CLIMATOGRAPHY OF THE

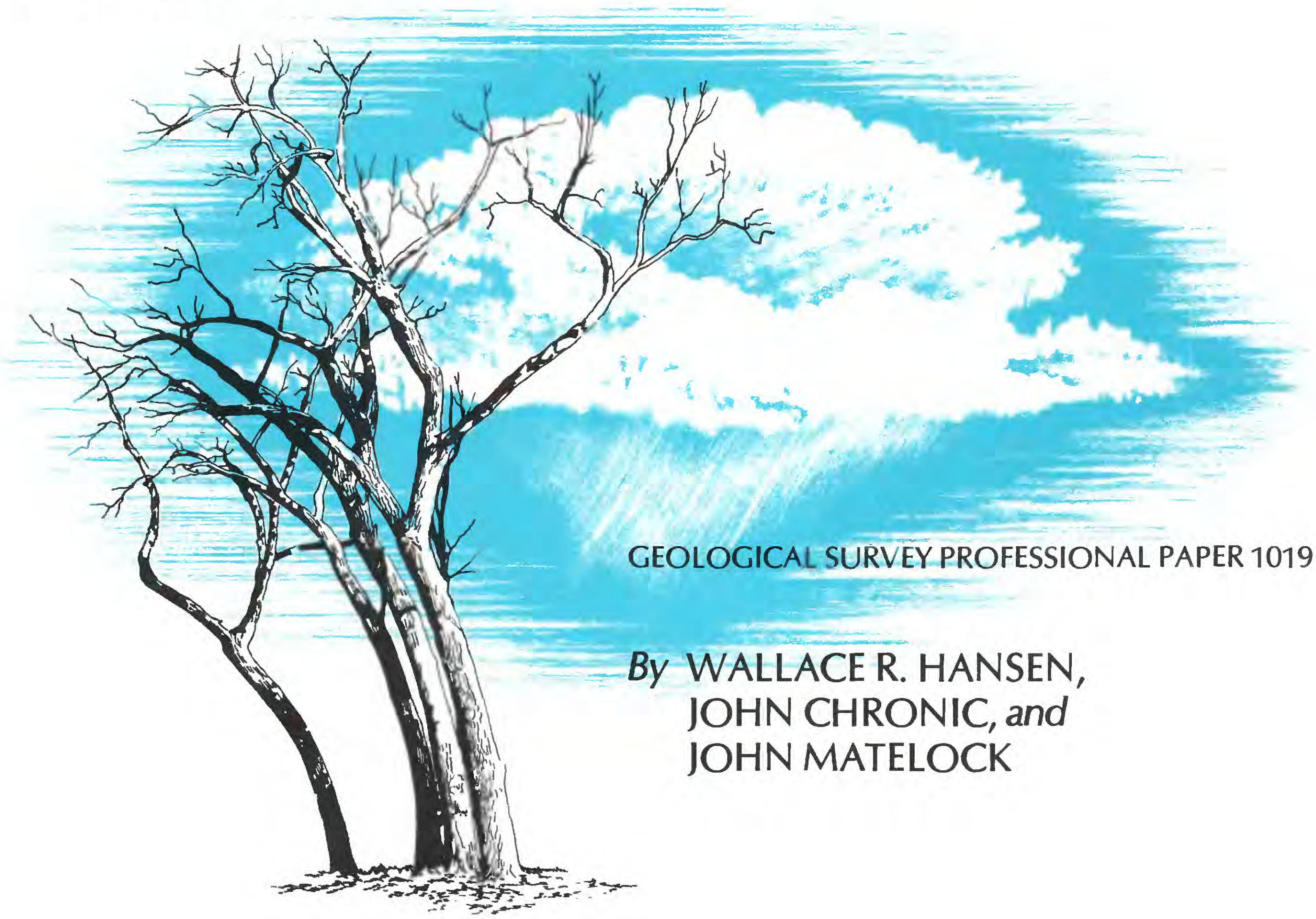
Front Range Urban Corridor

AND VICINITY, COLORADO

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1019

CLIMATOGRAPHY OF THE FRONT RANGE URBAN CORRIDOR AND VICINITY, COLORADO

A graphical summary of climatic conditions in a region of varied physiography and rapid urbanization



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CLIMATOGRAPHY OF THE FRONT RANGE URBAN CORRIDOR AND VICINITY, COLORADO

By Wallace R. Hansen, John Chronic,[1] and John Matelock[1]

INTRODUCTION

Why climatography?

The organized history of previous weather conditions of a region is called the climatic summary. Customarily, one or two weather elements, such as temperature and precipitation, are used to assign a general climatic type. In the Front Range Urban Corridor and vicinity of Colorado, however, extremes of topography so modify the local climate that no simple designation is possible. On a global scale the climate is semiarid temperate continental, sometimes referred to as a "middle latitude steppe" (Trewartha, 1961, map facing p. 8), but in some mountain valleys the climate is subhumid subarctic, and above timberline it is alpine arctic.

When climatic measurements are converted to graphic form, the study is called "climatography." This climatographic summary divides climate into weather elements that can be shown on maps to provide a synoptic overview of entire regional relationships. These weather elements include variables of temperature, humidity, cloudiness, precipitation, and wind, which together characterize the area's particular climate. With this information, the user can then reach his own general conclusions as to what weather conditions are likely to exist at various times in his own place of interest. A climatic summary is a useful tool in helping to guide decisions concerning land use, construction, agriculture, gardening, vacationing, and other activities.

Acknowledgments

Most of the statistical information on which this report is based was derived from climatic summaries for Colorado prepared by the National Weather Service and its predecessor the U.S. Weather Bureau. These summaries were provided to us by William H. Haggard, Director, Environmental Data Service, National Climatic Center, National Oceanic and Atmospheric Administration (NOAA), Asheville, North Carolina. The University of Colorado Library also provided miscellaneous publications and climatological data about various parts of the area. Roger Gallet of NOAA, Horace F. Quick of the University of Colorado Geography Department, Raymond L. Parker of the U.S. Geological Survey, and Bruce H. Bryant of the U.S. Geological Survey kindly reviewed the manuscript. Patrick J. Kennedy of the National Center for Atmospheric Research in Boulder, Colorado, reviewed the section on destructive winds. Sigrid Asher-Bolinder, Susan J. Kropschot, and Robert K. Wells, all of the Geological Survey, edited the entire report and ferreted out many weaknesses; Arthur L. Isom contributed special art effects.

[1] University of Colorado

Physical setting and its effect on the local climate

Map 1 identifies the major physical features of the area and the locations of various weather observation stations. This area has some of the most varied landscapes on the continent, and the effect of these landscapes on the local climate, although explained in greater detail by the succeeding maps, needs some explanation here. First, the total topographic relief is more than 9,500 feet and the change in climate with altitude is large and well known. For example, when the temperature of freely circulating air on a sunny July afternoon in Denver is, say, 95°F, the temperature on Mount Evans, 35 miles west and approximately 9,000 ft higher might be only 45°F; in the bright sunshine at that high altitude, the air might feel appreciably warmer, but in protected shade, it might be chilled to near freezing.

Second, as the temperature falls in a given mass of air, the relative humidity rises, and the air approaches saturation. Precipitation, therefore, generally increases over the Front Range with increased altitude — the climate of the high mountains is distinctly wetter than the climate of the plains. Note on the succeeding maps the marked differences between the climates of the Front Range and those of the Colorado Piedmont, South Park, and Middle Park.

Third, differences in exposure produce marked local climatic variations in short horizontal distances, the so-called microclimates (fig. 2). A south-facing slope in the foothills might support dryland plant forms, such as juniper, mountain mahogany, bunchgrass, yucca, and cactus, whereas a nearby north-facing slope might harbor boreal forms such as Douglas-fir, spruce, aspen, wild rose, and even mosses. High above timberline a south-facing slope might support a host of alpine wildflowers while an adjacent north-facing slope shelters a perennial snowbank. In the foothills, snow remains much longer in the winter on north-facing slopes than on south-facing slopes, as mountain residents long ago became aware. Persons contemplating specific land uses should first consider the implications of the local microclimate.

Fourth, altitude and exposure profoundly affect precipitation patterns. Distinctive climatic units, therefore, coincide with major topographic elements. Increased precipitation falls to the windward side of large mountain masses, and precipitation shadows lie to the lee. Even small hillocks affect the local weather. The Front Range itself, an element of the Southern Rocky Mountains, is a huge climatic island surrounded by warmer drier domains. It also is the dominating climate modifier of the region.

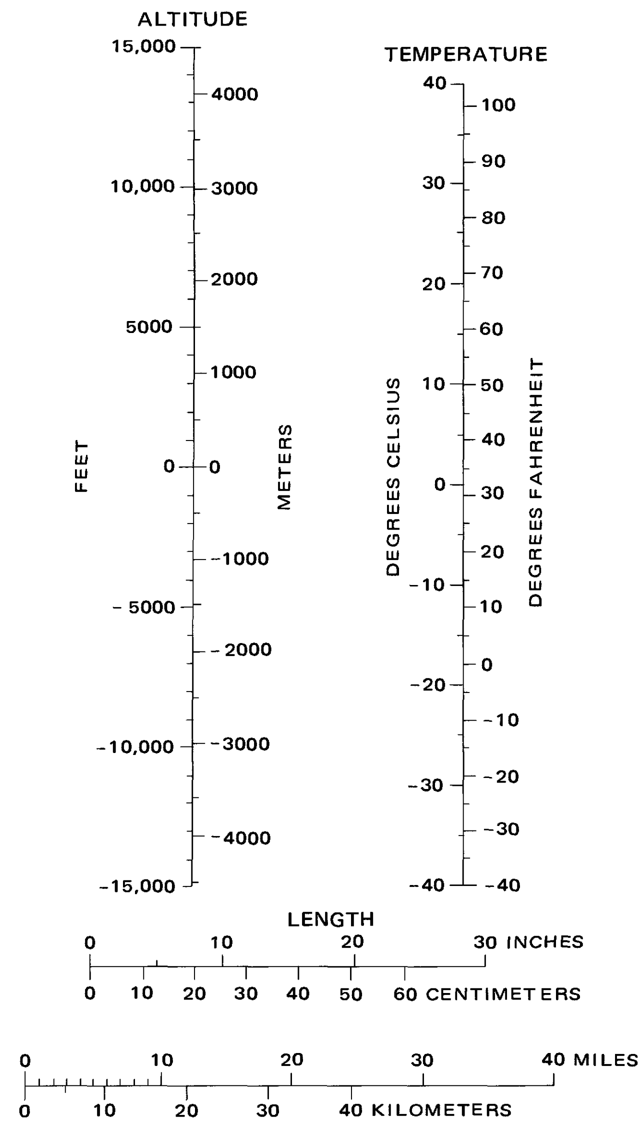
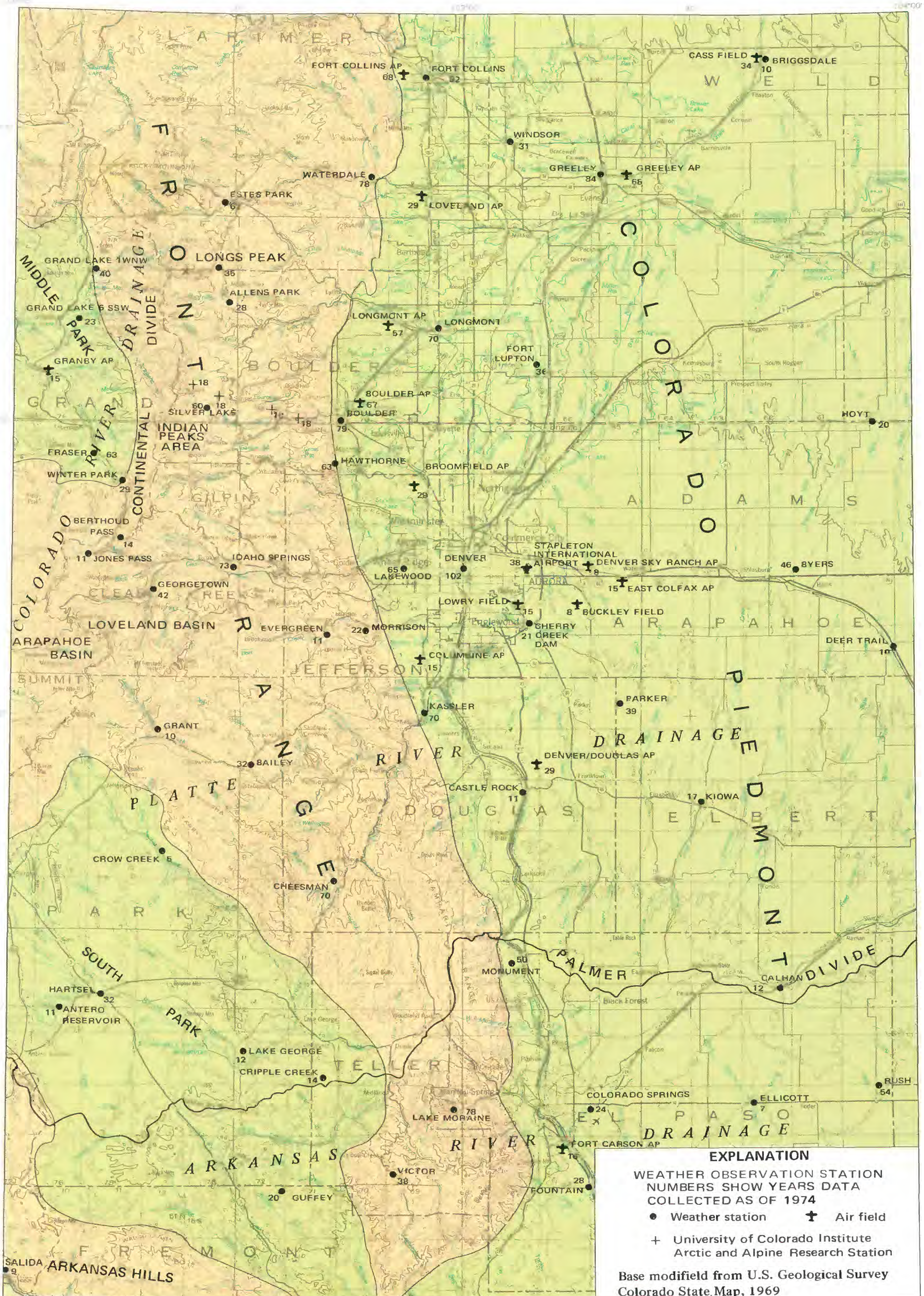
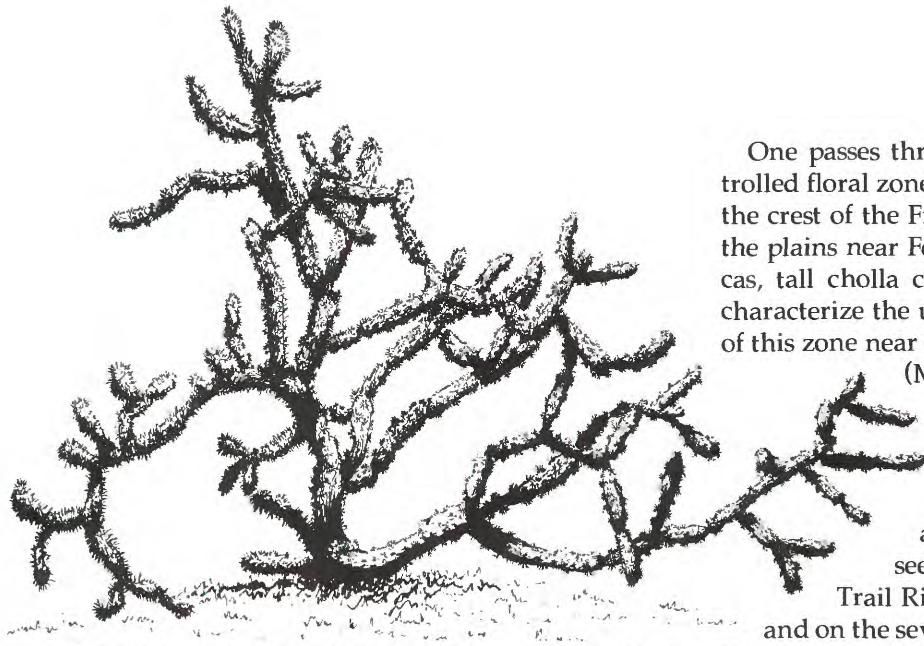


FIGURE 1. — Comparative English and metric scales for temperature and distance. All past and present United States weather data are reported in units of the English system; temperature in degrees Fahrenheit and precipitation in inches and feet. That system, therefore, is used in this paper. Temperatures are easily converted from degrees Fahrenheit (F) to degrees Celsius (C) and back by the following formulas: $F=9/5C+32$ and $C=5/9(F-32)$. Measurements of distance are easily converted from one system to the other as follows: to convert inches to centimeters, multiply inches by 2.54; centimeters to inches, multiply centimeters by 0.394; feet to meters, multiply feet by 0.305; and miles to kilometers, multiply miles by 1.61.



MAP 1. — Major physical features and locations of weather observation stations, Front Range Urban Corridor and vicinity.



Opuntia imbricata, *picturesque cholla cactus of the semidesert shrubland*

One passes through several distinct climatically controlled floral zones in ascending from the Great Plains to the crest of the Front Range. Southeast of Pikes Peak on the plains near Fort Carson, for example, abundant yuccas, tall cholla cacti, and other semi-arid plant forms characterize the upper-Sonoran life zone. A counterpart of this zone near Denver is called the "Plains Grassland" (Marr, 1964, p. 36). Traversing up toward the summit of Pikes Peak one then ascends successively through the lower and upper montane forests, the subalpine forest, and finally, the alpine tundra. Similar floral zones are seen on Mount Evans west of Denver, on Trail Ridge in Rocky Mountain National Park, and on the several other high mountain passes along the Continental Divide.

FIGURE 2. — Asymmetrical vegetation distribution pattern in the foothills of the Front Range west of Denver. South-facing slope supports sparse vegetation, owing to high insolation, high evapotranspiration, and low soil moisture. North-facing slope supports dense boreal forest. This pattern is prevalent up to altitudes of 9,000–10,000 feet.

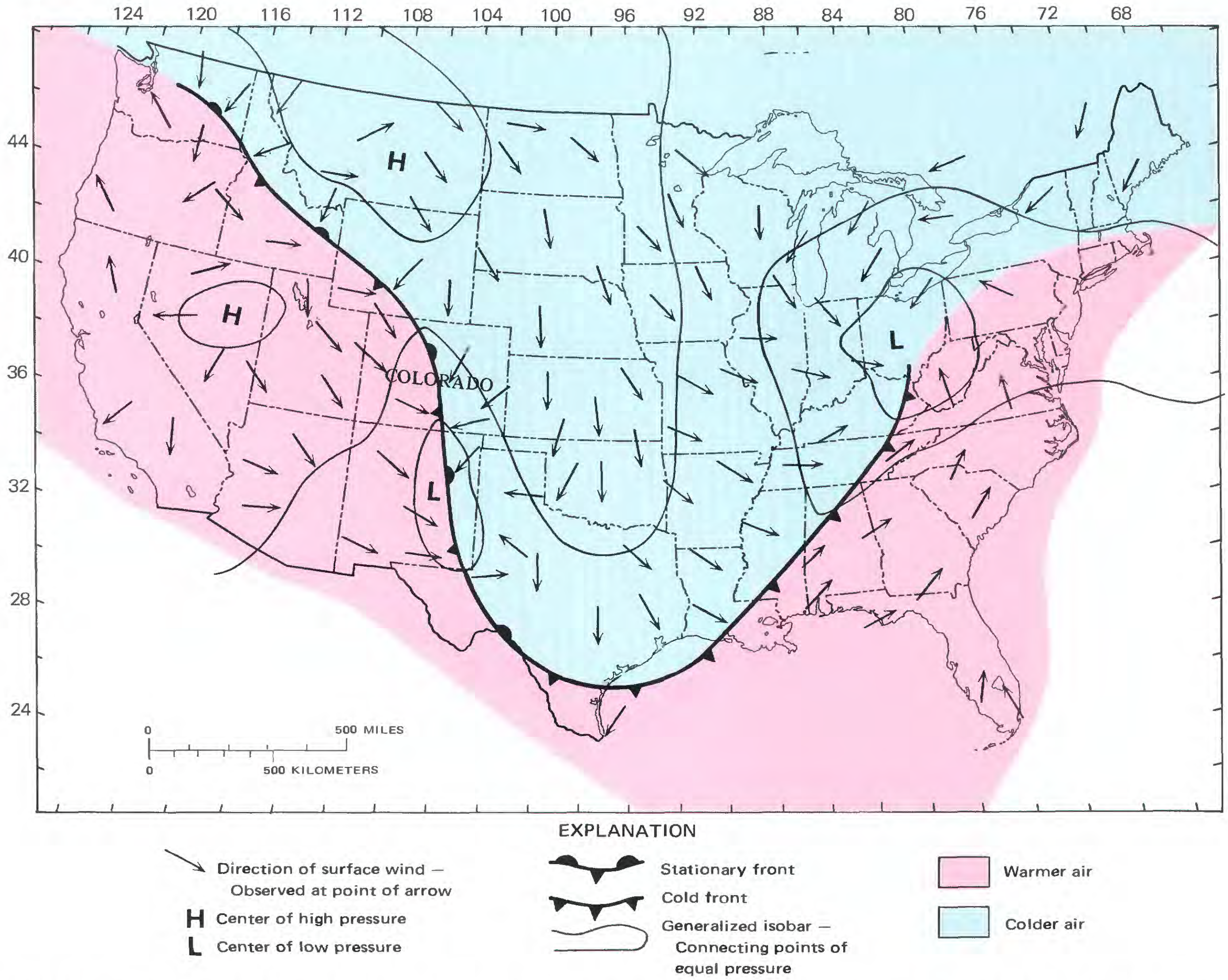


FIGURE 3. — Map showing an effect of the Rocky Mountains on the movements of air masses. Southward spread of polar air across the midcontinent is arrested over the Rocky Mountains along a stationary front that extends from the Pacific Northwest to West Texas. Rocky Mountains have halted further spread of the air toward the west. A cold front extends from Texas to Ohio as the cold air presses southeastward. Upslope flow of air brings precipitation to eastern Colorado as fair weather dominates west half of the state. This weather pattern is repeated frequently during the winter months. Simplified from National Weather Service map of February 5, 1975, 2100 hours, Greenwich mean time.

The Front Range

The Front Range is a major barrier to the free flow of air masses (figs. 3 and 4). It inhibits or modifies the movement of the air by blocking or deflecting the air upward, downward, and sideward. In winter, chilled polar air spreading southward over the Great Plains, for example, often is arrested against the east front of the range, so that temperatures on the plains sometimes are appreciably colder than temperatures at higher altitudes only a short distance away. Similarly the Front Range modifies the eastward flow and character of Pacific air entering the region from the west and, in so doing, often triggers heavy snowfalls in the mountains while sunny skies and dry air bathe the plains. The Front Range also arrests the northwestward flow of humid Gulf air from the southeast, often setting off heavy showers on the Colorado Piedmont and on the eastern slope of the range itself.

The Colorado Piedmont

The Colorado Piedmont, at the eastern foot of the Front Range, is a subdivision of the Great Plains. Here live most of the region's people; the salubrious climate attracts immigration and is a principal reason for the high rate of population growth along the Front Range Urban Corridor. The Front Range markedly affects the behavior of air masses moving across the Colorado Piedmont at all seasons of the year.

Between Denver and Colorado Springs the topography and climate of the Colorado Piedmont are modified by the "Palmer Divide," a wide cool highland along the watershed of the South Platte and Arkansas Rivers. This divide reaches an altitude of about 7,500 feet, or about 2,000 feet higher than either Denver or Colorado Springs. The climatic effect of the divide is clearly shown by the several succeeding maps.

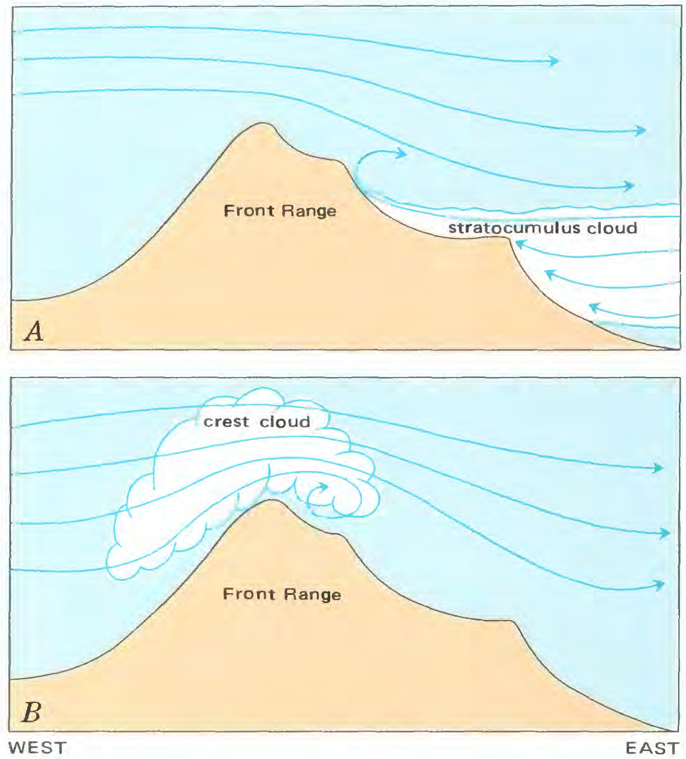
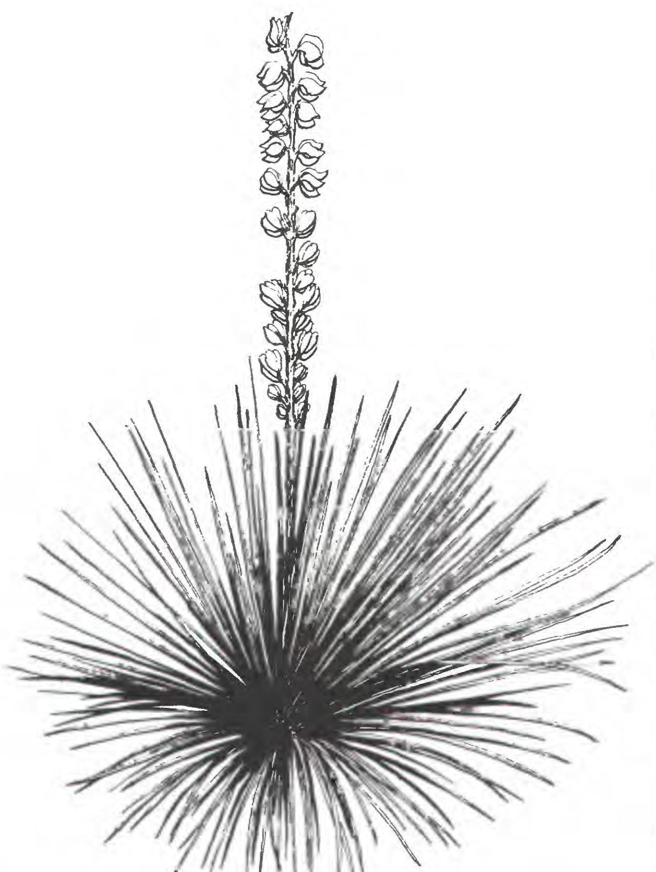


FIGURE 4. — Airflow patterns (arrows) modified by the Front Range (written commun., 1974, William Marlatt, Colorado State University). *A*, Easterly, upslope, circulation on the eastern slope of the Front Range. *B*, Westerly, downslope, circulation on the eastern slope of the Front Range.



Yucca glauca, *Spanish bayonet, the lily of the Colorado Piedmont*

Middle Park and South Park

Middle Park and South Park, west of the Front Range, are distinctive climatic units. Both parks are broad mountain valleys surrounded by higher mountains and both are characterized by relatively dry, cool, and in winter often bitterly cold climates. North Park, a similar valley, barely extends into the map area from the northwest. One effect of the enclosure of these valleys by high mountains on all sides is the entrapment, stagnation, stratification, and radiative chilling of cold air. Even in summer, nighttime temperatures often fall below freezing. Inasmuch as shallow thermal inversions accompany such chilling, the temperature near the ground is often several degrees colder than it is a few tens or hundreds of feet above. Smoke from chimneys and campfires spreads horizontally at such times, especially in the evenings and early morning when the upward rise of the smoke is arrested by the inversion layer.

Great diurnal variations in temperature also characterize these mountain valleys. A 50°F range from daily low to high is not uncommon in winter or summer. The "thinness" of the air at high altitude contributes to the rapid nighttime loss of heat and the rapid surface warming in daytime under the intense radiation of the sun.

Observation stations and data evaluation

The weather stations shown on map 1 have provided most of the basic data for the succeeding maps. All stations, except those at Calhan and Hartsel, were in operation when the paper was in preparation (1974–75). The station at Fraser has since suspended operation also. Map 1 also shows how long each station has been in operation. Not all stations record all weather elements and, consequently, fewer data points are available for some of the maps than for others. Stations near to, but outside, the map area at Fort Morgan, Agate, River Bend, Canon City, Buena Vista, and Dillon provided additional data control. A few stations that had been set up for short-term or specialized purposes, or stations that keep incomplete records, were used as general guides in plotting climatographic data.

Weather stations throughout the map area are under varied maintenance. The U.S. National Weather Service maintains stations at Denver and Colorado Springs. The U.S. Federal Aviation Agency maintains them at airfields. Other stations are operated by private individuals, power companies, cities that have an interest in water storage and supply, and by such agencies as the U.S. Forest Service, U.S. Bureau of Reclamation, U.S. National Park Service, and U.S. Army Corps of Engineers.

One of the chief sources of data for our maps was the Decennial Census of United States Climate published by the U.S. National Weather Service (formerly the U.S. Weather Bureau). The series was discontinued after the last of these censuses was published in 1964 for the decade 1951 through 1960. However, annual summaries by state of some weather elements are still being prepared, and a check of these indicates that more recent information is not likely to materially change the conformations or conclusions presented on the maps in this paper.

In plotting isolines from thermal and hyetographic data, consideration was given to topography, slope, and exposure, as discussed by Russler and Spreen (1947), especially for the large parts of the area where station data are scanty. Because of the varied local climates in the Front Range Urban Corridor and vicinity, weather recording stations are too few to permit precise climatographic detailing; allowance for this fact should be made by users of the paper. In less complex climatological regions, fewer observation points might yield higher levels of interpolative confidence, but here the wide gaps in available information combined with the varied physiography introduce large potential margins of error into the interpolations necessary for drawing the map. Broad areas lack any weather recordings at all, and the climate in such places can be categorized only in a general sort of way. Nevertheless, most of the isolines shown on the accompanying maps are probably within half an interval of true accuracy at any given locality. The limitations of the observed data, therefore, should not subtract from the value of this climatographic atlas in portraying important, if somewhat generalized, regional climatic relationships.

Pinus ponderosa *dominates the lower montane forest*

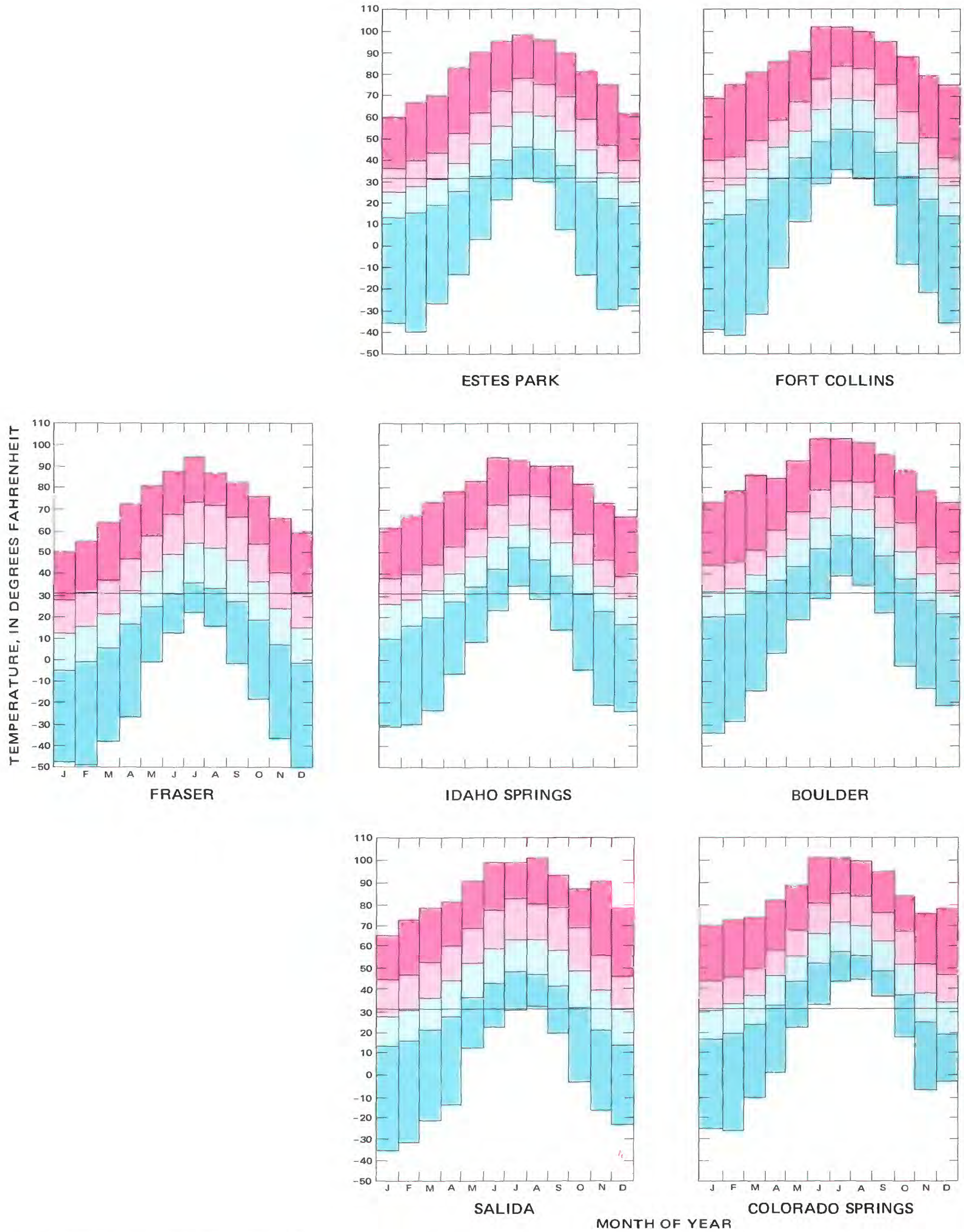
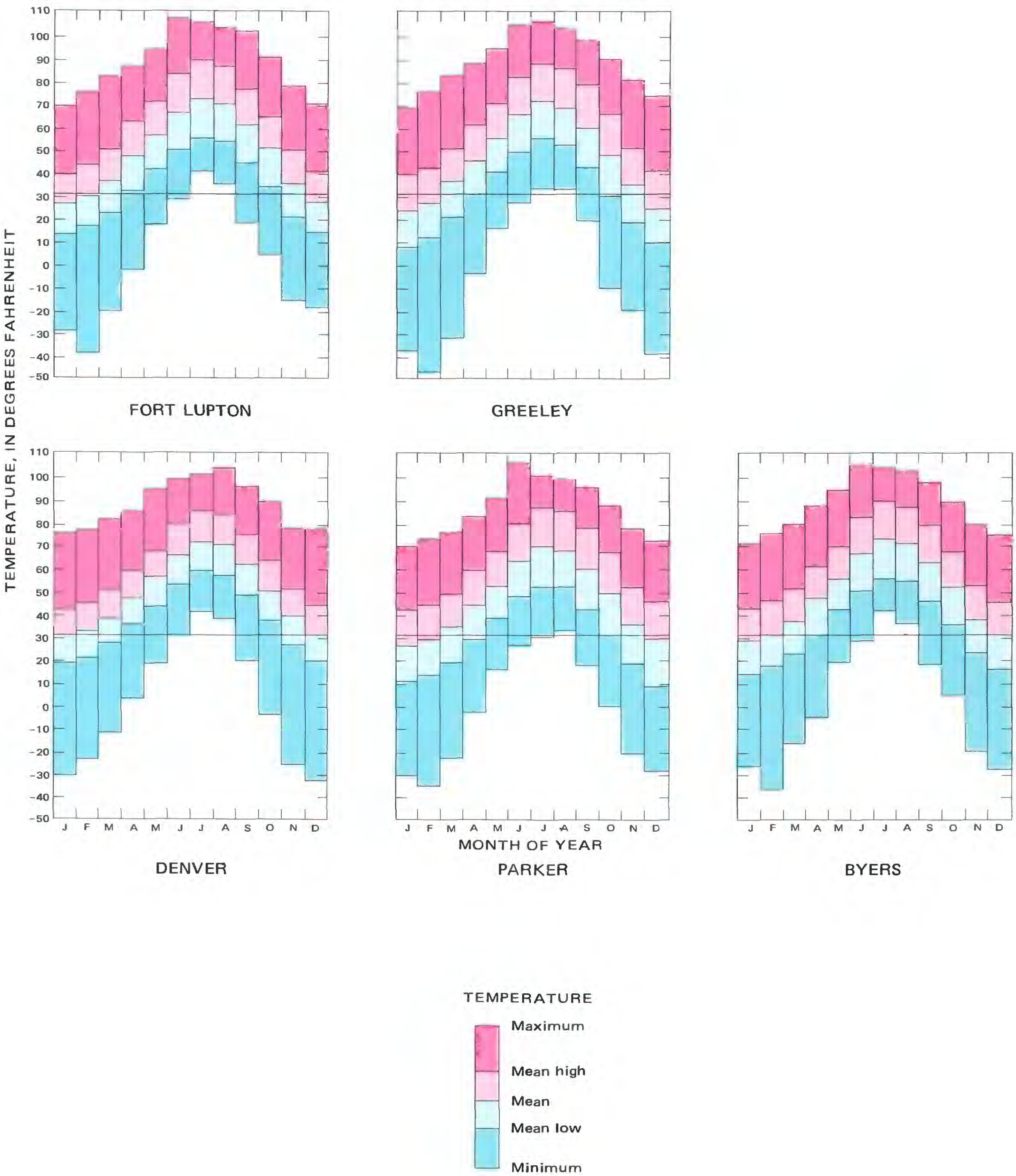


FIGURE 5 (Above and right).— Monthly maximum, mean, and minimum temperatures at 12 selected weather stations, Colorado. Histograms are arranged in approximately west to east and north to south transects, to show how temperature varies geographically across the area. Note the general rise in temperatures from west to east, and on the plains, from north to south.


TEMPERATURE, IN DEGREES FAHRENHEIT
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
FORT LUPTON
GREELEY
DENVER
PARKER
BYERS
J F M A M J J A S O N D
MONTH OF YEAR
TEMPERATURE
Maximum
Mean high
Mean
Mean low
Minimum

CLIMATOGRAPHY

Temperature

Because air temperature so affects man's activities, it is recorded by more weather stations and in greater detail than any other weather element. In the mountains air temperature fluctuates markedly within short distances, owing to the varied exposure, topography, and local relief. Ordinarily, the air temperature diminishes with altitudes at a lapse rate of about 3°−5°F per thousand feet (6°−10°C per km). The lapse rate depends partly on the humidity, inasmuch as dry air tends to have a steeper lapse rate than moist air. But besides humidity, factors such as exposure, prevailing wind direction and speed, vegetation cover, and the character of the ground all cause local temperature variations that are difficult to isolate on a small-scale map. In valley bottoms, moreover, the stagnation of cool or chilled air may even lead to temperature inversions, by which the air aloft is warmer than the air at the ground surface.

Colorado columbine, Aqualegia caerulea, *ranges through a vertical mile from the coniferous forest to the alpine tundra*

Monthly mean temperatures

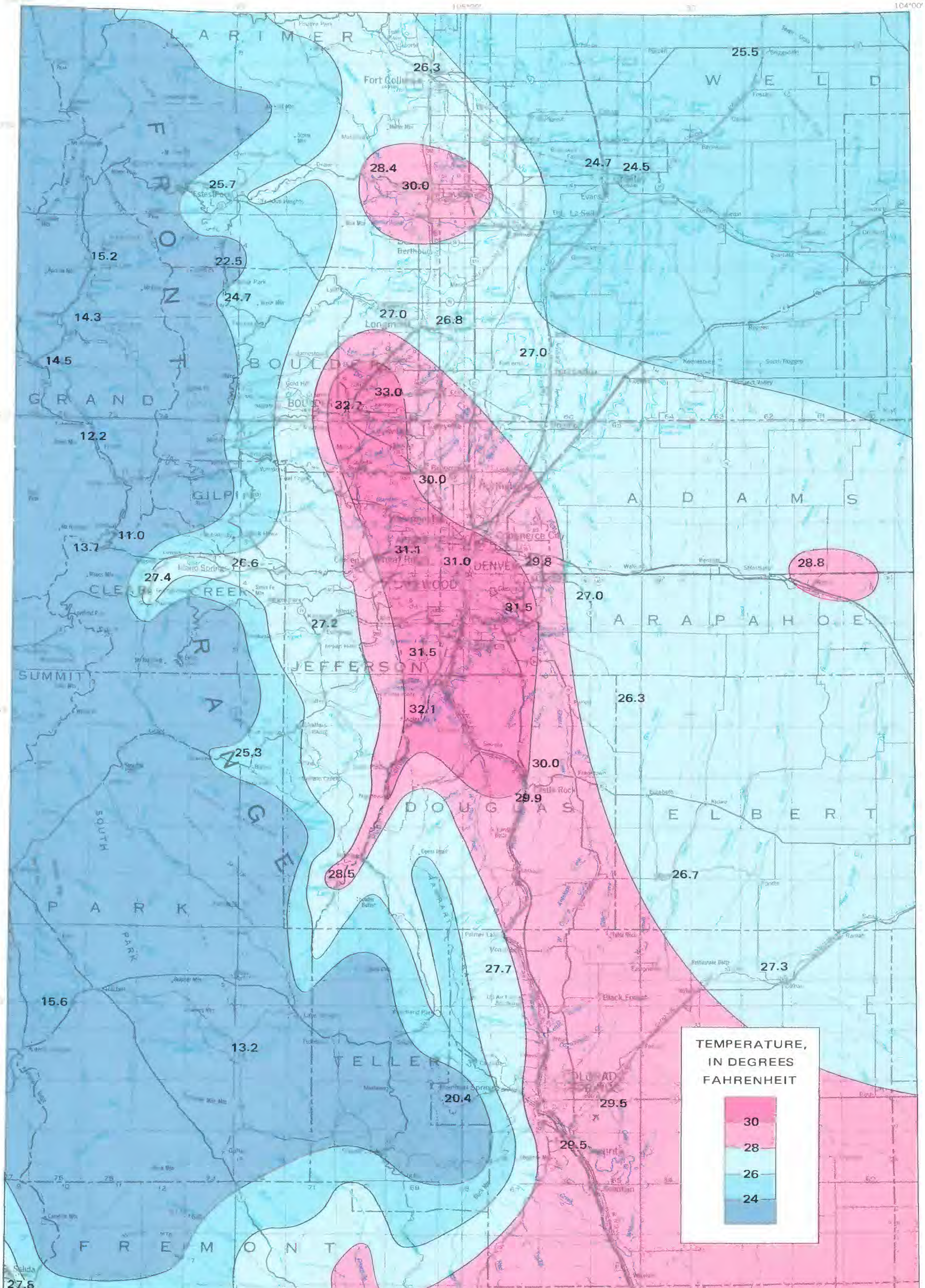
Figure 5 shows maximum and minimum recorded temperatures, mean highs and lows, and temperature means for each month for twelve representative stations. Most of these stations have summer maximums that exceed 100°F and winter minimums below −30°F. In general, temperatures increase across the area from west to east.

On the Colorado Piedmont monthly mean temperatures generally range from about 70°F in July to about 28°F in January. The maximum temperature for any one month may vary from about 100°F in summer to about 60°F in winter.

Fraser, in Middle Park, has minimum temperatures consistently about 20°F colder than those of most other stations; its summer maximum, however, occasionally reaches well into the nineties, only 5°−10°F less than eastern-slope stations. Even so, nighttime frost is probable at Fraser in every month of the year.

January mean temperature

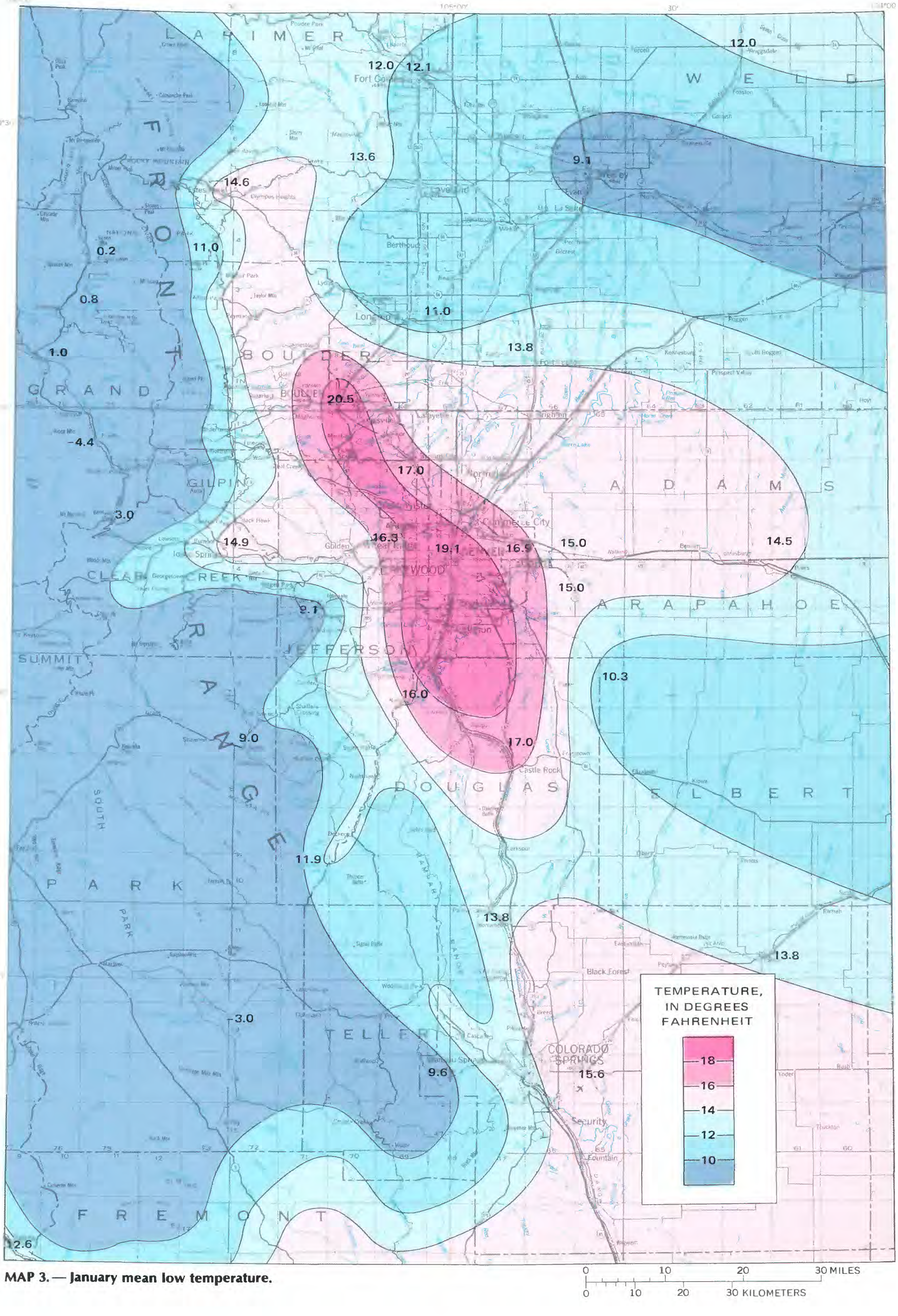
At most stations the lowest mean monthly temperatures of the year are in January, although the record lows are likely to be in February. January mean temperatures along the Urban Corridor are characterized by a gentle ridge of relative warmth extending the length of the map just east of the mountains. The Greater Denver area forms a well-defined heat island, with mean temperatures of about 31°−32°F. The highest means are near Boulder, the lowest along the Continental Divide.



MAP 2. — January mean temperature.

January mean low temperature

This map resembles map 2 in the general distribution of higher versus lower temperatures. Relatively warm temperatures (12°–20°F) at the foot of the Front Range separate the colder zones in the mountains to the west from those on the plains to the east. An elongate thermal high at a mean low temperature of about 18°F is centered over Denver, extending northwestward to Boulder and southeastward to Happy Canyon. A saddle of moderately low temperatures (12°–14°F) extends east from the mountains across the highland north of Palmer Divide; chilled air (colder than 10°F) extends down the valley of the South Platte east from Greeley toward Fort Morgan (off the map 50 miles east of Greeley). Mean low temperatures below zero are recorded at stations in the mountain valleys, such as Fraser (−4.4°F) in Middle Park and Lake George weather station (−3°F) in South Park. These temperatures, at altitudes of about 8,500 feet and 8,000 feet respectively, are appreciably colder than the mean January low at Berthoud Pass (+3°F) on the Continental Divide at an altitude of 11,315 feet. Nighttime radiation and cold-air drainage into the valleys are probably the cause; at Berthoud Pass, better circulation and air mixing prevent such chilling. The low readings in the South Platte valley east from Greeley probably are caused by cold-air drainage also.

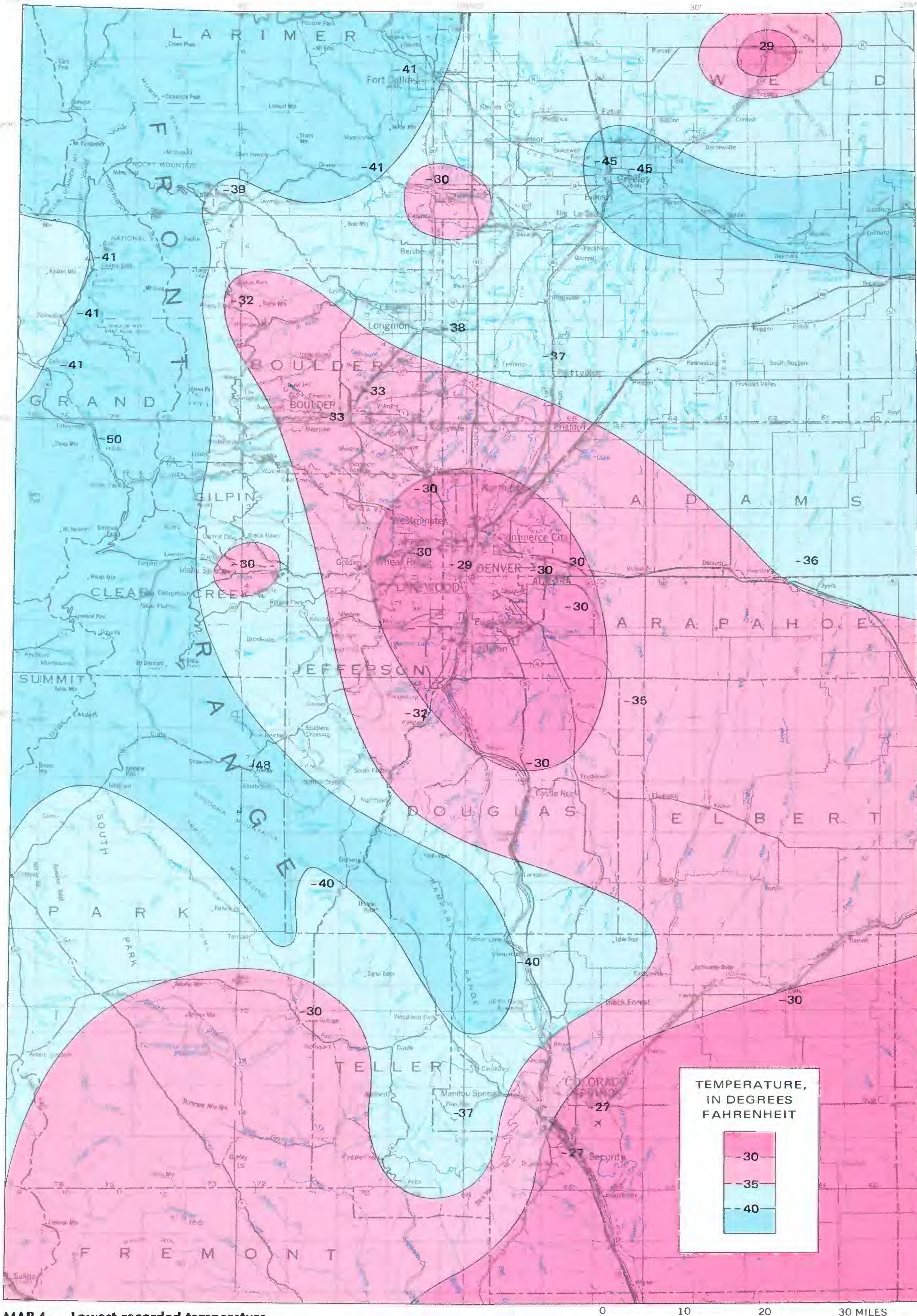


MAP 3. — January mean low temperature.

Lowest recorded temperature

Record low temperatures have been measured at most stations in February, although a few stations have reported them in January and December.

Record low temperatures are expressed as isotherms on this map only in the most general fashion, inasmuch as (1) local conditions greatly modify the regional climatic pattern, (2) data points are not isochronous, and (3) statistically meaningful details are not warranted by the wide scatter of observation points. Temperature variations of several degrees are likely within short distances, especially over varied terrain. Extreme lows are likely to occur in valley bottoms, owing to cold-air drainage, stratification, and stagnation — the lowest temperature on record for the map being at Fraser (–50°F) in Middle Park. Denver has a noticeably warmer minimum temperature than might be expected, probably because of the city heat-island effect. Colorado Springs, with a record low of –27°F, has the highest recorded minimum temperature in the Urban Corridor.



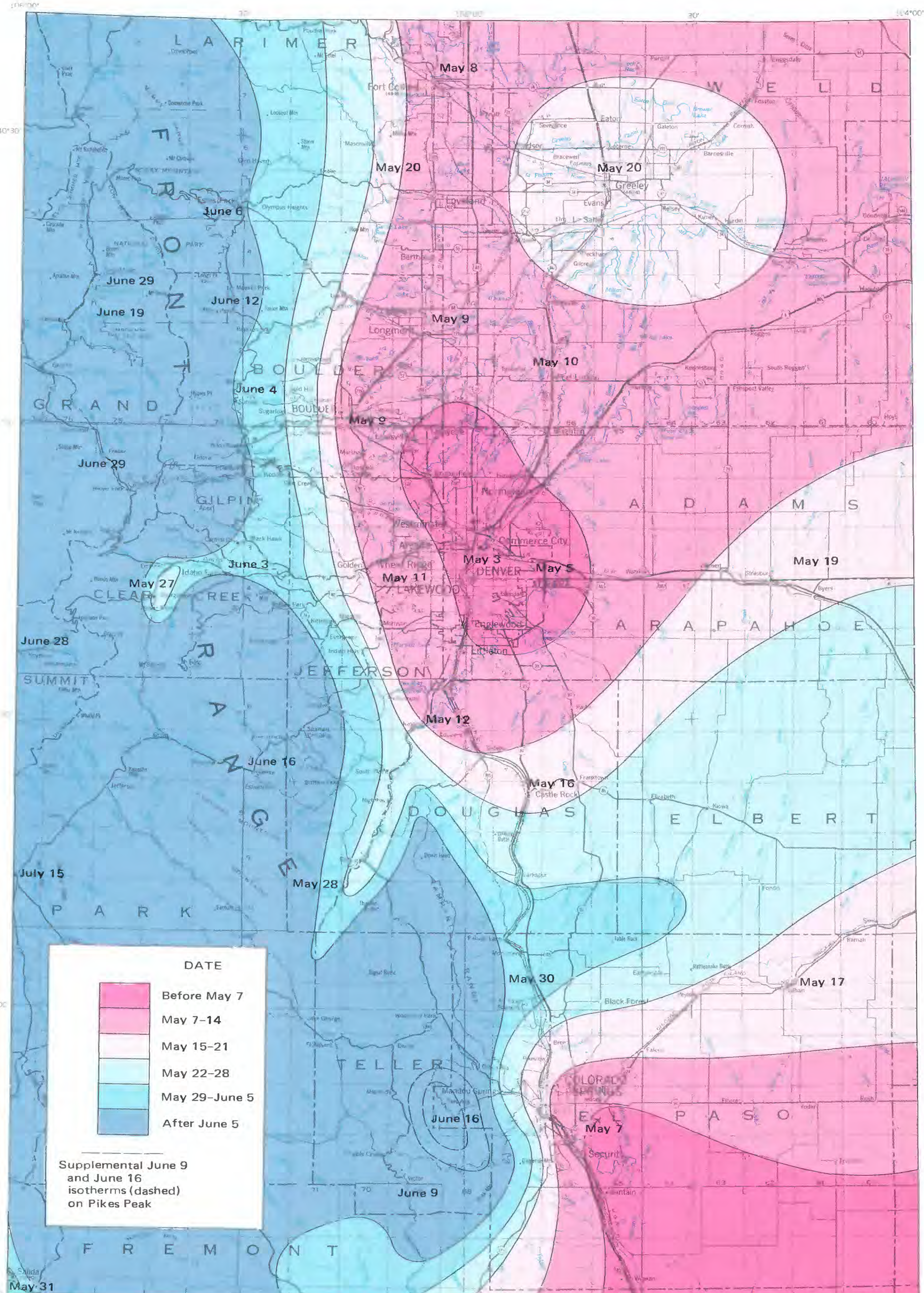
MAP 4. — Lowest recorded temperature.

Mean date of last spring frost

This map is contoured isochronously by weekly intervals, showing the average date of the latest seasonal frost. Each isochron is also a 32°F isotherm for the particular date shown. The conspicuous gradient between the mountains and the plains is modified by a pronounced late seasonal ridge of cool air along the Palmer Divide between the South Platte and Arkansas River drainages. This ridge of cool air is a manifestation of the relatively high altitude (about 7,500 ft) of the highest part of the divide.

In the high mountains above 9,000–10,000 feet and in parts of South and Middle Parks, nighttime frosts are likely during any month of the year.

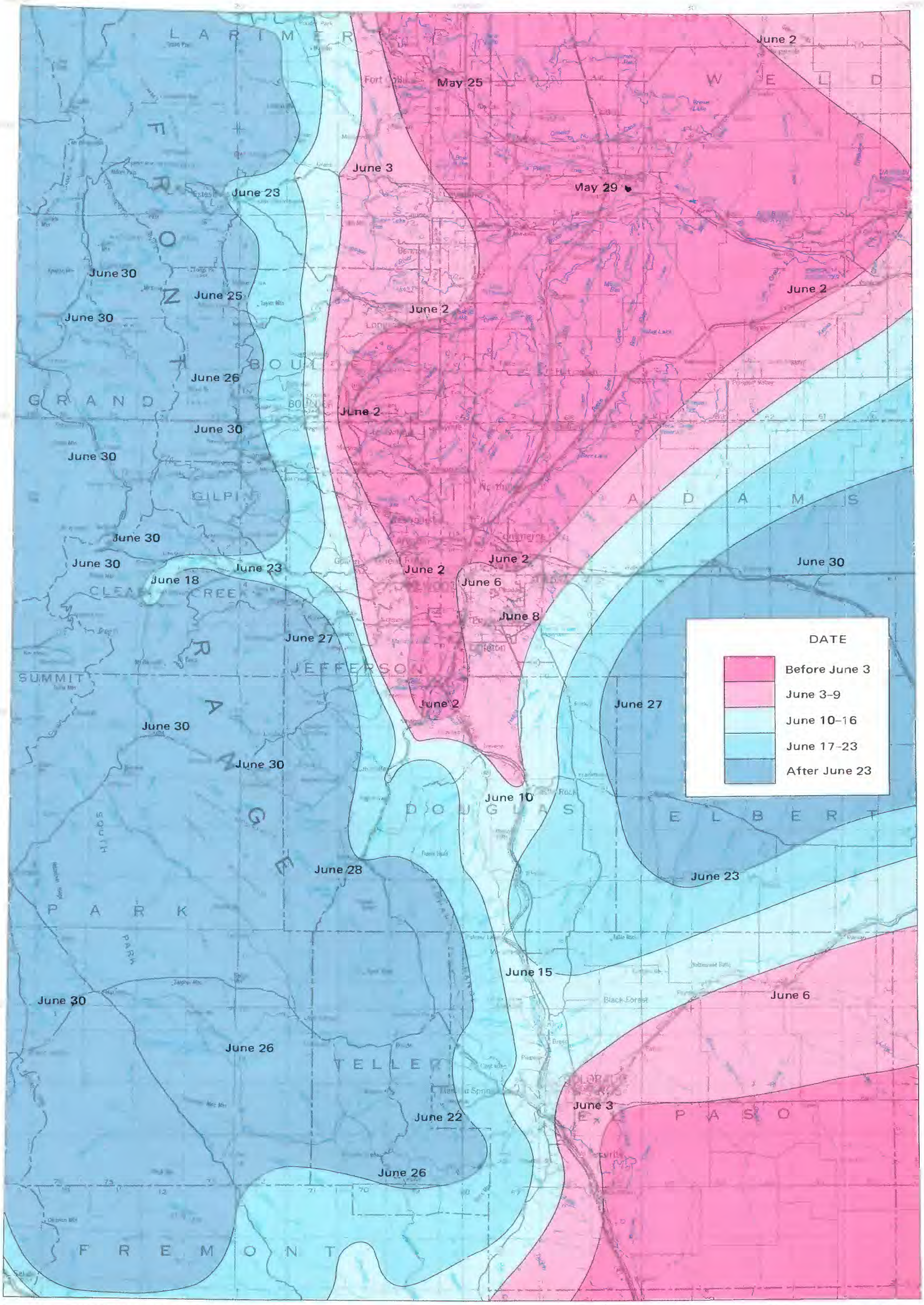
The heat island effect over Denver is clearly illustrated by the earliest mean dates of latest frost in the entire area (May 3–5). A "cold island" of relatively late frost (May 20), on the other hand, occurs at Greeley, possibly owing to cold-air drainage in the South Platte and Cache la Poudre River valleys. A conspicuous late frost island (June 16) occurs over Pikes Peak, where the last date of frost at Lake Moraine on the east flank is 5 weeks later than at nearby Colorado Springs, 4,265 feet lower.



MAP 5.— Mean date of last spring frost.

Latest occurrence of frost in spring

Palmer Divide again strongly influences the position and time of the 32°F isotherm. In the spring a broad lobe of cool air lies just north of the divide. Note that the latest spring frost at Byers, 40 miles east of Denver, is nearly a month later than it is in most of the South Platte River valley. Frost in most mountain communities also lingers 3 or 4 weeks longer than in the South Platte River valley and in the valley of Fountain Creek, just southeast of Colorado Springs.

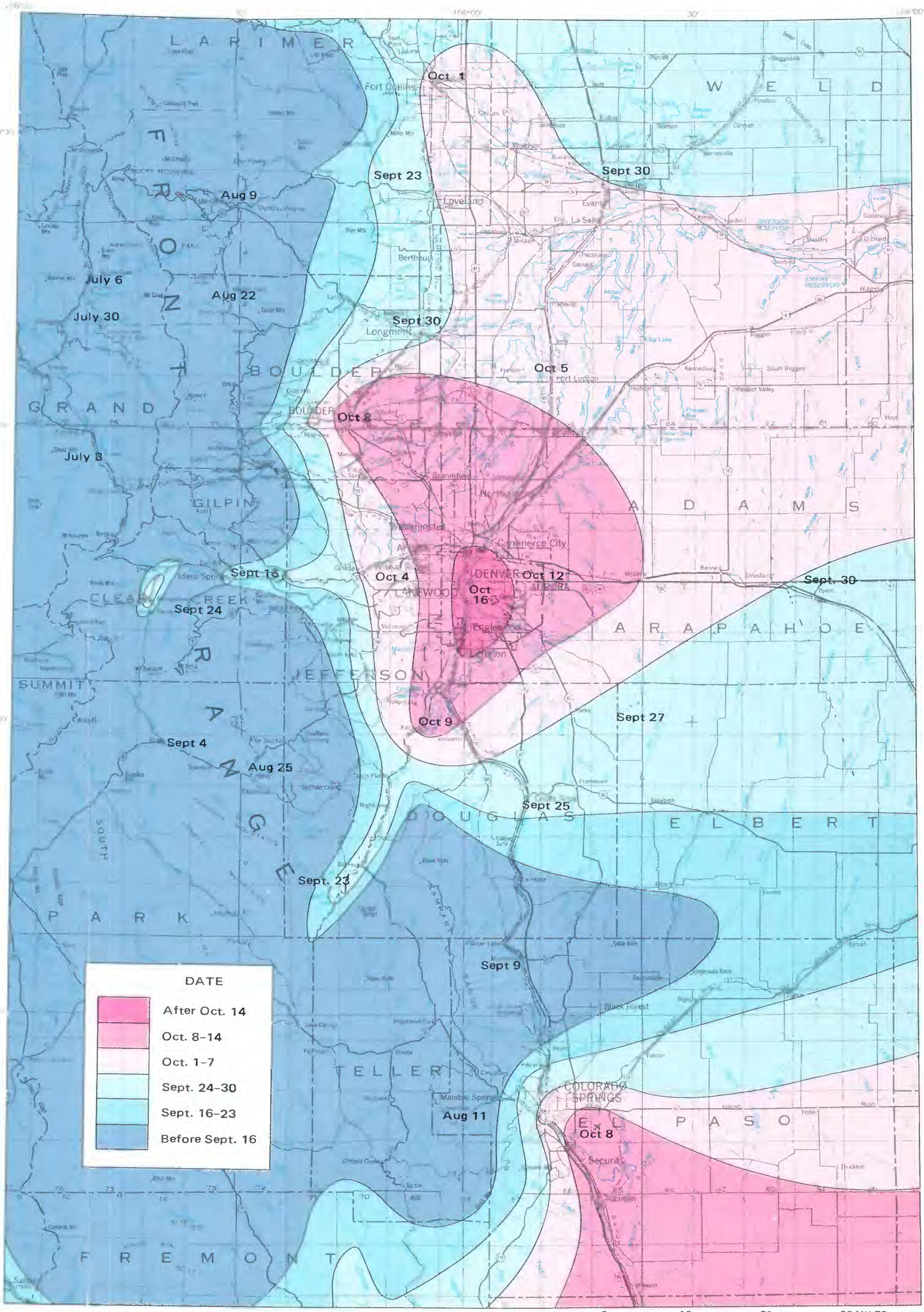


MAP 6. — Latest occurrence of frost in spring.

Mean date of first fall frost

This map closely parallels map 8, which shows the earliest occurrences of frost in the fall. In the fall, the gradient from the mountains to the plains is again modified by cool air over the Palmer Divide and by the heat island over Greater Denver. The October 16 mean date of downtown Denver's first frost is the latest in the entire area. Pikes Peak is a conspicuous early frost island, although the date of September 11 at Lake Moraine on the east flank is surprisingly late for its relatively high altitude. Note that, on the average, frost is expectable in Fraser on July 3. Frost usually occurs at Fraser during all seasons, July and August included.

The times of the first and last frosts are affected locally by minor variations in topography and exposure, even on relatively flat parts of the Colorado Piedmont. At the scale of mapping used here, however, and with the sparsity of data points, detailed local variations of small magnitude are not evident.

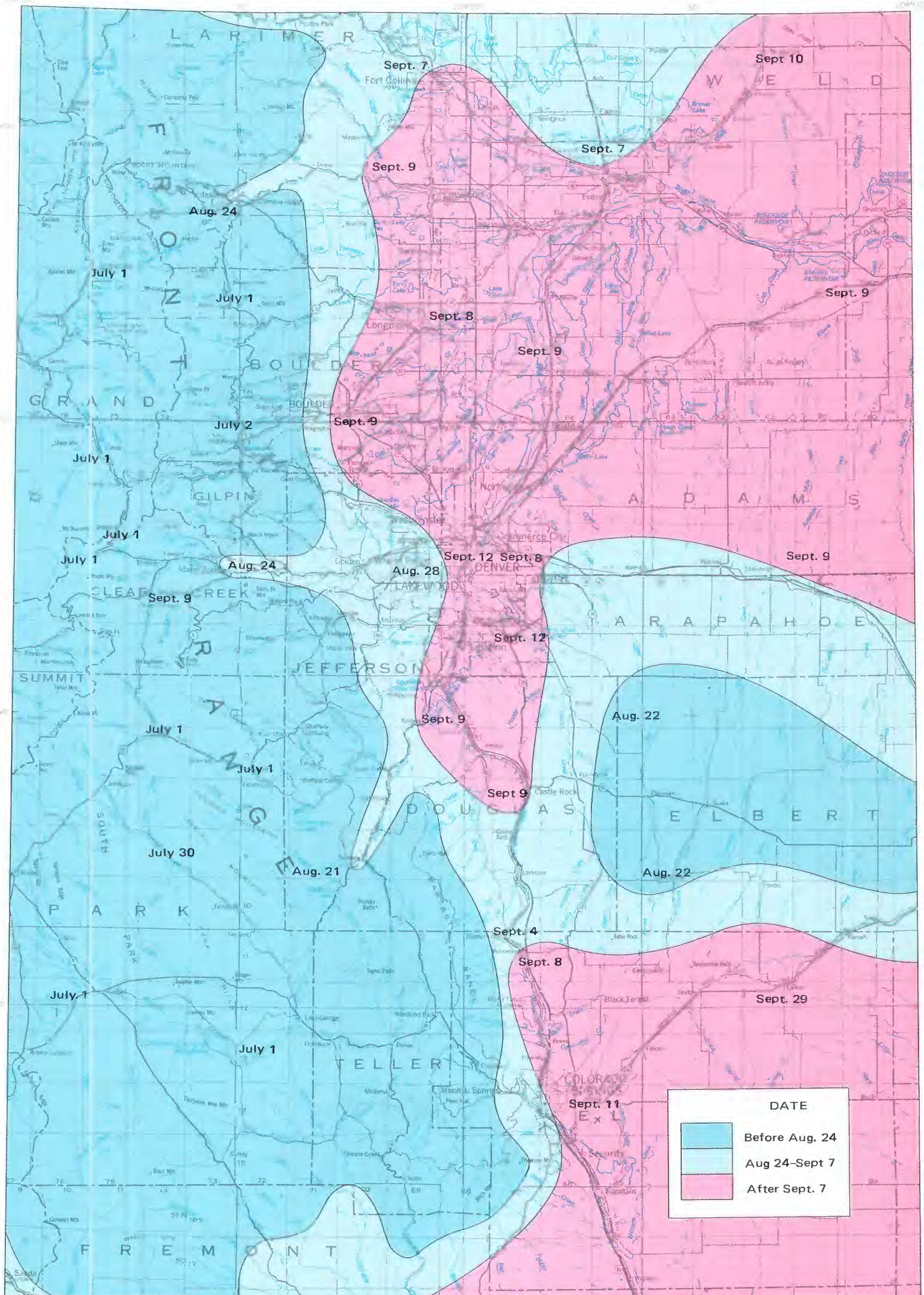


MAP 7.— Mean date of first fall frost.

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Earliest occurrence of frost in fall

All reporting stations west of the mountain front have recorded freezing temperatures on or before August 24, and many of the higher stations can expect frost at any time of the year. East of the mountains, frosts prior to August 24 have been recorded only in Elbert County, east of Parker and at the town of Elbert north of the Palmer Divide. Elsewhere on the Colorado Piedmont frost has not been recorded before September.



MAP 8. — Earliest occurrence of frost in fall.

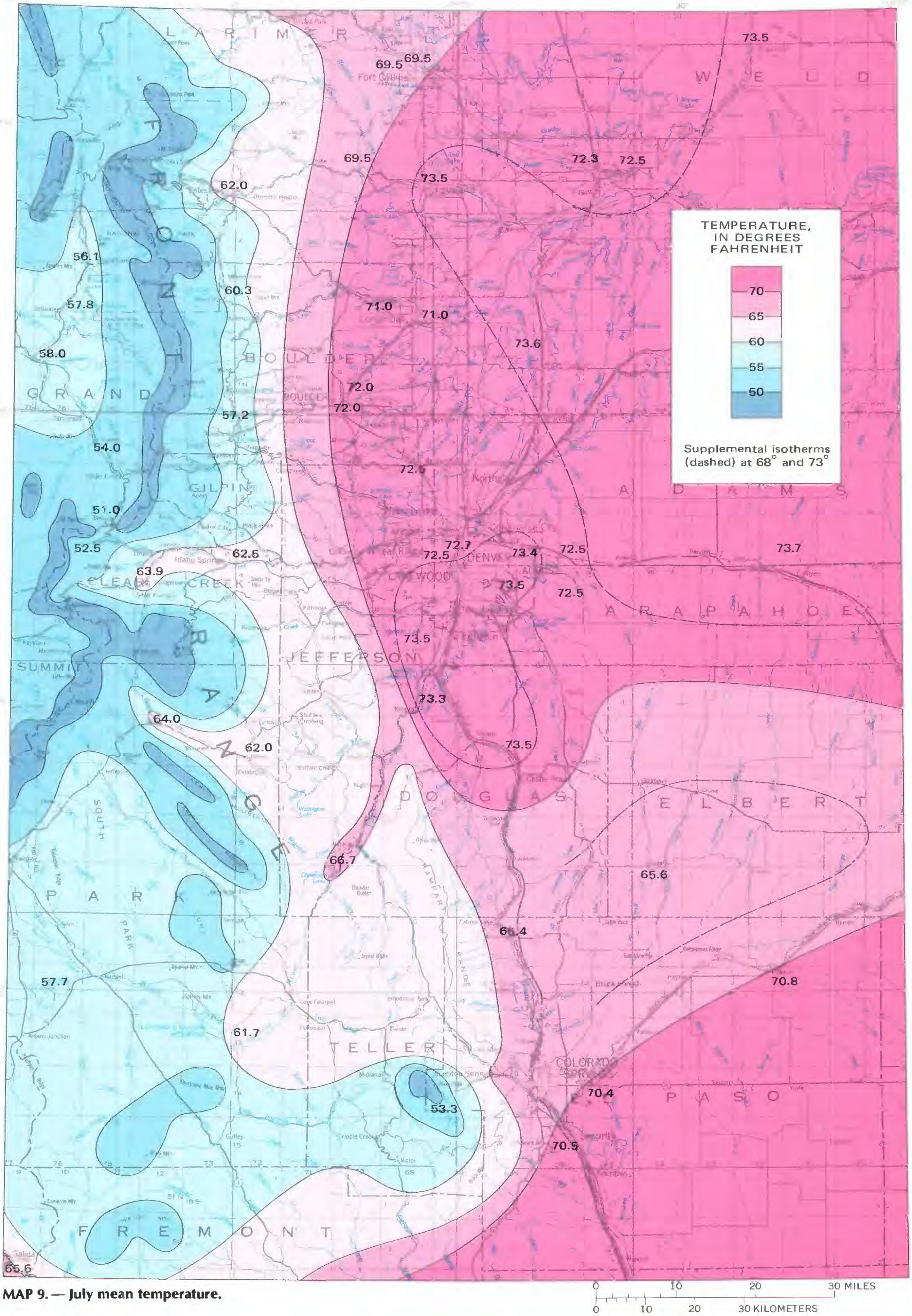
Bristlecone pine, buffeted by the gales at timberline

July mean temperature

In July, the Denver heat island is fairly well marked, with a mean temperature of about 73°F spread over an area extending from Castle Rock to Wheat Ridge, and from Chatfield Reservoir to Aurora.

A ridge of cool temperatures occurs over the Palmer Divide area between Denver and Colorado Springs, with summer mean temperatures well below those to the north and south. This cool ridge is linked to the altitude of the area.

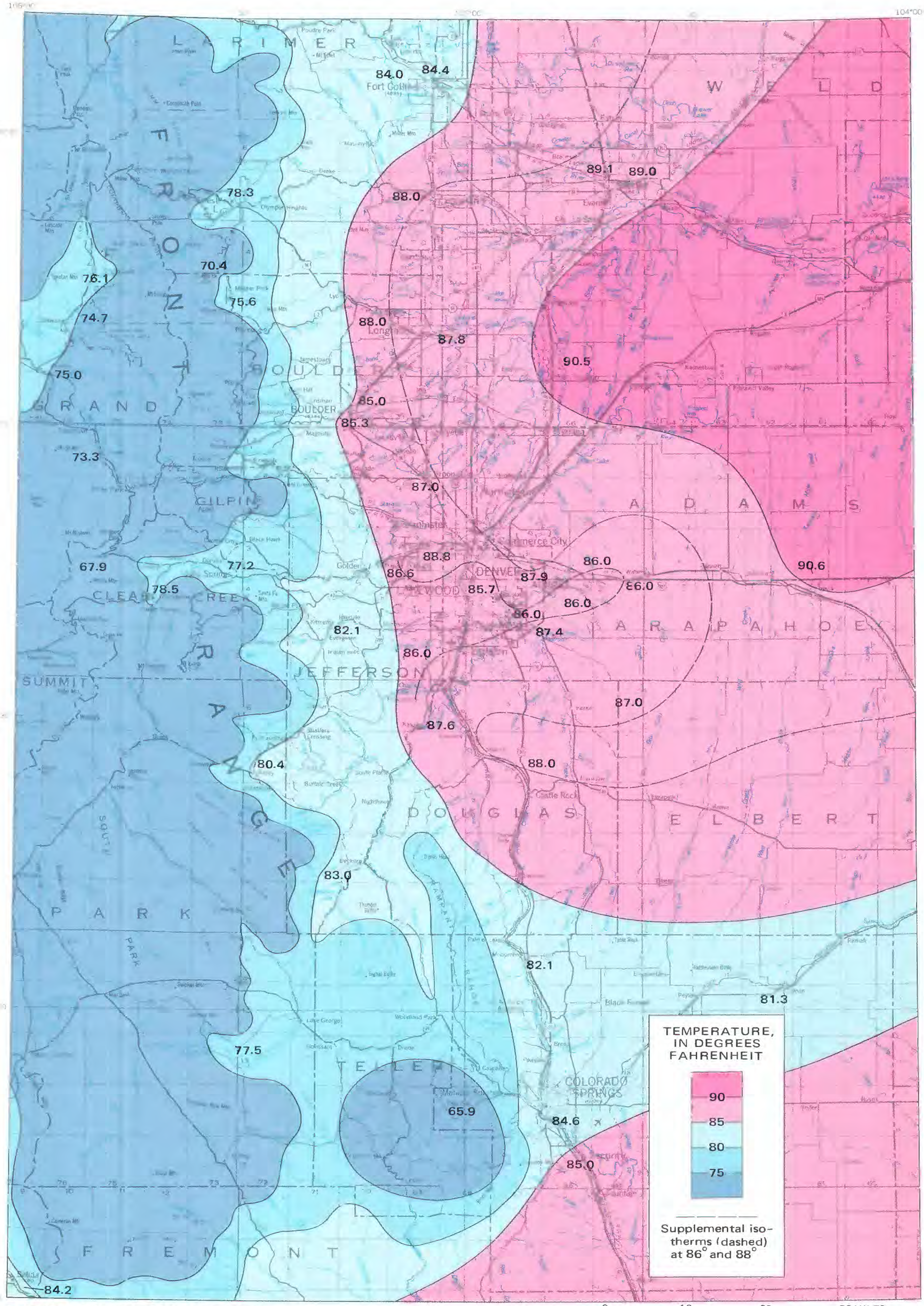
In the mountains the 50°F isotherm in July coincides approximately with timberline at 11,000–12,000 feet along the Front Range. Timberline and the 50°F isotherm bound the arctic-alpine climatic zone and separate the subalpine forest below from the alpine tundra above. Note the isolated climatic island over Pikes Peak, a striking effect of altitude.



MAP 9.— July mean temperature.

July mean high temperature

The distinct thermal gradient of low to high, from the mountains to the plains is modified by a ridge of lower temperatures extending eastward along the Palmer Divide and by local effects in the Greater Denver area. The highest temperatures shown on the map define a broad lobe northeast of Denver. Note again the distinct cool island over Pikes Peak, an effect of altitude, standing apart from the larger mass of cool air over the main body of the Front Range.



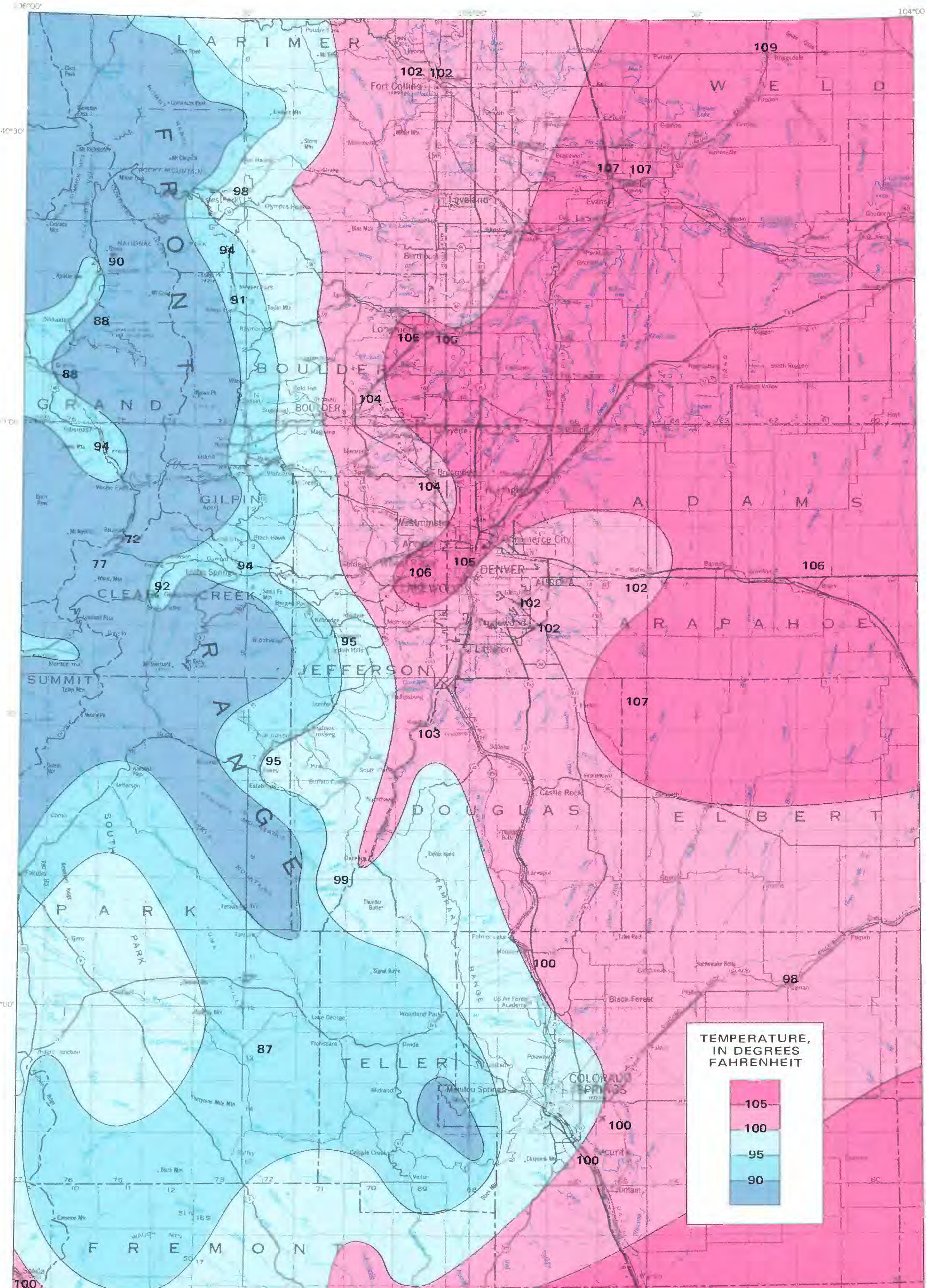
MAP 10.— July mean high temperature.

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Mare's-tail cirrus herald the warm front

Highest recorded temperature

Data points are rather sparse on this map, but the effect of altitude on temperatures is nevertheless obvious in the steep thermal gradient away from the mountains. The highest highs (109°F) are in the lowest part of the map area, in the South Platte Valley northeast of Greeley. The lowest highs are along the Continental Divide (Berthoud Pass, 72°F). In the short distance from Greeley or Denver to the Continental Divide (35–55 miles), the temperature change in summer approximates that from southern Texas to northern Canada. The temperature gradient between the South Platte Valley and the Continental Divide closely approximates the adiabatic lapse rate of dry air, about 5.3°F per thousand feet, or about 10°C per kilometer. The Denver heat island is inconspicuous and, based on the few data points available, perhaps is not statistically meaningful, but the commonly recognized thermal high over the hot inner core of downtown Denver during the summer probably would be confirmed if detailed temperature recordings throughout the Denver area were available. Record high temperatures at various stations in the map area have been recorded almost equally in the months of June and July.



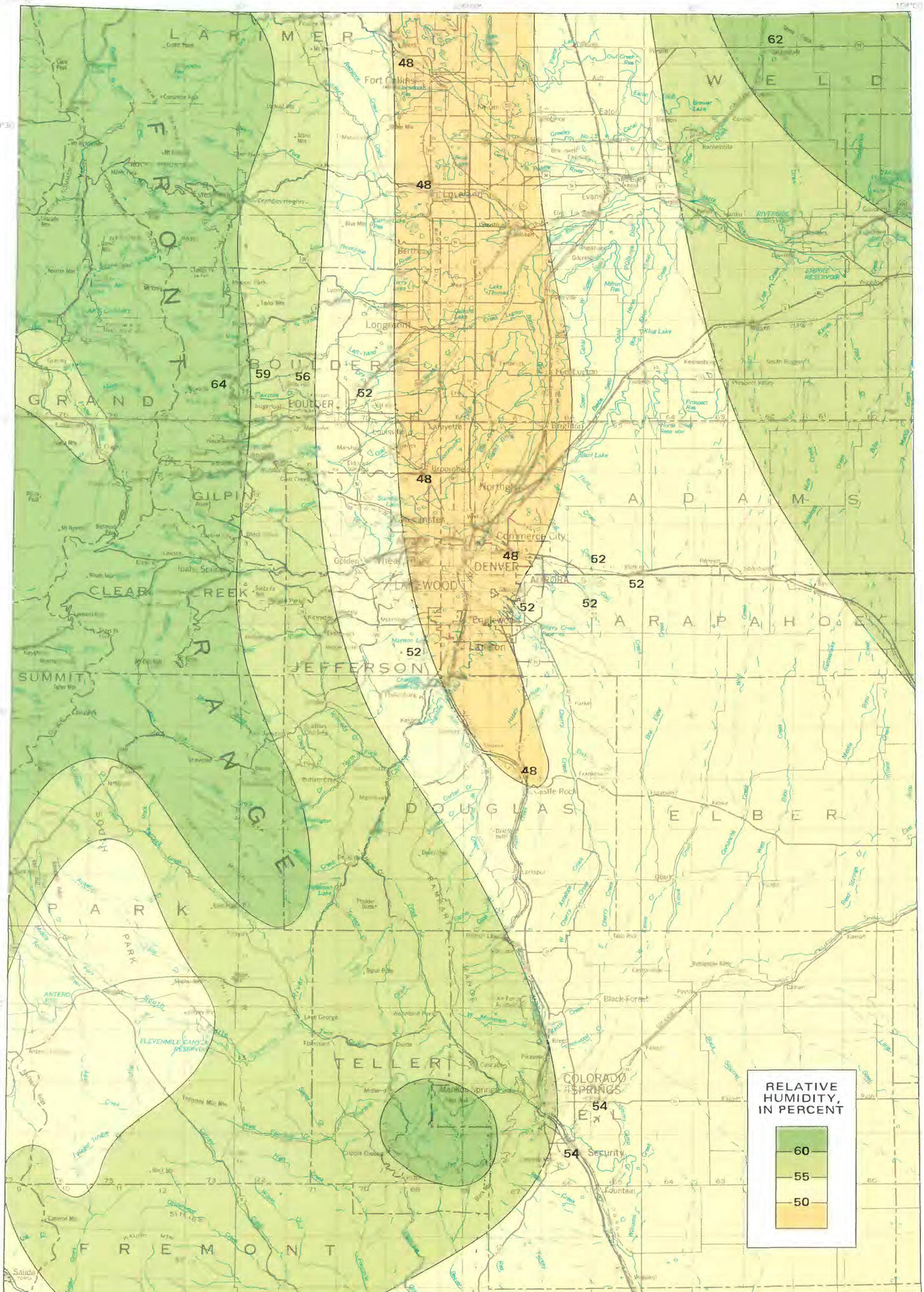
MAP 11. — Highest recorded temperature.

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Humidity

Mean annual relative humidity

This map is necessarily generalized because of the sparsity of control points. At the same time, the small spread of recorded values across the entire map — only 16 percent — indicates that more readings would not greatly alter the simplicity of the map. Although the Colorado Piedmont has a dry semiarid climate, the mean annual relative humidity near the ground exceeds 50 percent everywhere except in a narrow belt just east of the mountain front along the Front Range Urban Corridor, where the air is dried by the warming effect of the downslope westerly air flow. Daytime relative humidity on the Colorado Piedmont is usually only 20–30 percent and often is much lower. Nighttime radiative cooling, on the other hand, often raises the humidity to 100 percent near the ground and causes early morning dew to form in summer and frost in winter. Higher relative humidity over the mountains is related to orographic cooling.



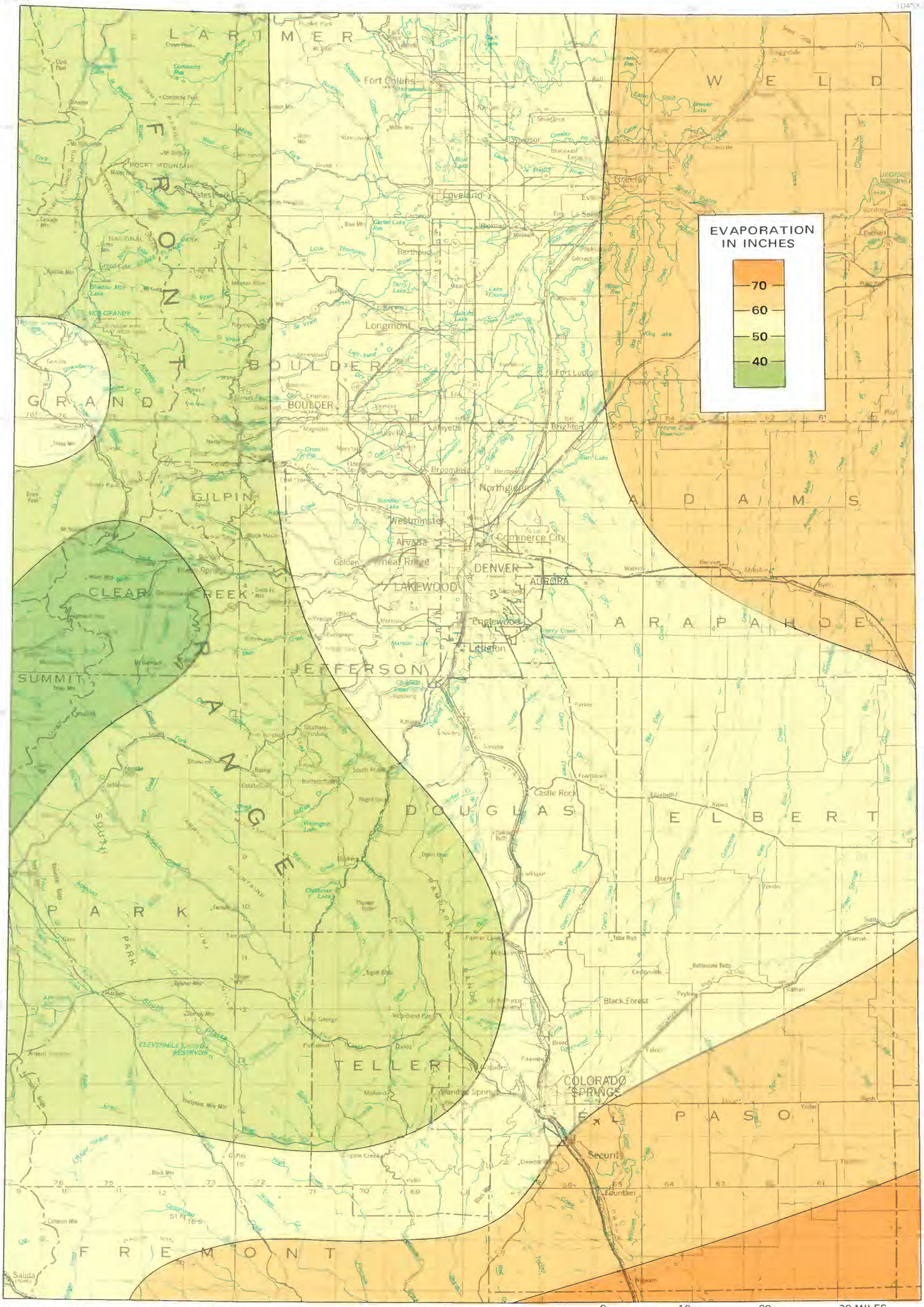
MAP 12. — Mean annual relative humidity.

Mean annual evaporation

This highly generalized map is based on information provided by the National Weather Service in Denver (written commun., 1974).

Meteorologists use various devices to obtain evaporation rates. A common way is by measuring water losses from a standard-size flat-bottomed pan 4 feet in diameter. Evaporation from natural water bodies such as lakes or streams, or from moist soil, might vary appreciably from the value obtained from a standard evaporation pan. Note that throughout the area mean annual evaporation exceeds mean annual precipitation, shown on map 16. Climates are regarded as semiarid when mean evaporation exceeds precipitation. The evaporation rate, moreover, increases generally from west to east and southeast because of the general eastward increase in aridity on the Great Plains.

Many local factors not apparent on the map modify the gross evaporation pattern; these factors include mean relative humidity, slope, ground cover, wind direction, and wind velocity. The prevailing downslope winds on the east flank of the Front Range are very effective drying agents.



MAP 13. — Mean annual evaporation.

Lenticular altocumulus, stationary lee cloud of the mountain wave

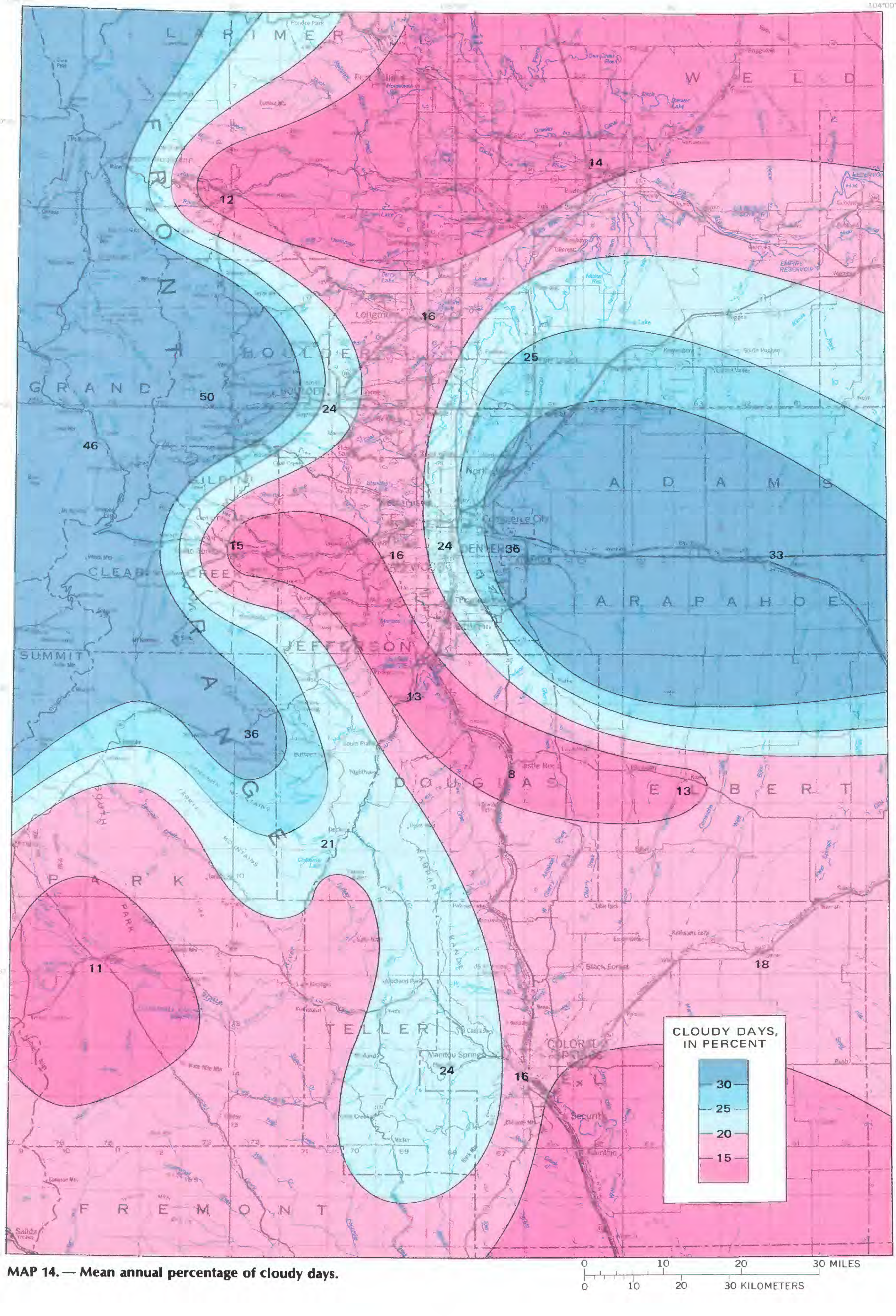
Cloud cover

Mean annual percentage of cloudy days

Cloudy days are defined as those when eight-tenths or more of the sky is covered by clouds. Cloudiness is affected by humidity, altitude, topography, wind direction, and air stability. Inasmuch as the prevailing winds aloft are westerly across the Front Range, the mountains cause a marked precipitation shadow over the foothills, the Piedmont, and South Park. The precipitation shadow, in turn, is expressed by diminished cloudiness immediately east of the mountains. Conversely, the high percentage of cloudy days over the Continental Divide and just west of the divide is obviously orographic, caused by condensation in the atmosphere as the air is forced aloft and is cooled over the mountains. (See figure 4.)

Map 14 shows greater cloudiness in the area east of Denver than in areas to the north and south. At Stapleton International Airport, 36 percent of the days are recorded as totally cloudy; at Byers, 35 miles further east, 33 percent of the days are totally cloudy. The northeastern and the southeastern parts of the Urban Corridor area are much less cloudy, with only 15 percent of the days totally cloudy.

The reason for the high percentage of cloudiness over the plains east of Denver, relative to areas north and south, is problematical; it might be related to atmospheric instability caused by the heat-island effect, to upslope effects on the east margin of the Platte River Valley and, perhaps, to the availability of condensation nuclei in the atmosphere downwind from Denver.

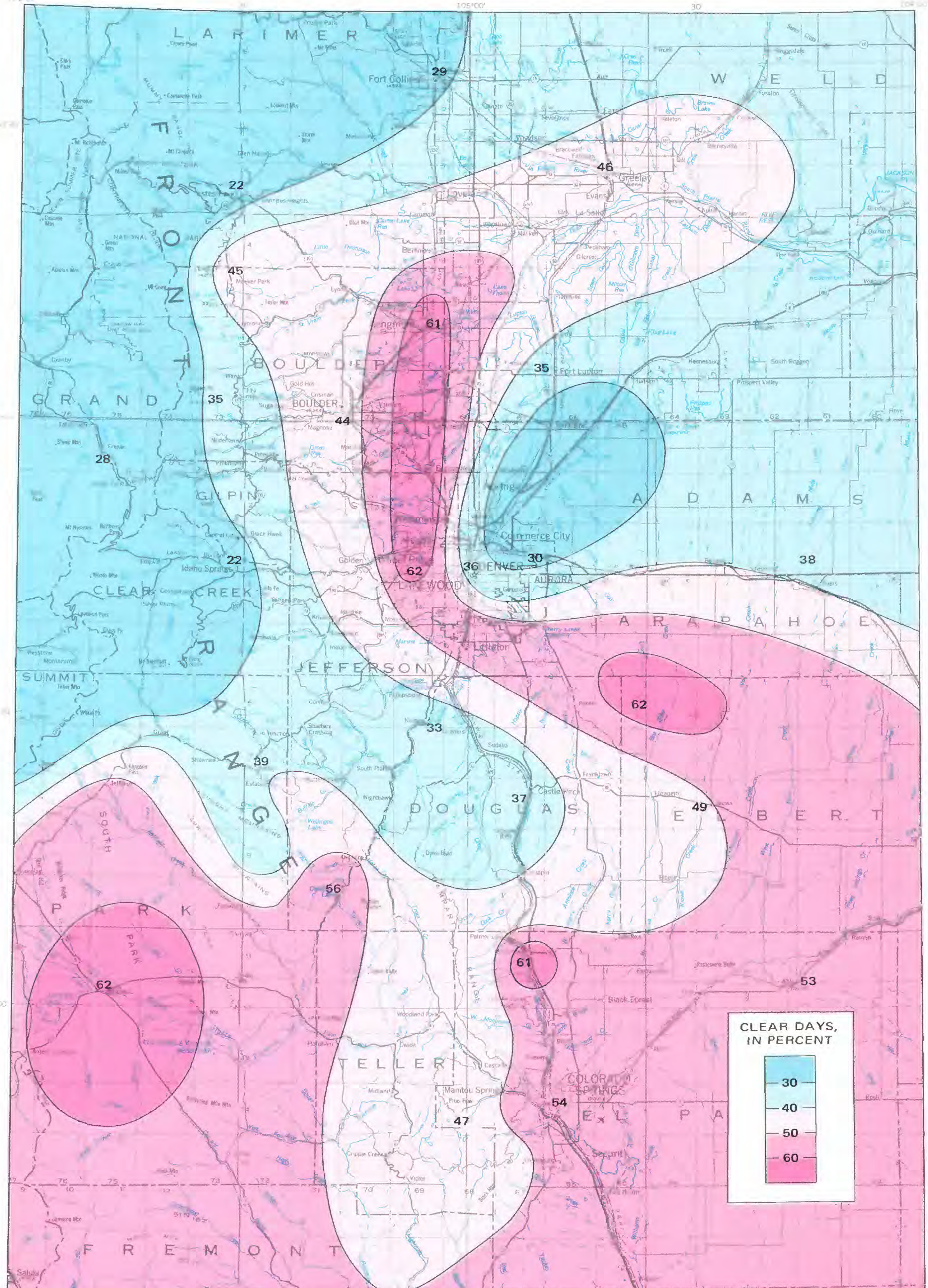


MAP 14.— Mean annual percentage of cloudy days.

Mean annual percentage of clear days

This map is essentially the reciprocal of map 14, which shows the mean percentage of cloudy days. Clear days are those when cloudiness covers three-tenths or less of the sky. The map shows the orographic effect of increased cloudiness west of and along the Continental Divide and the precipitation-shadow effect of reduced cloudiness east of the mountains and over South Park.

A complex pattern of clear days is shown on map 15. The area northeast of Denver has distinctly fewer clear days than the surrounding areas, possibly because of the atmospheric effects inferred in the previous section. There is a statistical "plume" of cloudier weather downwind or northeast of Denver. An elongate zone of clear skies extends from about Lakewood to Longmont, perhaps because of orographic drying as the prevailing westerly wind carries the air down the east slope of the Front Range toward the plains. The bulge of cloudiness over Douglas County and the adjacent part of Elbert County probably is a statistical result of upslope airflow related to the Palmer Divide. Especially in summer, the Palmer Divide is a focus of airmass activity associated with cloudiness and thundershowers.



MAP 15.— Mean annual percentage of clear days.

Precipitation

Mean annual precipitation

In general, precipitation increases with altitude along both slopes of the Front Range, from lows of less than 12 inches at points on the Colorado Piedmont, to more than 34 inches on the Continental Divide at Berthoud Pass. Even greater amounts might fall elsewhere in the mountains where measurements have never been taken. Note, however, that South Park, at an altitude of more than 9,000 ft, is a high cold semidesert. South Park is completely surrounded by high mountains that cast precipitation shadows over the Park from all directions. To a lesser degree, the Fraser River valley in Middle Park shares the same attributes.

Pikes Peak and the Rampart Range form a conspicuous orographic storm center surrounded by areas of lower precipitation. The Palmer Divide also causes a marked rise in precipitation relative to adjacent parts of the plains to the north and south. East of the Greater Denver area, a small east-trending moisture high is indicated by a barblike projection of the 14-inch and 16-inch isohyets. This high, which parallels increased cloudiness east of Denver, might be a precipitation response to airborne particulates, coupled with atmospheric instability related to the heat island effect.

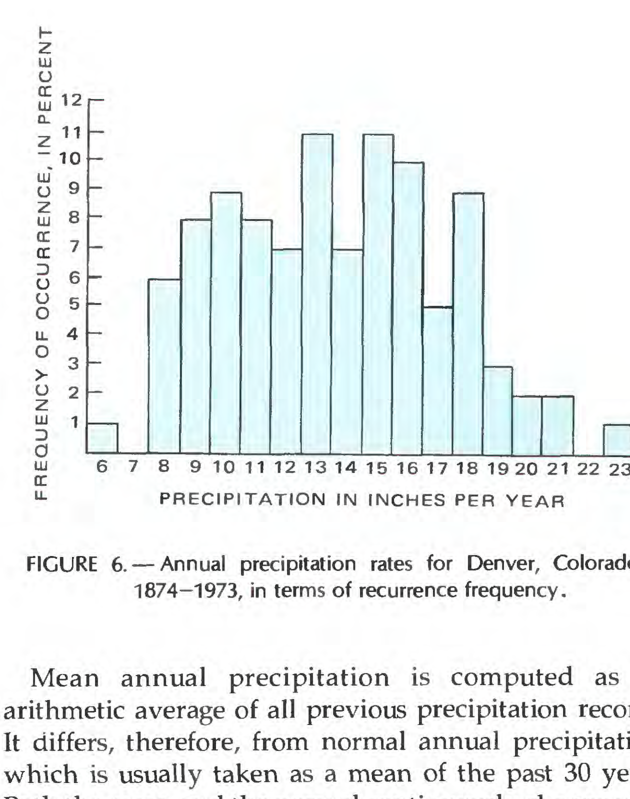
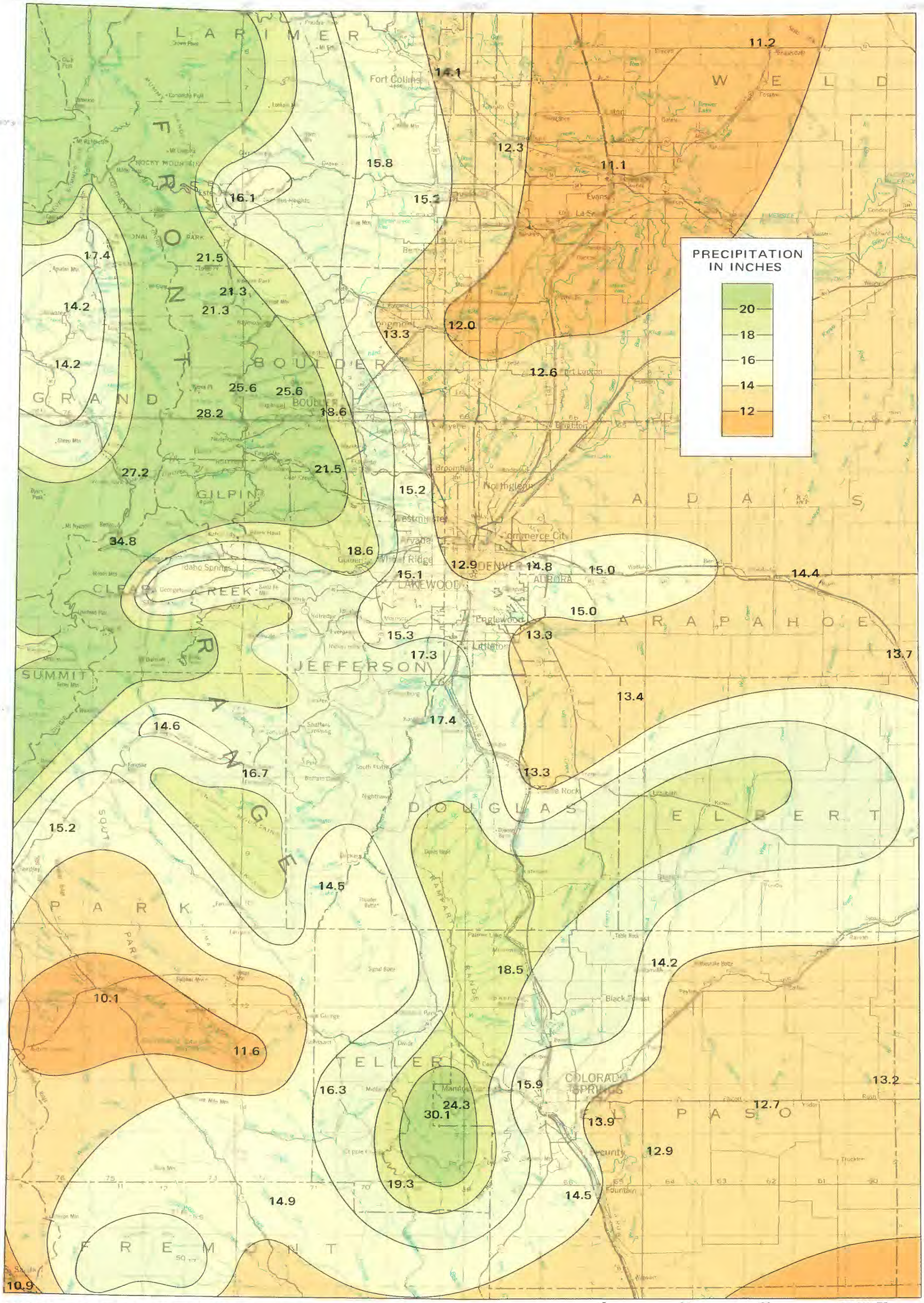


FIGURE 6.—Annual precipitation rates for Denver, Colorado, 1874–1973, in terms of recurrence frequency.

Mean annual precipitation is computed as an arithmetic average of all previous precipitation records. It differs, therefore, from normal annual precipitation, which is usually taken as a mean of the past 30 years. Both the mean and the normal continuously change with time, being derived from alternate short periods of above average and below average precipitation; because of climatic variability from year to year, few years actually closely approach the mean (fig. 7).

The variability of annual precipitation is also illustrated by figure 6, which summarizes the measured annual rates of precipitation for Denver, expressed in frequency of recurrence for the period 1874–1973. Figure 6 shows how often each annual rate recurred in 100 years, and it conveys some idea, therefore, as to how often a given rate is likely to recur in the future.



MAP 16.— Mean annual precipitation.

Cumulonimbus, storm cloud of summer, may tower to 60,000 feet

Maximum annual precipitation

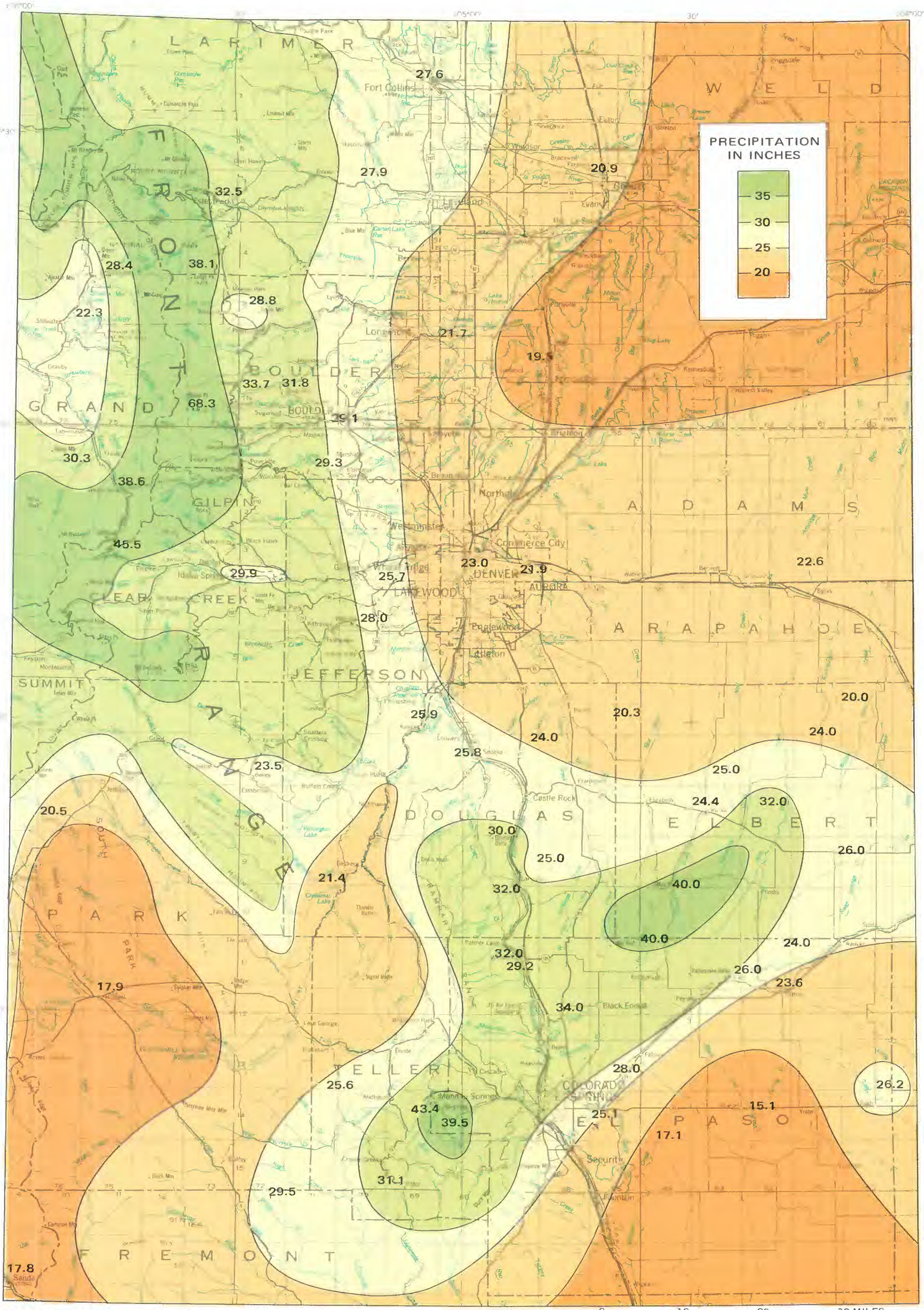
The Front Range Urban Corridor and vicinity are characterized by much variability in seasonal and yearly weather patterns. Maps or records that show only the mean weather conditions tend to obscure the variations that actually make up the climate.

This map conveys some idea as to what the precipitation pattern might be in an exceptionally wet year. The reliability of the isohyetal lines is not uniform over the whole map. Where the control is best and the information most reliable, as at Denver where records have been kept for more than 100 years, the maximum precipitation is about 160 percent of the mean. Figure 7 shows clearly the variability of precipitation rates from year to year in Fort Collins, Boulder, Denver, and Colorado Springs. In Denver, for example, the highest annual precipitation recorded between 1872 and 1974 was 22.96 inches in 1909, whereas the mean is about 14 inches. Note that annual precipitation of 20 inches or more fell in Denver four times in the fifty years between 1872 and 1923, but has not recurred in the fifty-three years since.

Reliable records from mountain stations west of the Urban Corridor are too sparse to permit plotting meaningful maximum isohyetal lines greater than about 35 inches, although maxima greatly exceed that amount in many mountain locations; the Indian Peaks area west of Boulder and the Mount Evans area south of Idaho Springs are two examples.

The high totals shows for the area near the Palmer Divide were deduced from totals measured during the exceptional storms of May 1935 and June 1965, combined with the projected mean annual precipitation for that area, as shown on map 16. Continuous long-term station records are not available for most of that area, and the actual maximum precipitation might have exceeded the amounts shown on the map.

The greatest annual precipitation ever recorded in the map area fell near the Indian Peaks at the Boulder Water Reservation station four miles east of Arapahoe Glacier, and about 16 miles west of Boulder, where 68.3 inches fell in 1921. The same locality also has the distinction of having had the heaviest 24-hour snowfall ever recorded in the conterminous United States, at least through 1976. Seventy-six inches of snow fell there on April 14 and 15, 1921; more than 90 inches fell before the storm ended after about 30 hours (Paddock, 1964, p. 29; Baldwin, 1973, p. 25).



MAP 17.— Maximum annual precipitation.

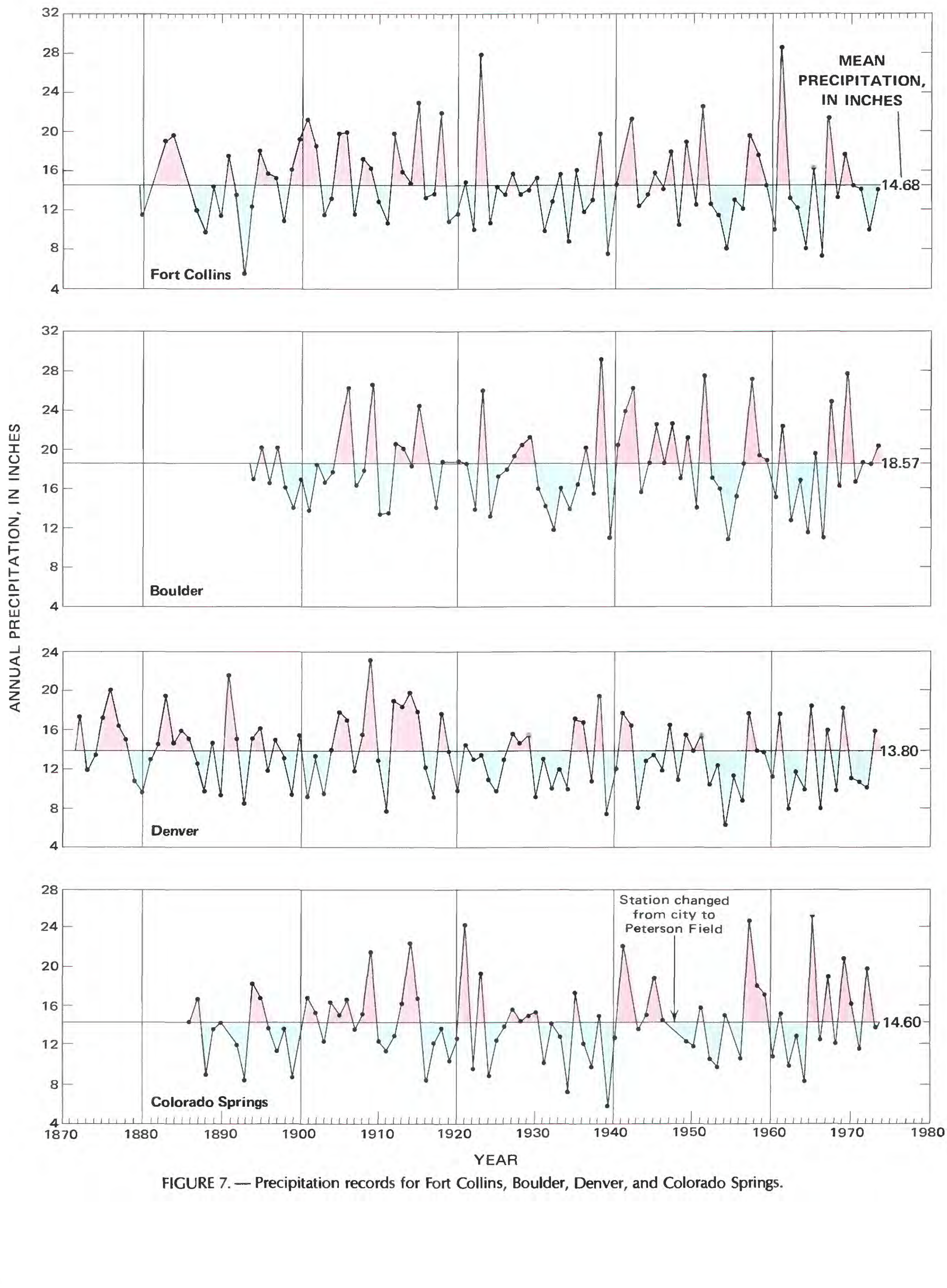


FIGURE 7. — Precipitation records for Fort Collins, Boulder, Denver, and Colorado Springs.

Record maximum precipitation in 24 hours

Each precipitation maximum shown on the map represents a peak measurement from a single intense storm. In some places, two or more exceptionally intense storms have centered at different times over nearly the same areas, but the intensities shown on the map represent single events and convey no measure of repetition. The isohyetal lines are interpolations, therefore, between points of maximum-recorded downpours at many different times.

Most downpours were associated with widespread shower activity elsewhere along the Front Range, although the downpours themselves were mostly localized cloudbursts that had downpour patterns only a few miles across. The distribution of such storms across the map indicates that few areas are likely to be immune from infrequent rains of 3–4 inches or more in a 24-hour period, especially east of the Continental Divide.

Many of these storms caused destructive flooding along water courses far downstream, some taking the lives of people living nearby. The historical records contain many accounts of such floods, dating back to pioneer days, and although some of these accounts note the intense accompanying downpours, few accounts document the actual intensities. If more early flood accounts had included measurements of the rainfall that caused the flooding, the map probably would show many additional maxima greater than 4 inches. Even today, many localized cloudbursts escape the official record because they do not fall at official recording stations. Repeated floods along some drainages, such as the section of Denver near Cherry Creek, were caused by distant cloudbursts in remote headwaters, and one might assume that unrecorded storms comparable to those shown on the map have centered in the map area many times in the past 100 years. Every major drainage east of the Continental Divide has had repeated historic flooding, some several times (table 1). Follansbee and Sawyer (1948) and Matthai (1969) provide excellent documentation. Flooding in late spring or early summer is likely to be reinforced by mountain snowmelt; late summer floods result almost entirely from cloudburst activity. Figure 8 shows the historic distribution of flooding by month in 10-day increments. Note that the activity is distinctly bimodal, with peaks near the first week of June and the first week of August.

The storm of July 31–August 1, 1976 over the Big Thompson River near Estes Park, Colorado, was one of the most tragic events in Colorado history. Ten inches of rain fell at the center of the storm 4 miles east of Estes Park during the nighttime hours of July 31. The resulting floods on the Big Thompson, its North Fork, and their tributaries caught hundreds of vacationers and weekend campers without warning and took the lives of at least 139 people. Preliminary isohyets plotted for this storm by the National Weather Service and other cooperating agencies are shown on map 18.

Intense cloudbursts are likely to fall on the Front Range Urban Corridor at any time from late spring through late summer. Although all parts of the region are susceptible, some places are more susceptible than others. The large triangular area between Castle Rock, Colorado Springs, and the forks of Bijou Creek, south of Byers, has a history of repeated cloudbursts and floods that is unequaled elsewhere in the Corridor and that includes probably the greatest single downpour in Colorado history. The localization of cloudbursts in this area is influenced by

TABLE 1.— Floods on major streams of the Front Range Urban Corridor, 1864–1976

[Data compiled by R. A. Parnell, L. W. Anderson, and W. R. Hansen, chiefly from Water-Supply Papers of the U.S. Geological Survey]

	–1870	1870–1880	1880–1890	1890–1900	1900–1910	1910–1920	1920–1930	1930–1940	1940–1950	1950–1960	1960–1970	1970–
Bear Creek		X		X X				XX X	XX X	X	X	X
Big Thompson River	X			X	X	X	X X	X	X	X		X
Boulder Creek	X	X		X		X	X	X				
Cache La Poudre River	X	X	X		X		X X		X			X
Cherry Creek	X	X X	X			X	X	X	X X		X X	X
Clear Creek	X	X	X	X				X X	X			X
Fountain Creek	X	X	XX	X	X		X	X X			X	
St. Vrain Creek	X	X		X			X	X	X	X		
South Platte River	X	X		X			X	X X	X X X	X	X	X

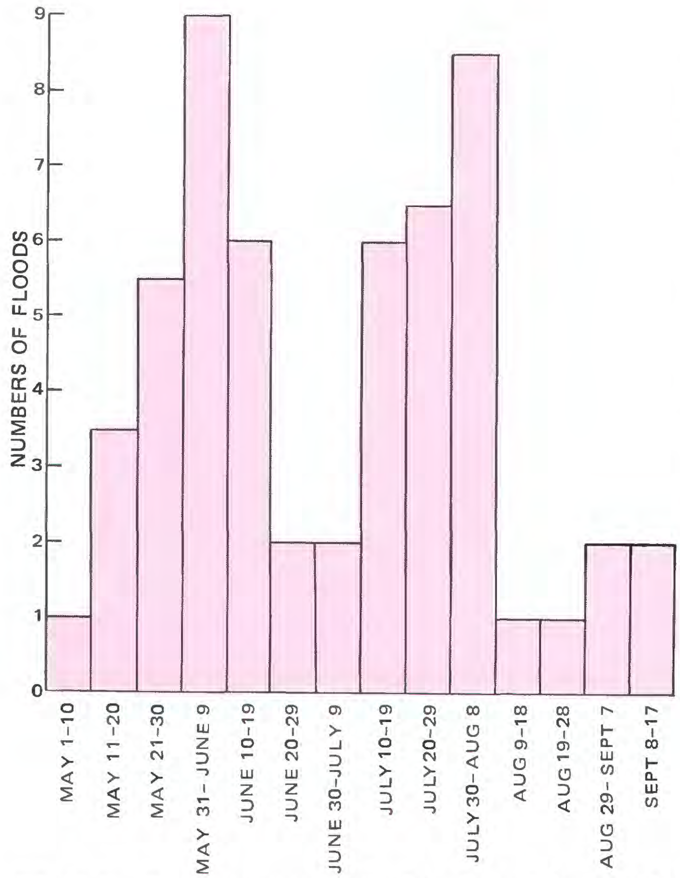


FIGURE 8. — Flood occurrences in the Front Range Urban Corridor, 1864–1976, in 10-day increments. Columns with half intervals indicate floods that straddled two increments. Prepared from data compiled by R. A. Parnell, L. W. Anderson, and W. R. Hansen.

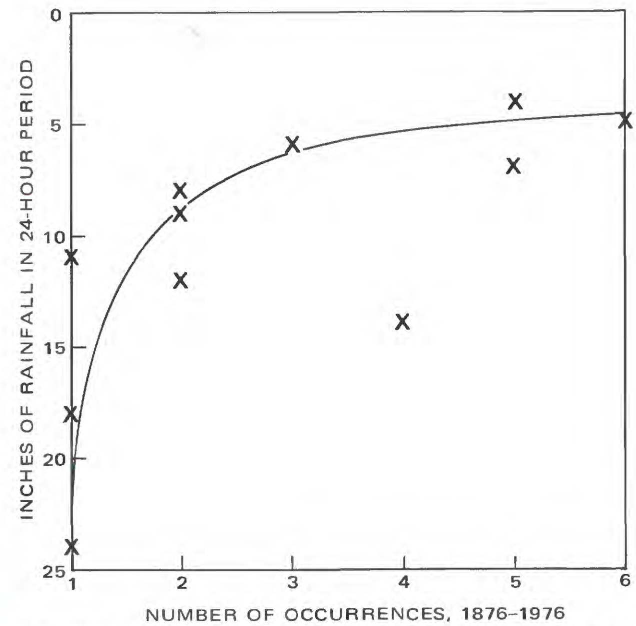


FIGURE 9. — Frequencies of heavy cloudbursts in the Front Range Urban Corridor area and vicinity, 1876–1976 inclusive. All the 14-inch downpours plotted here happened during the extraordinary general storm of June 16–17, 1965; although each downpour fell from a separate cloudburst cell, they all could be regarded as parts of a single event and, if so, would fit much closer to the plotted curve.

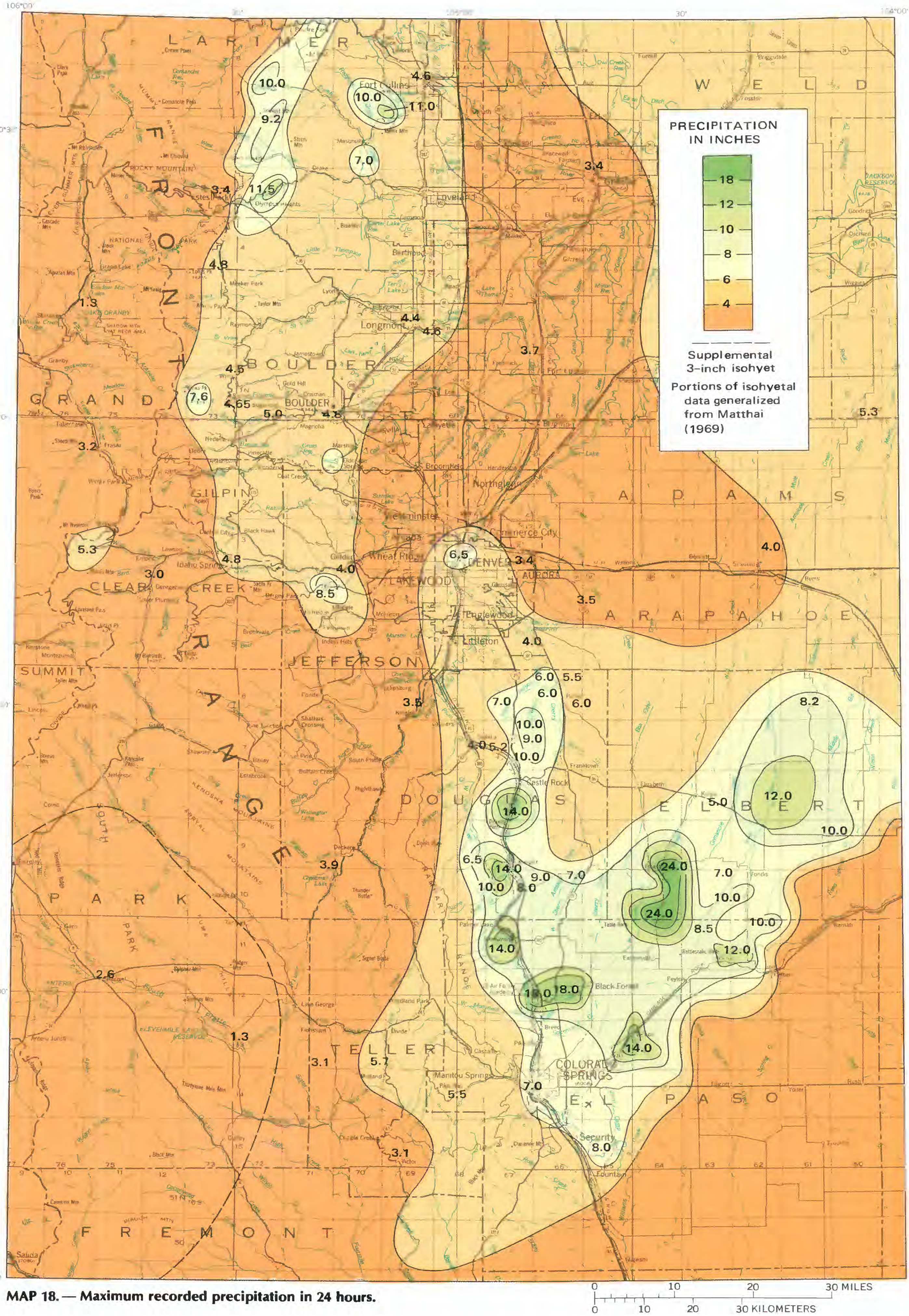
the orographic effect of the Palmer Divide. Precipitation rates from some of these storms have been truly astonishing and have rarely been equaled, even by tropical hurricanes.

The heaviest downpour on record centered over the watersheds of Bijou, Kiowa, Monument, and Fountain Creeks on May 30, 1935 when 24 inches of rainfall was recorded by improvised rain gauges at Elbert and at a point about 6 miles south of Elbert (Follansbee and Sawyer, 1948, p. 70). The storm lasted from 5 a.m. to 6 p.m., but most of the 24 inches of rain fell between noon and 4:30 p.m. Other cloudburst cells in the same general storm dropped 18 inches of water on the Black Forest east of the present Air Force Academy, and 7 inches on the northwest part of Colorado Springs. This incredible storm exceeded by factors of 2–3 the heaviest downpours ever recorded anywhere else in the Front Range Urban Corridor.

Other great storms in the vicinity of the Palmer Divide, and numerous historical accounts of floods on the streams that drain it, further reaffirm the storm-gathering propensity of that area. The historic storms of June 14–17, 1965, which caused more than $500,000,000 damages to the Greater Denver area, dropped as much as 14 inches of rain from four separate storm cells over the Plum, Kiowa, Bijou, Monument, and Fountain Creek drainages; most of the rain fell in about only three hours during the afternoon (Matthai, 1969, p. B3). Matthai's comment (p. B2–3) is noteworthy: "Residents of the South Platte River basin will not forget the flood of June 1965. Some stories may be exaggerated in traditional Western style; but when most of 14 inches of rain falls in about 3 hours, it is raining harder than most people have ever seen or will ever see. When one experiences a storm like this and sees the consequences, exaggeration is difficult — and pointless." Flooding from this storm exceeded that of the tragic Big Thompson flood of 1976 by at least an order of magnitude. Fortunately, far fewer lives were lost.

Although storms equal to these have never been recorded elsewhere in or near the Corridor, impressive amounts of precipitation have fallen in many places. Some of these storms are listed in table 2. Many storms that failed to achieve record 24-hour falls, moreover, dropped large quantities of rain over periods of a few days on different parts of the Corridor.

Figure 9 shows the recurrence frequency of cloudbursts of various magnitudes in the Front Range Urban Corridor area during the period 1876–1976 inclusive. Inasmuch as the actual number of cloudbursts of the magnitudes indicated undoubtedly exceeded the number recorded, the curve shown in figure 9 would shift to the right if more complete data were available. The curve gives some indication — perhaps minimally — of expectable cloudburst frequencies in the future.



MAP 18. — Maximum recorded precipitation in 24 hours.

TABLE 2. — Some representative high precipitation totals recorded at various points in or near the Front Range Urban Corridor[1]

Location	Dates	24-hour total in inches	Remarks
Big Thompson Canyon[2] — 4 miles east of Estes Park	7/31/1976	10	At least 139 lives lost.
Bijou Creek	5/30/1935	12	Nearby, 8, 15, and 18 inches.
Black Forest	5/30/1935	18	East of USAF Academy.
Boxelder — off map 29 miles north-northwest of Fort Collins.	5/20–21/1904	8	Fell in 6 hours.
Castle Rock[3] (near Castle Rock)	6/16/1965	12	Fell in about 4 hours. Measured 3 1/2 miles south southwest of Castle Rock.
Cherry Creek	8/2–3/1933	9	
Cold Spring Gulch	9/2/1938	5	Tributary of Bear Creek.
Colorado Springs	5/30/1935	7	10:30 a.m. –12:45 p.m.
Denver	5/22/1876	6.5	
Do	8/11/1936	6.5	
Elbert	5/30/1935	24	Maximum intensity 1:30–4:30 p.m.
Eldorado Springs	9/2–4/1938	6	
Falcon[3]	6/17/1965	14	
Fort Collins	9/3/1938	3.54	9/1–4/38 total 5.09 inches.
Hosa Lodge — 3 miles east-northeast of Bergen Park	9/2–3/1938	8	During night.
Lake Moraine — eastern slope Pikes Peak	5/30/1894	5.5	
Larkspur[3] (near Larkspur)	6/16/1965	14	In about 4 hours. Measured 1 mile southwest of Larkspur.
Longmont	6/3/1921	4.4	
Missouri Canyon — 3 miles south of Masonville	9/10/1938	7	Fell within 1/2 hour.
Monument[3]	6/16/1965	14	
Mount Vernon Canyon — 4 miles east-northeast of Bergen Park.	9/2/1938	8.5	Near Mt. Vernon Country Club.
Parker[3]	6/16/1965	6	
Pikes Peak	5/30/1894	4.57	
Sand Creek tributary, near Stapleton International Airport[4].	5/6/1973	4.38	
Silver Lake — 15 miles west of Boulder	4/14–15/1921	7 est.	
Do	6/8/1921	4	6/2–8/21 total 10.88 inches.
Spring Canyon — 6 miles southwest of Fort Collins	9/2/1938	11	Overflowed 12 inch bucket.
Sugarloaf — 6 miles west of Boulder	5/31/1894	5	
Sunset — 10 miles west of Boulder	5/30/1894	4.65	
Ward — 12 miles west northwest of Boulder	5/30/1894	4.5	8.54 inch total in 3 days.

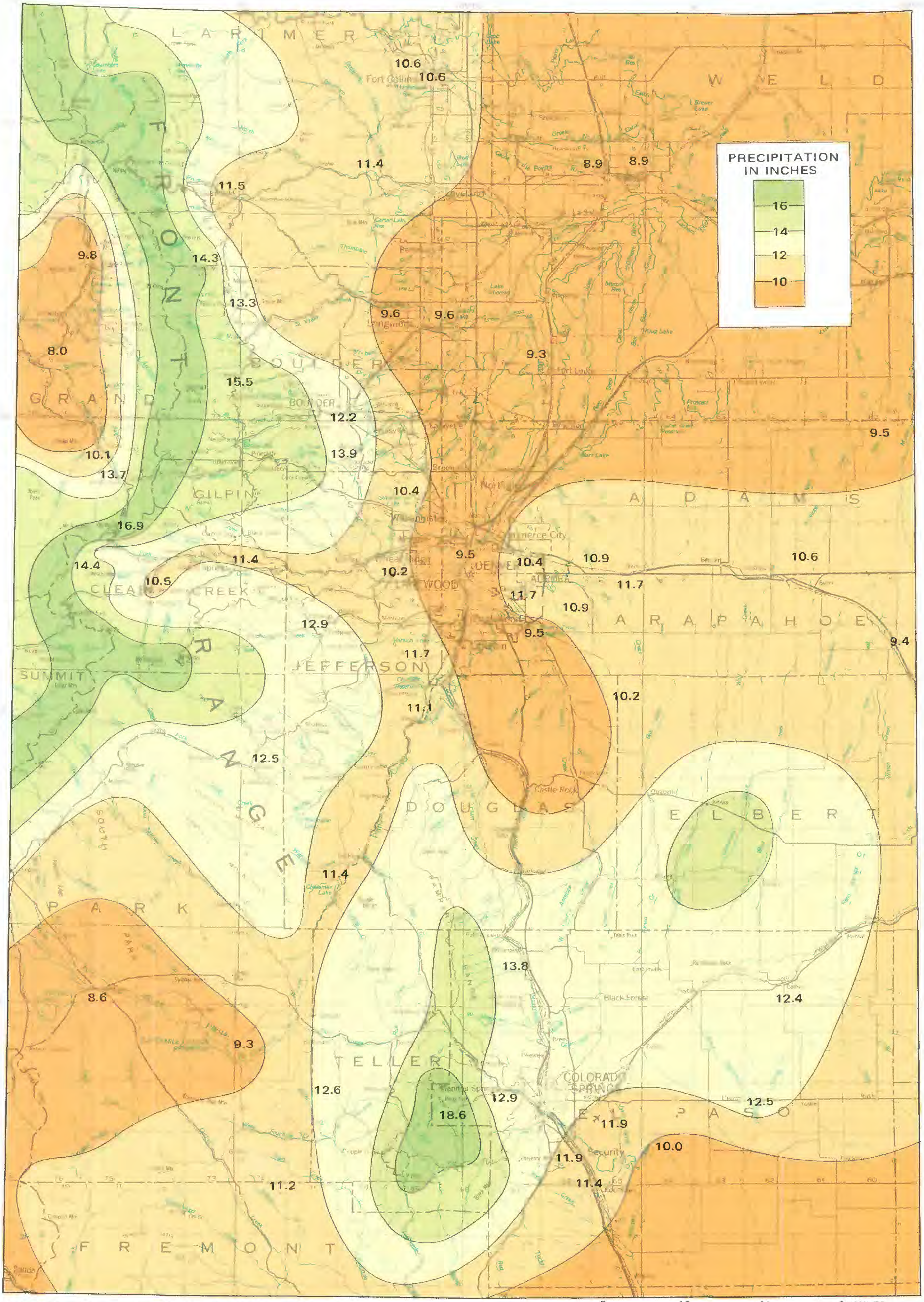
[1] Data from Follansbee and Sawyer (1948) except as indicated.
[2] Data from National Weather Service, 1976.
[3] Data from Matthai (1969).
[4] Data from Ducret and Hansen (1973).

Mean monthly precipitation

The histograms in figure 10 show the distribution of precipitation by months at 12 selected stations. At all stations except Fraser, maximum precipitation is in the spring and summer months, mostly with highest peaks in May and with secondary peaks in July. At Fraser, the precipitation is distributed more evenly throughout the year, although appreciably more of it falls in December through May than in June through November.

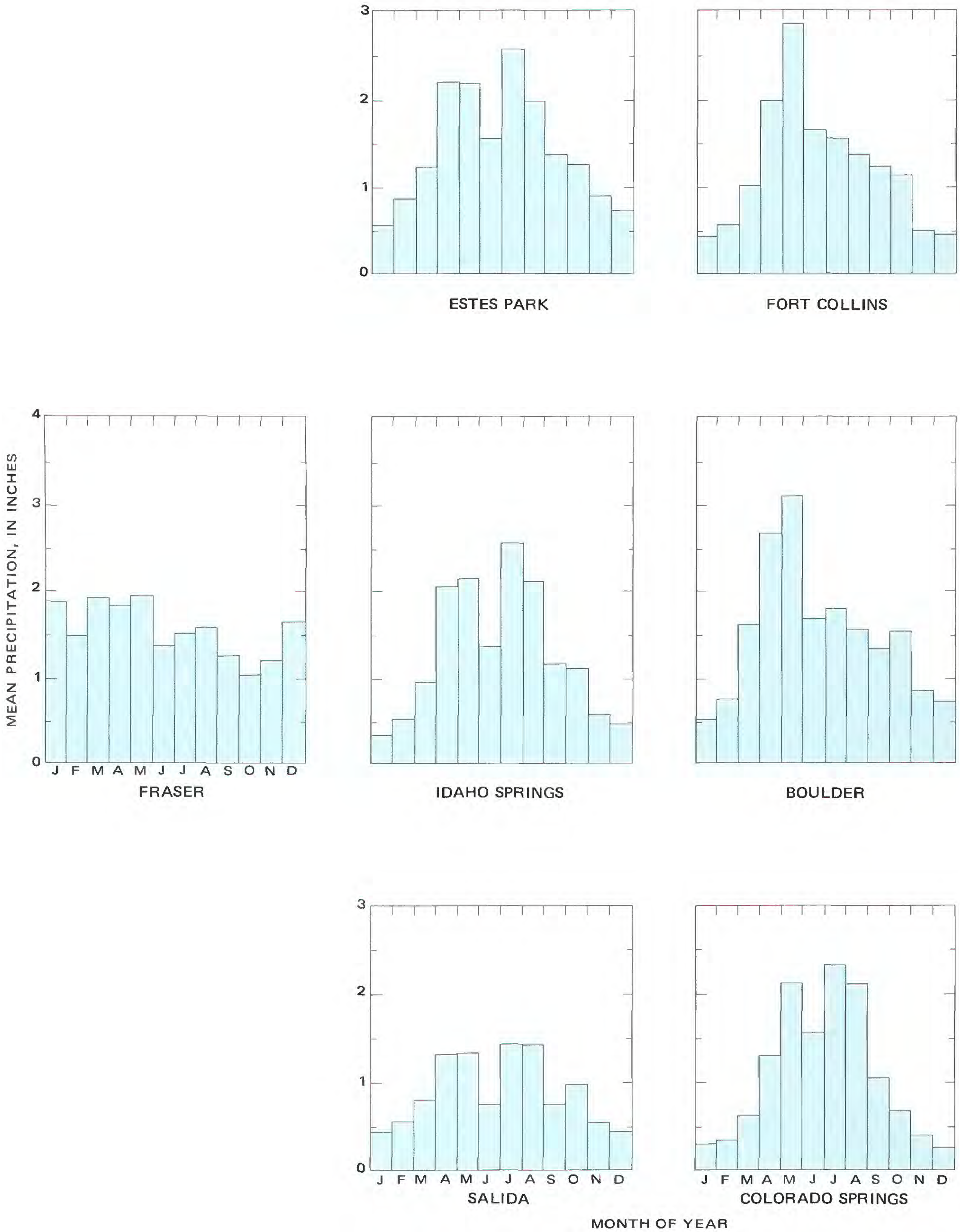
Mean precipitation, April through September

The Front Range Urban Corridor is favored by nature in that most of its precipitation falls during the growing season, April to September, when it is most needed for agriculture. This seasonal distribution is clearly shown by comparison of map 19 with map 16, mean annual precipitation. It also is obvious on the histograms (fig. 10).



MAP 19. — Mean precipitation, April through September.

0 10 20 30 MILES
0 10 20 30 KILOMETERS



MEAN PRECIPITATION, IN INCHES
0
1
2
3
4
ESTES PARK
FORT COLLINS
FRASER
IDAHO SPRINGS
BOULDER
SALIDA
COLORADO SPRINGS
J F M A M J J A S O N D
MONTH OF YEAR

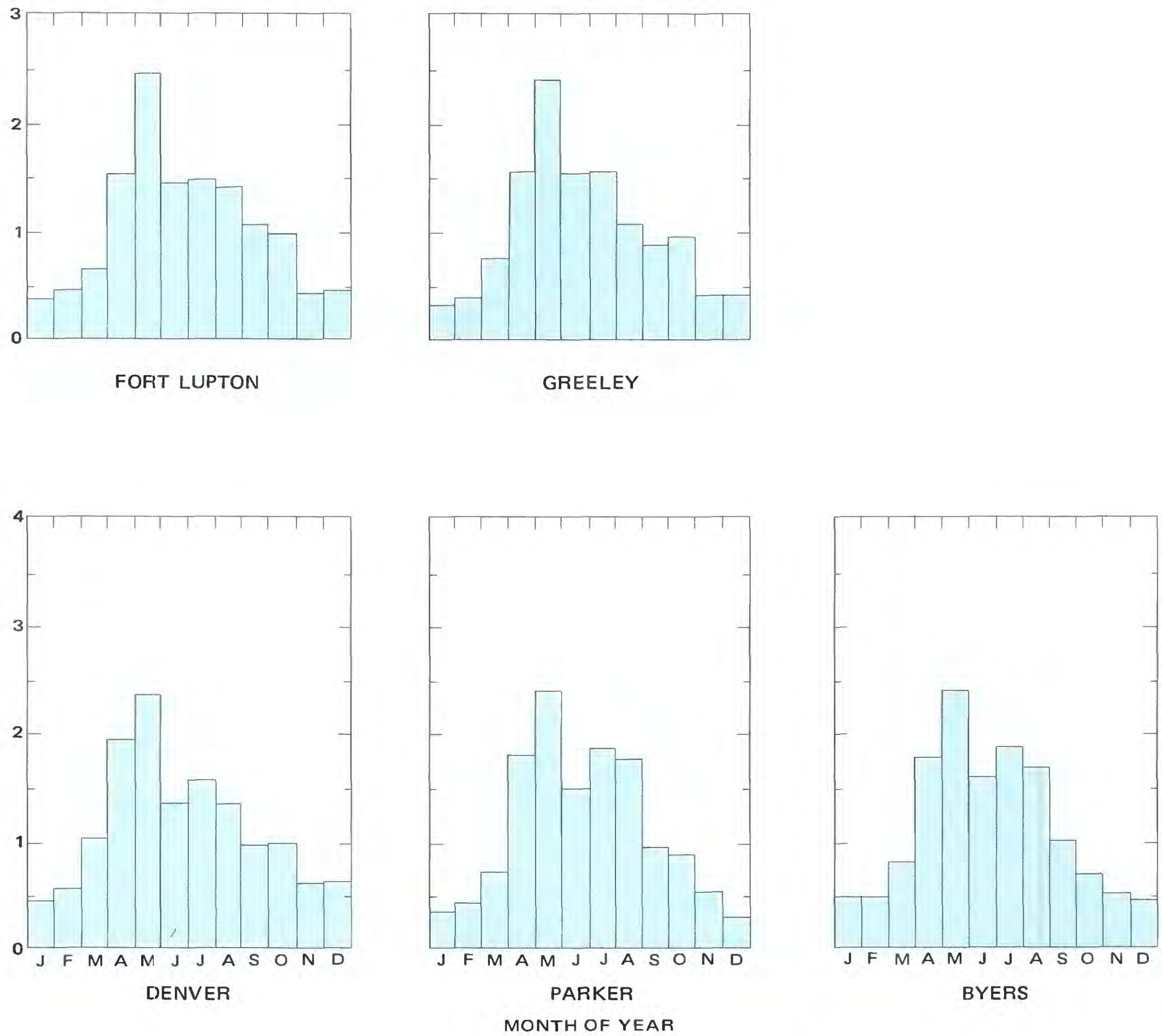
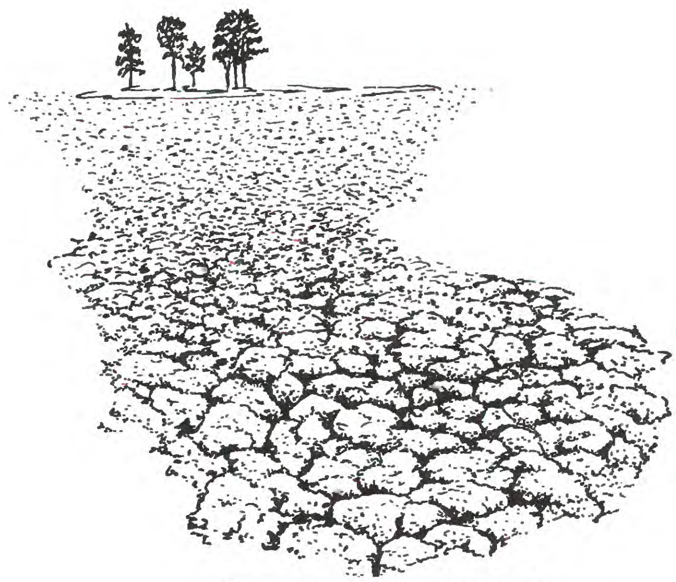


FIGURE 10 (Above and left). — Monthly mean precipitation at 12 selected weather stations, Colorado. Histograms are arranged in approximately west to east and north to south transects to permit ready comparisons of data.

During this period, numerous rainshowers are generated by upslope easterly air flow and convection, especially in warm moist air that flows northward up the Great Plains from the Gulf of Mexico. Prodigious amounts of moisture sometimes fall from late afternoon and evening thundershowers during these months (Matthai, 1969).

The form and distribution of isohyetal lines on the map clearly define the several topographic elements that affect the climate of the area — the Front Range, the Colorado Piedmont, the Pikes Peak–Rampart Range massif, the Palmer Divide, South Park, and the Fraser River valley all are outlined as well-defined precipitation highs or lows.

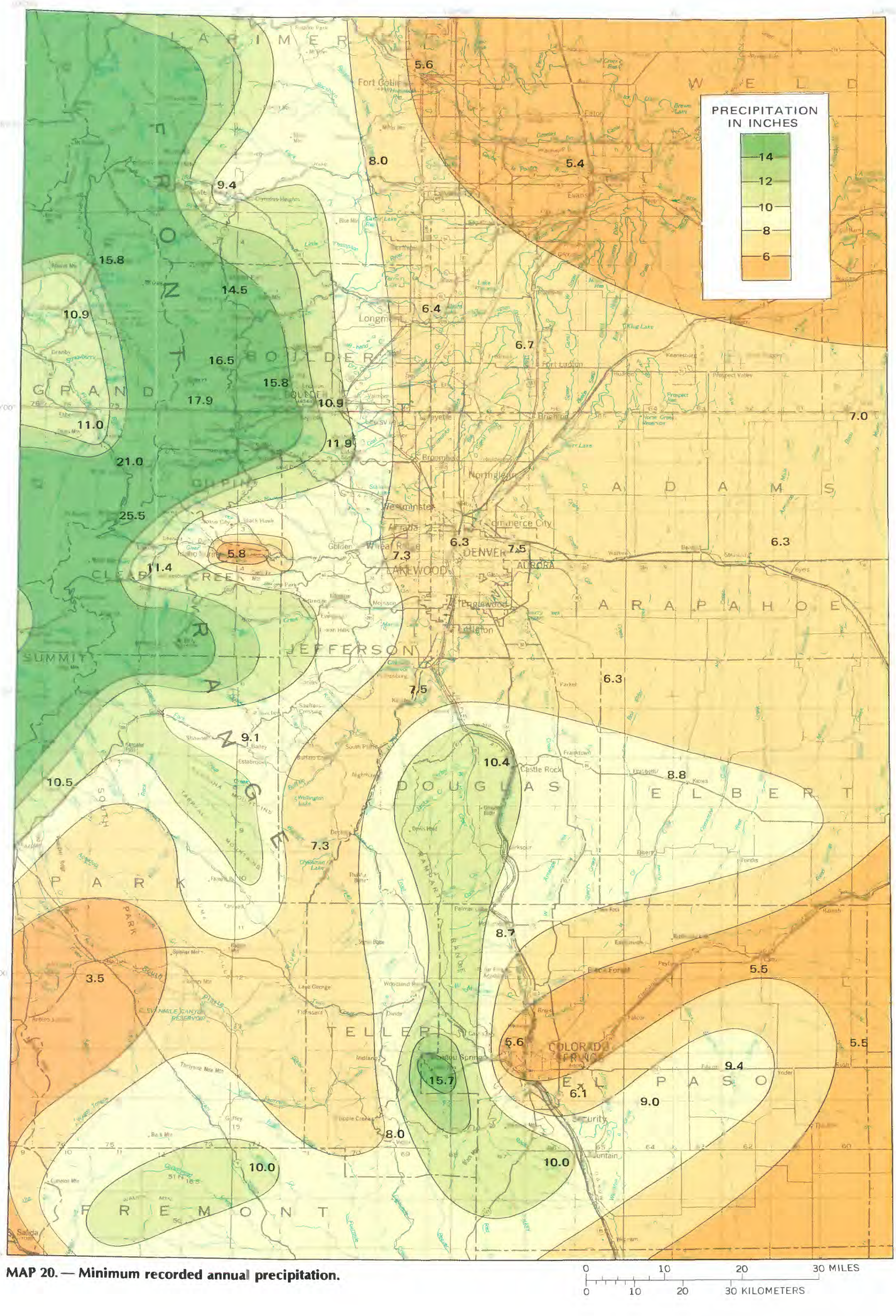


Desiccation cracks on a dried mud flat

Minimum recorded annual precipitation

This map is a composite of the minimum annual precipitation records for each reporting station, without regard to year, and it conveys some idea, therefore, as to what the precipitation pattern would be like in a year of extreme drought. Precipitation in such a year might approach the amounts shown here or, locally, might even be less. Note that in one year Denver received less than 7 inches of moisture and Colorado Springs and Greeley received less than 6 inches. The lowest recorded annual amount in the map area is 3.55 inches at Hartsel in South Park. Droughts of this severity along the Front Range are likely to recur very infrequently, but figure 7 shows that less than 10 inches of annual precipitation has fallen in Denver 20 percent of the time since weather measurements began in 1872 (through 1974, or 21 out of 101 years). Less than 9 inches of precipitation has fallen in Denver 8 times in 101 years, and 8 inches or less has fallen 5 times since 1939. Thus, moderate to severe droughts can be expected in the Denver area and elsewhere in the Front Range Urban Corridor every few years. Their recurrence frequency is suggested by figure 6.

Annual precipitation totals alone, however, do not necessarily indicate the existence or nonexistence of drought. In the semiarid climate of the Front Range Urban Corridor, one heavy storm might bring the annual precipitation up to "normal" in a year that had been severely short of rainfall most of the time. Conversely, a low annual total would not constitute drought if adequate rain had fallen in the growing season. Thomas (1962, p. A-3, A-4), citing the views of several other authorities, has described drought as insufficient moisture to sustain the needs of transpiring plants. Native plants are adapted to rainfall approaching the average condition for their particular habitat, and adequate rainfall for the Front Range Urban Corridor might be a disastrous drought in Iowa or Louisiana or New England. Native plants on the Colorado Piedmont, moreover, will flourish on moisture that is insufficient to sustain most types of non-native crops. With irrigation and holdover storage in reservoirs, and with modifications to drainage, soil moisture, and runoff caused by urbanization, drought is a complicated relative condition that means different things to different people.



MAP 20. — Minimum recorded annual precipitation.

Mean annual snowfall

Mean annual snowfall along the Front Range correlates generally with altitude — the higher the altitude, the higher the mean. The totals in South Park, however, at altitudes of 9,000–10,000 feet, are comparable to amounts at much lower altitudes east of the mountains, inasmuch as South Park is in the precipitation shadow of high mountains on all sides.

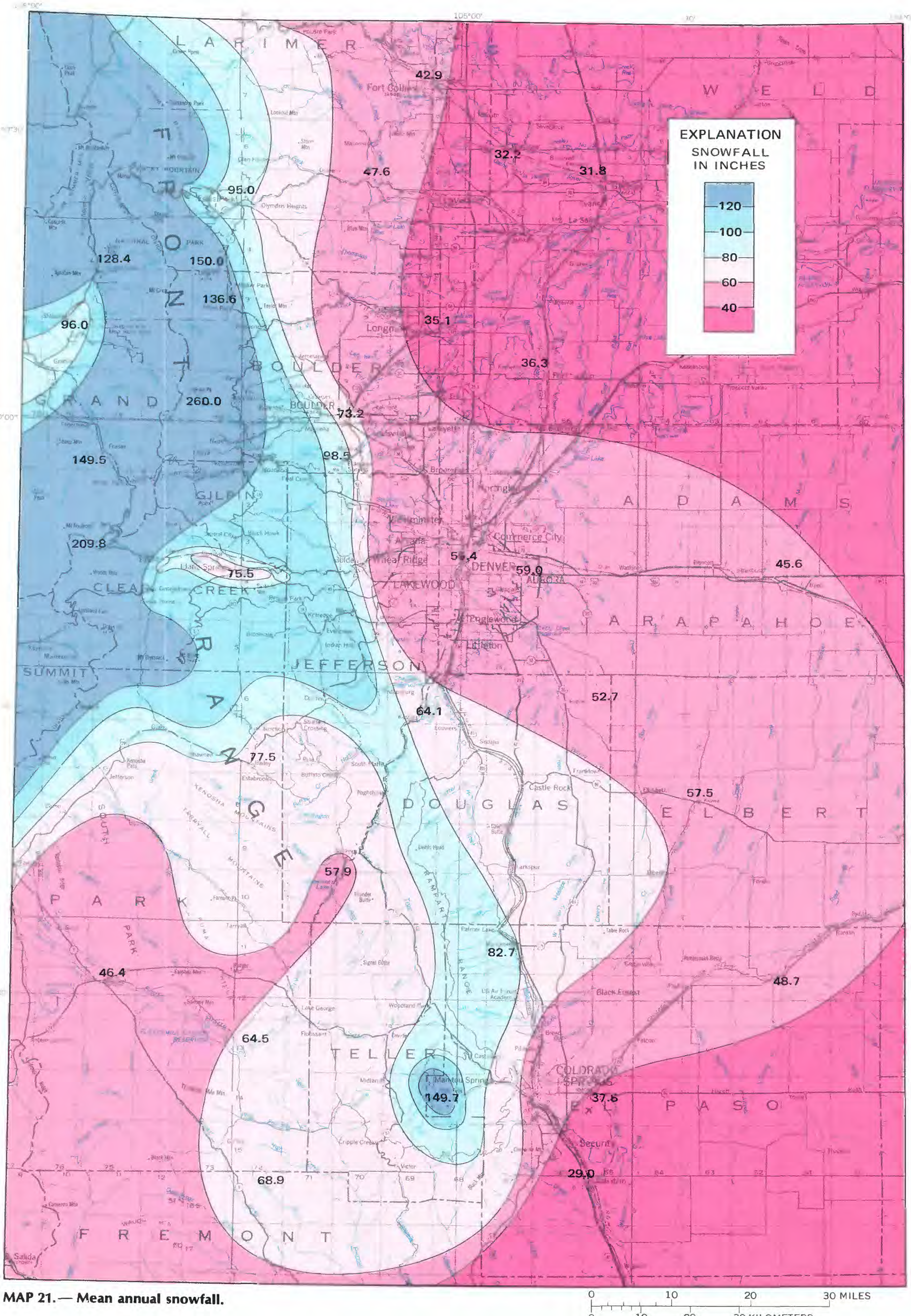
The highest mean annual snowfall recorded in the Front Range area is at Berthoud Pass (altitude 11,315 ft), although records there and at other high mountain stations are less complete than at most lower altitude localities. During the period 1931–1939 the mean September-June snowfall at Berthoud Pass was 413 inches; in 1950–1964 it was 361 inches (Judson, 1965, p. 28). In the calendar year 1957, 518 inches fell at Berthoud Pass. According to Judson (p. 8) Berthoud Pass averages about 20 percent more snowfall than other mountain stations at Loveland Basin, Arapahoe Basin, Breckenridge, and Climax. (Breckenridge and Climax are west of the map area.) Comparable, but unmeasured, amounts of snow might fall elsewhere in the high mountains of the Front Range. An average of about 260 inches falls at the Boulder Water Reservation station (altitude 10,400 ft) about 16 miles west of Boulder, and 4 miles east of Arapahoe Glacier.

Arapahoe Glacier, near Boulder, is nourished mainly by drifting snow

FIGURE 11. — Middle Park in winter. The distribution of snowfall in the map area is very uneven; the heavy snowfall at mountain stations bears little relation to the light snowfall on the plains.

The presence of several small glaciers along the Continental Divide in the northern Front Range probably is more a result of snow drifting into shielded cirques than of prodigious total snowfall. Strong winter winds build enormous snow cornices at the heads of favorably oriented cirques, and these deposits nurture the glaciers below (Outcalt and MacPhail, 1965, p. 2).

The relatively light mean annual snowfall in the Denver area and elsewhere on the Colorado Piedmont may surprise some people who are used to thinking of Denver as being in the nation's snowbelt. Heavy snowfall at high mountain stations (fig. 11) bears little relation to the light snowfall on the Colorado Piedmont, where most of the precipitation falls as rain during the warmer months of spring and summer (fig. 10). Denver receives more snow than most large cities in the country but less, for example, than Albany or Buffalo, New York, Worcester, Massachusetts, Portland, Maine, or Salt Lake City, Utah (U.S. National Oceanic and Atmospheric Admin., 1974). Snow in Denver, moreover, seldom remains on the ground for more than a few days at a time; rapid melting accompanies intervening periods of fair weather and bright sunshine.



MAP 21.— Mean annual snowfall.

Wind

Directions and velocities

In the middle latitudes, which includes all the conterminous United States, the winds aloft are dominated by a stong westerly airflow, the prevailing westerlies. Surface winds, however, are highly variable because of local orographic and other effects, such as gravity flow. In the mountains, moreover, local weather is recorded mostly at valley stations where, because of funneling effects, the wind usually blows with the valley trend regardless of the regional circulation. In valleys where the wind direction is persistent, the trunks and limbs of large trees such as cottonwoods often lean conspicuously downwind. The valleys of South Boulder Creek south of Boulder and Van Bibber Creek north of Golden are good examples.

Out on the plains the mean directions of surface winds are highly variable, but the wind becomes more directed as its velocity increases. Histograms (fig. 12) of the direction of *greatest* monthly velocity of surface winds at Denver and Colorado Springs show that these directions

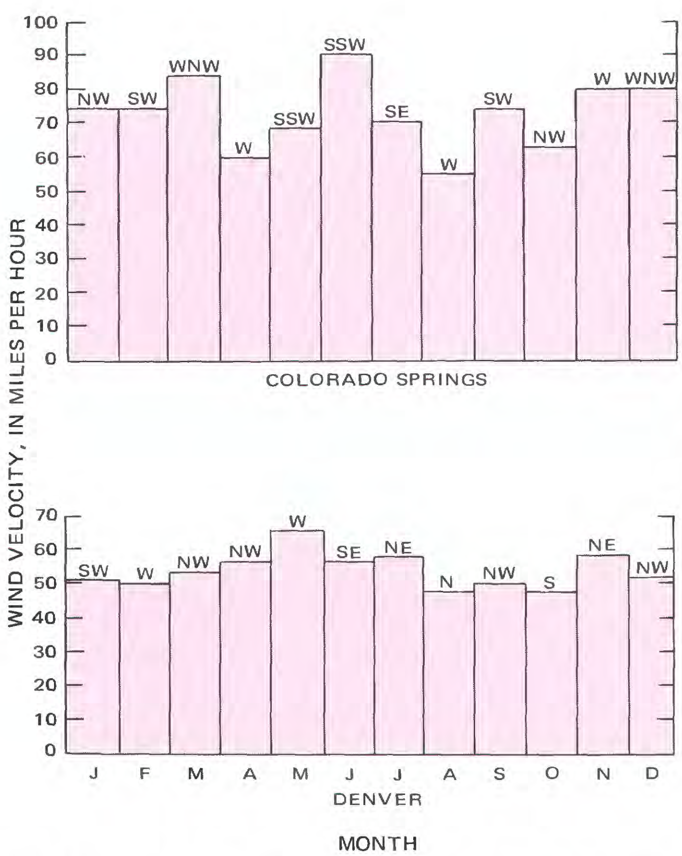


FIGURE 12.—Direction and greatest velocity, by month, of surface winds in Colorado Springs and Denver.

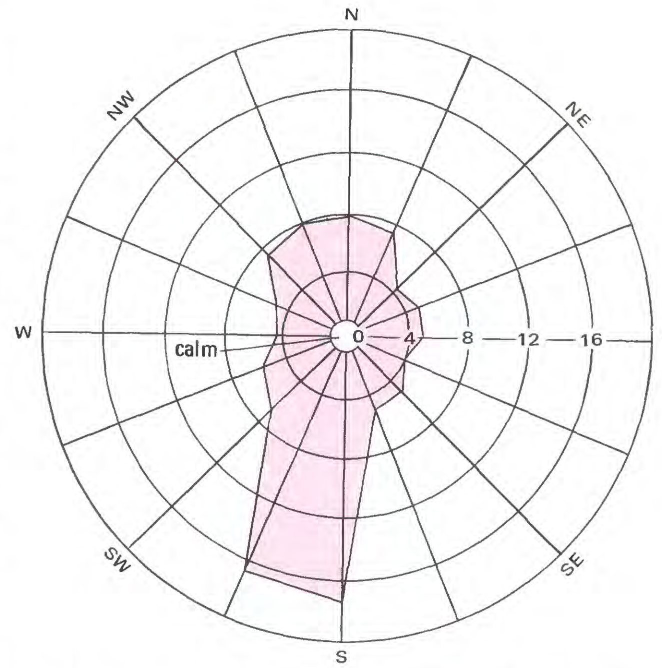
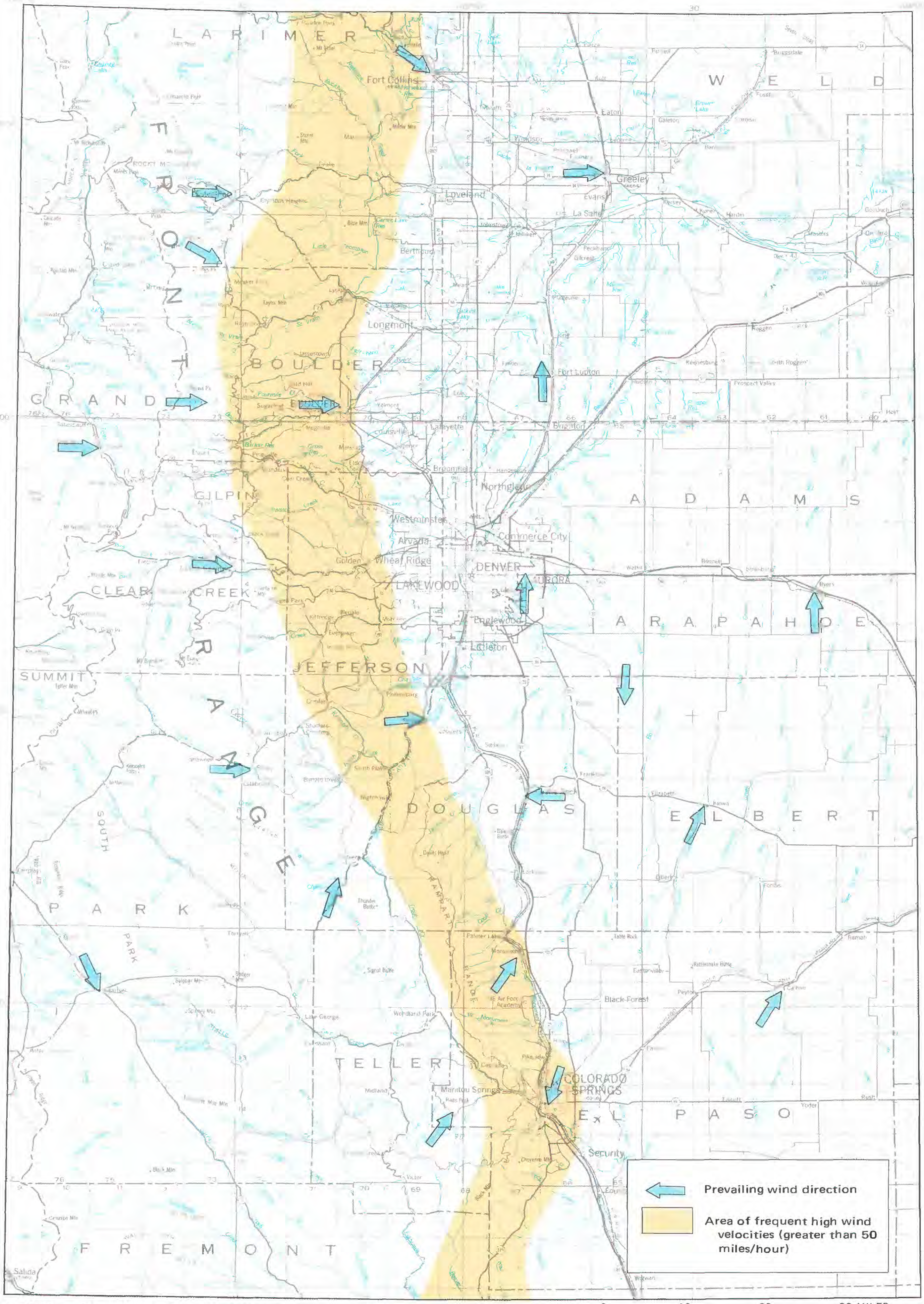


FIGURE 13.—Yearly wind rose for downtown Denver. All wind velocities are weighted equally. Numbers are percent of time.

usually have westerly components. A wind rose for *all* velocities at Denver (fig. 13) shows predominant southerly winds. Atmospheric pollutants generated in the Denver area, therefore, tend to be carried northward down the valley toward Brighton, Fort Lupton, and even Greeley; times of weak circulation, when gravity flow carries the air northward, tend to coincide with times of serious air pollution. Figure 14, moreover, shows that low velocities, and therefore weak circulation, predominate.

As the westerly wind blows across the Rocky Mountains and descends the eastern slope of the Front Range it is warmed adiabatically and its relative humidity is lowered. This is the well-known foehn or chinook effect, and it is common on the lee of mountain ranges throughout the world. During times of strong circulation such winds often attain hurricane force and are capable of inflicting severe damage to property. In southern Europe the foehn sometimes triggers avalanches in the Alps and even forces the closure of transportation routes. In Chile the extreme aridity of the Atacama Desert is a consequence of subsidence, warming, and drying of the air in the lee of the high Andes. Along the Front Range Urban Corridor the chinook is welcomed in winter as it breaks the chill of the cold and quickly melts the snow



MAP 22. — Prevailing surface wind directions.

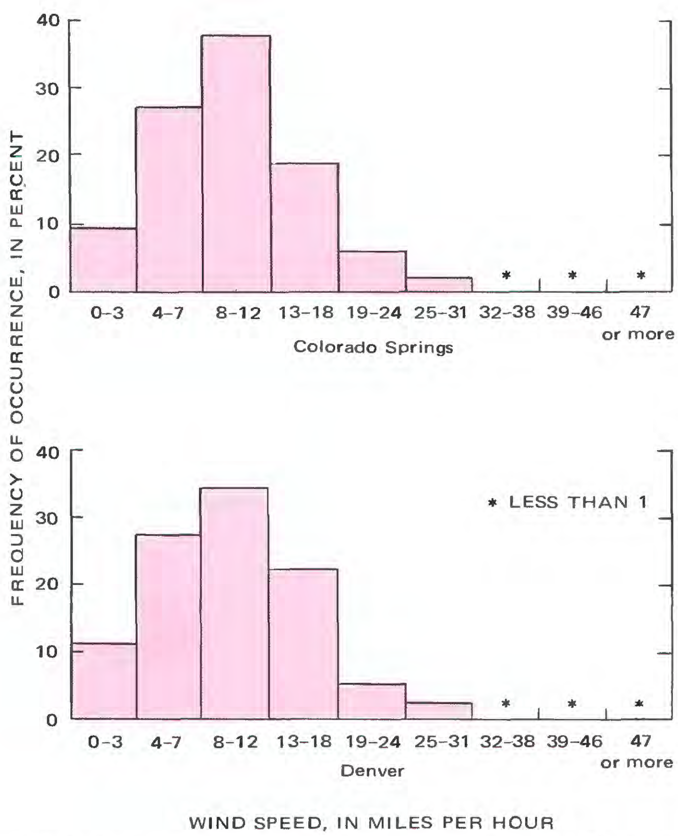


FIGURE 14.—Wind speed and frequency of occurrence at Colorado Springs and Denver.

from streets and roads, but it sometimes blows hard enough to damage houses and other buildings near the mountain front.

The chinook that descends the east slope of the Rocky Mountains, according to classic theory, is caused by a combination of three main factors: (1) Strong circulation brought on by steep pressure gradients associated with well-developed weather systems, (2) the release into the atmosphere of the latent heat of condensation, that had been "stored" in the air, as the air rises, cools, and precipitates moisture over the western slope of the Front Range, and (3) thermodynamic heating caused by compression as the air descends the east slope. Because of the released heat of condensation, the air gains a net increase in temperature as it crosses the range from west to east (fig. 15). This increase amounts to about 2°F per thousand feet, but it varies with the amount of moisture in the air. The second factor (2) might in fact contribute less to the warming effect of the chinook than might the breakup, by the wind, of the wintertime ground inversion normally formed by nighttime chilling. This breakup is simply a mixing of the air near the ground, but it may mean a rise of as much as 25°F in the nighttime temperature. (See discussion by Cook and Topil, 1952, p. 44.) In addition, the chinook effect is most marked when warmed Pacific air flowing across the mountains displaces cold polar air east of the mountains. At such times the temperature on the Colorado Piedmont might rise 50°F or more in just a few hours.

Destructive winds

Destructively strong winds are experienced annually along the east slope of the Front Range when the wind velocity exceeds about 50 mph. These winds usually, but not always, are characterized by the chinook effect described earlier. Destructive winds are most common in winter when steep pressure gradients accompany the passage of deep low-pressure systems well to the north of Colorado in eastern Montana or Manitoba (Harrison, 1956, fig. 3 and p. 7). High pressure lies to the west at such times, and a low-pressure trough lies just east of the mountains. A deep temperature inversion overlies the

At Lena Gulch the cottonwoods lean with the gentle but prevailing downvalley breeze

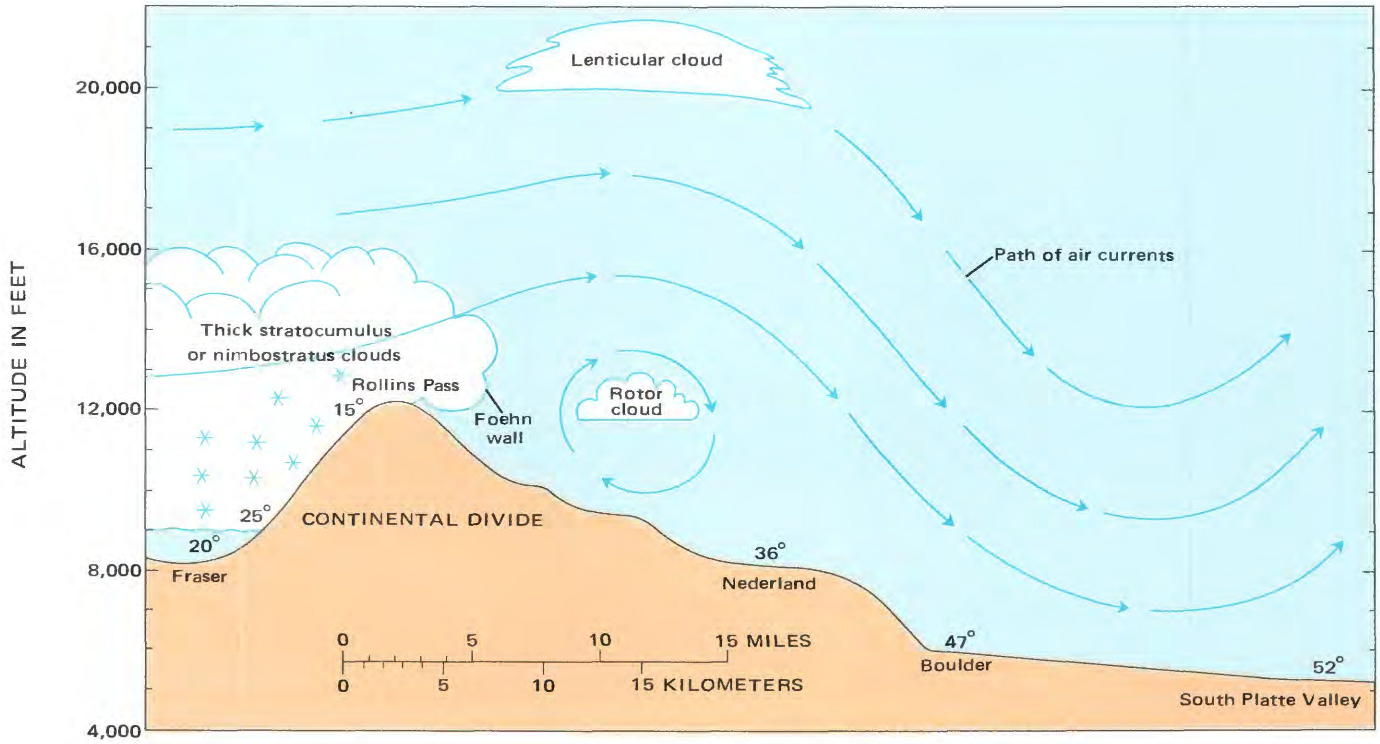


FIGURE 15. — The chinook effect, showing the adiabatic and thermodynamic heating of the air as it flows across the Front Range from the vicinity of Fraser in Middle Park to the South Platte River valley east of Boulder. At left, snow falls from saturated air ascending the west slope of the Front Range, cooled by expansion at the saturation-lapse rate of 3.2°F per 1,000 feet. Leading edge of cloud bank forms "foehn wall" along Continental Divide. Lenticular cloud, characteristic of the chinook, forms at the crest of large standing air wave to the lee of the divide. Rotor cloud indicates severe turbulence east of the divide. Dry, or unsaturated, air (blue) descends east slope of Front Range at a lapse rate of about 5.3°F per 1,000 feet, heated by compression as it subsides and increasing in velocity as it nears the mountain front. Note difference in air temperature at Fraser and at Nederland — both places at about the same altitude.

Front Range and areas to the west (Zipser, 1972, figs. 9, 10). These winds have become the subject of intensive research by the National Center for Atmospheric Research (NCAR), the U.S. National Oceanographic and Atmospheric Administration (NOAA), and the University of Colorado (Miller and others, 1974). Besides damage to fixed structures, high winds frequently overturn and destroy mobile homes, grounded aircraft, cars, and sheds, and inflict damage on trees. Damage also is frequently caused by flying debris (White and Haas, 1975, p. 299).

The distribution and timing of high winds east of the mountains indicate that the winds accompany huge standing waves in the atmosphere that form over the Front Range when strong westerly winds blow across the Continental Divide. These waves are analogous to ripples downstream from a cobble in a brook (Scorer, R. S., 1961, p. 124). They cause severe turbulence aloft that occasionally jostles aircraft over or just east of the divide (fig. 15).

Winds as strong as 135 mph have been recorded at NCAR headquarters at Boulder. According to Paddock (1964, p. 28–29) peak gusts rarely exceed 100 mph along the Front Range Urban Corridor, although gusts exceed 70 mph annually (minimum hurricane velocity is 75 mph) and exceed 90 mph about every 5 years. These figures are valid averages for the Front Range Urban Corridor as a whole, but there are notable exceptions, and the geographic variation is striking; one station about a mile east of the foothills in Boulder reports wind gusts around 100 miles per hour several times each year, whereas another station in Boulder reports a wind gust over 80 miles per hour only once every four or five years (Patrick J. Kennedy, NCAR, written commun., 1976). Velocities usually are highest close the mountain front and, seemingly, near the mouths of major canyons although the effect of topography, according to Miller and others (1974, p.83), is uncertain. Detailed understanding of the distribution and intensities of strong winds along the Front Range Urban Corridor is hampered by a lack of an area-wide reporting network. A detailed local network for wind study at Boulder has been operated by NCAR and NOAA since 1968, and some conclusions about the winds at Boulder might be extrapolated to nearby areas. Two wind roses for Rocky Flats, just south of Boulder, show the westerly constancy of high winds at that particular place (fig. 16). At low velocities (0–29 mph) direc-

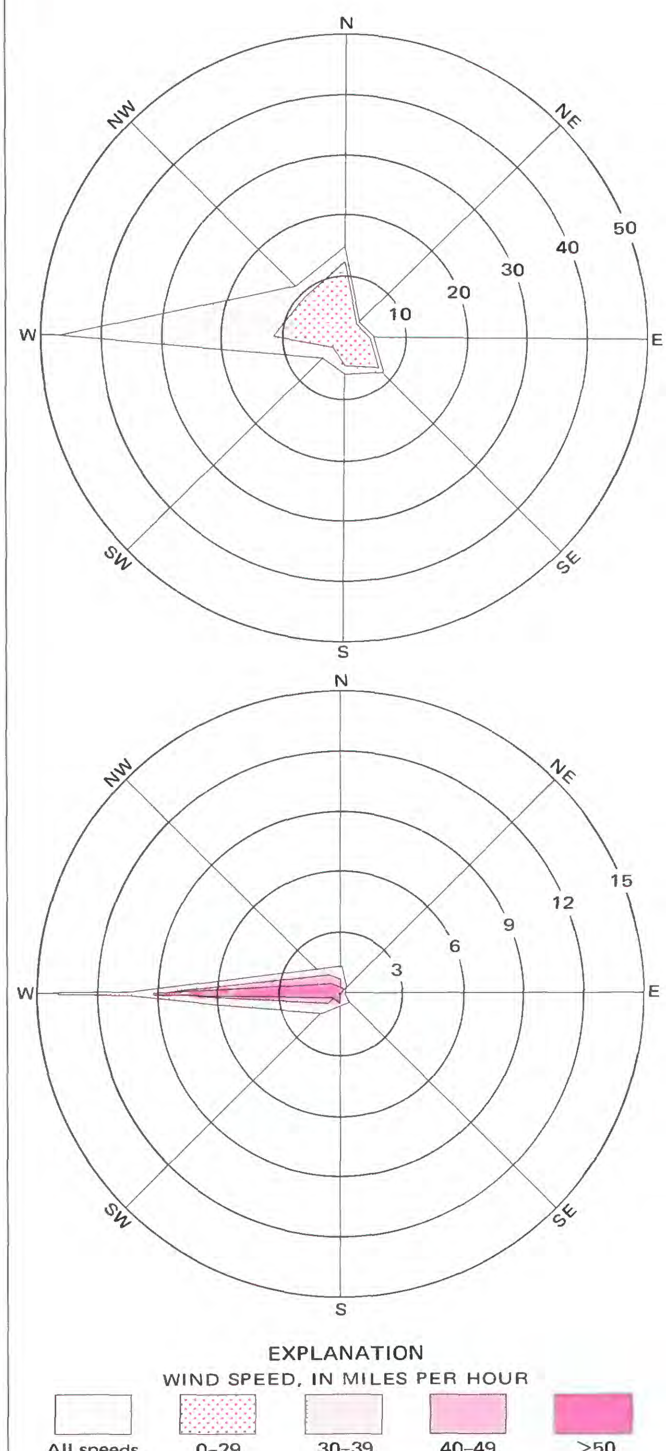


FIGURE 16.—Wind roses for Rocky Flats, Colorado, showing wind direction and frequency, in percent, of wind speed.

tions are more variable. Little is known, however, about the frequency and magnitude of winds in many sparsely populated parts of the Front Range and Colorado Piedmont.

THE CLIMATE SUMMARIZED

The climate of the Front Range Urban Corridor, in summary, is characterized by:

- Highly variable weather elements along the Front Range and the Colorado Piedmont; areas of high altitude in general have the lowest mean temperatures, the greatest cloud cover, the greatest precipitation, and the great variability in most other weather elements.
- Strong seasonal variations of most weather elements.
- General semi-aridity at the lower altitudes, with average rainfall of 12–14 inches per year on the Colorado Piedmont and 2 or 3 times as much precipitation near the crest of the Front Range.
- About 70 percent of the annual precipitation falling in the warm season between April and September, except along and west of the Continental Divide, where the distribution is more uniform throughout the year.
- Completely clear weather on about half the days; except just northeast of Denver, where cloudiness frequently builds up during the afternoon especially in summertime, and along the crest of the Front Range, where cloudiness is caused by orographic uplift.
- Cloudy weather less than a third of the time over two-thirds of the area.
- A persistent well-defined "heat island" over the Greater Denver area caused by broad expanses of heat-absorbant and heat-radiant material, such as streets and buildings, and by the release of artificially generated heat energy.
- A persistent climatic "ridge" extending eastward across the Colorado Piedmont in the vicinity of the Palmer Divide between the drainages of the South Platte and Arkansas Rivers; caused by the orographic effect of the divide on local airmasses.
- A north-south belt of occasionally very strong foehn or chinook winds, especially in winter, concentrated in the foothills and the immediately adjacent piedmont.

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