Measurements and Modeling of the Effects of Ambient Meteorology on Nocturnal Drainage Flows

P. H. GUDIKSEN AND J. M. LEONE, JR.

Lawrence Livermore National Laboratory, University of California, Livermore, California

C. W. KING, D. RUFFIEUX, AND W. D. NEFF

NOAA/ERL Wave Propagation Laboratory, Boulder, Colorado

(Manuscript received 5 September 1991, in final form 14 January 1992)

ABSTRACT

An experimental and modeling investigation of nocturnal drainage flows within the Mesa Creek valley in western Colorado revealed their wind and temperature characteristics and the effects of the ambient meteorology on their development. The valley, located about 30 km east of Grand Junction, is situated on the north slopes of the Grand Mesa. It is surrounded by ridges on three sides with low terrain toward the north. The terrain at the higher elevations is characterized by steep slopes that become shallower at the lower elevations. A network of seven meteorological towers and a monostatic sodar collected data within the study area from December 1988 through November 1989. Analysis of the experimental data indicated that shallow drainage flows generated over the many individual slopes at the higher elevations converge at the lower elevations to form deeper flows that join with those generated within adjacent drainage areas. The characteristics of the flows generally deviated from those displayed by idealized slope flows due to both internal circulations within the valley and external influences. During the summer, the depths of the flows were typically a few tens of meters along the upper slopes and about 100 m over the upper part of the lower slopes, while during the winter, the depths decreased to about 10 and 60 m, respectively. Their frequency of occurrence was highest during the summer or fall, about 50%, when the synoptic-scale influences were minimal. The flows along the upper slopes were particularly susceptible to influences by the ambient meteorology due to minimal terrain shielding. When the larger-scale ambient flows over the Grand Mesa were greater than about 5 m s^{-1}, the surface cooling along the slopes was unable to develop and maintain the surface temperature inversion needed to generate strong drainage flows. The radiative cooling rates of the sloped surfaces, as characterized by net radiation measurements, were correlated with the downslope wind speeds observed along the upper slopes. Thus, a decrease in the observed net radiation level will produce a corresponding decrease in the downslope wind speed. Since temporal changes in net radiation levels are primarily governed by variations in atmospheric moisture, the effect of increased atmospheric moisture is to retard the development of the drainage flows.

In order to place the observations in proper perspective, it was necessary to employ numerical models that account for the physical processes governing the dynamics of the flows. The general features of the wind and temperature characteristics of the valley circulations and the influence of strong ambient winds and atmospheric moisture on the drainage flows over the upper slopes could be accounted for by numerical modeling techniques based on solving the equations of momentum, continuity, and energy coupled with a surface energy budget and a radiation module.

1. Introduction

The Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) program has conducted a series of field experiments in mountain valleys in northern California and western Colorado to improve our understanding of the wind, temperature, and turbulence structure of nocturnal drainage flows (Clements et al. 1989; Gudiksen et al. 1984). These experiments, which were primarily focused on the study of well-established drainage flows, also demonstrated, however, that these locally generated flows are often influenced by the ambient meteorology. In particular, increases in atmospheric moisture can reduce the longwave radiative cooling of the sloped surfaces needed to develop these local circulations, and strong ambient winds may completely overpower even well-established drainage flows. Barr and Orgill (1989) demonstrated that the depth and strength of the drainage flows observed within a mountain valley, as well as the direction and strength of the winds above the valley, may be significantly affected by even subtle changes in the radiative characteristics of the atmosphere. This has also been shown by Davidson and

Corresponding author address: Dr. Paul H. Gudiksen, University of California, Laurence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550.

Rao (1963), who conducted field studies of local circulations within valleys in Vermont.

One of the ASCOT-sponsored studies was focused on a climatological investigation within the Mesa Creek valley in western Colorado to evaluate the characteristics of drainage flows, their seasonal frequency of occurrence, and the effects of the ambient meteorology on their development. This study involved integration of meteorological measurements collected within the valley by this program with numerical modeling to further our understanding of the physical processes responsible for generating the drainage flows and the effects of atmospheric moisture and strong ambient winds on their characteristics. The Mesa Creek study area is situated on the north slope of the Grand Mesa. It encompasses a roughly 10-km × 20-km area located approximately 30 km east of Grand Junction. The topographic features of the Mesa Creek drainage area and its surroundings are shown in Fig. 1. The layout of the meteorological measurements network, consisting of seven meteorological towers and a sodar, is also shown in Fig. 1. The study area is bounded on the south and west sides by the Grand Mesa, on the east side by a ridge, and toward the north by low terrain. The terrain at the higher elevations consists of steep slopes that become shallower at the lower elevations. The elevations range from about 3000 m above sea level on top of the Grand Mesa to about 1600 m at the bottom of the valley. The drainage flows produced over the numerous individual slopes at the higher elevations drain into the valley where they merge with those generated within adjacent drainage areas and possibly even with the larger-scale drainages generated over the western slopes of the Rocky Mountains. The summation of these flows subsequently drains westward into the Colorado River drainage area.

This study, undertaken jointly by the Lawrence Livermore National Laboratory and the National Oceanic and Atmospheric Administration Wave Propagation Laboratory, involved operation of the meteorological measurements network within the Mesa Creek study area over a period of one year, extending from December 1988 through November 1989. These measurements were augmented periodically by tethersonde observations for detailed definition of the vertical profiles of the wind and temperature structure over the sloped surfaces. The layout of the instrumentation was designed to characterize the ambient flows over the Grand Mesa, the radiative cooling characteristics of the sloped surfaces, and the wind and temperature characteristics of the drainage flows along the upper and lower slopes. Thus, one of the meteorological towers was situated on top of the Grand Mesa (site 4), while three towers were located along the upper northern slopes of the Grand Mesa, and the remaining three were located along the lower slopes. The sodar was situated within the upper part of the lower slopes at site 5. The towers, instrumented at two levels (7 and 18 m), provided measurements of hourly averaged wind velocity, temperature, and net radiation, while the monostatic sodar

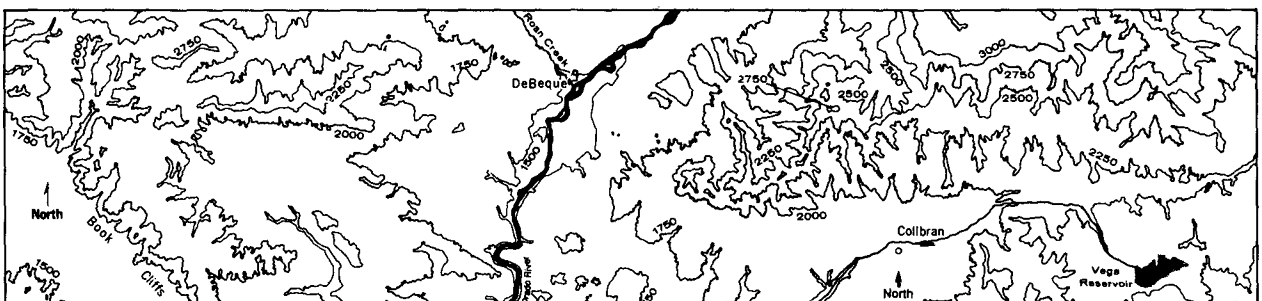

FIG. 1. The topography of the Mesa Creek valley and its surroundings. The valley is situated along the north slopes of the Grand Mesa. The numbered designations indicate the locations of the individual meteorological towers within the Mesa Creek valley. The location of the sodar is denoted by the open triangle.

measured the detailed structure of the drainage layer over the lower slopes. The hourly averaged tower data were obtained from 1-s instantaneous values. The three towers, sites 1, 2, and 3, along the upper slopes were located within clearings in an otherwise heavily forested region of evergreens and aspen groves, while those at the lower elevations, sites 5, 6, and 7, were situated in large open areas. The instrumentation included lightweight cup and vane anemometers, thermister temperature sensors, and Fritschen net radiometers that fed their signals to a microprocessor data logger for subsequent transmission to the Lawrence Livermore National Laboratory by means of the NOAA Geostationary Operational Environmental Satellite (GOES). The monostatic sounder recorded its signals on facsimile paper that was manually changed and sent to the Wave Propagation Laboratory for analysis. The observations acquired from this network were used in conjunction with two different modeling approaches that included a three-dimensional planetary boundary layer model to account for the valleywide circulations and a one-dimensional slope-flow model for studying the effects of the ambient meteorology on the drainage flows along the upper slopes of the valley.

This paper summarizes our findings in regard to 1) the wind and temperature characteristics and seasonal frequencies of the nocturnal drainage flows observed within the study area, 2) the effects of the ambient meteorology on the drainage-flow characteristics, and 3) the results of our numerical modeling to improve our understanding of the physical processes governing the development of drainage flows and their interactions with the ambient meteorology.

2. Characteristics and seasonal frequencies of nocturnal drainage flows

Nocturnal drainage flows within the Mesa Creek valley are generated along terrain slopes during periods when the ambient winds over the slopes are weak and the skies are clear, permitting strong radiative cooling at the surface. As the drainage flows generated over the many steep elevated slopes converge, they deepen over the lower elevation slopes. The cooling process along the upper slopes produces a surface-based temperature inversion that typically extends up to a few tens of meters above the surface, depending on the distance from the top of the slope and the cooling rate. A characteristic temperature distribution along the slopes is shown by the vertical cross-sectional view illustrated in Fig. 2. This north–south cross section extends from the top of the Grand Mesa to near the bottom of the valley. The data were acquired from both tower and tethersonde measurements performed on 21 September 1989. The relative vertical spacing of the isotherms reveal the formation of a shallow drainage layer along the upper slopes. As expected, this layer becomes deeper over the lower slopes as the individual drainages merge

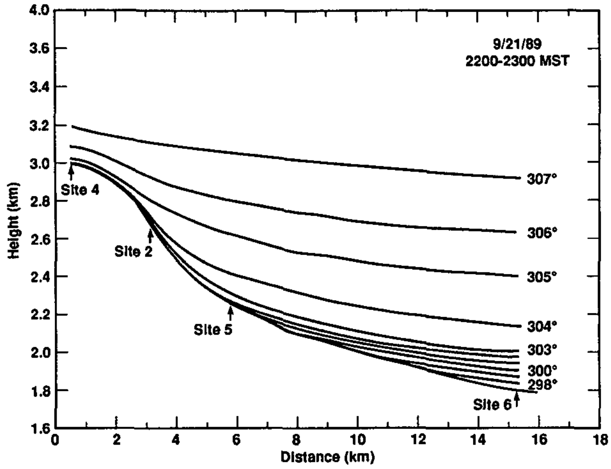

FIG. 2. A typical potential vertical temperature profile (K) along a north–south cross section of the Mesa Creek valley during a period of well-established drainage flows.

and become part of the larger-scale pool of drainage flows generated largely from adjacent drainage areas. This gives rise to the presence of the cold stable layer over the lower slopes that typically ranges from 100–200 m in depth depending on the slope location.

The drainage flows along the upper slopes, where terrain shielding is minimal, are greatly influenced by the larger-scale ambient winds over the Grand Mesa and the merging of individual slope flows. Thus, it is rare to see a well-defined nocturnal wind-speed maximum within the drainage layer along the upper slopes; a characteristic that is typical of pure drainage flows over simple slopes. The data in Table 1, which were derived from an ensemble of well-established drainage-flow situations that are defined later in this section, reveal that during summer and winter seasons there is considerable variability in the average downslope wind speeds along the upper slopes of the valley. Thus, the wind speeds measured at towers 1, 2, and 3 vary from about 1 to 6 m s^{-1}, with the winds at the top of the towers generally being slightly stronger than those measured at the lower levels. The few available tethersonde observations indicated drainage depths of about 30 m near the middle of the upper slopes in the vicinity of tower 2. As one moves down onto the lower slopes, which are less steep, the drainage-flow depths typically increase to about 100 m at the sodar site during the summer. During the winter, when snow cover is present over most of the valley, somewhat comparable downslope wind speeds are observed; however, increased vertical stability and considerably shallower flows are also observed, even though the net radiative losses at the surface were similar to those observed during the summer. The depths of the flows along the upper slopes during the winter are generally less than 10 m, and those along the lower slopes are about 60 m in the vicinity of site 5. On this basis, it appears that the

TABLE 1. Seasonal variations in drainage-flow characteristics.

	Summer			Winter		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Average downslope wind speed (m s^{-1})						
7 m	4.0	3.0	1.4	6.5	3.2	1.3
18 m	5.6	3.1	2.3	6.8	2.4	1.3
Average drainage depth (m)						
Upper slope*		30			<10	
Lower slope**		100			60	

* Based on a few tethersonde measurements at site 2. Normal variations are within ±10 m.

** Based on extensive sodar records at site 5. Normal variations are with ±20%.

net downslope volume fluxes are considerably lower during the winter; a characteristic that may be due to the increased vertical stability inhibiting the entrainment of air from above into the stable drainage layer.

The temperature and wind characteristics of these drainage flows are frequently perturbed over periods ranging from minutes to hours. For example, the sodar record for the night of 25–26 June 1989, shown in Fig. 3, gives a typical illustration of these perturbations. Note the initial development of a roughly 100-m-deep drainage layer at approximately 2050 MST. The layer underwent several minimal perturbations prior to midnight, when a major disturbance essentially destroyed the drainage flows until approximately 0130 MST, whereupon the flows reveal the recurrence of a well-defined drainage layer. Such a major disruption frequently occurs at about midnight during apparently good drainage-flow conditions. The effects of these perturbations are also reflected in the wind and temperature measurements acquired from the adjacent tower, as shown in Fig. 3. Note the relatively high values of σ_θ, the standard deviation of the horizontal wind-direction fluctuations, and the low temperature differences between the two instrumented levels on the tower indicating a significant decrease in stability during the disturbance. The cause of these disturbances is not at all clear but may be related to the circulations associated with the merging of the flows from adjacent drainage areas situated outside the study area. This hypothesis is based on the generally higher values of σ_θ obtained from the towers (sites 6 and 7) situated within the flow convergence area relative to those obtained from the towers located on the upper slopes. There appears to be no evidence for synoptically driven flows causing these perturbations, since the ambient winds measured on the top of the Grand Mesa remained calm and the clear skies permitted strong continuous radiative cooling at the surface. Thus, it is likely that the perturbations are related to the coupling of drainage flows from adjacent valleys; a phenomenon that is poorly understood.

The climatological aspects of this study involved a determination of the seasonal variations of the frequencies with which nocturnal drainage flows occurred during the measurement period. A classification scheme was developed by King et al. (1990) on the basis of the ambient meteorology, as measured by the tower network, and the extent of the interruptions of the drainage flows detected by the sodar. Each night's flows were categorized into one of four categories: A—well-established slope flows with minimal interruptions by external influences; B—well-established slope flows with major interruptions by external influences; C—

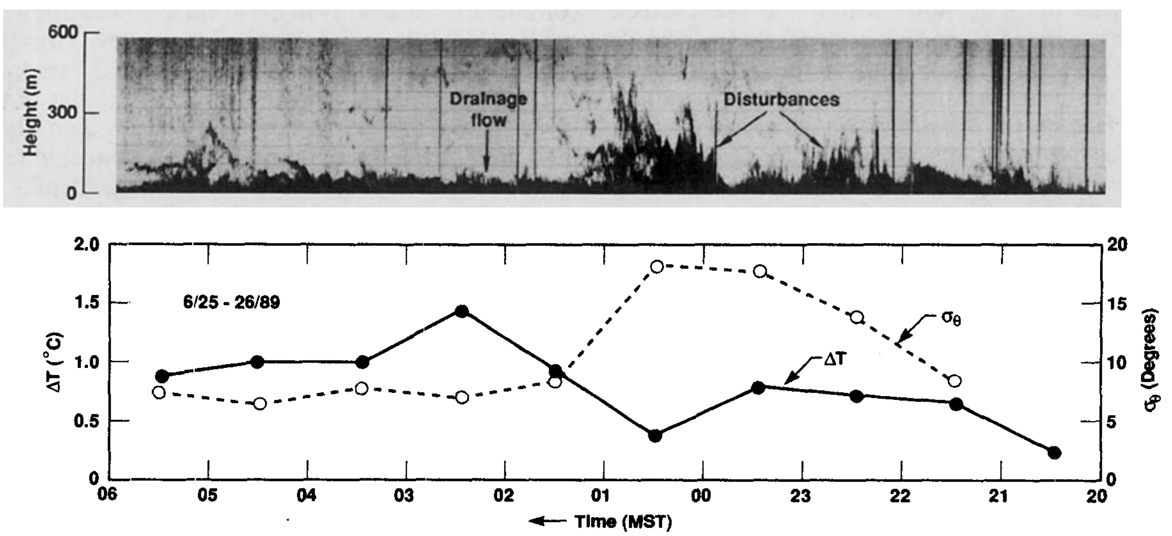

FIG. 3. Sodar and tower records for the night of 25–26 June 1989 showing typical interruptions to the drainage flows. The major interruptions, shortly after midnight, resulted in decreased stability as indicated by the variations in ΔT and σ_θ. The depth of the undisturbed drainage flow is about 100 m, while the disturbed flows extend up to about 400 m.

weak slope flows with major interruptions by external influences; and D—minor or no drainage. The criteria used to define these categories are as follows.

- The wind directions at each of the three tower sites along the upper slopes had to be within 30° of the downslope direction for at least 8 h for the A and B categories and 6 h for the C category.
- The average temperature difference between the upper and lower levels of the three towers situated along the upper slopes must equal or exceed 1°C for the A and B categories and at least 0.2°C for the C category.
- The average net outgoing longwave radiation over the upper and lower slopes must exceed 30 W m^{-2} for the A and B categories and 15 W m^{-2} for the C category.
- Steady drainage or slightly interrupted drainage flows over the lower slopes (as evidenced by the sodar records) are shown in category A; significantly interrupted flows are shown in categories B and C; and little or no evidence for drainage flows are shown in category D.

Using the hourly averaged slope wind, temperature, and net radiation data from the three towers situated along the upper slopes (sites 1–3) and the sodar measurements collected over the lower slopes in conjunction with the above criteria, the frequencies of occurrence of each category during each season were derived. The resulting seasonal frequency distributions are shown in Fig. 4. The seasons were defined as winter (December–February), spring (March–May), summer (June–August), and fall (September–November). The summer and fall months recorded the highest percentage of category A cases, 34% and 36%, respectively, while the winter and spring months recorded the lowest percentages of 23% and 22%, respectively. Combining categories A and B into one category representing well-established slope and basin flows with either minimal or major disturbances again shows the summer and fall with the highest percentages of 53% and 52%, respectively, with the winter and spring following with 42% and 29%, respectively. The winter and spring months also show high percentages of no drainage cases when compared with the summer and fall periods. These results are in reasonable agreement with the climatological data collected at the Grand Junction National Weather Service station. During the winter and spring months, the occurrence of synoptic-scale disturbances that are capable of preventing the development of the drainage flows are far more common than during the summer and fall months.

By averaging the wind-direction and wind-speed observations collected at each tower location for the category A cases, the primary flow pattern of the valley drainage flows was derived. Figure 5a shows the primary flow pattern associated with the well-established

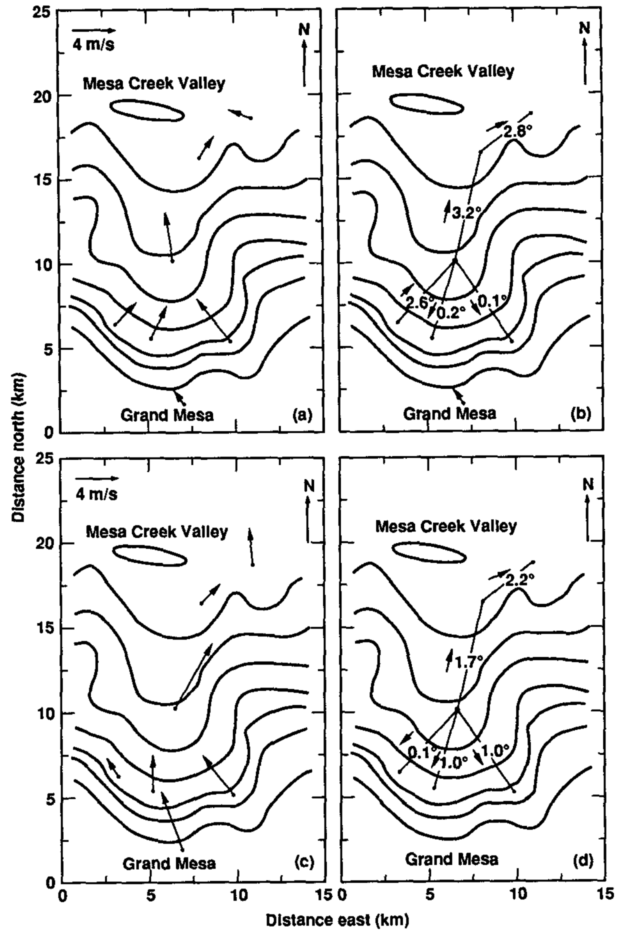

FIG. 5. The primary flow patterns and the surface potential temperature gradients between measurement locations during periods of well-established drainage flows [(a) and (b)] and during periods of strong ambient flows over the Grand Mesa [(c) and (d)]. The arrows in (b) and (d) indicate the direction of decreasing temperature.

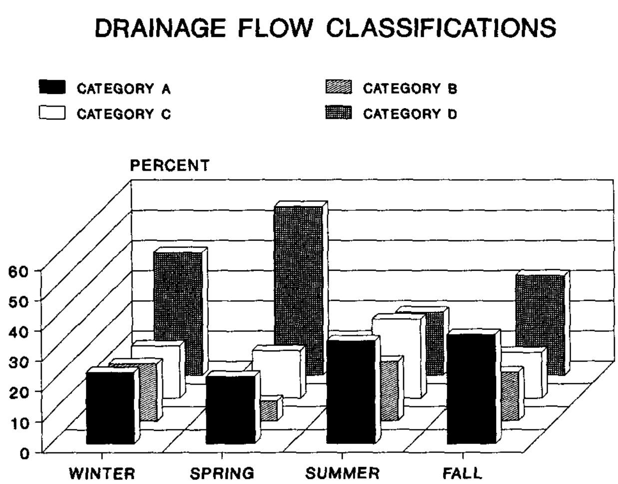

FIG. 4. Seasonal frequency distribution of the drainage-flow categories derived from both sodar and meteorological tower data.

drainage-flow periods that occurred during the summer months. The flows observed over the Grand Mesa were generally highly variable and decoupled from the flows within the valley. Note the merging of the drainage flows over the lower slopes and their subsequent merging with the flows generated within adjacent drainage areas. The variability in the strength of the flows over the upper slopes is believed to be primarily due to the size of the individual source regions and the terrain. Thus, on the southeast side of the valley, the slope flows are relatively strong due to the large Mesa Lakes source area (not shown in the figure) and topographic channeling, while those on the southwest side of the valley are weaker due to a much smaller source region. The corresponding spatial variations of the potential surface temperature gradients observed along the upper and lower slopes during the category A cases for the summer months are shown in Fig. 5b. Note that the gradients are generally near zero along the upper slopes, except for the unusually warm temperatures observed at site 3. These relatively warm temperatures, which are probably correlated with the weak flows observed at that site, are possibly due to a combination of local effects (the tower is situated in a small opening within a forested area) and the limited source region available for drainage-flow development within this part of the study area. At the lower elevations, however, the temperature gradients between the tower locations are about 3 K due to the pooling of cold air from the various drainage areas.

3. Effects of the ambient meteorology

One of the objectives of this study was to evaluate the influence of the ambient winds and atmospheric moisture on the development and characteristics of the nocturnal drainage flows within the valley. It was noted that whenever the ambient winds over the Grand Mesa exceeded 5 m s^{-1}, even well-established drainage flows, particularly along the upper slopes, were significantly affected. Since the flows over the Grand Mesa are predominantly from the southeast, the flows observed over the upper slopes during periods of strong ambient winds over the mesa exhibit a southeasterly cross-slope component, while the flows over the lower slopes appeared to be less affected due to terrain shielding. This is illustrated in Figs. 5c,d which also portray the surface potential temperature gradients between the various tower locations in an analogous fashion to the data of Fig. 5b. It is of interest to note that the temperature gradients along the upper slopes are approximately adiabatic, and the gradients over the lower slopes are somewhat smaller than those associated with well-established drainage flows. This forcing of the flows along the upper slopes is also reflected in the strength of the surface temperature inversion that exists below the drainage-flow jet. Using the average temperature differences observed between the 7- and 18-m levels on the three upper-slope towers, Fig. 6 shows the change in the vertical temperature gradients as a function of the ambient southeasterly wind speeds measured over the top of the Grand Mesa during summertime conditions. Even though there is considerable scatter in the data, an inverse relationship between the vertical temperature gradient and the ambient wind speed is clearly evident. Thus, during periods of weak ambient winds over the Grand Mesa, one observes a relatively strong vertical temperature gradient of about 0.1°–0.2°C m^{-1}, while during periods of strong ambient winds over the mesa, the gradient decreases to about 0.05°C m^{-1}, indicating that the radiative cooling process is unable to develop and maintain the strong surface temperature inversion that is needed to generate the drainage flows. The best analytical fit to the data consist of an exponential component that describes the relationship during calm conditions and an inverse linear relationship for the strong ambient-flow conditions.

The effect of atmospheric moisture on the strength of the drainage flows was investigated somewhat indirectly since moisture sensors were not available for this study. This involved the use of net radiometers for measuring the difference between the incoming and outgoing longwave radiation at the surface at night. This difference, which denotes the extent of the radiative cooling that is occurring at the surface, is governed by a number of factors that include both surface and atmospheric characteristics (Arya 1988; Coulson 1975). These include, for example, the type of vegetative cover, the surface radiating temperature, the vertical temperature distribution in the atmosphere, and the concentrations of atmospheric carbon dioxide and water. The temporal variability in the net radiation measurements at these fixed semiarid locations, however, is primarily due to changes in atmospheric mois-

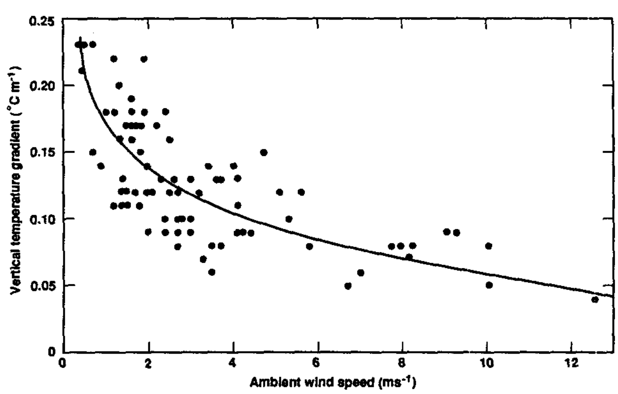

FIG. 6. The effect of the ambient winds over the Grand Mesa on the strength of the vertical temperature gradients derived from the ΔT measurements on the towers situated along the upper slopes. The curve is based on a two component fit to the data that includes an exponential term at low ambient wind speed and a linear term at the high wind speeds.

ture content, both as water vapor and as clouds. The presence of atmospheric moisture increases the downward longwave radiative flux, thus decreasing the net radiation and the subsequent surface cooling rate. Thus, we used the output from the net radiometers as general indicators of atmospheric moisture, and correlated the downslope wind speed along the upper slopes with the net radiation levels. These correlations were performed using data acquired during summertime periods when the ambient winds over the Grand Mesa were less than 1 m s^{-1}, thus minimizing the effect of wind erosion. The results are illustrated in Fig. 7. In spite of the scatter in the data, a linear relationship appears to exist, as shown by the best straight-line curve fit, between the net radiation levels and the average downslope wind speeds measured at the 18-m levels of the three towers situated on the upper slopes. The straight-line fit does not pass through the origin as one might expect due to the data scatter that reflect a wide range of effects that influence the net radiation measurements.

4. Numerical model simulations

To place the measurements shown in Figs. 2–7 in proper perspective for improving our understanding of the dynamics governing the flows observed within the Mesa Creek valley, two different modeling approaches were used. One approach was designed to enhance our ability to account for the general features of the valleywide three-dimensional wind and temperature structure associated with well-established nocturnal drainage flows, while the second approach was directed toward a more detailed analysis of the effects of the ambient meteorology on the flows observed along the upper slopes of the valley.

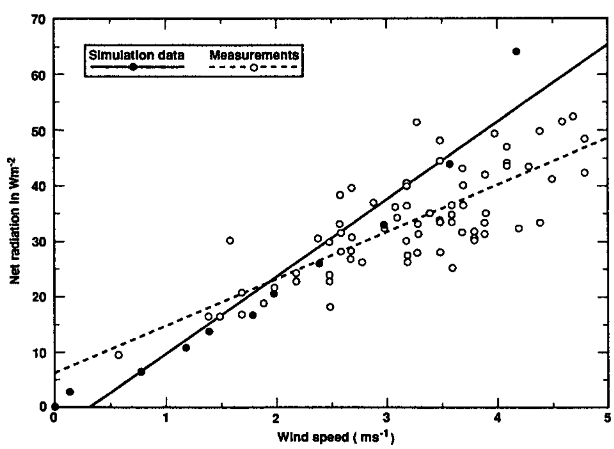

FIG. 7. The measured and model-simulated strength of the drainage flows along the upper slopes of the valley as a function of net radiation. Since the net radiation levels are a strong function of atmospheric moisture, these data provide a general indication of the effect of atmospheric moisture on the strength of the drainage flows.

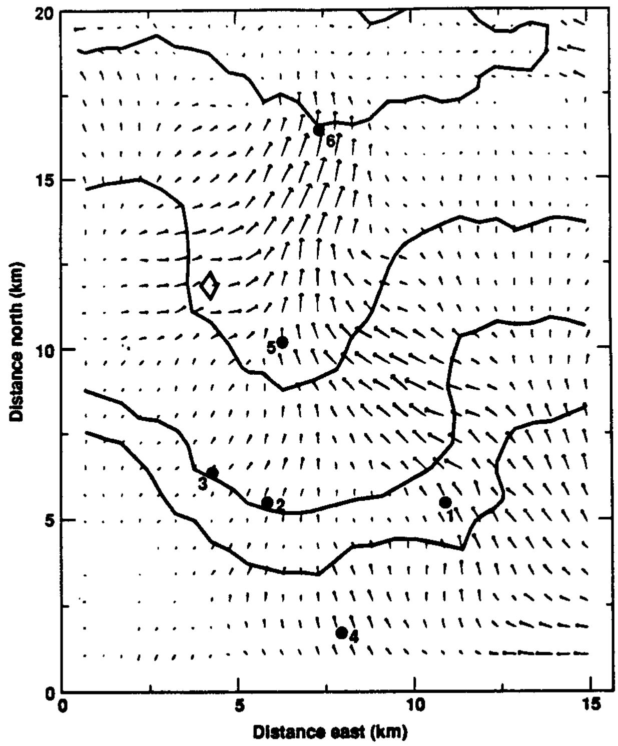

FIG. 8. Model-calculated horizontal wind field at a height of 7.5 m above the terrain. Terrain contours every 400 m, starting at 3000 m, and the locations of the measurement sites are provided for reference.

a. *Valleywide model simulations of drainage flows*

A three-dimensional prognostic boundary-layer model was utilized. The model, described by Leone and Lee (1989), solves the three-dimensional nonhydrostatic, Boussinesq equations of momentum, continuity, and energy with a suitable turbulence parameterization. The finite-element solution technique is employed to approximate the spatial variation of the dependent variables, and the Galerkin technique is used to generate a set of discrete ordinary differential equations that describe the temporal evolution of the solution. These techniques permit considerable flexibility in the design of grid meshes for complex terrain applications. This model simulated the three-dimensional structure of well-established drainage flows during conditions of strong surface cooling and no ambient wind forcing. Thus, the simulation was based on the large-scale geostrophic wind being zero, as was the initial velocity field. The initial potential temperature field was slightly stable, with a vertical gradient of 1 K km^{-1}, and horizontally uniform. The surface cooling rate was assumed to be −40 W m^{-2} and uniform over the entire model domain. The horizontal diffusivity was assumed to be constant with a value of 100 m^2 s^{-1}, while the vertical diffusivity was modeled using a parameterization developed by McNider and Pielke (1981). The model-calculated horizontal wind field, at a height of

7.5 m above the valley's surface, is presented in Fig. 8. Note the excellent qualitative agreement with the primary flow pattern depicted in Fig. 5a. The calculated wind field appears to exhibit three distinct drainage regions along the upper slopes. One originates along the southeast side of the valley, a second from the top of the Grand Mesa, and a third from the west side of the valley with subsequent merging of the individual flows over the lower slopes in a manner that is consistent with the observations. The model predicts stronger flows over the southeastern side of the valley relative to those on the southwestern side, supporting the concept that the strengths of the individual drainage flows are proportional to the areal size of the source regions and the extent of terrain channeling. The vertical temperature structure of the flows along the upper and lower slopes are shown in Fig. 9. A strong surface-based temperature inversion is present over the entire valley due to the radiative cooling process. The largest temperature deficit occurs over the lower slopes, as expected. A review of the vertical temperature profiles at the individual tower sites indicated that the least cooling occurred over the southwestern side of the valley where the flows are the weakest, in concert with the observations. The model-predicted drainage-flow depth of about 200 m over the lower slopes at site 5, however, is about a factor of 2 or more than that observed.

b. *Model simulations of the effects of ambient meteorology on drainage flows*

A one-dimensional second-order closure slope-flow model that includes a detailed surface energy budget, radiative cooling, and a turbulence parameterization was used to evaluate the effects of the ambient meteorology on the wind and temperature characteristics of the drainage flows along the upper slopes of the valley. Since a detailed description of this model was provided by Neff and Ruffieux (1990), only its main features will be discussed here. The model uses the downslope equation of motion that includes 1) the influence of mesoscale pressure gradients for generating down- and cross-slope accelerations, 2) accelerations due to the temperature deficits caused by surface cooling, and 3) the divergence of the vertical turbulent flux of the downslope momentum. The model assumes uniform cooling over the slope, and the slope flow is of uniform depth along the entire slope. The temporal variation of potential temperature is assumed to be dependent on the vertical turbulent temperature flux and the net longwave radiative flux. It uses the second-order turbulence parameterization of Brost and Wyngaard (1978, 1979), where the turbulence length scale is taken as a harmonic mean of the distance from the surface and a local buoyancy scale that reflects a partition of potential energy and vertical turbulent kinetic energy. A surface energy budget is based on a surface slab overlying a substrate as proposed by Blackadar (1976). The radiative cooling module incorporates upward and downward broadband infrared irradiances computed according to the model of Yamada (1983). By accounting for these processes, the model was able to derive a reasonable approximation of the observed relationship between the magnitude of the downslope winds along the upper slopes of the valley as a function of the net radiation levels. This result was based on the use of the average slope of the terrain, an approximation of the valley's surface-roughness characteristics, a typical summer temperature profile during the evening transition period for initialization, and a variance of the atmospheric moisture content in the model to achieve the desired net radiation levels. The calculated and measured winds, shown in Fig. 7, are normalized to a height of 18 m above the surface. One notes generally good agreement even though the slope of the calculated curve is slightly greater than that of the best linear fit to the measurements. Thus, it confirms the notion that the strength of the downslope drainage flows is primarily governed by the surface cooling rate, which in turn is primarily dependent upon the atmospheric moisture content.

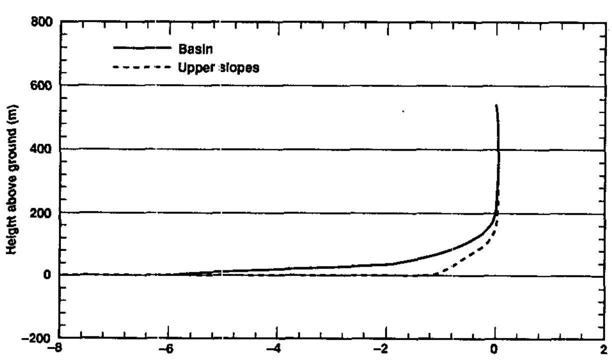

FIG. 9. Vertical profiles of the calculated temperature deficit over the valley's upper slopes (site 2) and the lower slopes (site 5).

The effect of the ambient winds on the characteristics of the drainage flows along the upper slopes of the valley is more difficult to simulate. Since the model is unable to directly impart an ambient wind speed on the slope flows, a mesoscale pressure gradient was imposed to produce a downslope acceleration that simulated the influence of the ambient winds over the Grand Mesa. Thus, by varying the downslope acceleration that would produce ambient winds similar to those observed, it was possible to evaluate their effects on the vertical temperature gradient below the nocturnal jet. The results of these simulations, shown in Fig. 10, may be compared with the measured data in Fig. 6. Note the similarity in the general shape of the curves, indicating the erosion of the temperature inversion with increasing

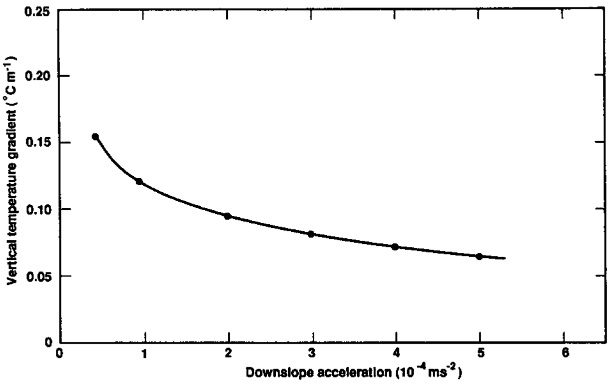

FIG. 10. Simulation of the effect of the ambient winds over the Grand Mesa on the vertical temperature gradients of the drainage flows over the upper slopes by imposing a downslope acceleration due to mesoscale pressure gradients. The general trend in these data may be compared with that in Fig. 6 to show that strong ambient flows may erode the drainage flows.

ambient wind speed. It is apparent that the stronger the ambient flows are, the more difficult it is to maintain the temperature inversion and, thus, the greater is the tendency to override the nocturnal drainage flows.

5. Conclusions

Integration of experimental data acquired from within the Mesa Creek valley with model simulations has yielded the following conclusions in regard to the wind and temperature characteristics of nocturnal drainage flows generated within the valley, their seasonal frequency of occurrence, and the effects of ambient meteorology on their characteristics.

- The radiative cooling of the valley's surfaces at night generated drainage flows along the upper slopes of the valley. The flows from individual slopes converge to form deeper flows over the lower slopes and subsequently merge with the drainage flows from adjacent drainage areas situated outside of this study area. During the summer, the depths of the flows are typically a few tens of meters along the upper slopes and about 100 m over the lower slopes, while during the winter, the corresponding depths decrease to less than 10 and about 60 m, respectively.
- The seasonal frequency of occurrence of well-established drainage flows was highest during the summer and fall months when large-scale synoptic influences were minimal.
- The strength of the drainage flows along the upper slopes during good drainage conditions appears on the basis of the model simulations and is supported by measurements to be related to the size of the source region and terrain channeling.
- The drainage flows along the upper slopes, where terrain shielding is minimal, are greatly influenced by the larger-scale ambient winds over the Grand Mesa. When the southeasterly ambient flows exceeded 5 m s^{-1}, the surface cooling was not able to develop and maintain the temperature inversion needed to generate strong drainage flows.
- The net radiation measurements along the upper slopes were generally correlated with the downslope wind speeds, revealing that increases in atmospheric moisture, which strongly reduces the net radiation levels, will inhibit the development of the drainage flows.
- The main features of the valleywide circulation were reasonably simulated by using a three-dimensional prognostic boundary-layer model that solved the equations of momentum, continuity, and energy with a turbulence parameterization and a surface energy budget to account for the advective and diffusive properties of the atmosphere and surface cooling.
- The effects of atmospheric moisture and strong ambient winds on the characteristics of the drainage flows along the upper slopes were reasonably accounted for by a one-dimensional slope-flow model that incorporates a detailed surface energy budget, radiative cooling, and a second-order turbulence parameterization.

Thus, it is apparent that in order to account for the observations on the basis of the physical processes responsible for generating and maintaining the drainage flows along sloped surfaces and the effects of the ambient meteorology on the drainage flows, it is necessary to resort to numerical modeling concepts that are based on solving the conservation equations of momentum, continuity, and energy with appropriate turbulence and surface energy budget considerations. No simple relationships were found between the wind and temperature fields that could be generalized for use in other valleys.

Acknowledgments. We would like to acknowledge the valuable support provided by K. P. Ellis in installing and maintaining the meteorological towers. We are also greatly indebted to C. A. Russell for her valuable assistance in collecting and analyzing tethersonde and sodar data. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

REFERENCES

Arya, S. P., 1988: *Introduction to Micrometeorology.* Academic Press, 307 pp.

Barr, S., and M. M. Orgill, 1989: Influence of external meteorology on nocturnal valley drainage winds. *J. Appl. Meteor.,* **28,** 497–517.

Blackadar, A. K., 1976: Modeling the nocturnal boundary layer. Preprints, *Third Symp. Atmospheric Turbulence, Diffusion, and Air Quality,* Raleigh, NC, Amer. Meteor. Soc., 46–49.

Brost, R. A., and J. C. Wyngaard, 1978: A model study of the stably stratified planetary boundary layer. *J. Atmos. Sci.,* **35,** 1427–1440.

——, and ——, 1979: Reply. *J. Atmos. Sci.,* **36,** 1821–1822.

Clements, W. E., J. A. Archuleta, and P. H. Gudiksen, 1989: Experimental design of the 1984 ASCOT field study. *J. Appl. Meteor.,* **28,** 405–413.

Coulson, K. L., 1975: *Solar and Terrestrial Radiation, Methods and Measurements.* Academic Press, 322 pp.

Davidson, B., and P. K. Rao, 1963: Experimental studies of the valley-plain wind. *Int. J. Air Water Pollut.,* **7,** 907–923.

Gudiksen, P. H., and M. H. Dickerson, 1983: Executive summary: ASCOT Technical Progress Report FY-1979 through FY-1983, ASCOT 84-2, Lawrence Livermore National Laboratory, 41 pp.

King, C. W., P. H. Gudiksen, and C. A. Russell, 1990: Sodar-derived nocturnal drainage flow classifications. *Proc. Fifth Conf. on Mountain Meteorology,* Boulder, CO, Amer. Meteor. Soc., 244–250.

Leone, J. M., and R. L. Lee, 1989: Numerical simulation of drainage flow in Brush Creek, Colorado. *J. Appl. Meteor.,* **28,** 530–542.

McNider, R. T., and R. A. Pielke, 1981: Diurnal boundary layer development over sloping terrain. *J. Atmos. Sci.,* **38,** 2198–2212.

Neff, W. D., and D. Ruffieux, 1990: The effect of radiative flux divergence and crosswinds on the initiation and structure of nocturnal drainage flows. *Proc. Fifth Conf. on Mountain Meteorology,* Boulder, CO, Amer. Meteor. Soc., 260–265.

Yamada, 1983: Simulation of nocturnal drainage flows by a q^2–l turbulence closure model. *J. Atmos. Sci.,* **40,** 91–106.