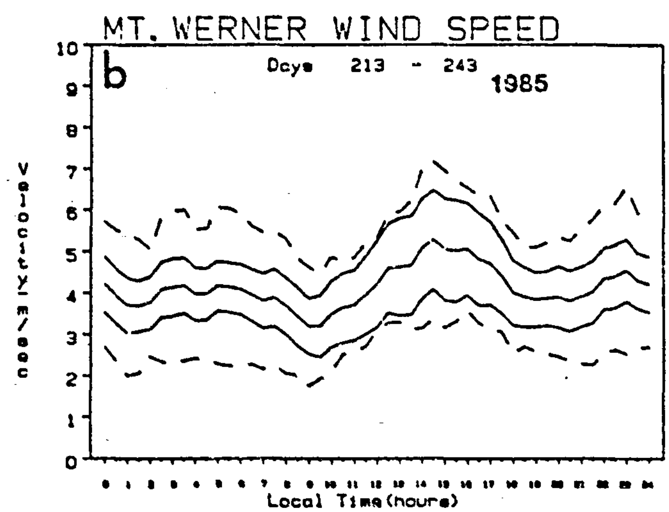


Fig. 10(a) Diurnal cycle of average wind speed at Mt. Werner for August 1984. The dashed outer curves represent ± one standard deviation of the daily mean values. The solid outer curves represent ± the average standard deviations of the actual wind fluctuations.

Fig. 10(b) As in Fig. 10(a) but for August 1985.

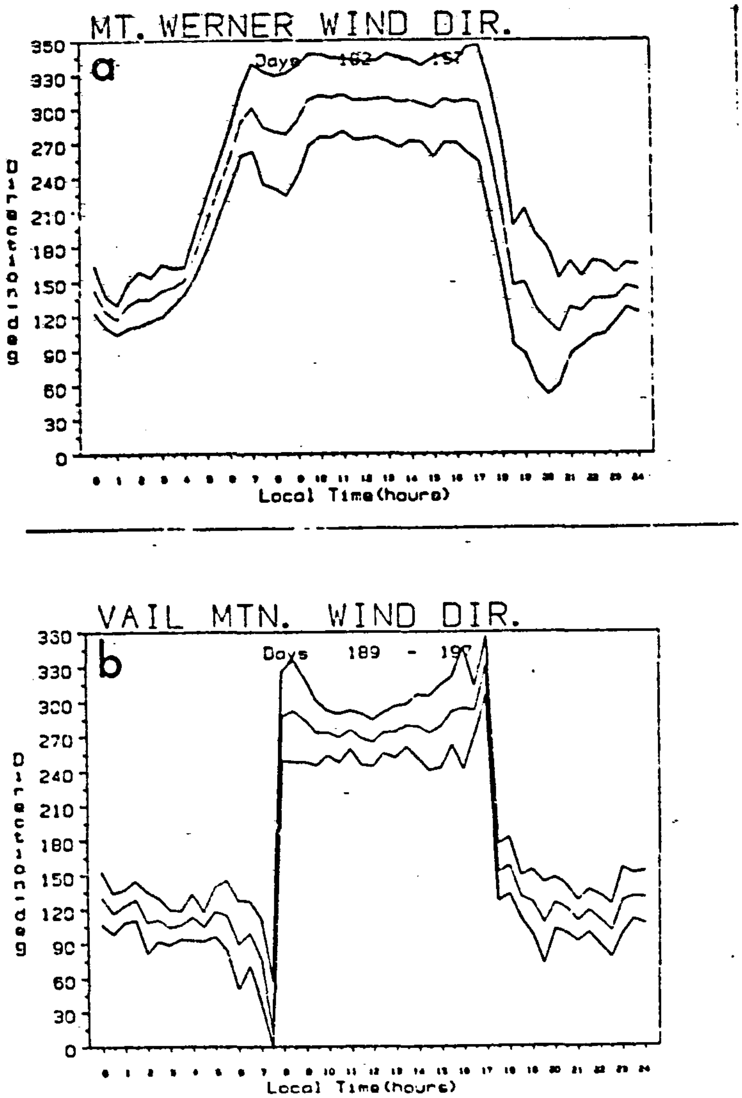


Fig. 11(a) Average diurnal cycle of wind direction at Mt. Werner for July 1 to July 16, 1985.

Fig. 11(b) As in Fig. 11(a) but for Vail (Site C3) for July 8 to July 16, 1985.

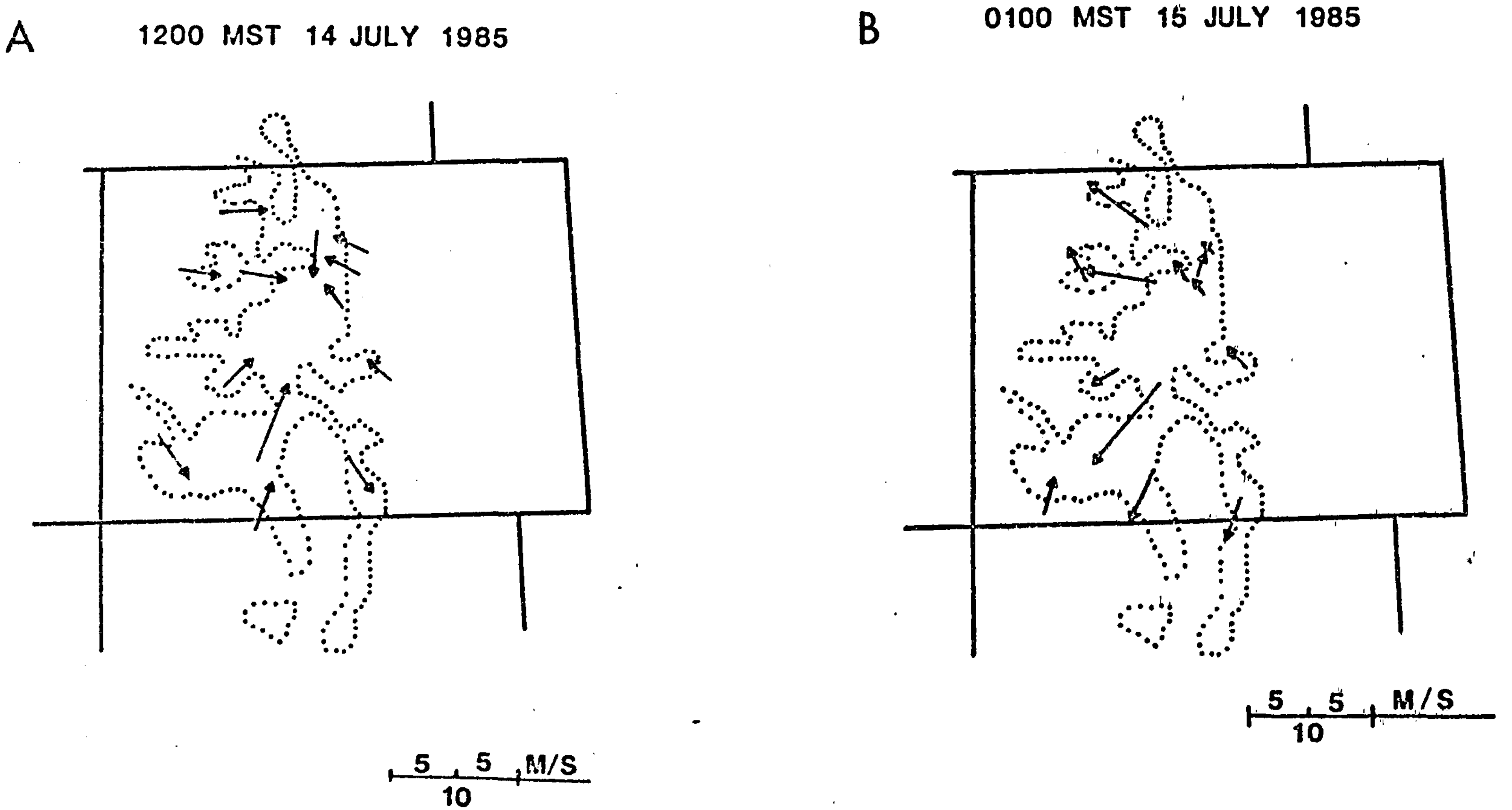


Fig. 12(a) Analyses of averaged wind speed (15 min. means) at ROMPEX sites (for which data are presently available) ofr 1200 on July 14, 1985. The arrows indicate the direction of airflow and the length of the arrows is proportional to speed. Strongest winds in these figures are slightly greater than 10 m/s. The point of each arrow indicates station locations.

Fig. 12(b) As in Fig. 12(a) except for 0100, 15 July 1985 and the tail of each arrow is now at the station location.

westerly winds were observed aloft during this period. Our analyses of pibal data taken at Mt. Werner suggest that this brief southerly shift of the winds, which began at about 1900 MST, extended through a layer at least one kilometer thick. The analysis in Fig. 13 suggests a wave length scale of about 200 km. and a propagation speed of about 50 km./hr. Although the diurnal heating cycles of plateau areas have been suspected before of causing vortex phenomena similar to what appears to occur in Fig. 13 (Shen et al., 1985), little observational data have been obtained to document their existence. Allowing that such vortices are also believed to propagate downwind and provide upper level support for the development of mesoscale convective complexes in low-lying areas, the possibility may exist for observing such effects in real time at mountaintop. Hopefully, a complete analysis of the data will clarify this prospect.

2. Heat Balance Analyses

During the ROMPEX-85 program the surface energy balance was monitored at four mountaintop sites as shown in Fig. 1. We have recently completed a preliminary study of the principal radiative components for these sites for August 1985. These results are summarized in Table 3 which also includes comparable data for Mt. Werner (site C1) for August 1984.

Inspection of Table 3 reveals that the interannual differences between 1984 and 1985 at Mt. Werner are generally greater than the local differences between the 1985 sites. The notable differences between 1984 and 1985 at Mt. Werner include both lower incoming and net solar fluxes and enhanced terrestrial infrared fluxes in 1984. In addition to these differences the smaller visible albedo and slightly larger near infrared albedo at Mt. Werner in 1984 may all be attributed to the presence of increased atmospheric moisture and precipitation.

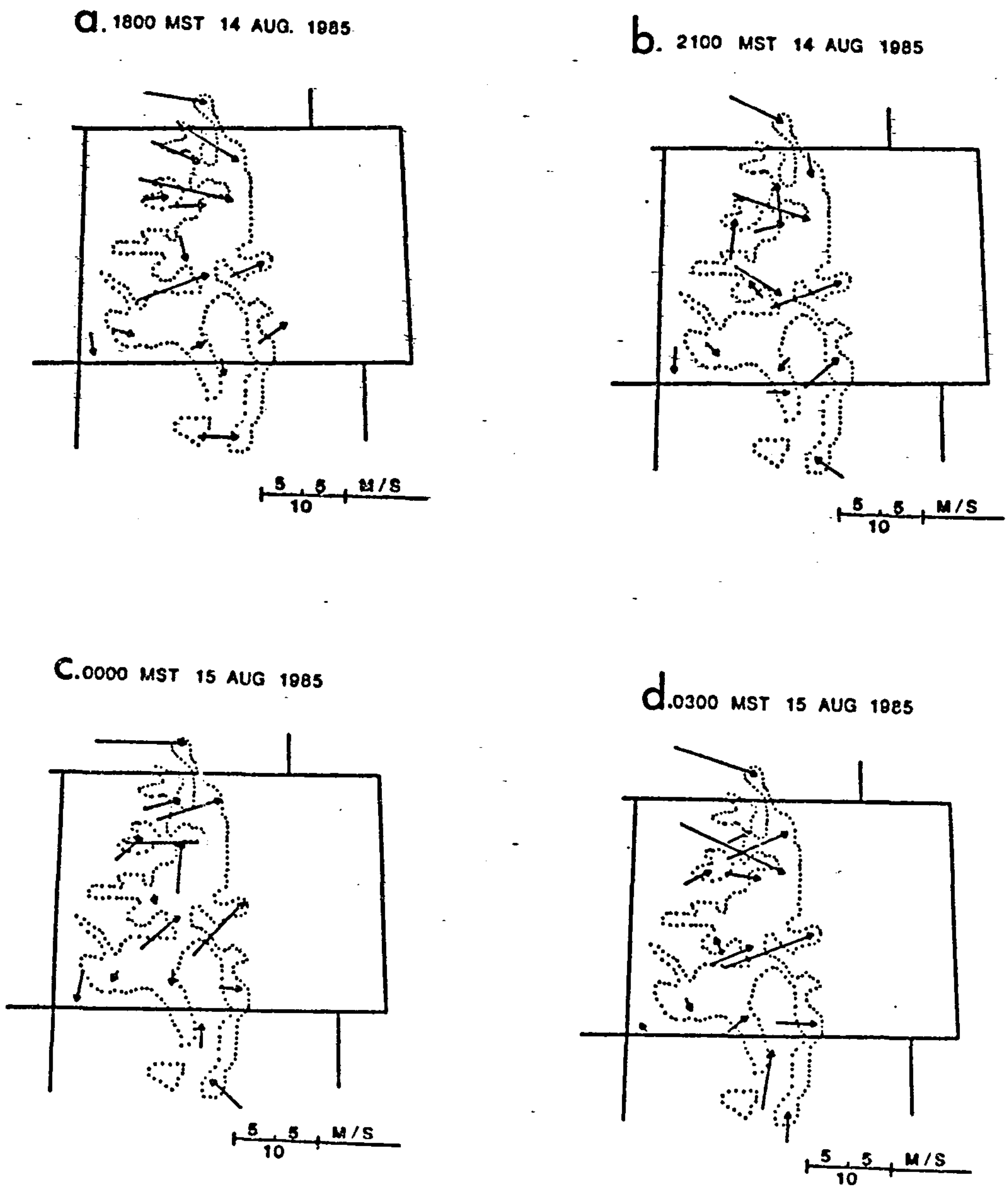


Fig. 13. As in Fig. 12(a), but for August 14 and 15, 1985.

TABLE 3. August heat balance statistics for ROMPEX-85 plus '84 Mt. Werner data.

Parameter	Mt. Werner (C1) 1984	Mt. Werner (3200m)	Vail (C3) (3353m)	Flattops (C2) (3441m)	Crested Butte (C5) (3353m)
			-Stations-		
Radiation (W/m^2)					
Total Solar (K)	-247.5	-284.6	-272.4	-286.6(L)	-272.3(S)
Visible (V)	-118.1	-136.1	-130.0(S)	-138.4(L)	-133.2
Near IR (N)	-129.7	-148.6	-142.4	-148.7(L)	-139.1(S)
Atmospheric IR (L↓)	-315.0	-284.6(L)	-266.8	-261.1(S)	-279.0
Surface IR(L↑)	+385.0	378.0	363.4(S)	366.4	+381.1(L)
Net Radiation (Q*)	-134.8	-140.1(L)	-118.4(S)	-124.5	-124.6
K*	-204.5	-233.8(L)	-215.3(S)	-229.5	-226.5
V*	-113.2	-127.4	-122.6(S)	-128.0(L)	-123.4
N*	-96.1	-106.4(L)	-92.5(S)	-101.5	-103.1
L*	70.1	93.5(S)	96.6	105.3(L)	102.1
Albedos (%)					
A_k	17.4	18.0	21.3(L)	20.5	16.4(S)
A_v	4.3	6.3	5.9	7.4(L)	5.3(S)
A_n	29.5	28.6	35.5(L)	31.4	26.6(S)
EBBTemps (^oK)					
EBBT ↓	272.6	266.0(L)	261.7	260.4(S)	264.5
EBBT ↑	286.5	285.3(L)	282.4(S)	282.9	285.2
Wind Speed (m/s)	4.69	4.25	4.54(L)	3.53	1.70(S)
Air Temp (^oC)	11.4	12.1(L)	11.6	10.6(S)	11.8
Rel. Humidity (%)	47.5	39.3(S)	42.8	45.4(L)	44.5

(L) and (S) designate the largest and smallest 1985 values,respectively.

The results for 1985 indicate that Station C2 (Flattop) experienced a generally dryer atmosphere than the other sites. Evidence for the latter observation include both the smaller mean atmospheric emittance and larger solar flux components at that site. Whereas Mt. Werner (site C1) experienced the strongest mean atmospheric emittance, the incoming solar components were also comparatively strong. This condition suggest that a detailed comparative study of time series data for each site will be required to determine how the mean values in Table 3 are actually obtained.

Figures 14 through 17 show the mean diurnal cycles of radiative components for August at each of the 1985 stations. The August 1984 data for Mt. Werner are also included. To simplify intercomparison between these plots, we have superimposed the diurnal cycle of several key components of the 1985 Mt. Werner data onto each figure.

The effects of our compromises on site selection can be observed in the analyses for Crested Butte (C5) and Flat Tops (C2). The early morning data for both of these stations and afternoon data at Crested Butte show undulations due to the presence of shadows cast by nearby trees. In addition to these problems the atmospheric emittance data at Crested Butte appear to be contaminated by infrared emittance from nearby trees in the early afternoon.

One interesting result in these data is the strong decrease in the atmospheric emittance at Mt. Werner between 1984 and 1985. The 1984 data show the presence of the active monsoon in the form of greater afternoon cloud cover and a much wetter/warmer nocturnal atmosphere. A decrease in the net solar fluxes is also evident in 1984 data in Fig. 14.

The surface cover of three of the four ROMPEX sites consisted primarily of sparse grass and lichens with a fairly large component of bare, rocky soil.

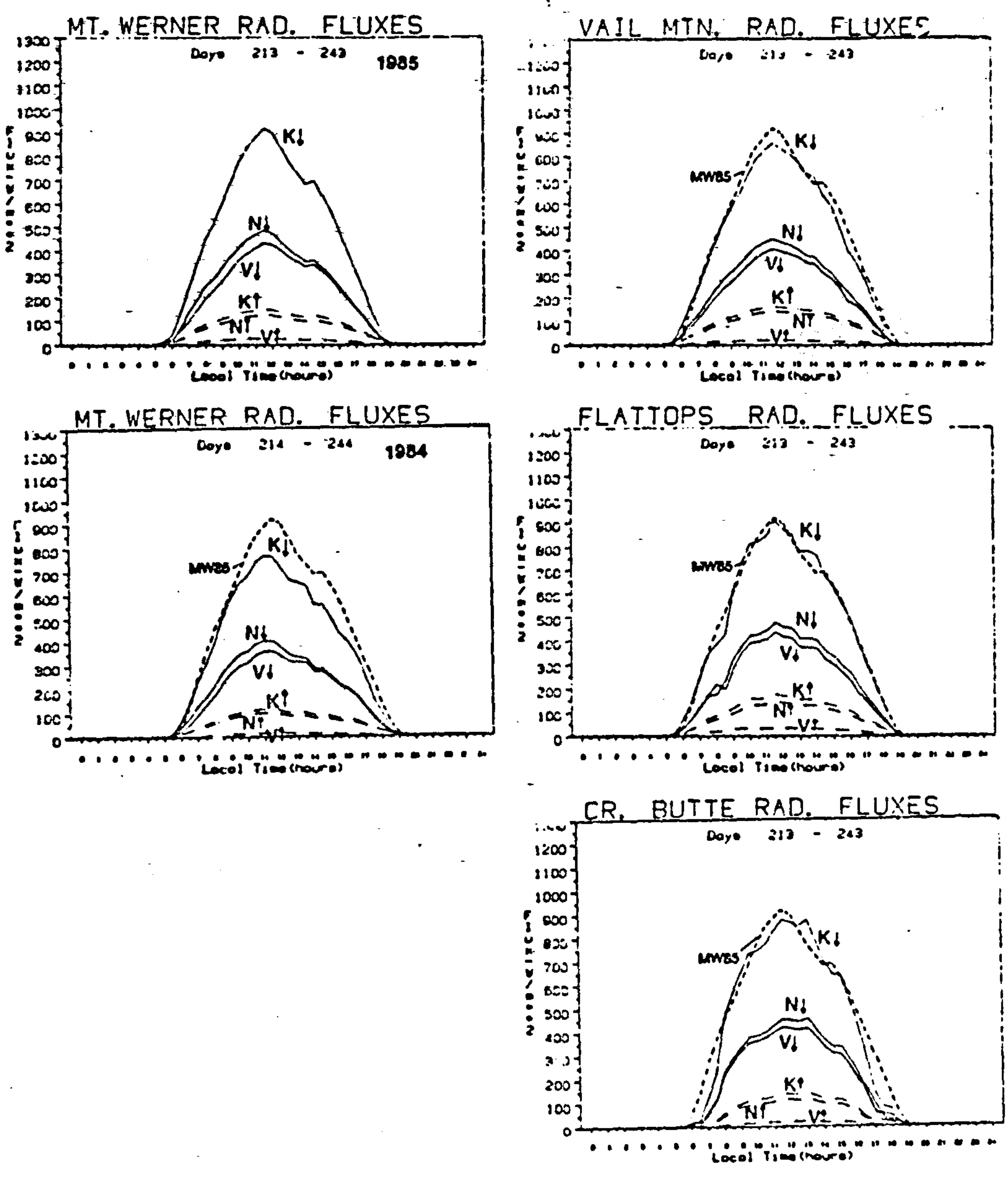


Fig. 14. Diurnal average values for incoming and reflected components of solar radiation during August 1984 at Mt. Werner and at the 1985 ROMPEX sites. Label designations are total solar (K), near infrared (N), and visible (V). The dashed curve labeled mw 85 in several of the plots represents the K↓ value for the Mt. Werner site for August 1985.

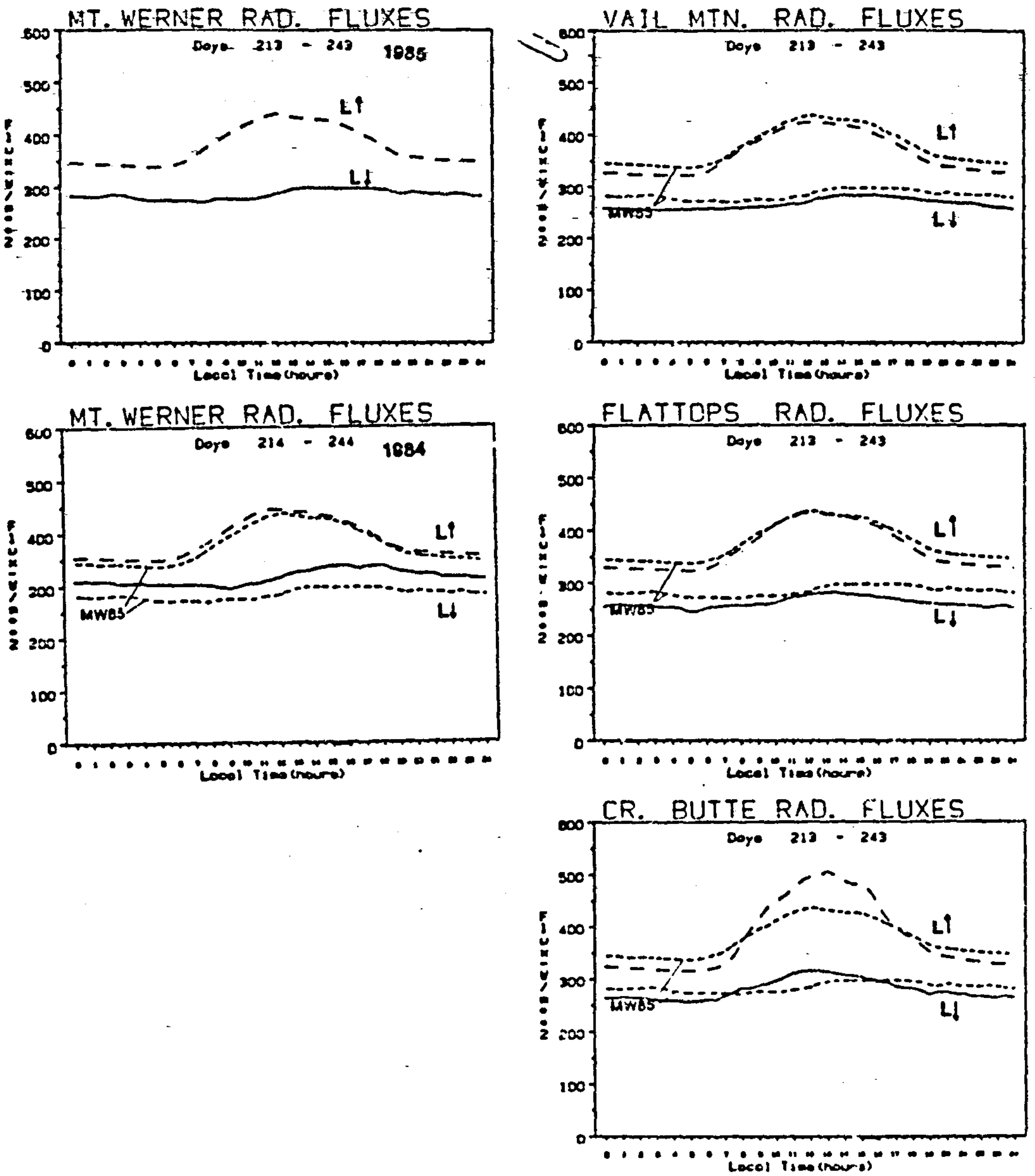


Fig. 15. As in Fig. 14 but for atmospheric (L↓) and surface (L↑) emitted infrared radiation. The 1985 Mt. Werner data are again included for comparison.

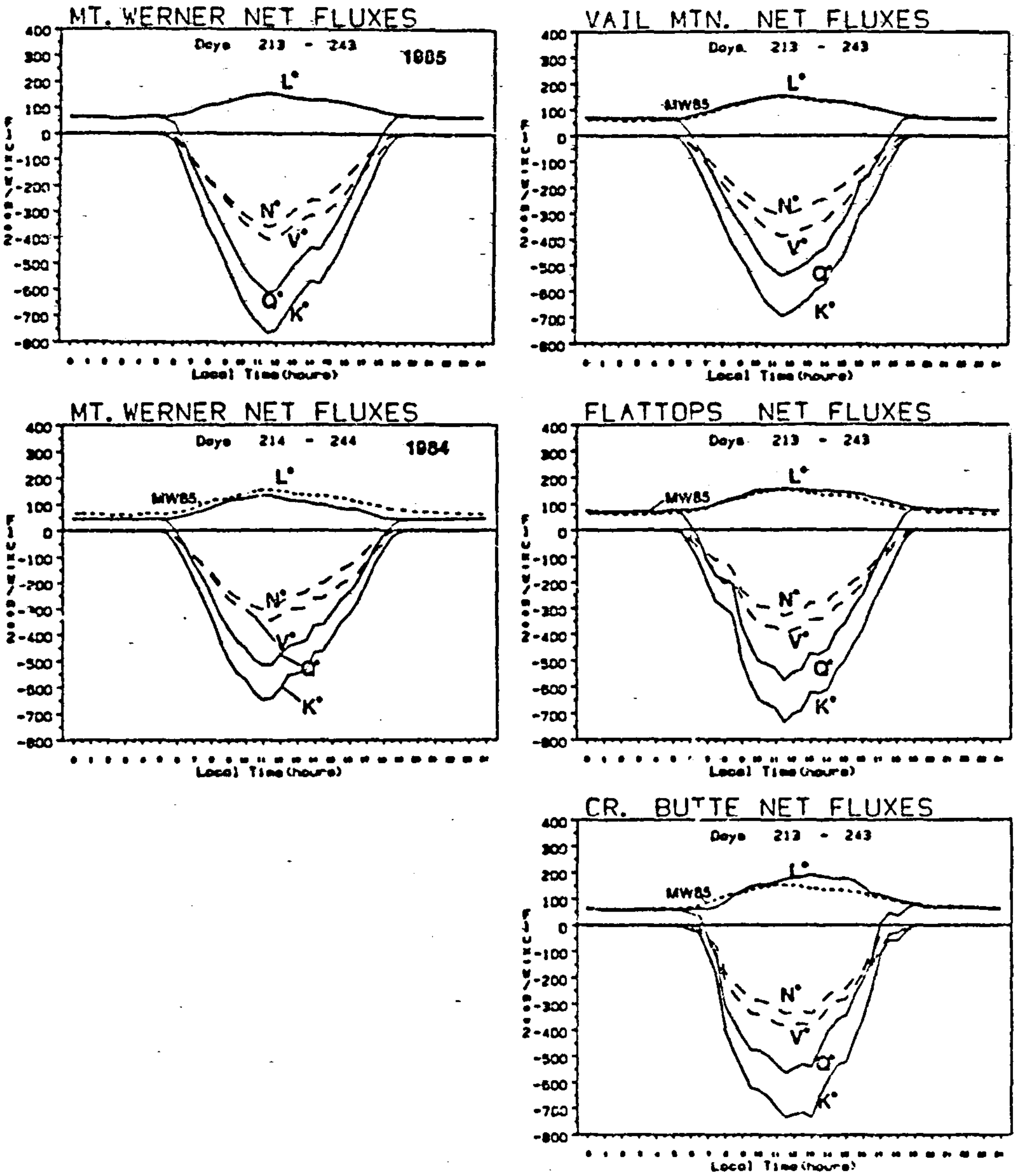


Fig. 16. As in Fig. 14 but for the net radiative fluxes. The 1985 L* value for Mt. Werner has been added to some of the plots.

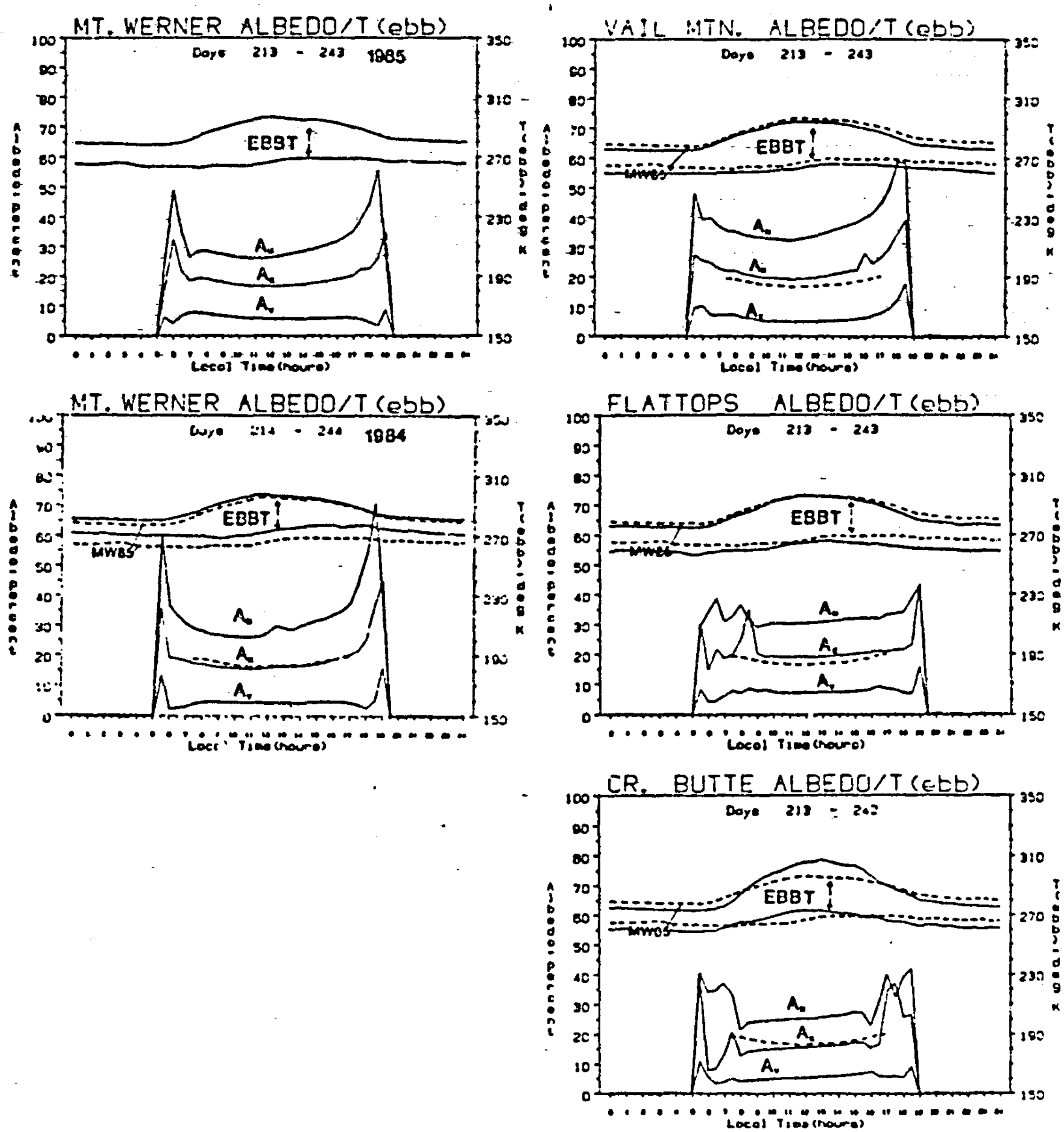


Fig. 17. As in Fig. 14 but for the surface albedo and EBBT values for each site. The 1985 EBBT curves and a portion of the A_K (total solar albedo) curve for Mt. Werner have been included in some plots.

The exception was at Vail (C3) where a comparatively dense mixture of grass and tundra flowers covered the ground. The surface at Vail had a notably larger albedo for near infrared radiation as shown in Fig. 17 and Table 3. In spite of this value, the averaged albedo values for total solar radiation in Table 3 are generally rather similar. The smaller albedo values at Crested Butte, especially for the near infrared, are probably due to an approximate five percent slope of the surface at this site which has not yet been compensated for in the data.

We had hoped to place the four energy budget monitoring stations in sites with effectively equivalent local exposure to winds and radiation. Constraints imposed by time and staffing, as noted previously, ultimately precluded this deployment plan. Consequently we have obtained extensive good quality data for sites that are all distinctly different in exposure or surface cover, in addition to being 100 km. or more apart. While this diversity might be desirable in an advanced stage of our work it complicates the present task of computing a complete energy budget by partitioning turbulent fluxes into latent and sensible components at each site.

Allowing that the soil heat flux can be determined fairly accurately from soil temperature and soil moisture values observed at six levels, the total turbulent flux becomes the residual after computing the net radiative energy balance, Q*. Estimating the surface mixing ratio over diverse vegetation cover is a very difficult task. Consequently, we have chosen to use surface EBBT data to compute the sensible heat flux, as described in section C-1, and then obtain the latent heat as the residual component. Unfortunately, several complications unique to mountain peak environments require that we proceed cautiously in computing the sensible heat fluxes.

The latter complications include a very limited effective upwind fetch for the true peak sites and several stability regimes not typically encountered in boundary layer research. These regimes include a) air flow from the free atmosphere impinging directly onto the site when light winds and deep valley inversions limit mixing. In this case the site becomes a source region for subsiding slope flows. b) Under strong heating and convective conditions, the peaks are the upper limit for upslope flows; Hence, in this case the sites may be in the centers of persistent localized thermal plumes. c) For moderate winds with mixed convection, large-scale mechanical and thermal eddies may create a turbulence regime at these sites which is more typical of the outer boundary layer than the lower boundary layer conditions. The extent to which effects of any or all of these regimes can be identified as important at each site is a necessary preliminary step in the complete energy budget analysis.

Detailed multilevel tower data (eight meter tower) collected at Mt. Werner during our 1984 program and similar, but generally superior data collected during 1985 at Crested Butte should be useful for these studies. The Crested Butte data (20 meter tower) also include advective components [that is $\overline{(U' T')}$, $\overline{(U' q')}$, etc.] computed from one-second samples, in addition to the usual vertical covariance statistics for wind, temperature and humidity. In addition, several snowfall periods which occurred during August and September 1985 will also allow a limited set of turbulent flux studies identical to those in section C-1 to be performed at several of the sites.

D. <u>WORK TO BE DONE DURING REMAINDER OF GRANT PERIOD</u>

1. Prior to departure for Tibet we intend to calibrate the response characteristics of the UVW anemometers and thermistors with sonic anemometers and high-frequency thermistors.

2. Field tests with the solar photometer will be carried out in Tucson and Fort Collins, prior to departure for Tibet.

3. Our estimates of IR radiation flux convergence above (melting) snow surfaces will be refined. These analyses will then be submitted to the open literature. Implications on remote sensing from space and on spring runoff predictions and flooding potential will be studied.

4. Short-period variability of radiation and other energy flux components from all data sets will be investigated using frequency spectrum analyses techniques.

5. The ROMPEX data will be analyzed in detail to study the variability of radiation fluxes with changes in the synoptic conditions and in the meso-scale wind fields.

6. The effects of radiation and precipitation on saturation point and mass characteristics will be investigated for periods with pronounced inflow into, and outflow from, convective systems in the ROMPEX 1985 data.

7. With the help of Dr. Tom Charlock we will compare our radiation and EBBT data with AVHRR data for the purpose of providing ground truth calibration. This work will be carried out for Rocky Mountain and Tibetan locations.

8. Analysis of Tibetan radiation and surface energy budget data which will become available by August 1986.

9. We intend to activate the Mt. Werner radiation station and an additional station at lower elevations after our return from China. These data should give us more indications of interannual variability and of slope effects.

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