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THE BIOCLIMATES OF THE COLORADO FRONT RANGE

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ABSTRACT This paper delineates bioclimatic zones of the Colorado Front Range. It develops a methodology which might be useful for making inventories of mountain bioclimates in other parts of the world. Following a description of the vegetation and the climate of the Front Range some insight is gained into the bioclimatic systems of the area by examining the applicability of established climatic classifications. The main part of the paper explains procedures for distinguishing the bioclimatic zones. The variables employed in determining the zones are the ratio of growing season thawing degree days to growing season precipitation, summer mean temperature, and growing season soil moisture deficit. Aspect is examined as a possible method of determining second order bioclimatic divisions. In attempting to determine the bioclimatic divisions, the study (1) establishes the feasibility of applying existing climatic classifications to the area, (2) identifies important bioclimatic variables, (3) points out the limits of present understanding of the role of aspect in the area, and (4) provides information on the possibility of extrapolating the bioclimatic zones identified in Boulder County to other parts of the Front Range and beyond.

RÉSUMÉ *Les bioclimats des contreforts des Montagnes Rocheuses au Colorado.* Cette étude définit les zones bioclimatiques des contreforts des Montagnes Rocheuses au Colorado, et présente une méthodologie qui pourrait être utilisée, sous une forme ou une autre, pour inventorier les bioclimats montagnards dans d'autres parties du monde. Partant d'une description de la végétation et du climat des contreforts des Rocheuses, l'étude donne un aperçu des systèmes bioclimatiques de la région en examinant l'applicabilité des classifications climatiques actuelles. La majeure partie de cette étude concerne les techniques permettant de différencier les zones bioclimatiques. Les variables utilisées pour déterminer les zones sont le rapport entre les degrés jours de dégel et la précipitation pendant la saison de croissance, la température moyenne pendant l'été, et le déficit d'humidité du sol pendant la saison de croissance. L'orientation est également considéré comme un moyen possible de déterminer les divisions bioclimatiques du second ordre. Cette tentative de détermination des divisions bioclimatiques a permis d'accomplir les tâches suivantes: (1) établir la validité d'appliquer à cette région les classifications climatiques actuelles, (2) identifier les variables bioclimatiques importantes, (3) considérer les limites de la connaissance actuelle sur le rôle de l'aspect dans la région, et (4) obtenir de l'information sur la possibilité d'extrapoler les zones bioclimatiques identifiées dans le comté de Boulder à d'autres parties des contreforts des Montagnes Rocheuses et ailleurs.

ZUSAMMENFASSUNG *Die bioklimatischen Zonen in Colorado's Vorbergen.* Diese Veröffentlichung beschreibt die bioklimatischen Zonen im Gebiet der Colorado Vorberge. Eine Methodik wird entwickelt, die auch für bioklimatische Zonengliederung in Berggebieten anderer Teile der Welt infrage kommt. Nach einer Beschreibung der Vegetation und des Klimas der Vorberge kann man die Anwendbarkeit bestehender klimatischer Klassifikationen überprüfen und so Einblick in die bioklimatischen Systeme eines Gebietes gewinnen. Der Hauptteil dieses Beitrags erklärt die Methodik, die zur Unterscheidung bioklimatischer Zonen angewandt wurde. Die ausgewählten Variablen sind, während der Wachstumsperiode, das Verhältnis der frostfreien Tage zu den Zeiten mit Niederschlag und das Defizit in Bodenfeuchte, und außerdem die mittlere Sommertemperatur. Es wird untersucht, ob die Hanglage eine mögliche, wenn auch nur untergeordnete Rolle bei der Feststellung bioklimatischer Gliederungen spielt. Der Versuch, zu bioklimatischen Einteilungen zu kommen, ergab folgende Einblicke: (1) die Möglichkeit, existierende klimatische Einteilungen für das Gebiet anzuwenden, (2) die Identifizierung der wichtigsten klimatischen Variablen, (3) das beschränkte gegenwärtige Verständnis über die Rolle, die die Hanglage in einem Gebiet spielt, (4) die Anwendungsmöglichkeit der bioklimatischen Zonen—im Landkreis Boulder gewonnen—auf andere Vorgebirgsregionen und darüber hinaus.

INTRODUCTION

The bioclimatic zonation of the Colorado Front Range has long intrigued natural scientists. At the beginning of this century, Francis Ramaley referred to the area that is the focus of the present study as "an excellent natural scientific laboratory" (Ives, 1980). Seventy years later Ives described the sequence of vegetation belts rising from the short grass prairie of the high plains to the alpine tundra close to the Continental Divide as being nothing less than "spectacular". Indeed, he pointed out that the vegetational transition across an east-west distance of barely 25 km is equivalent to a northward journey in the latitudinal sense of some 2,500 km (Ives, 1980). The present study primarily employs that part of this "natural scientific laboratory" which lies in Boulder County (Figure 1) to gain a further understanding of the bioclimatic systems that exist therein, by means of an exercise in delimiting bioclimatic zones. The exercise also represents a means of inventorying the bioclimates of the area—a process that is, with a few exceptions (Gams, 1984), rarely undertaken, yet is so important to effective resource management. As such, the study may serve as a model which might be followed or form the basis for adaptation for other mountain areas of the world where development is in progress or is likely.

The delimitation of bioclimatic zones is similar in many ways to the process of climatic classification. Much of the theory (Hare, 1951) and many of the techniques of climatic classification are relevant here. This study approaches climatic classification under the restriction, however, that atmospheric factors may be specified only by using generally accessible observational data and no special measurements, such as direct energy budget observations, are required. This restriction will allow the methods employed in this study to be used in mountain areas of the world where usually meteorological data are very sparse.

VEGETATION ZONES IN THE FRONT RANGE

Several investigators have made important contributions in the description of the vegetation zones of the Front Range (Marr, 1961; Löve, 1970; Barry and Ives, 1974). The vegetation classification used in this paper follows the later work of Peet (1981).

Peet derived a model of the forest composition from elevation and topographic conditions inferring moisture gradients. His model is originally presented in a two-dimensional form with vegetation distribution plotted against a moisture gradient which is essentially represented by aspect. In this study Peet's model is collapsed to a one-dimensional form by considering only the altitudinal vegetation distribution described by Peet for open slopes aligned in an east–west orientation. Under these circumstances the following six vegetation zones may be distinguished.

The lowest elevational community series is the Grassland and Shrubland zone (Zone I) consisting predominantly of graminoides (Figure 2). A sharp boundary exists between Zone I and the next higher community series which begins at 1,650 m. Larsen (1930) has attributed the presence of grasses to their association with finer textured soils while the Ponderosa pines are found on coarser soils. The next zone is the Ponderosa (*Pinus ponderosa*) woodland (Zone II). This series occurs on the dry lower slopes of the foothills of the Front Range, and generally does not exceed 2,300 m, except on the most exposed sites. The forest type consists almost exclusively of *P. ponderosa*. The *Pinus ponderosa pseudotsuga* forest series which may be termed the Ponderosa–Douglas Fir zone (Zone III) is found on east–west oriented slopes between 2,300 and 2,550 m. It is also found on the more moist sites in the foothills and at slightly higher elevations, up to 3,100 m. The Lodgepole Pine (*Pinus contorta*) forest (Zone IV) is a transition zone found between 2,550 and 3,150 m. It is dominated by extensive even-aged stands of *P. contorta,* with *Populus tremuloides* being co-dominant on some sites. In his description of disturbances to the forests of the Front Range, Peet (1981: 9) notes that Lodgepole pine (*Pinus contorta*) is believed to become established following fire. This possibility recognizes that the role of disturbance of vegetation should be acknowledged in a study of the present kind. Higher in elevation is the Spruce–Fir forest (Zone V). This zone, between 3,150 and 3,500 m, is dominated by *Picea engelmannii* and *Abies lasiocarpa* and corresponds fairly well with the subalpine forest as defined by Marr (1961), but it also includes most of the forest–alpine ecotone. The upper limit of this forest type is the treeline or, more specifically, the upper part of Marr's subalpine forest–alpine ecotone or Löve's (1970) subalpine zone. The alpine tundra (Zone VI) is composed of fell-fields and meadows and is characterized by the strong influence of microclimate particularly as manifested by soil moisture gradients and duration of snowpack.

THE CLIMATE OF THE FRONT RANGE

The climate of the Front Range is controlled by its mid-latitude and interior continental location. This combination leads to a climate subject to extremes of temperature and to the impact of several fundamentally different types of air masses. Detailed climatographies of the area have been given by Barry (1973) and Hansen *et al.* (1978). Further useful descriptions of aspects of Front Range climate are provided by James (1966), Greenland (1978), and Barry (1984).

The present study uses principally climatic data from four stations in Boulder County from which almost continuous records for the period 1952–1982 are available (Table 1). The stations included are the U.S. Weather Bureau stations at Longmont and Boulder, and the University of Colorado stations of Como (C1) and Niwot Ridge (D1) operated by the Institute of Arctic and Alpine Research (INSTAAR) (Department of Commerce, 1952–82; Barry, 1972; Losleben, 1983). Data from two lower INSTAAR stations were discarded due to breaks in the precipitation record. It is also known that some of the pre-1965 data for the D1 station are unreliable—the unreliability being associated mainly with the difficulty of winter access and the lack of wind shields for the precipitation gauges. Misrepresentation in the present analyses due to this unreliability is minimized by a concentration on variables based on observations taken from seasons other than winter. Further, where winter precipitation values from the pre-1965 period are used, a correctional adjustment

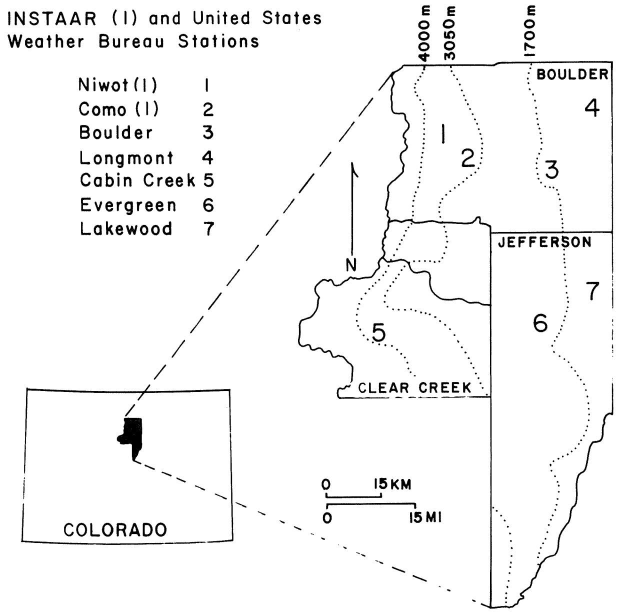

FIGURE 1. The location of the meteorological stations in Colorado used in the present study.

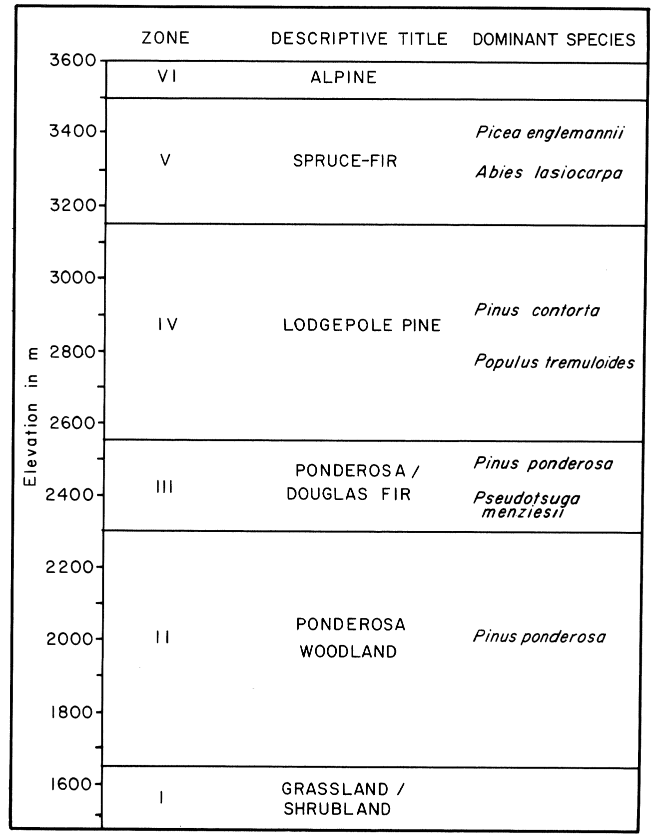

FIGURE 2. Vegetation zones in the study area.

has been made (see section on the Effect of Aspect). Elevational and geographic data for the stations are presented in Table 1. Monthly mean or total data were extracted for maximum and minimum and daily mean temperature and precipitation totals. A number of secondary parameters were derived from these data and are listed in Table 2. As mentioned above, a guideline was that only data that are readily available in most parts of the world would be employed in the bioclimatic division so as to maximize the possibilities for its wider use.

CLIMATE CLASSIFICATION IN THE FRONT RANGE

There are many existing climatic classifications which attempt to relate climatic variables to vegetation. Previous attempts to apply global climatic classifications to the smaller geographic areas of mountains, where there is spatial heterogeneity of climate due to altitudinal variation, have often provided insights both into the bioclimatic systems of the study area and, in some cases, into the applicability of the classifications themselves (Holdridge, 1947; Daubenmire, 1956).

The classification schemes of Köppen, as modified by Trewartha (1957), Thornthwaite (1931, 1948), Holdridge (1947), and Papadakis (1966) were applied here and others were also considered. The results of applying the first four of these classifications to the four Boulder County stations are seen in Table 3. The Köppen classification is difficult to apply to the Longmont station where the precipitation value falls directly between the Steppe and Desert subdivisions. When applied to Front Range stations outside Boulder County, the scheme classifies Evergreen, which is clearly situated in Ponderosa pine woodland, as being in a Steppe climate. More importantly, the Köppen classification has always been enigmatic in separating B climates in terms of aridity while the other four are characterized by temperature. In an area such as the Front Range, where temperature is an important factor at the higher elevations and aridity is important at the lower elevations, it would be preferable to use a classification that treated temperature and aridity (or precipitation) as continua rather than as discrete variables.

The 1931 Thornthwaite classification places Longmont and Boulder in separate climatic regions (Longmont–Steppe, Boulder–Grassland). There may be a vegetational basis for this as evidenced by the existence of tallgrass prairie remnants near Boulder (Moir, 1972). It is more likely, however, a problem with the classification itself since the other Front Range stations, Lakewood, and the high elevation stations of Evergreen and Cabin Creek, all are classified in the grassland climatic region. In addition, it classifies the very different Lakewood and Evergreen localities as being climatically identical. One of the major difficulties with this classification is the doubtful method by which evaporation is estimated. This problem appears to be exaggerated in the Front Range situation. The 1948 Thornthwaite classification places all the Boulder County

TABLE 1
Location and elevation of climate stations in the study

Station	Elevation (metres)	Latitude (north)	Longitude (west)	Years of record
Colorado, Boulder County				
Longmont	1508	40°10′	105°04′	1952–82
Boulder	1638	40°02′	105°16′	1952–82
Como (C1)	3048	40°02′	105°32′	1952–82
Niwot Ridge (D1)	3749	40°03′	105°37′	1952–82
Colorado, Clear Creek and Jefferson counties				
Lakewood	1707	39°45′	105°08′	1969–82[1]
Evergreen	2134	39°38′	105°17′	1968–81[2]
Cabin Creek	3048	39°39′	105°42′	1968–82[3]
Wyoming, Albany County				
Laramie 2 NW	2176	41°20′	105°30′	1975–81
Centennial Ranger Station	2573	41°18′	106°09′	1975–81
Telephone Lakes	3277	41°22′	106°16′	1975–81

[1] 12 years from this period.
[2] 7 years from this period.
[3] 8 years from this period.

stations in different and reasonable climatic zones and it is also more effective in noting the difference in the other Front Range stations. However, it fails to distinguish between Lakewood and Evergreen in terms of moisture (both are Dry Subhumid) and between Evergreen and Cabin Creek in terms of thermal properties (both being Microthermal). An extrapolative method has to be employed to obtain a value of the Heat Index (I) for the high-altitude stations when this classification is used. There also exist all of the doubts surrounding the Thornthwaite method of estimating potential evapotranspiration (Sibbons, 1962). More importantly, compared to many of the other classification systems examined here, the 1948 Thornthwaite system is difficult to utilize because of the large number of calculations required in its application. Nevertheless, this still remains one of the simplest methods by which the important soil moisture variable may be taken into account, and its method of estimating soil moisture deficits is used below.

The Holdridge Life Zone model (Holdridge, 1947, 1967; Holdridge *et al.*, 1971) uses mean annual biotemperature and average annual precipitation as a basis for a climatic classification of life zones on a global scale. Mean annual biotemperature is computed as the mean temperature of those months whose average temperature is greater than 0°C and below 30°C. The system is further divided into associations differentiated by local environmental conditions. A third part of the classification entails the subdivision of associations by means of the actual vegetation cover. Holdridge assumes that vegetation has adapted through evolution to existing environmental conditions of an area. The ability of the Holdridge scheme to display environmental gradients graphically makes the approach potentially attractive for the present study.

TABLE 2
Variables used in discriminant and principal component analysis

Variable	Abbreviation
Annual mean temperature	ANTEMP
Winter mean minimum temperature	WTMIN
Spring mean minimum temperature	SPTMIN
Summer mean minimum temperature	STMIN
Fall mean minimum temperature	FTMIN
Winter mean maximum temperature	WTMAX
Spring mean maximum temperature	SPTMAX
Summer mean minimum temperature	STMAX
Fall mean maximum temperature	FTMAX
Winter mean temperature	WTMEAN
Spring mean temperature	SPTMEAN
Summer mean temperature	STMEAN
Fall mean temperature	FTMEAN
Winter precipitation	WPPT
Spring precipitation	SPPPT
Summer precipitation	SPPT
Fall precipitation	FPPT
Growing season precipitation	GSPPT
Number of growing season months	GSMO
Growing season thawing degree days	GSTDD
Freezing degree days	FDD
Annual precipitation	ANPPT

Note: Winter, spring, summer, and fall are defined as the months of December to February, March to May, June to August, and September to November, respectively. The seasonal mean temperature is taken as the mean of the monthly mean temperatures of the months in a particular season. Growing season is defined as all the months with a mean daily minimum temperature >0°C. Growing season thawing degree days (GSTDD) is defined as the sum from the first growing season month to the last growing season month of the product of the monthly mean minimum temperature for a particular month and the number of days in that month.

Table 3
Classification of Front Range stations by recognized classification systems

	Longmont	Boulder	Como (C1)	Niwot Ridge (D1)
Köppen	BSk or BWk Dry Steppe cold or Dry Desert cold	BSk Dry Steppe cold	Dwc Snow climate; Dry winter; Cool short summer	ET (H) Polar Tundra due to high altitude
Thornthwaite (1931)	DC'dc Semiarid; Microthermal Moisture deficit in all seasons; Summer precip. concentration	CC'db Grassland; Microthermal Moisture deficit in all seasons; Summer precip. concentration	BD'rc Humid Forest Taiga; Abundant moisture; Summer precip. concentration	AE'rd Wet Rainforest; Tundra; Abundant moisture; Summer precip. concentration
Thornthwaite (1948)	$EB'_1db'_3$ Arid; Mesothermal; No water surplus	$DB'_1db'_4$ Semiarid; Mesothermal; Little water surplus	$B_4C'_1rb'_1$ Humid; Microthermal; Little water deficit	$AD'rc'_1$ Perhumid Tundra; Little water deficit
Holdridge	Cool; Temperate; Montane; Perarid	Cool; Temperate; Montane; Perarid	Boreal; Subalpine; Arid	Subpolar; Alpine; Arid

The Holdridge model has been tested in southwestern Colorado in the San Juan Mountains (Thompson, 1966). It was found to delineate vegetation and climatic types on a general basis. Thompson suggested, however, that biotemperatures should be derived from daily data since it was suspected that annual biotemperatures computed from monthly mean values are underestimates of the true value in mountainous terrain. Holdridge *et al.* (1971) also suggested the use of daily data but recognized that such data would often be unavailable. Another problem in applying the Holdridge model lies in the apparent lack of a physical basis for the choice of the value of 58.93 as the factor used in multiplyng the mean annual biotemperature to calculate the mean annual evapotranspiration. Finally, the Holdridge assumption of the attainment of evolutionary adaptation to climate may not hold in the Boulder area. Consequently, the use of this scheme was not pursued further.

Daubenmire (1956) attempted, with little success, to apply the four preceding climatic classifications to the western sides of mountain ranges in Washington and Idaho. He was forced to use climographs with resolution of the first and second six months of the year in order to seek clear relationships between observed vegetation and climatic zones. His techniques were employed in the initial stages of the present study to assess differences and similarities among the four stations of Boulder County.

The Papadakis (1966) classification places emphasis on average daily maximum and minimum temperatures, the water budget, the inter-relationship of humid, intermediate, and dry seasons within a year, and the recognition of the importance of the climatologic growing season to develop a crop–ecological classification. The classification was originally developed for facilitating the transfer of agricultural crop species from one location to another. While it is recognized that the majority of vegetation zones encompassed in the Front Range are not associated with agricultural crops, the biological significance of the climatic parameters employed by Papadakis was considered carefully in the selection of potential variables for input into the present exercise. The same holds true for the important, and again globally oriented, bioclimatic classification of Box (1981).

BIOCLIMATIC DIVISION

The application of earlier climatic classifications to the Front Range indicates that while some had certain advantages none was entirely appropriate. Possibly more important in developing an understanding of the Front Range bioclimatic system is an attempt to develop a new system of division.

Procedure for Development

A two-step procedure for developing such a system was employed by first using a statistical filter and then applying a biological filter to the potential variables that might be taken into the scheme. The variables that survived these filters were then graphed against the vegetation zones of different altitudes. The points of intersection of the variables with the vegetation zone boundaries were taken as the major factors in determining the first-order bioclimatic boundaries. A second-order division that effectively incorporates the effect of aspect was also considered but was not developed because it is not yet clear what actual effect aspect has in the study area. It is recognized that the vegetation zone boundaries are often not discrete in reality. The approach used here treats them as if they were distinct because the alternative of establishing bioclimatic boundaries with the equivalent of "ecotones" would introduce unnecessary complexity at this stage.

The statistical filter was applied as follows. First, principal component and discriminant analyses were applied to all of the direct and generated variables listed in Table 2. Water-budget-related parameters were assumed to be important, following the work of Box (1981), and were carried directly into a later stage of the analysis. The statistical analysis was applied simply to identify those variables, or groups of variables, that were *statistically* different between the four climate stations in Boulder County. The principal component analysis was unsuccessful because of the high intercorrelation between the direct variables and the derived variables. The discriminant analysis was more helpful in determining the climatic variables that accounted for the variation in the data between the four stations. The more important variables in order of importance were: annual mean temperature (ANTEMP), fall mean minimum temperature (FTMIN), winter mean minimum temperature (WTMIN), growing season thawing degree days (GSTDD), spring precipitation (SPPPT), summer mean minimum temperature (STMIN), growing season precipitation (GSPPT), duration of growing season in months (GSMO), freezing degree days (FDD), fall mean maximum temperature (FTMAX), and mean winter temperature (WTMEAN). This analysis provides a helpful initial guide. However, it is well known that discriminant analysis is seldom conclusive (Johnston, 1978).

The second filter provides further scrutiny of possible inter-relationships. The same variables were subjectively evaluated on the basis of the investigators' knowledge of specific plant/climate relationships. Those variables felt to be of biological significance were kept in the analysis. Those variables that appeared to have little biological significance, or effectively duplicated information (such as winter minimum and winter mean temperatures), were eliminated from further consideration.

After the application of the above filters, which demonstrated the importance of the parameters growing season precipitation and thawing degree days, together with summer mean temperature, and with the addition of water-budget-related parameters, the remaining variables for graphing against the vegetation zones were: annual potential evapotranspiration (AN PET), annual actual evapotranspiration (AN AET), growing season moisture deficit (GSMDEF), growing season precipitation (GSPPT), growing season thawing degree days (GSTDD), and summer mean temperature (STMEAN). The three water-budget parameters were computed using the standard techniques presented in Thornthwaite and Mather (1957) with a soil moisture field capacity of 100 mm at all sites. The value of 100 mm field capacity is based on measured field capacities of about 15 percent by weight in the alpine soils of the Southern Rockies (Webber *et al.*, 1976: 225) and an assumption that only the upper 30 cm of soil is involved in evapotranspiration. The data for these graphs are shown in Table 4. The graphs fell into two categories. One category, composed of the variables summer mean temperature and growing season moisture deficit, showed decreasing values of the variables with altitude over all the zones. A second category which included the other four variables listed above displayed a similar relationship except for the lower elevational part of the graph. Here lower air temperatures at Longmont, compared to Boulder, caused an "inversion" in the graphs of all four variables. Without discussing the topoclimatic factors that might lead to the lower temperatures at Longmont, the presence of the inversion renders these variables, by themselves, unsuitable for making altitudinal divisions in climate. However, a combina-

TABLE 4
Front Range bioclimatic data

Station	Elevation (m)	AN PET (mm)	AN AET (mm)	GSMDEF (mm)	GSPPT (mm) T mean	GSPPT (mm) T min
Longmont	1508	613	345	268	299	232
Boulder	1638	647	445	202	432	324
Como	3048	370	351	19	371	217
D1	3749	270	261	9	247	189

Station	Elevation (m)	GSTDD T mean	GSTDD T min	STMEAN °C	GSTDD/GSPPT °C/mm T min
Longmont	1508	3641	1535	20.9	6.62
Boulder	1638	4103	1999	20.3	6.16
Como	3048	1405	355	10.5	1.63
D1	3749	710	265	5.5	1.40

AN PET = annual potential evapotranspiration.
AN AET = annual actual evapotranspiration.
GSMDEF = growing season moisture deficit.
GSPPT = growing season precipitation (growing season is defined as all the months with a mean daily or daily minimum temperature >0°C).
GSTDD = growing season thawing degree days.
STMEAN = summer mean temperature.

tion of two of the variables in the form of the ratio growing season thawing degree days to growing season precipitation (GSTDD/GSPPT) produces a relationship in which the value of the ratio consistently decreases with altitude (Figure 3). This is an attractive ratio because it combines two biologically significant variables. Also, if there is a relationship between air temperature and available radiative energy (Sellers, 1965: 172) or, more specifically, between growing season thawing degree days and net radiation, then there is an analogy to Budyko's (1958) Radiational Index of Dryness. Thus, three variables emerge from this analysis that are potentially useful for making first order bioclimatic divisions.

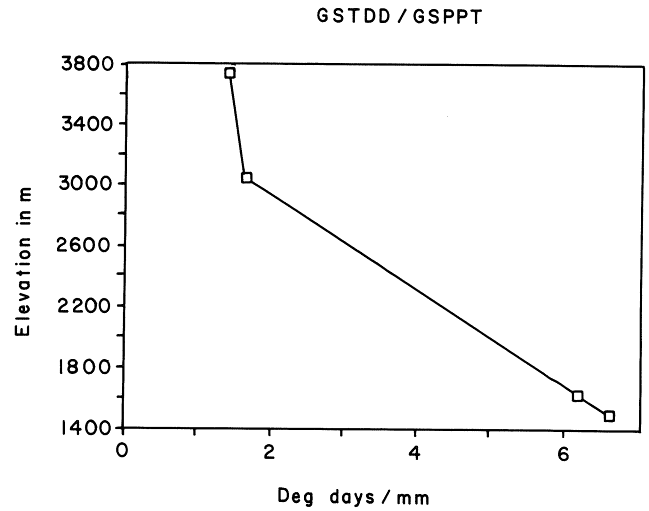

Figure 3. The variation with elevation of the ratio of growing season thawing degree days to growing season precipitation (GSTDD/GSPPT) in Boulder County.

The Effect of Aspect

It was originally intended to use aspect, or some derivative thereof, as a second order factor in the proposed bioclimatic zonation scheme. There are good reasons for believing aspect plays a major role in the bioclimatic systems of the Front Range. Vegetational differences exist between north- and south-facing slopes in Zones II and III although such differences are less marked in the upper zones. Possibly more important, aspect, directly or indirectly, plays a fundamental part in Peet's vegetation model. In this model the horizontal scale represents a moisture gradient which, principally through potential radiation, is related to aspect. Furthermore, major vegetation variations, both in the model and reality, appear to be related to this moisture gradient/aspect variable. Thus, an examination of the effect of aspect using available climatic observations and other data is warranted.

Part of Marr's (1961) original examination of the Front Range ecosystems involved the establishment of climate stations supplementary to the principal altitudinal stations. Near each of the latter three other stations were located, one on a north-facing slope (which was assigned the number 2), one on the south-facing slope (3), and one in a nearby valley location (4). Records were taken, therefore, for 16 stations during 1952–53. The records of monthly means of daily maximum, minimum, and mean temperature and monthly precipitation totals for the Niwot Ridge stations (D1–4) and the Ponderosa stations (A1–4), where A1 is at an elevation of 2,195 m, were first subjected to Student's t tests. Prior to the analysis, precipitation values for winter months at the D stations were multiplied by 1.5 in an attempt to allow for the fact that the precipitation gauges were not shielded in the first few years of the record and were subsequently found to have underestimated the catch of snowfall (Barry, 1973). None of the Student's t tests showed any significant difference between the four sets of records at either the A or the D stations. However, this is not an entirely appropriate statistical test to apply because it assumes normal distribution of the observed values and also physical independence of the sets of records. Neither of these assumptions is fulfilled in this case. Visual inspection of the mean monthly temperature records for both the A and D stations (Marr, 1961) suggests that aspect plays a rather small role at both sites. The temperatures in the valley site at the A stations are about 3°C lower than those at the other three sites at this location, a fact first recorded by Barry (1973). This phenomenon is more related to the special topoclimate of deep valleys rather than to aspect. Cold-air drainage at the A stations may account for the lower temperatures in the valley. At the D stations more frequent high wind conditions may overshadow the cold air drainage phenomenon. Both Marr (1961) and Peet (1981) identify unique vegetation assemblages for the valley areas of the Front Range, but this is not a topic which will be discussed in detail here.

Peet (1981) infers that it is available soil moisture rather than aspect *per se* which, along with altitudinally-related parameters, determines the vegetation distribution. He indirectly derived a soil moisture index from a consideration of potential solar radiation receipt and degree of site exposure. He did not take into account precipitation values. In the present analysis, potential direct solar radiation values for the A and D stations were computed using the method of Garnier and Ohmura (1968). Ridge sites (A1, D1) and valley sites (A4, D4) were assumed to have zero slope gradient while the north-facing sites (A2, D2) and the south-facing sites (A3, D3) were assigned slope gradients of 10° which is representative of slopes immediately either side of the east–west transect. The resulting absolute values of the potential radiation (K) to precipitation (PPT) ratio (Table 5) have a wide range due to the occurrence of high numbers during months of low precipitation amounts. Nevertheless, the values tend to vary closely and in the same direction at all four sites at the A and D locations. Thus, using the methods employed here, it is not possible to detect noteworthy differences in the values of climatic variables in association with aspect differences.

This is not to say that aspect related differences do not exist. It may be that more sophisticated methods are required to detect them. Furman (1978), for example, working with temperature data from seven mountain stations

TABLE 5

Selected aspect data from Front Range stations. Suffixes 1, 2, 3, and 4 refer, respectively, to ridge, valley, north-facing, and south-facing meteorological sites. K is potential global solar radiation (MJ/sq. m./day) and PPT is precipitation (mm) at site

Month	A1 K/PPT	A2 K/PPT	A3 K/PPT	A4 K/PPT
Jan.	0.66	0.48	1.06	0.66
Feb.	0.42	0.27	0.46	0.44
Mar.	0.38	0.31	0.43	0.38
Apr.	0.42	0.35	0.45	0.42
May	0.36	0.33	0.39	0.33
June	0.72	0.69	0.69	0.77
July	0.33	0.36	0.34	0.46
Aug.	0.38	0.32	0.40	0.33
Sept.	10.52	10.33	9.36	4.21
Oct.	1.73	1.17	2.40	1.73
Nov.	0.19	0.14	0.29	0.25
Dec.	0.42	0.37	0.73	0.37
Mean	1.38	1.26	1.42	0.86
Month	**D1 K/PPT**	**D2 K/PPT**	**D3 K/PPT**	**D4 K/PPT**
Jan.	0.08	0.07	0.06	0.08
Feb.	0.26	0.18	0.14	0.12
Mar.	0.23	0.17	0.14	0.15
Apr.	0.31	0.21	0.22	0.19
May	0.21	0.18	0.17	0.18
June	0.43	0.41	0.56	0.43
July	0.29	0.27	0.35	0.30
Aug.	0.32	0.30	0.37	0.28
Sept.	1.12	1.03	1.56	1.20
Oct.	2.02	2.35	3.61	1.73
Nov.	0.21	0.11	0.15	0.12
Dec.	0.09	0.06	0.08	0.06
Mean	0.46	0.45	0.61	0.40

in Idaho applied time series analysis and probability analysis. He concluded that terrain-induced variation was contained in seasonal means and not in the series of deviations from the sample mean. Joseph (1973) reached similar conclusions for the east slope of the Colorado Front Range. Neither investigator considered precipitation. Some studies have detected aspect-related differences in climatic variables of the Front Range, especially at the higher elevations (Isard, 1984). The present examination suggests that relatively simple quantitative techniques do not readily display aspect-related differences that can be easily assimilated into a bioclimatic zonation scheme. Future studies on the relationship between aspect and vegetation distribution should measure directly more important biological variables such as soil moisture.

Bioclimatic Zonation of the Front Range

Summer mean temperature, the ratio of growing season thawing degree days to growing season precipitation, and growing season soil moisture deficit were identified as being potentially usable for making bioclimatic divisions of the Front Range. Several possibilities exist concerning how the values of these variables could be fitted to the vegetation zones. First, a linear interpolation could be used between observed data points (as demonstrated in Figure 3); second, a curve could be fitted by hand between the data points; third, a curve could be fitted by standard curve-fitting procedures between the data points. Little information is available on the question of whether linear or curvilinear interpolation is most appropriate. With respect to temperature values, Barry (1973) reports that a normal lapse rate (*i.e.*, linear) of temperature exists during the day but that there is a tendency for the topographic lapse rate to be affected by local conditions at night. Conolly (1977, 1979) found that although temperatures at the A, B, and C stations might be explained in terms of normal lapse rates there appeared to be a marked discontinuity between the temperatures at the C and D stations. This might be because of the distinct microclimatic change across the tree-line area as partially noted by Hansen-Bristow (1981). Barry (1973) also reports that the vertical distribution of precipitation varies markedly with season but, owing to the small amount of data available from the A and B stations, the actual pattern is still not clear cut.

Given these uncertainties in both the data and the lack of detailed knowledge of the physical processes at work, it was decided to minimize the general uncertainty as much as possible by fitting curves statistically to the altitudinal variation of the three variables. Cubic splines were fitted to the three data sets. In most cases the limits of the bioclimatic zones were obtained by taking the intersection point of the climatic variables as described with a cubic spline with the vegetation boundary presented in Figure 2. There were a few cases where the result of interpolation with a cubic spline was not physically plausible. In these cases linear interpolation was used to provide the boundary values. These cases and the boundary values themselves are presented in Table 6 which represents a systematic delimitation of the bioclimatic divisions of the Front Range in Boulder County.

Extrapolation of Bioclimatic Zonation

Although there is a lack of truly comparable data, certain insights may be gained into the bioclimates of the Front Range by examining the degree to which the bioclimatic zones identified above are applicable outside the area for which they were developed. Data from Clear Creek and Jefferson counties, south of Boulder County, and from the Snowy Mountain Range in south-central Wyoming (Rechard and Smith, 1972; Wesche, 1982) are selected for examination. Stations from both areas suffer from brevity of climatic record (Table 1). In addition, there are many breaks in the Wyoming records. Computations were made of the values of the variables STMEAN, GSMDEF, and the ratio GSTDD/GSPPT for the Colorado (Clear Creek and Jefferson counties) and Wyoming stations listed in Table 1. The resulting values and the bioclimatic zones in which they place the stations are given in Table 7.

Bioclimatic zones identified by the bioclimatic variables for the Colorado stations correspond quite well to the actual vegetation zones. In two out of three cases the GSTDD/GSPPT ratio is able to identify the actual vegetation zone. The other two variables correctly identify the vegetation

Table 6
The bioclimatic zones of the Front Range

Altitude limits (m)	Zone number	Descriptive title	GSTDD/GSPPT (degree day/mm)	STMEAN (°C)	GSMDEF (mm)
Above 3500	VI	Alpine	Less than 1.48*	Less than 7.4	Less than 13*
3150–3500	V	Spruce–Fir	1.49 to 1.57	7.5 to 9.9	14* to 17*
2550–3150	IV	Lodgepole pine	1.58 to 2.81	10.0 to 14.3	18* to 83*
2300–2550	III	Ponderosa/Douglas Fir	2.80 to 3.66	14.4 to 16.2	84* to 116*
1650–2300	II	Ponderosa woodland	3.65 to 6.12	16.3 to 20.2	117* to 196
Below 1650	I	Grassland/Shrubland	Greater than 6.12	Greater than 20.2	Greater than 196

*Values determined by linear interpolation rather than by cubic splines.

Table 7
Bioclimatic zonation of selected stations (units of bioclimatic variables are as in Table 4)

	Zonation by bioclimatic variable (and value of variable)			
Station	STMEAN	GSMDEF	GSTDD/GSPPT	Actual vegetation zone
Lakewood	I (20.9)	I (226)	II (6.00)	I
Evergreen	III (16.0)	II (164)	II (4.45)	II
Cabin Creek	IV (12.3)	IV (63)	IV (2.82)	IV
Laramie 2 NW (Lagoons)	III (15.3)	I (207)	I (6.53)	I
Centennial Ranger Station	III (14.6)	II (138)	II (4.40)	I
Telephone Lakes	IV (10.5)	IV (43)	IV (1.80)	V

zone at Evergreen, Cabin Creek, and Lakewood. This correspondence is good considering the many microclimatic factors operating at the individual sites. The temperature records at the Cabin Creek station, for example, are taken over concrete in fairly close proximity to the buildings of a hydro-electric power site. With respect to the Wyoming data much less may be said with confidence. Here both the GSMDEF and the GSTDD/GSPPT ratio variables miss the presumed Spruce–Fir vegetation zone (V) by one category but correctly identify the grassland zone. The STMEAN variable appears unable to characterize the actual vegetation zones in Wyoming. This may be due to microclimatic factors—particularly cold-air drainage. The higher latitude of the Wyoming sites may also have some effect in the case of the Laramie 2 NW and Centennial Ranger Station sites. Possibly more important, however, it is questionable whether the vegetation zones as described for the Boulder County area are directly applicable to the Wyoming area (Riebsame, pers. comm., 1985).

As might be expected therefore, the bioclimatic zones that describe the Boulder County part of the Front Range show close parallels in part of the Range to the south. However, extrapolation of the zones into southern Wyoming is more difficult. There is some reason to believe that all three variables employed here are effective in identifying bioclimatic zones but further studies are required to determine how widely they are applicable.

DISCUSSION

The selection of variables for the bioclimatic zonation of the Front Range is important both for the variables that were chosen and, to a lesser extent, for those potential variables that were finally omitted. All three variables selected are able to distinguish the bioclimatic zones of Boulder County in an unambiguous fashion and to relate to the biological processes occurring in the zones. Summer mean temperature is an index of the ambient temperature of the plant and controls the rate of biochemical processes in the plant at the time of its maximum growth rate and photosynthetic activity. Barry (1984) reports a correlation coefficient of 0.98 between summer daily mean temperatures at Niwot Ridge (D1) and the sums of cumulative deviations from the average daily mean temperature—an index proposed by Myers and Pitelka (1979) as an integrated measure of summer warmth. Growing season soil moisture deficit directly affects the plant's ability to absorb moisture and nutrients from the soil. However, this may not be such an optimal variable as the other two. The method used here for computing GSMDEF did not really allow for the fact that the vegetation in the four forest zones, especially the Ponderosa woodland, may obtain its moisture from quite deep in the soil. The use of surface soil moisture recognizes the importance of its role in seedling germination and survival. However, the necessary computations for evaluating water-budget parameters are quite time consuming and it may be argued that this variable would not be easily accessible to a biologist with little training in climatology. The GSTDD/GSPPT ratio, on the other hand, is easily computed. More importantly, it combines indices of the two most important factors with respect to plant development during the growing season—heat and moisture. Moreover, it does so in the sense of treating soil moisture availability. Although it does not do this in as direct a manner as Budyko's Radiational Index of Dryness, it clearly relates to soil moisture availability and partially duplicates information contained in the GSMDEF variable. It is possible, therefore, that the latter may be omitted. A particular advantage of the GSTDD/GSPPT ratio is that it combines in one variable an important fact of Front Range bioclimate: namely, that with increasing altitude, temperature is increasingly important while precipitation is decreasingly important.

Further information on the bioclimatic systems of the Front Range may also be obtained from considering some of the variables not brought into the final analysis in this study. The absence of radiation variables in the first order division testifies not to their lack of importance but more to a lack of observational and/or fine grid information on any radiation variables other than potential shortwave radiation. There is probably enough cloud cover variation to give rise to statistically significant variation in radiation receipt in the area and there are certainly large albedo variations. The relation of the components of the radiation balance to the vegetation zones of the study area would be a worthwhile investigation. Even more important would be a parallel study with respect to the question of aspect and vegetation. A second variable absent in the present study is wind. Apart from a lack of data on this variable, it is felt that it is primarily bioclimatically effective in Zones V and VI and particularly in the interaction between these zones. At lower elevations (Zones II and III), despite the occurrence of noteworthy wind-storms, there is little evidence of wind-throw in the forest vegetation. This may be partly due to the deeper rooting of the Ponderosa compared to Lodgepole pine, Engelmann spruce, and subalpine fir. The advection of warm, dry air from the west into the Grassland–Shrubland zone accelerates evapotranspiration but it is likely that high rates would occur anyway and lead to the xeric conditions of this zone.

One other important point that relates to both radiation and wind is the relative significance of aspect with respect to altitude across the Front Range. Peet's model of the Front Range vegetation displays, with the exception of the grasslands, an increasingly wide variation of vegetation zones as altitude decreases. This might imply that the role of aspect is more important in determining vegetation type in the lower part of the foothills as compared to the alpine tundra. If aspect is more important in Zones II and III, one reason may be that the markedly higher wind speeds prevalent at the higher elevations have the effect of mixing the thermal properties of the air such that the role of aspect is overshadowed by that of other climatic factors. This suggestion should be tested with observational evidence. The greater number of potentially dominant woody taxa at lower elevations, which are presumably temperature related, creates a greater potential for community differentiation. The apparent lesser importance of aspect in Zone V may be due to the smaller pool of woody species and the more limited logging and burning at these elevations (Veblen, pers. comm., 1984).

No discussion of the omission of variables should pass without mention that the authors realize the potential importance of non-climatological factors. Edaphic factors, particularly those relating to the nature of the parent material and moisture holding capacity, might be very important but have not been considered here. Human and other disturbance of the vegetation is also crucial. It is especially noteworthy that one of the bioclimatic zones distinguished here (Zone IV, Lodgepole Pine) is in fact usually considered to be a function of disturbance. It might be argued that it is inconsistent to use such a vegetation zone as part of a bioclimatic division system. However, it is suggested that the species of this zone interact with climatic factors just as much as those species of more advanced successional stages in other zones.

In a perceptive discussion of the nature of climatic classification Carter (1966) suggested that any sophisticated climatic classification should have three important characteristics. First, the meaning of "climate" for classification purposes should focus on factors that are *active* in a certain group of natural physical processes. Second, this focus on a particular meaning of climate will exclude the consideration of many atmospheric qualities which have more importance in other contexts. Third, it is the limits or boundaries of climatic types, rather than the cores of climatic regions, where research effort has produced the most effective results. The meaning of climate in the Front Range refers to the atmospheric factors affecting the present-day vegetation distribution. This study has focused on the climatic factors that are believed to be active in affecting and distinguishing the bioclimatic zones of the Front Range. Given the stated constraints under which the present study was performed, these factors have been identified as the ratio of the growing season thawing degree days to the growing season precipitation, the summer mean temperature, and the growing season soil moisture deficit. Second, as a corollary, there has been an elimination of many other climatic factors that may be more important in other contexts. The discussion of radiation variables and wind has been presented as an example of this. Third, it is a concentration of attention on boundaries, even if they have been unrealistically treated as being discrete, rather than the cores of the zones, that possibly produces the most effective results.

CONCLUSION

Considerable care has been taken in this study to distinguish the bioclimatic zones in as objective a manner as possible. In so doing several insights concerning the bioclimatic systems of the Front Range have come to light.

These include (1) determining the feasibility of the application of established climatic classifications to the area, (2) the identification of important bioclimatic variables, (3) the establishment of the limits of our understanding of the role of aspect in the area, and (4) the gaining of some knowledge as to the possibility for extrapolation of bioclimatic zones identified in Boulder County to other parts of the Front Range and beyond.

Presented here is a method of procedure for establishing bioclimatic zones that could be employed, or adapted for use, in resource inventorying in other mountain areas. Several topics that deserve further study have emerged. These include the need for an observational study of the role of aspect in determining vegetation types, and the use of aspect-related parameters and understory vegetation assemblages as possible variables to be employed in a second order bioclimatic division. The investigation should be extended to examine the bioclimatic divisions of the western slope of the Continental Divide and along an extensive north-south tract of the eastern slope. It may be, in the final analysis, that the bioclimatic secrets of Francis Ramaley's "natural scientific laboratory" may only be unlocked by looking outside it.

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