Potential for Regional Air Pollution Episodes in Colorado

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ABSTRACT

A climatological analysis of regionally potentially bad air quality days near Denver and Grand Junction, Colorado has been prepared. These bad air quality days are defined as days which have a small volume of atmosphere available for the dilution of contaminants released within the region. The atmospheric volume is represented by the product of a solar mixing height and average wind speed which leads to an hourly solar mixing area accumulated throughout the day to form a daily solar mixing area. Solar mixing height is calculated by a simple thermodynamic model using a percentage of the incoming solar energy (at the top of the atmosphere) and the morning rawinsonde temperature sounding. Wind speed is assumed to vary logarithmically with height and is fitted to the surface and 700 mb winds from the morning sounding. The average of the wind speed between the surface and the solar mixing height is multiplied by time to give the horizontal movement. The horizontal movement times the solar mixing height gives a solar mixing area. This value of solar mixing area is assumed to represent the mixing volume available for the dispersion of regionally released air pollution.

Twenty years (1959-1978) of rawinsonde soundings from Grand Junction and Denver, Colorado were used to perform the climatology. Disturbed days are defined to be good air quality days and are determined separately from climatological data. The results are the average monthly frequency of potentially bad air pollution days and the frequency and length of potential air pollution episodes on a seasonal basis.

In the Grand Junction region, the greatest number of potentially bad air pollution days and episodes exists in the fall and winter seasons, with very few potentially bad days in the spring and summer. Episodes of three days or longer occurred in the Grand Junction region an average of less than one time per spring and summer season, nearly five per fall season and nearly seven per winter season. Thus, these three day or longer episodes averaged 12.4 episodes per year. Very long episodes of potentially bad air quality are possible as illustrated by the 28 day episode of December 1976 and January 1977.

By comparing the western Colorado region around Grand Junction to the eastern Colorado region around Denver, a similar seasonal pattern can be found between the regions. However, the Denver region's episodes of three days or longer averaged four per fall season and five per winter season. Both the number and duration of potentially bad air quality episodes in fall and winter are greater in the area around Grand Junction.

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CHAPTER I

INTRODUCTION

The people of Colorado have a particular awareness of and concern for the quality of their air. The scenic beauty of the state, which is enhanced by the bright sunshine and clear dry air, has attracted many people. With the increasing number of residents came more cars, industry, and development to add to the anthropogenic sources of air pollution. This is of consequence because a brownish haze from an accumulation of pollutants is much more noticeable if it obscures the view of a snow-capped mountain. Also, there is fear that increased concentrations of pollutants will adversely affect vegetation and wildlife in wilderness areas.

Because development is expected to increase in Colorado, it is important to know how susceptible various regions around the state are to bad air pollution episodes. The purpose of this study is to determine the potential for regional air pollution in the areas surrounding Denver and Grand Junction, Colorado and, more specifically, what time of year this potential exists and how long it lasts.

According to Boettger, "air pollution potential may be defined, from the meteorological standpoint, as a set of weather conditions conducive to the accumulation of air pollutants in the atmosphere."[1] In

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[1] Boettger, C. M., 1959: Air pollution potential east of the Rocky Mountains--Fall 1959. United States Weather Bureau Research Station, Division of Air Pollution. United States Department of Health, Education and Welfare, Cincinnati, Ohio, p. 1.

this paper, the weather conditions which lead to increased concentrations of air pollutants within a region are considered to be those conditions which allow mixing in only a small volume of the atmosphere. Therefore, the interests are in mixing height for a constraint on the vertical dimension and wind speed for an indication of the horizontal dimensions. A simple thermodynamic model is applied to the 12Z (0500 LST) rawinsonde sounding, from a site within each region, to arrive at hourly mixing heights. Wind speeds at the 700 mb and surface levels of these soundings are employed in estimating horizontal transport.

It is important to realize the topography in the regions being studied; Figure 1 gives a simple topographic map of Colorado. In the Denver region, the Rocky Mountains are aligned basically north to south and rise abruptly just to the west of the city of Denver. The Palmer Ridge extends out from the main barrier south of the city, which has an altitude of 1611 m, sloping about five and a half meters per kilometer toward the north. The South Platte River flows down the ridge toward the north-northeast and then turns toward the east about 70 km north of Denver. The high plains to the east of Denver slope gently toward the east.

The region around Grand Junction is located on the western side of the Rocky Mountains, slightly south of the Denver region. The city of Grand Junction lies in the valley of the westward flowing Colorado River where the Gunnison River joins the Colorado. The terrain rises to heights of 2744 m to 3659 m in all directions within 97 km of the city (at 1474 m above sea level). The peaks continue to increase in elevation to over 4269 m at the continental divide, 200 km east of Grand Junction.

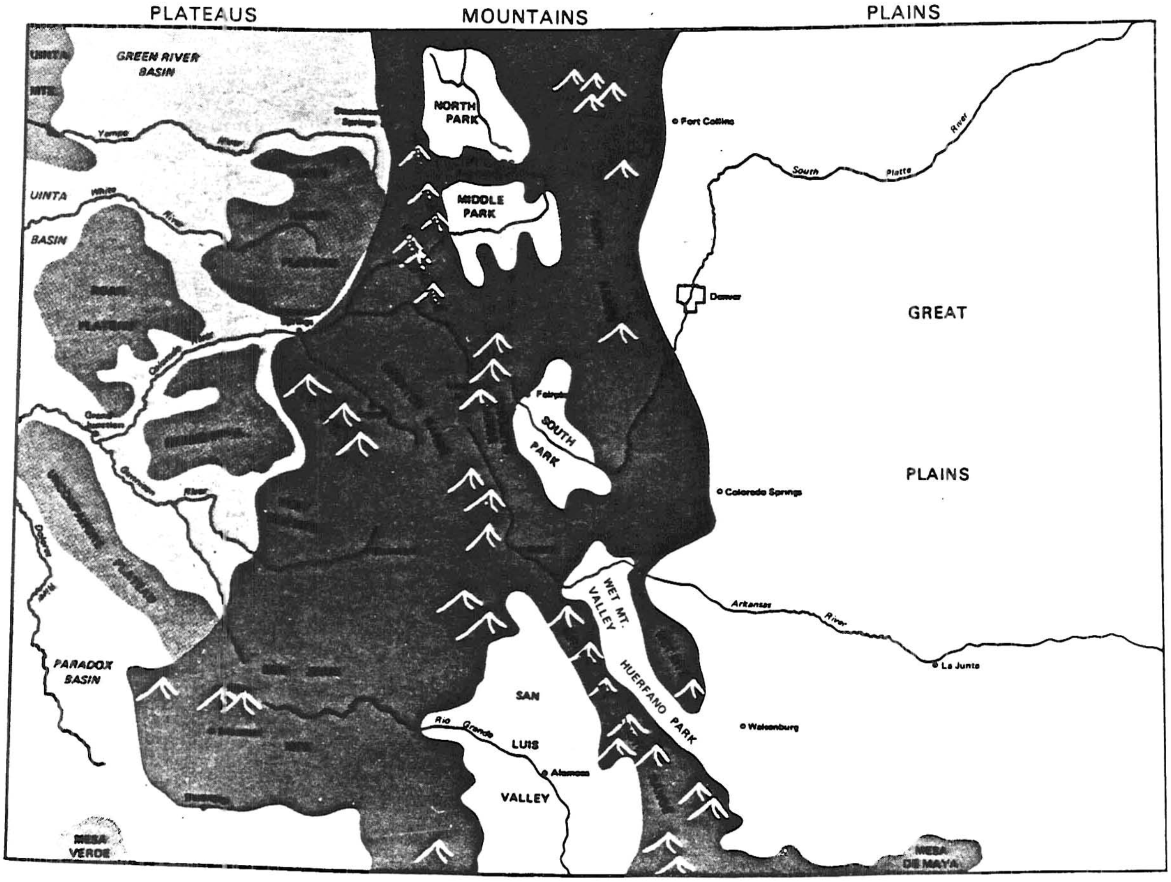

Figure 1. Topographic map of Colorado. From Chronic and Chronic (1972).

CHAPTER II

LITERATURE REVIEW

By the late 1950's, work had begun to study the meteorological conditions which lead to bad air quality. Boettger (1959) and Niemeyer (1960) were among the first to report on attempts to forecast the potential for air pollution. They both report on the experiment in the autumns of 1957, 1958, and 1959. By that time, wind speed and atmospheric stability were considered the "primary meteorological factors that determine the dilution of air pollution in the lower atmosphere."[2] Because small wind speeds and stable atmospheres were associated with quasi-stationary anticyclones, the criteria used to forecast bad air quality potential incorporated the conditions associated with these anticyclones. The criteria were:

1) surface winds less than 8 kt,
2) winds at no level below the 500 mb level greater than 25 kt,
3) subsidence below the 600 mb level,
4) simultaneous occurrence of the above with the forecast continuance of these conditions for 36 hours or more.

They found that the periods of highest concentration of particulate matter were, with a few exceptions, the periods when the criteria were met in the eastern part of the United States.

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[2] Niemeyer, L. E., 1960: Forecasting air pollution potential. Monthly Weather Review, 88, p. 88.

At about the same time, Korshover (1967) was studying the climatology of stagnating anticyclones in the eastern United States. He found the greatest number of stagnation days in the southeast, where the Bermuda High has a strong influence. Similarly, Hosler (1961) investigated the frequency of low level inversions found in rawinsonde soundings throughout the United States. From his study of four years of inversions or isothermal layers based below 500 ft, he concluded that areas having a higher frequency of relatively clear nights and light winds were also areas with a higher frequency of low level inversions. Inversions were most common in the Rocky Mountains and Appalachian Mountains, with some diurnally dependent inversions in the central plains.

Holzworth (1962) extended the forecasting of air pollution potential to the western United States. He considered three factors in forecasting high pollution potential:

1) a quasi-stationary anticyclone with a warm ridge aloft,
2) shallow mixing depths determined from rawinsonde soundings,
3) light surface wind speeds.

Afternoon mixing depths were estimated as the height where the adiabatic lapse rate from the observed maximum temperature intersects the vertical temperature profile. In comparison with measurements of particulate material, the forecasts were somewhat successful. However, the effects of irregular terrain created problems in dealing with the large area of the western United States. In a later study, Holzworth (1964) found variations in mean monthly mixing depths (and therefore, potential for air pollution) among several sites in the southwestern United States. For example, he discovered that Brownsville and San Antonio, Texas have their lowest mixing heights in the winter season while the southern coast of California experienced the lowest mixing heights in the summer and fall seasons.

Holzworth (1971) continued to research mixing heights and wind speeds for the continental United States. He estimated an additional morning mixing height to be the height where the adiabatic lapse rate from the 12Z minimum temperature plus five degrees intersects the vertical temperature profile of the 12Z sounding. He found that episodes of several days with low mixing heights and wind speeds are most common in the west.

Miller (1967) also proposed to forecast air pollution potential using predicted wind speed and mixing height. Mixing height was estimated from a regression curve based on predicted surface temperatures and virtual temperatures at 1000 mb, 850 mb, and 500 mb.

By the late 1960's, a national program for forecasting bad air quality days had been established (Stackpole, 1967; Gross, 1970; U. S. Environmental Protection Agency, 1971). The National Meteorological Center considered various criteria before issuing an air pollution potential advisory for an area of the country. These criteria included:

1) morning urban mixing depth no greater than 500 m, and the observed wind speed averaged through this depth no greater than 4 m/s,
2) the numerical product of the afternoon mixing depth and forecast average wind speed through this depth less than or equal to 6000 m^2/s, with forecast average wind not to exceed 4 m/s,
3) 30-hour forecast meets the above criteria,

4) observed (at 12Z) forecasts of 500 mb relative vorticities not to exceed $0.25*10^{-4}$ sec^{-1} for 36 hours,
5) forecast changes of vorticity should be less than $0.3*10^{-4}$ sec^{-1} for 36 hours,
6) affected area at least 4 degrees latitude-longitude square,
7) no significant frontal passages or precipitation observed or forecasted in the next 36 hours,
8) surface winds in the area average no more than 5 kt and no more than three individual wind speeds to exceed 8 kt in 24 hours.

The mixing depths were determined in the manner defined by Holzworth and the criteria were purposely made somewhat rigid because National Air Pollution Potential Advisories were included in the teletype forecasts to the public. They also found the most occurrences of potentially bad air quality days in the southeastern and western United States.

In a more recent study, Bentley and Schulman (1979) proposed a modification to Holzworth's mixing heights. They suggested that the surface maximum temperature used to find mixing height be changed to reflect any temperature changes which occur at the 700 mb level between the morning and afternoon soundings. They also switched to a nocturnal regime, where the mixing depth is dependent on surface wind speed and roughness, once the temperature falls by 25 percent of the daytime temperature range.

Wilbur and Chan (1980) studied high sulfur oxides pollution in California's San Joaquin Valley. They found that most episodes occurred after the passage of a cold front followed by a weak basin high east of California, with weak surface gradients. This and light and variable winds at night or less than 5 kt during the day caused cold, usually moist, air to be trapped in the valley by a subsidence inversion. Low visibility resulted.

Doty (1977) reviewed various methods of assessing air quality potential as they applied to concentrations of suspended particulate matter in the San Antonio, Texas area. He found that the Stability Array (STAR) adapted by Turner (1961), which estimates atmospheric stability from meteorological observations, was capable of determining air pollution potential but it predicted too many neutral days. He also found that calculated mixing height, in the method suggested by Holzworth, worked well and the predicted ventilation (the product of the afternoon mixing height and wind speed) also did well. In comparing inversions to measured air quality, he found that not just the presence of inversions but the height of their base was important.

Doty (1983) also gives a description of several of the procedures to predict air pollution potential currently used by the National Climate Center. These include STAR, mixing height, and inversion studies.

In Colorado, the people of metropolitan Denver began to notice an increasing degradation of visibility due to air pollution and studies were begun to find the causes in the late 1960's. Djordjevic, et. al. (1966) were among the first to report on their results. They found that coefficient of haze pollution periods were related to low wind speeds especially in connection with inversions. Riehl and Herkof (1972) found that day to day and diurnal variations of mixing height and wind speed helped explain the variations in the observed coefficient of haze. They also discovered that the pollutants tended to follow the drainage wind down the South Platte River valley at night and moved up the valley with the upslope winds during the day. Crow (1976) reported similar results.

Haagenson (1979) employed carbon monoxide measurements in Denver to study the meteorological factors which affect air quality there. He reported the influence of topography, as manifested in the up- and down-valley winds along the South Platte River, on these factors. He concluded that mixing depth and ventilation by the wind are the important factors affecting air quality in Denver, along with the stability above the adiabatic depth.

More recently and on a larger scale, Nochumson (1983) has adapted a regional pollution transport model to the four corners region of the southwestern United States. Concentrations of pollutants from present and future sources within and outside the region were modeled. He reported that the study region presently had excellent air quality but was sensitive to deposition and advective transport of pollutants from future sources including a substantial contribution from sources outside the region.

CHAPTER III

DESCRIPTION OF THE METHOD

Previous studies have described air pollution potential as the meteorological conditions which lead to the accumulation of air pollutants. If the meteorological conditions create a greater volume of atmosphere available for the dispersion of pollutants, the pollutant concentrations will be smaller and the pollutants will be less likely to accumulate and have a harmful effect on the region in which they are released. For the purposes of this study, potentially bad air quality days will be defined as days which have a small atmospheric volume available for mixing. This volume is determined from mixing height and horizontal transport by the wind. Both of these meteorological factors have been proven to be important in past studies. However, they have not been combined to lead to an integrated measure of atmospheric volume since only one per day values have been obtained. A method is needed which will account for the available atmospheric volume as a function of time through the day. The method developed in this section will incorporate an hourly measure of atmospheric volume which will be accumulated through the day to describe the regional potential for pollution.

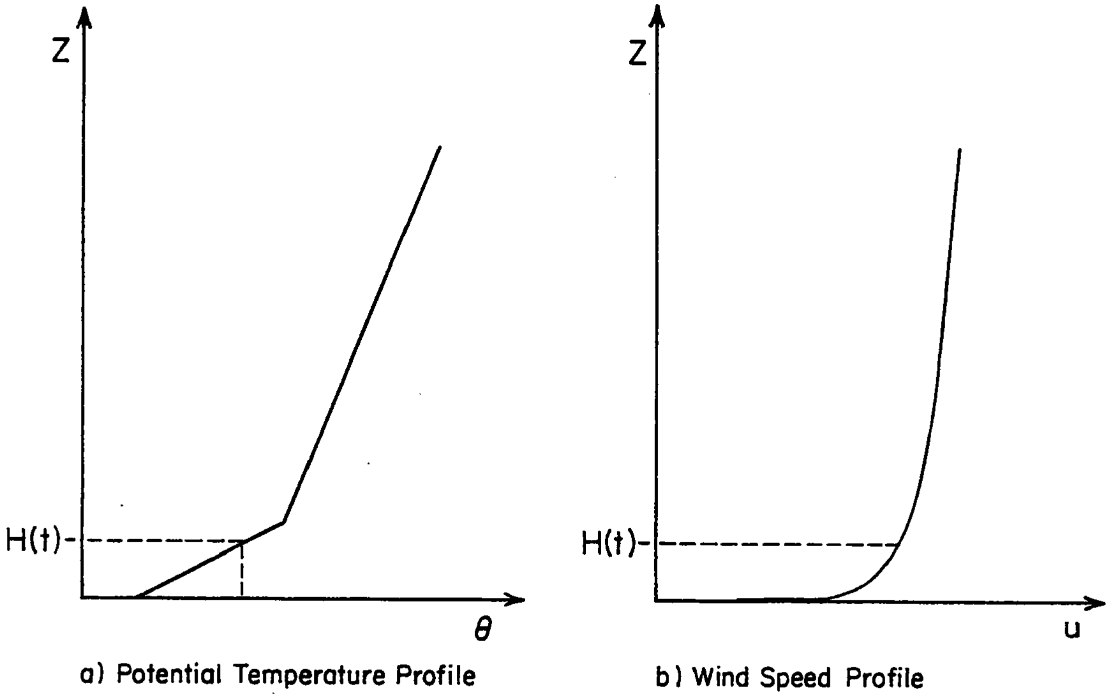
The atmospheric volume available for mixing is defined as a solar mixing area which is the integrated product of the solar mixing height and horizontal transport by the wind,

$$A = \int_{t_0}^{t} H(t)V(H,t)\,dt. \tag{1}$$

The solar mixing height is defined here as an estimate of the height to which vigorous mixing occurs, obtained by applying a percentage of the solar radiation energy to the temperature profile. H(t) is the solar mixing height which is a function of time and V(H,t)dt is the horizontal transport by the wind which is a function of solar mixing height and time.

A simple illustration of this idea is given in Figure 2. Figure 2a shows an idealized temperature profile in the early morning. An increment of energy is used to heat the air near the surface until the lapse rate becomes adiabatic. The depth of the adiabatic layer gives the solar mixing height H(t). Figure 2b gives a logarithmic profile of wind speed. The average of the wind speed from the surface to the solar mixing height gives V(H,t). From H(t) and V(H,t), the solar mixing area can be found.

A conservative estimate of the number of potentially bad air quality days is desired. Therefore, thirty percent of the incoming solar radiation at the top of the atmosphere is assumed as the amount of energy used to heat the lowest layers of the atmosphere. In some cases, this is an overestimate of the actual energy available. Clouds, increased albedo due to snow cover, and moisture available for evaporation could all reduce the energy which is actually used to heat the boundary layer. In these cases, the method overpredicts solar mixing heights and solar mixing areas. As a result, the method gives a conservative evaluation of the number of potentially bad air quality days.



a) Potential Temperature Profile

b) Wind Speed Profile

Figure 2. Idealized potential temperature (a) and wind speed (b) profile.

A. Solar Mixing Height

Determining an exact afternoon mixing height (the height to which vigorous mixing occurs) by inspection of temperature soundings can often prove to be difficult and quite subjective (Russell and Uthe, 1978). Also, rawinsonde soundings are only taken twice daily, and hourly values of mixing height would have to be interpolated.

Consequently, an approach is taken in which the hourly solar mixing height (SMH) is estimated through the use of a simple model. For this study, the First Law of Thermodynamics is applied to the morning rawinsonde temperature profile in a manner similar to the one used in Whiteman's (1980) thermodynamic model of valley inversion destruction. The First Law of Thermodynamics can be written as

$$Q = m\, c_p\, T/\theta\, \Delta\theta = \rho\, V\, c_p\, T/\theta\, \Delta\theta\ , \qquad (2)$$

where Q is the increment of energy required to increase the potential temperature of a mass m by the potential temperature increment $\Delta\theta$. T is temperature, c_p is the specific heat of air at constant pressure, and V is a volume of air. The air density ρ is assumed constant within each of the layers between recorded temperatures in the soundings. To assure the validity of this assumption, layers were maintained at thicknesses of 1000 m or less. If temperature is recorded at levels more than 1000 m apart, a new point was introduced in the sounding 1000 m above the lower level and temperature for the new point was linearly interpolated between the levels.

Figure 3 shows a typical potential temperature profile at some time after sunrise. Figure 3 is applied to the potential temperature profile by considering a set of areas which represent Q_1, Q_2, and Q_3. Q_2 is the

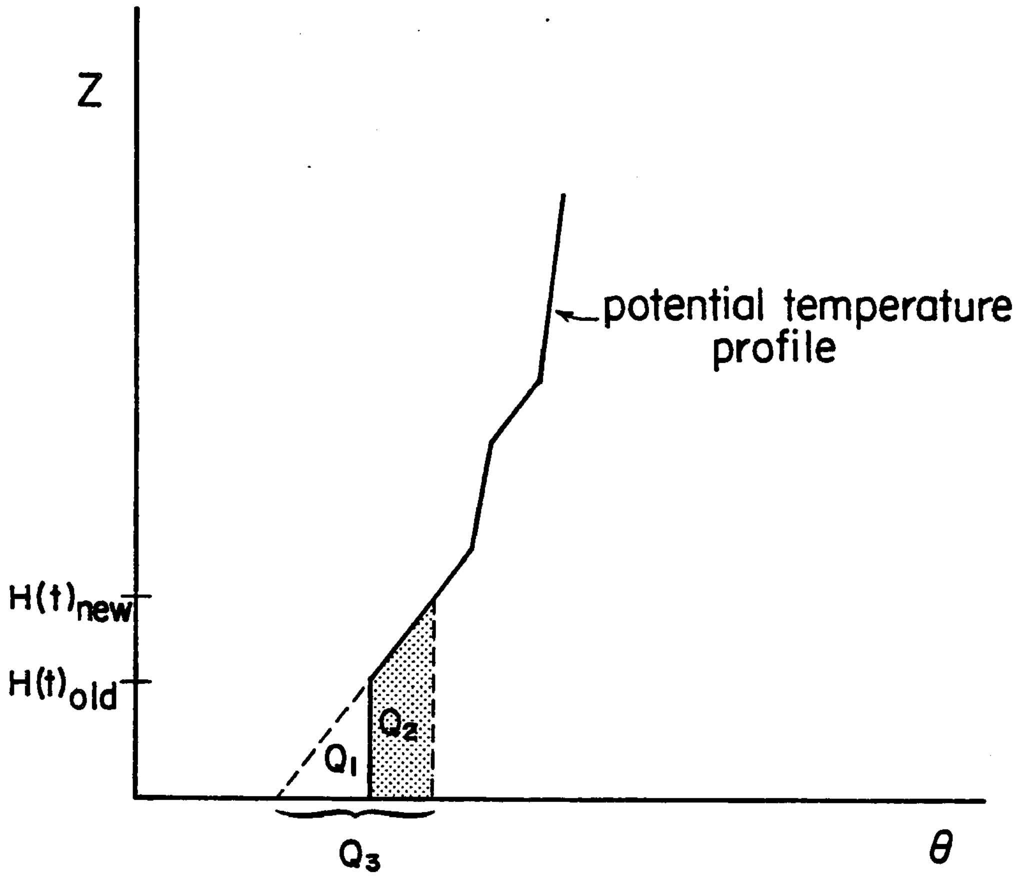


Figure 3. Typical potential temperature profile.

increment of energy required to heat the air below the new solar mixing height $H(t)_{new}$ to the potential temperature at that new SMH. Thus, the new temperature profile is adiabatic from the surface to the new SMH and remains the same above the new SMH. Q_2 is found from the difference of Q_3 and Q_1. Q_3 is the increment of energy required to heat the air below the new SMH to the potential temperature at $H(t)_{new}$ when the temperature lapse rate between $H(t)_{old}$ and $H(t)_{new}$ is extended down to the surface. Q_1 is the increment of energy required to heat the air below the old SMH to the potential temperature at $H(t)_{old}$ when the temperature lapse rate between $H(t)_{old}$ and $H(t)_{new}$ is extended down to the surface. In solving for Q_3 and Q_1, the temperature lapse rate γ between $H(t)_{old}$ and $H(t)_{new}$ is assumed constant so the potential temperature at a height $z \leq H(t)_{new}$ can be written as

$$\theta_z = \theta_{z=0} - \gamma(z-0) \ , \tag{3}$$

and

$$\Delta\theta = \gamma z \ . \tag{4}$$

Thus,

$$Q_3 = \rho \ c_p \ V \ T/\theta \cdot \gamma z \ . \tag{5}$$

If the temperature profile is assumed to be regionally homogeneous, equation (5) can be integrated to give the amount of energy per surface area needed to heat the air below $H(t)_{new}$ to the potential temperature at $H(t)_{new}$ if the temperature lapse rate between $H(t)_{new}$ and $H(t)_{old}$ extends down to the surface,

$$Q_{3/A} = \int_0^{H(t)_{new}} \rho\ c_p\ T/\theta\ \gamma z\ dz\ . \qquad (6)$$

In the same way, Q_1/A can written as

$$Q_{1/A} = \int_0^{H(t)_{old}} \rho\ c_p\ T/\theta\ \gamma z\ dz\ . \qquad (7)$$

Since

$$Q_{2/A} = Q_{3/A} - Q_{1/A} \qquad (8)$$

the actual energy per surface area needed to heat the air below $H(t)_{new}$ to the potential temperature at $H(t)_{new}$ is the difference between equation (6) and equation (7),

$$Q_{2/A} = \int_0^{H(t)_{new}} \rho\ c_p\ T/\theta\ \gamma z\, dz - \int_0^{H(t)_{old}} \rho\ c_p\ T/\theta\ \gamma z\ dz\ . \qquad (9)$$

If the energy (Q_2/A) is known, a new SMH can be found from

$$H(t)_{new} = \left[2\ (Q_2/A)\ \theta/(\rho\ c_p\ \gamma T) + H(t)^2_{old}\right]^{\frac{1}{2}} \qquad (10)$$

The analytical solution of equation (9) given by equation (10) is derived by assuming that the value of $\rho c_p T/\theta$ in the layer from $H(t)_{old}$ to $H(t)_{new}$ is constant and equal to the average $\rho c_p T/\theta$ for that layer. Also, this same value of $\rho c_p T/\theta$ is assumed to be constant down to the surface in equation (9). This second assumption could mean that the SMH is overestimated by about ten percent. However, this second assumption has the greatest effect on large SMHs and little effect on the small SMHs which help to produce a potentially bad air quality day.

Input energy (Q_2/A) for calculating SMH in the semiarid regions of Colorado is assumed to be thirty percent of the incoming solar radiation at the top of the atmosphere. Hourly values of extraterrestrial radiation were calculated using a computer program described by Conley and McKee (1983).

By calculating a SMH in this manner, inversions, their strength and their thickness, and the general stability of the atmosphere are taken into account.

B. Horizontal Transport

To estimate horizontal transport V(H,t)dt, 700 mb and surface (measured at a height of 20 ft at Denver and 22 ft at Grand Junction) wind speeds are used with a simple logarithmic variation assumed through these two points.

Holton (1979) describes the logarithmic wind profile within the surface layer as

$$u = (u^*/k)\ \ell n\ (z/z_0) \tag{11}$$

where k is the von Karman constant and z_0 is the roughness length, a constant of integration so that u=0 at $z=z_0$. The friction velocity u_* is defined to be the square root of the surface stress divided by the density of air.

This relationship holds true only through the surface layer and is not intended to represent the wind profile to depths as great as the SMH. However, in order to describe the wind profile through the SMH, an analogy to the logarithmic wind profile of the surface layer is used. Thus, in this study, the wind speed at a height z is represented by

$$u = (u^*/k)\ \ell n\ (z/z_0) + u_{sfc}\ , \tag{12}$$

where

$$u_* = (u_{700} - u_{sfc})\, k/\ell n\, (z_{700}/z_0) \;.$$

The subscripts 700 and sfc refer to the 700 mb and surface levels respectively. The roughness length z_0 is chosen to be 0.4 m and the von Karman constant k equal to 0.4.

For each time step, the average wind speed from the surface to the mixing height was used. The average wind speed can be expressed by

$$V(H,t) = \int_{z_0}^{H(t)} [u^*/k\ \ell n\ (z/z_0) + u_{sfc}]\, dz \Big/ \int_{z_0}^{H(t)} dz. \qquad (13)$$

To get a transport distance of pollutants by the wind, the mean wind speed is multiplied by the time increment and is written

$$V(H,t)dt =$$

$$\left\{ \left[\frac{[u_*/k\ (H(t)\ \ell n\ (H(t)/z_0) - H(t) - z_0)]}{[H(t) - z_0]} \right] + u_{sfc} \right\} dt \;. \qquad (14)$$

There were some restrictions placed on the wind calculations. For instance, a minimum wind speed of 2 m/s was imposed at both the 700 mb and surface heights in order to allow for the valley and slope flows which are likely to occur in the mountainous regions of Colorado. Also, there are times when the surface wind speed is greater than the 700 mb wind speed so, in these cases, the wind speed is kept constant with height above 700 mb to prevent artificially small values at those heights.

C. Solar Mixing Area

Hourly values of solar mixing height from equation (10) and horizontal transport by the wind from equation (14) are multiplied to give an hourly solar mixing area (SMA). This SMA represents the volume of atmosphere which is available during the hour for the dilution of air pollutants released within the region. Summing the SMAs until sunset represents the daily atmospheric volume available for the dilution of pollutants. Thus, days with small calculated SMAs are defined as possible bad air quality days.

Calculations of SMAs for the Grand Junction and Denver regions for October, 1980 were compared to synoptic maps. Days when the synoptic pattern shows the influence of high pressure at the surface with a ridge of high pressure aloft and low wind speeds are typically found to be days with small SMAs. However, this method is not capable of determining precipitation and disturbances which occur after the morning sounding and help cleanse the air of pollutants. Consequently, thunderstorm and measurable precipitation days are determined separately from climate records and assumed to be good days for this study.

CHAPTER IV

APPLICATIONS FOR COLORADO

Because of the concern with air quality in Colorado and the probable development there, the method described in the previous chapter has been applied to the regions surrounding Grand Junction and Denver, Colorado. The Grand Junction region was chosen because that area of western Colorado is likely to experience growth in the future in energy development and mining. Along with these, an increase in population is expected. At the same time, the Denver region was chosen so that a comparison could be made between regions on the west and east sides of the continental divide.

Rawinsonde soundings for the years 1957-1978 were available on a magnetic tape at the Colorado Climate Center. However, prior to 1959, rawinsonde soundings were recorded at 03Z and 15Z. For this study only the 12Z (0500 LST) soundings after 1958 were used. To conserve file space on the computer, only the lower levels of the sounding, below 500 mb, were utilized. Thus the 500 mb level height imposes an upper limit on the SMH calculation. This is based on the assumption that if a SMH reaches the 500 mb level, the area calculated is already large enough to qualify the day as a good air quality day and any extension of the mixing height beyond the 500 mb level would be unnecessary.

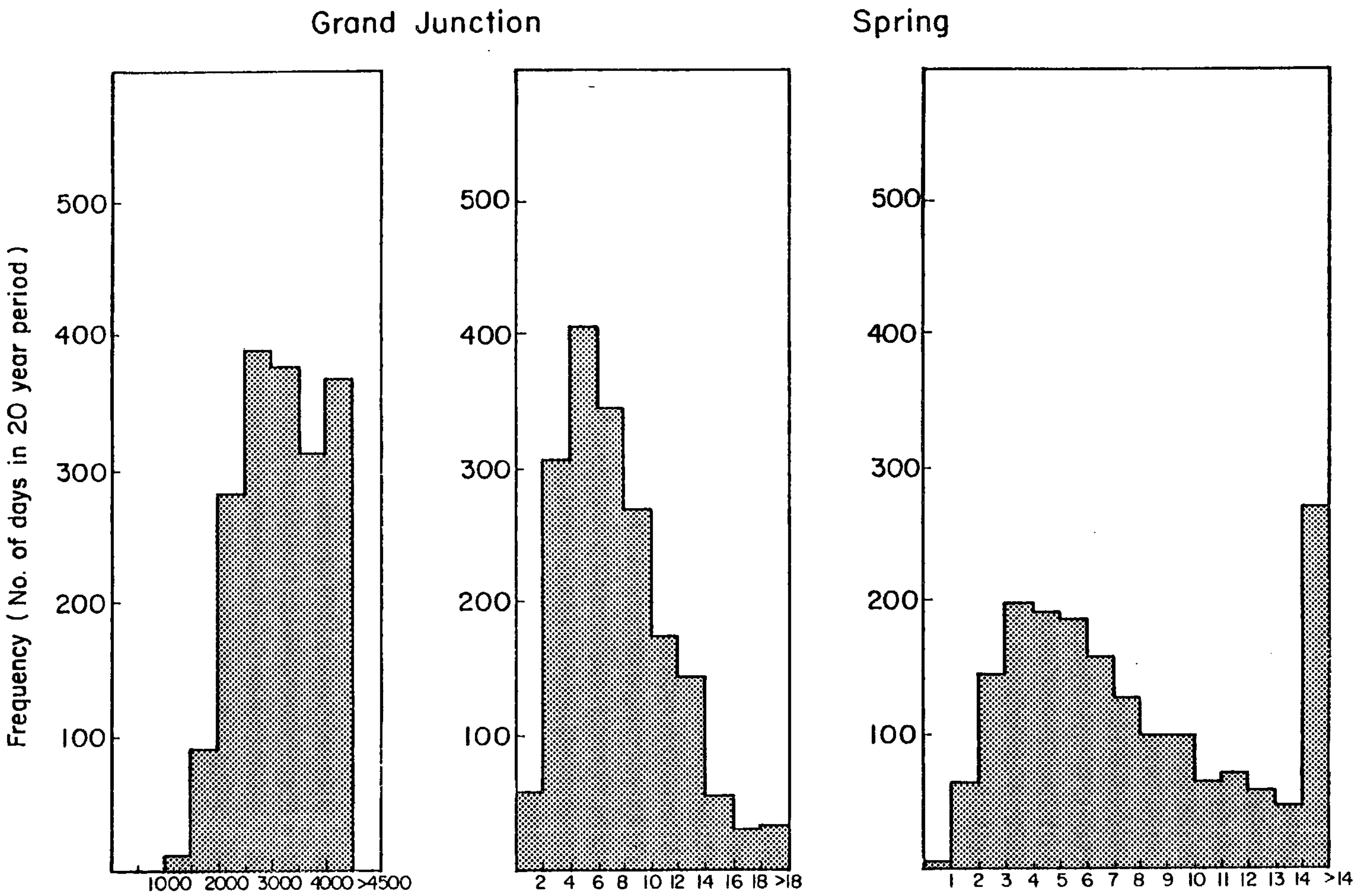
If the daily value of the SMA was below the threshold of $3*10^8$ m^2, the day was labeled as a potentially bad air quality day for this current study. This threshold value is consistent with one of the criteria used in the National Air Pollution Potential Advisories. The afternoon ventilation (wind speed times the mixing height) requirement of less than 6000 m^2/s used by the National Meteorological Center for issuing National Air Pollution Potential Advisories (Gross, 1970), if multiplied times 14 hours, approximately yields an area of $3*10^8$ m^2. For illustrative purposes, those days with a SMA calculation between $3*10^8$ m^2 and $6*10^8$ m^2 were called marginal. Days with an SMA greater than $6*10^8$ m^2 were called potentially good air quality days.

At the same time, days with weather disturbances were determined separately from the Local Climatological Data (1959-1978) for Denver and Grand Junction. Days which showed no record of thunderstorms or measurable precipitation were defined to be undisturbed days. Undisturbed days which also show no record of trace precipitation were defined as non-precipitation days.

A. The Frequency of Potentially Bad Air Quality Days

Figures 4-11 show seasonal frequency distributions of the calculated SMH, average wind speed through the mixed layer, and the total calculated SMA reached by sunset. The 500 mb height limit prevents any of the SMHs from extending above 4500 m and enhances the peak between 4000 m and 4500 m in the summer. The seasonal change in SMHs is quite obvious with greater frequencies of higher SMHs in summer and greater frequencies of lower SMHs in the winter months when solar insolation is at a minimum.

Figure 4a gives the frequency distribution of spring SMHs at Grand Junction. The peak frequency is at heights 2500 m to 3000 m. There are 365 days in the 4000 m to 4500 m range while none of the final daily

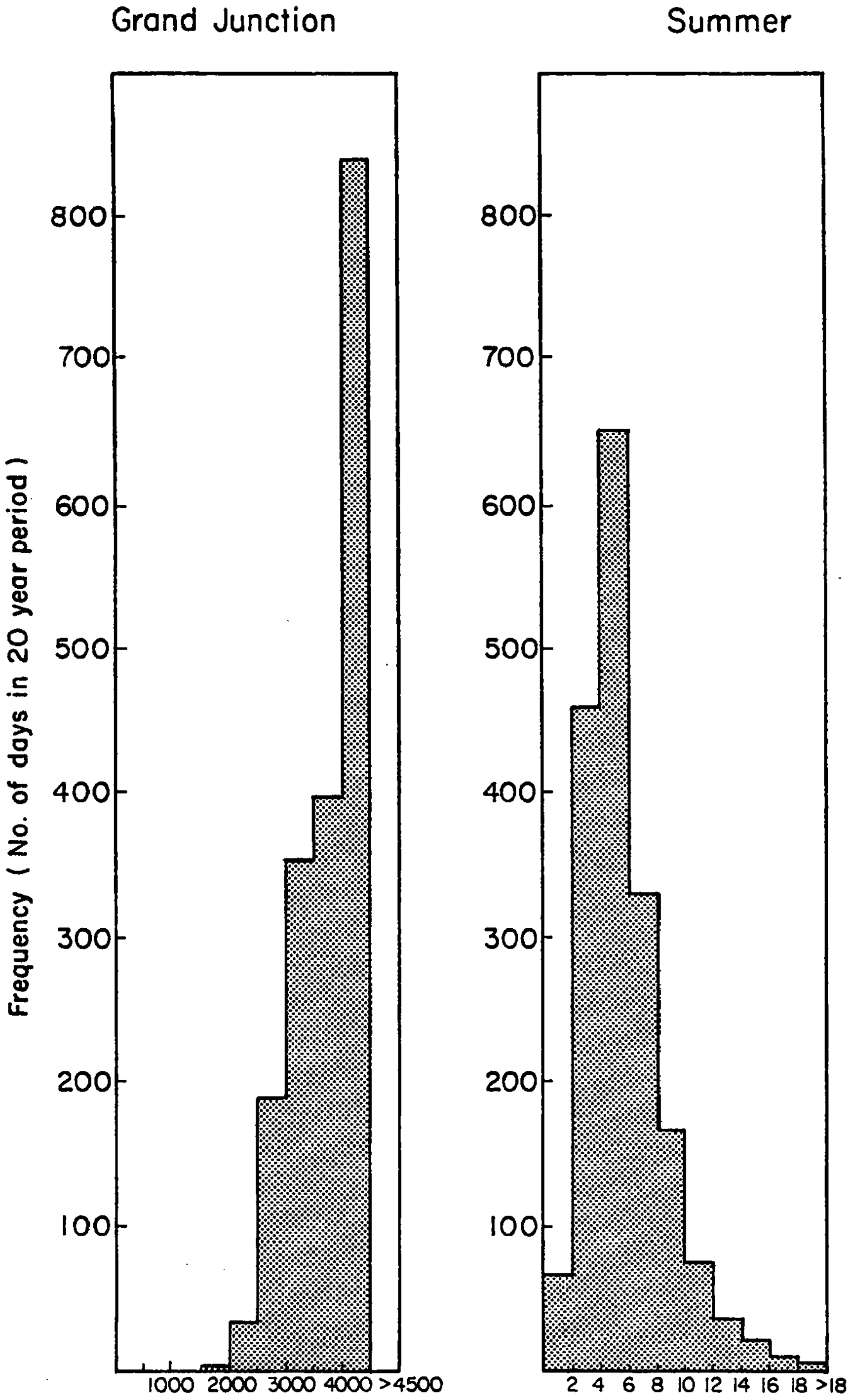


a) Final Daily Solar Mixing Height (m)

b) Final Average Wind Speed (m/s)

c) Final Daily Sum of Solar Mixing Areas (10^8 m^2)

Figure 4. Frequency distributions of final daily solar mixing height (a), final average wind speed (b), and final daily sum of solar mixing areas (c) for the Grand Junction for the months of March, April, and May.



a) Final Daily Solar Mixing Height (m)

b) Final Average Wind Speed (m/s)

Figure 5. Frequency distributions of final daily mixing height (a), and final average wind speed (b) for the Grand Junction region for the months of June, July and August.

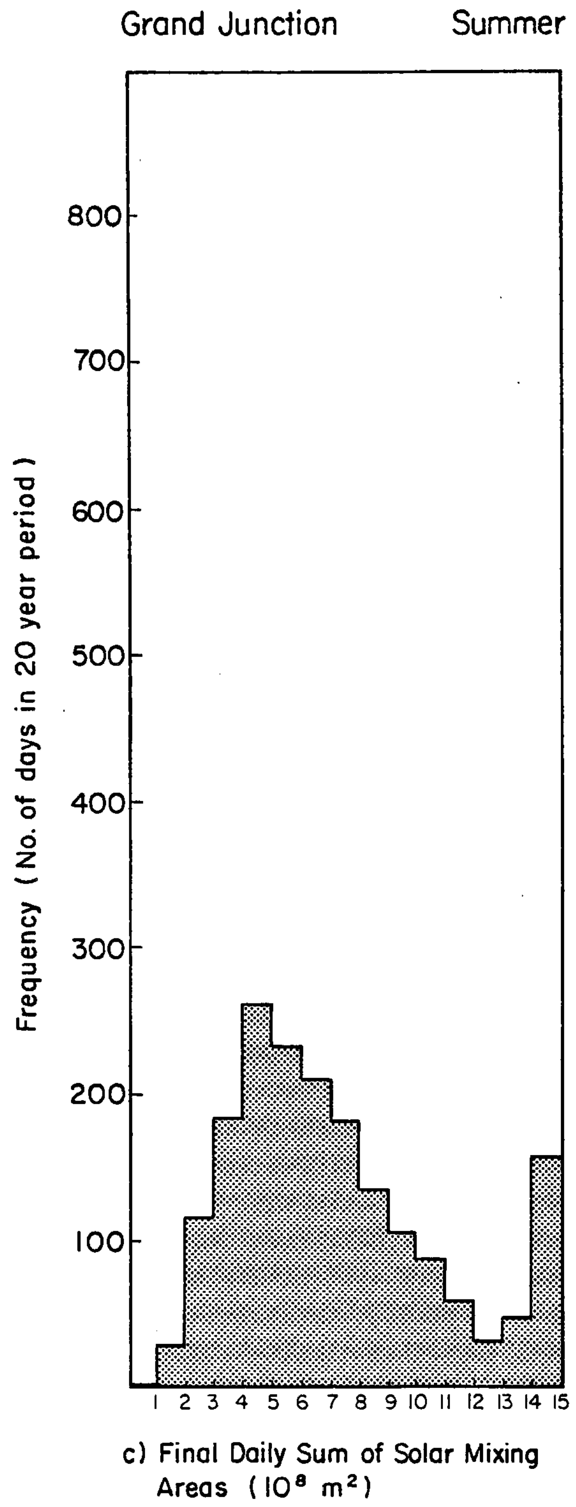
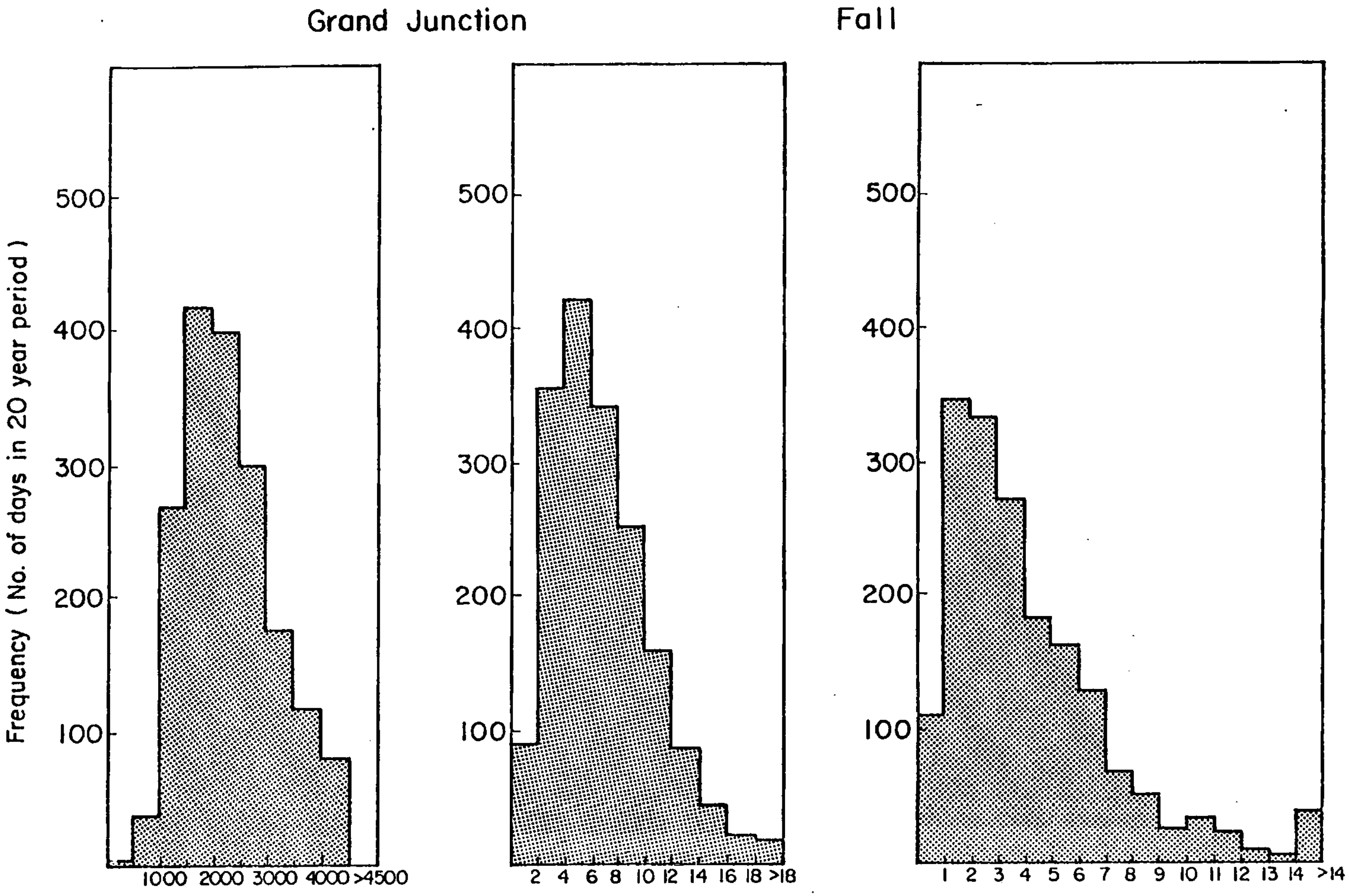


Figure 5 continued. Frequency distribution of final daily sum of solar mixing areas (c) for the Grand Junction area for the months of June, July, and August.

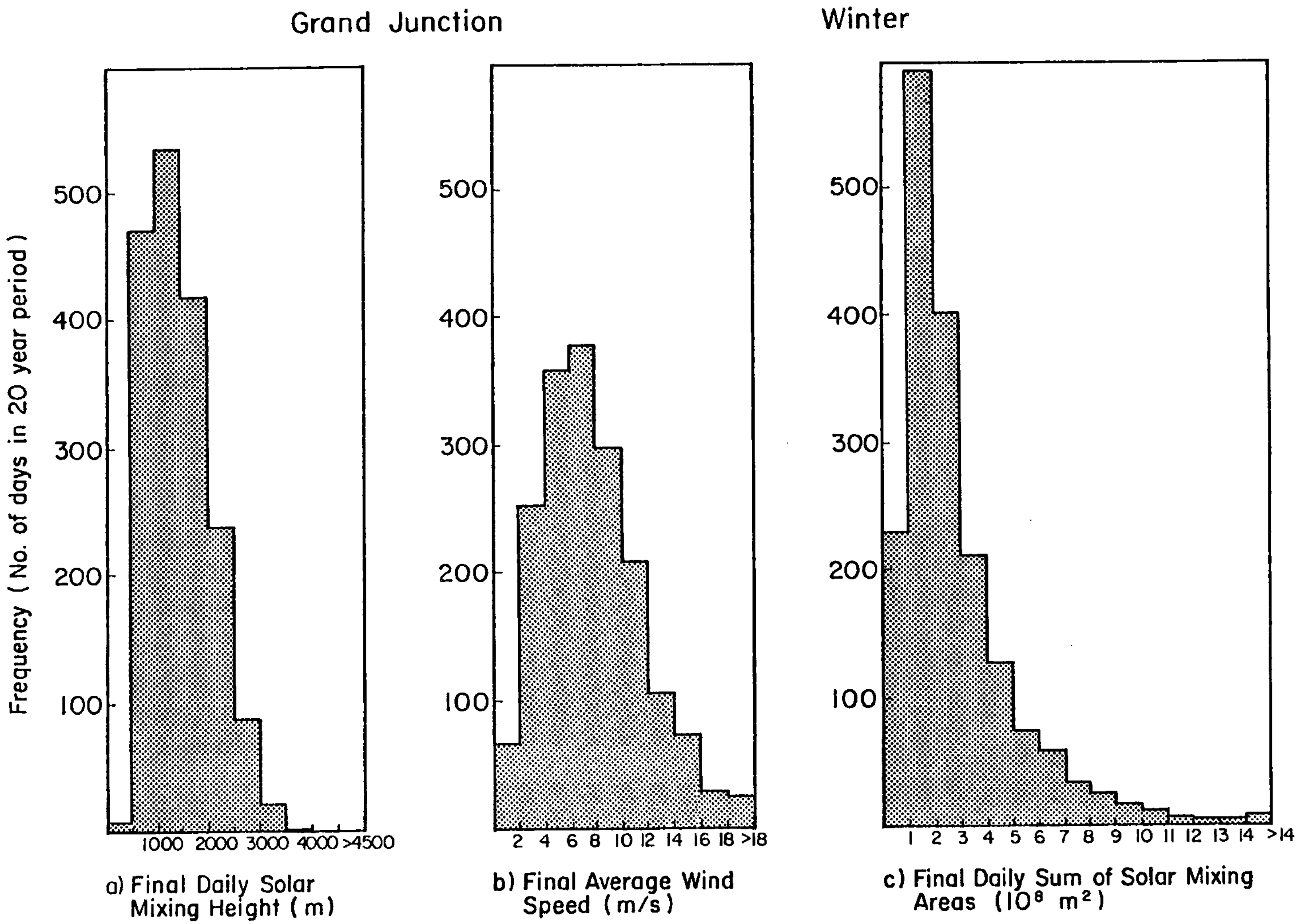


a) Final Daily Solar Mixing Height (m)

b) Final Average Wind Speed (m/s)

c) Final Daily Sum of Solar Mixing Areas (10^8 m^2)

Figure 6. Same as Figure 4 but for the months of September, October, and November.

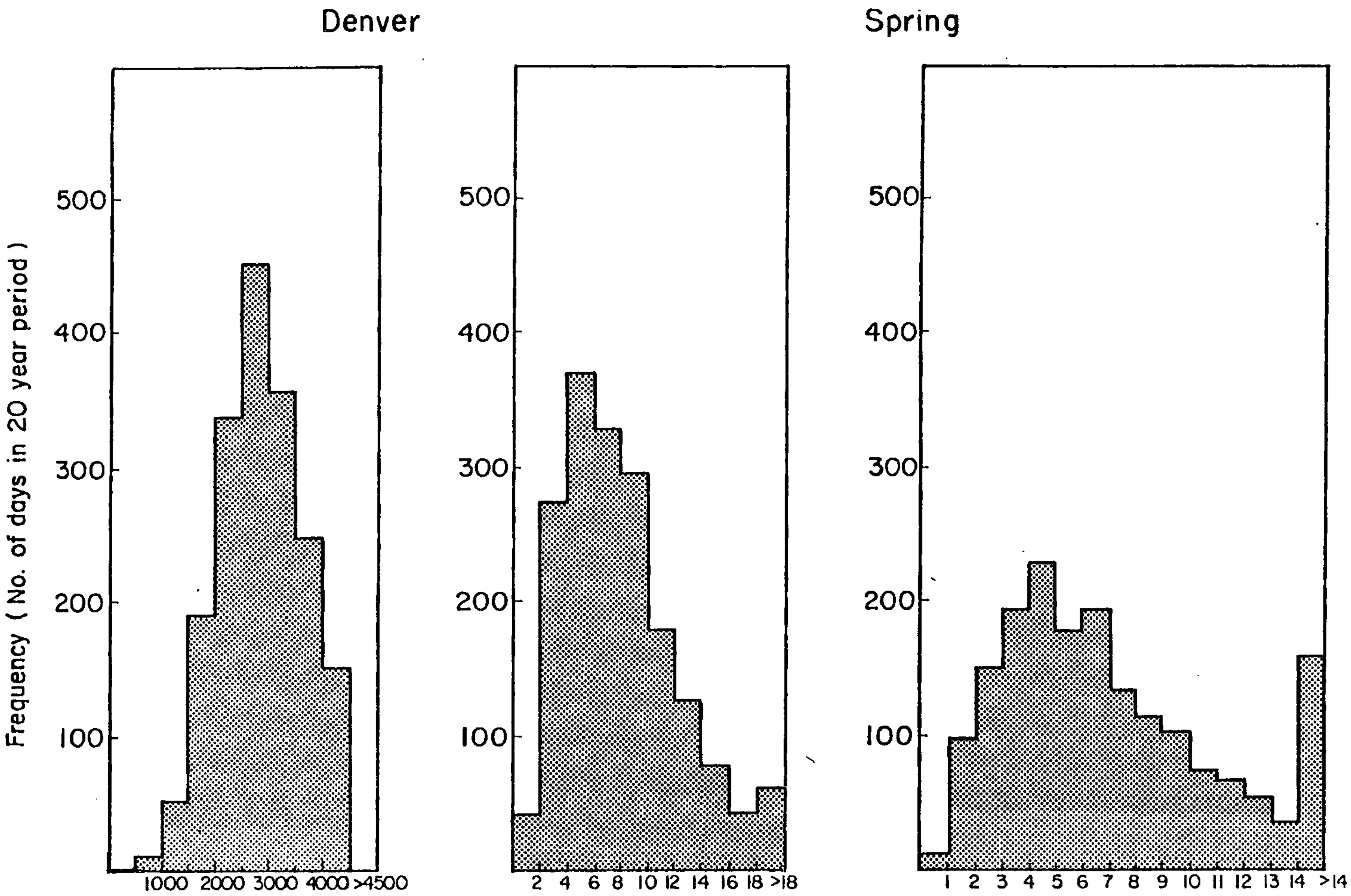


a) Final Daily Solar Mixing Height (m)

b) Final Average Wind Speed (m/s)

c) Final Daily Sum of Solar Mixing Areas (10^8 m^2)

Figure 7. Same as Figure 4 but for the months of December, January, and February.



a) Final Daily Solar Mixing Height (m)

b) Final Average Wind Speed (m/s)

c) Final Daily Sum of Solar Mixing Areas (10^8 m^2)

Figure 8. Frequency distributions of final daily solar mixing height (a), final average wind speed (b), and final daily sums of solar mixing areas (c) for the Denver region for the months of March, April, and May.

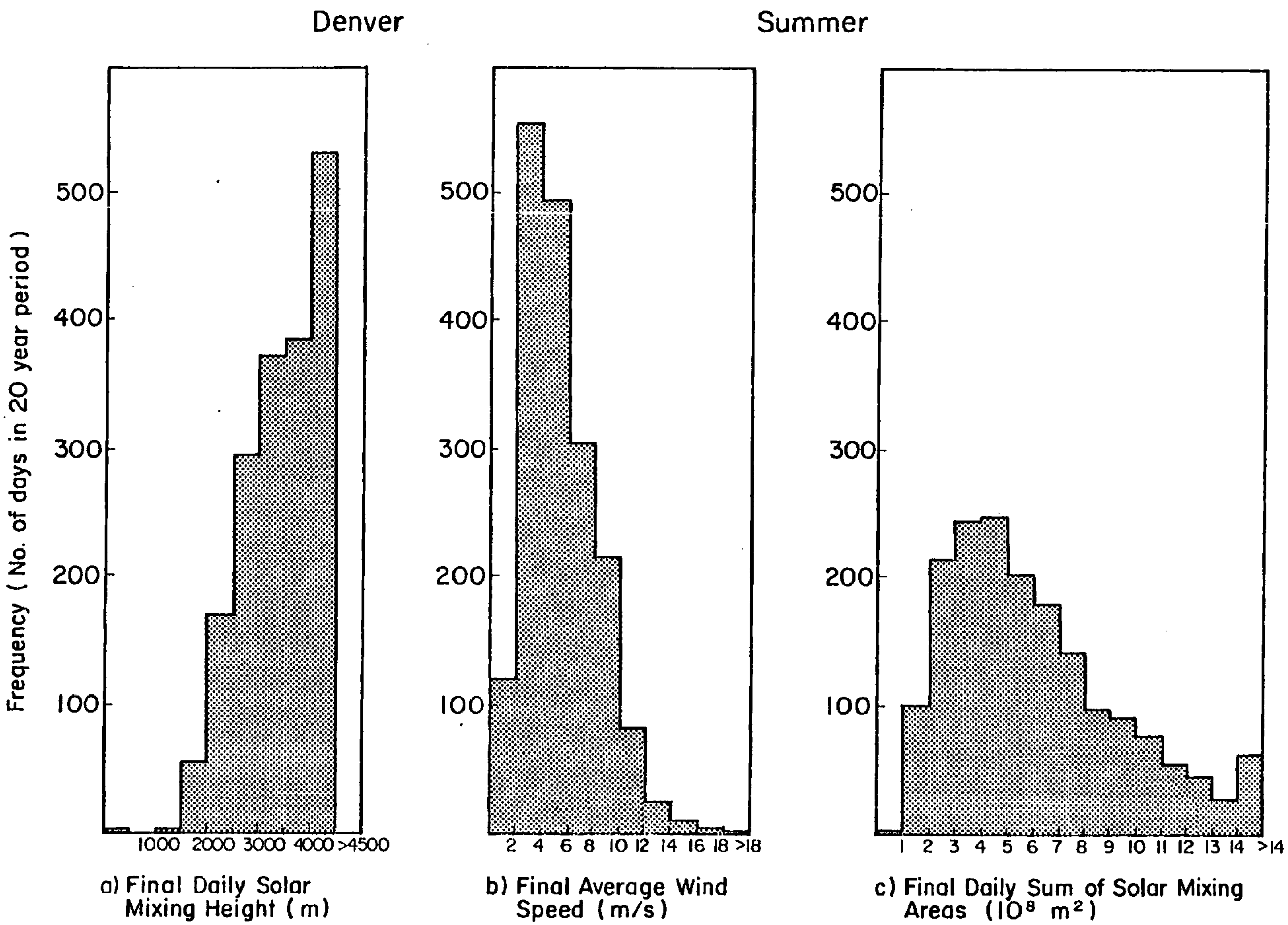
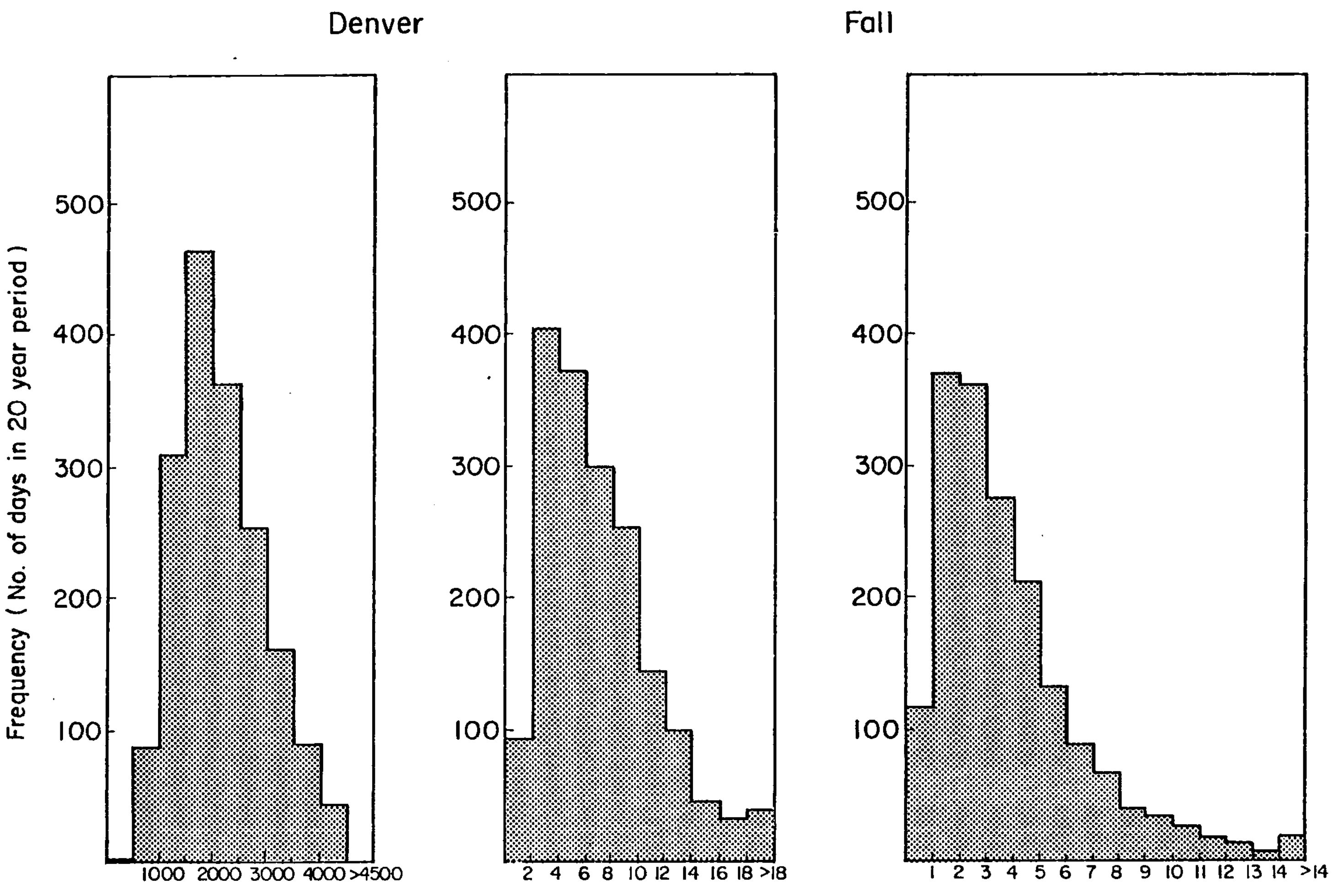


Figure 9. Same as Figure 8 but for the months of June, July, and August.

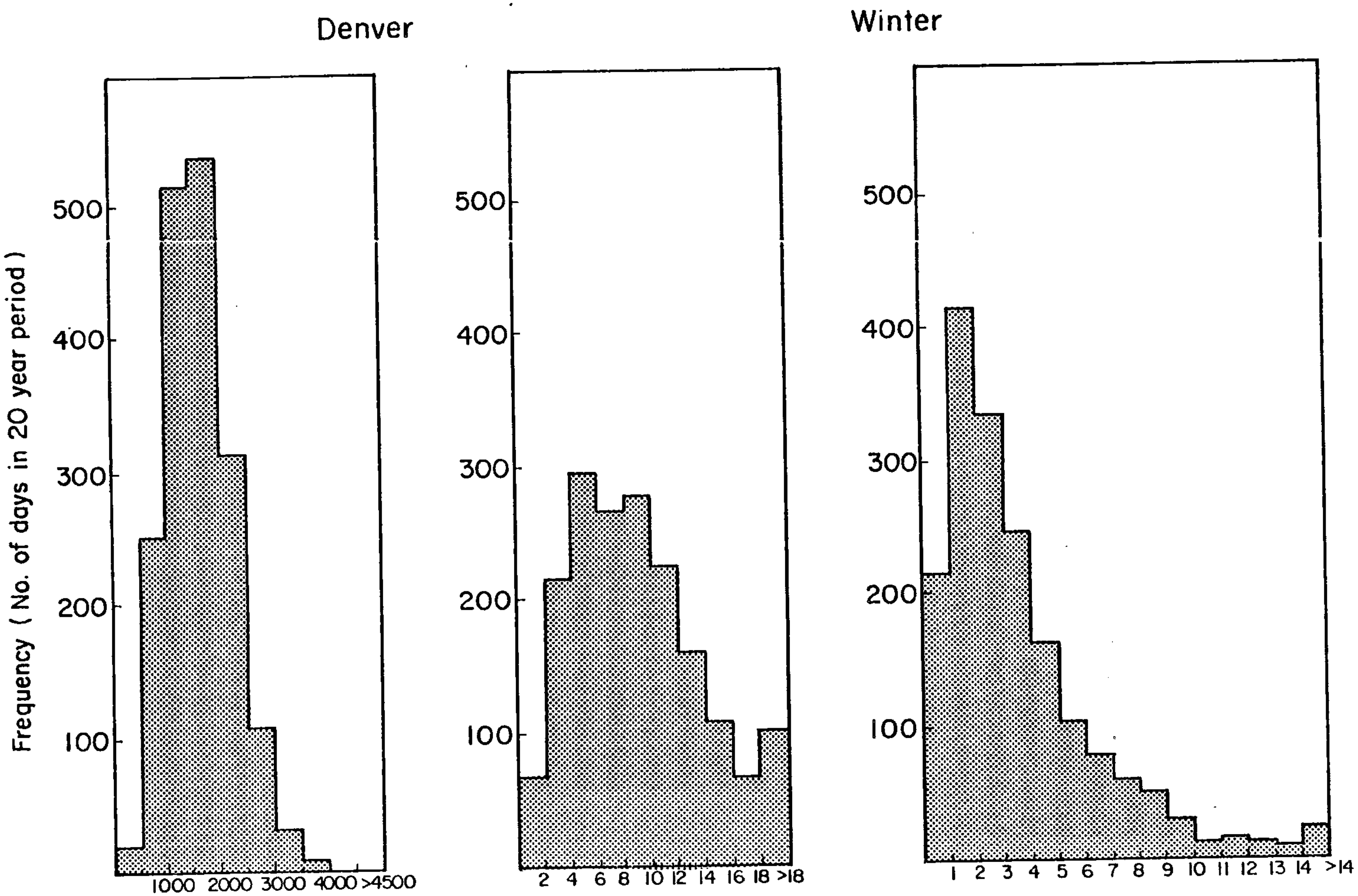


a) Final Daily Solar Mixing Height (m)

b) Final Average Wind Speed (m/s)

c) Final Daily Sum of Solar Mixing Areas $(10^8 \ m^2)$

Figure 10. Same as Figure 8 but for the months of September, October, and November.



a) Final Daily Solar Mixing Height (m)

b) Final Average Wind Speed (m/s)

c) Final Daily Sum of Solar Mixing Areas (10^8 m^2)

Figure 11. Same as Figure 8 but for the months of December, January, and February.

SMHs are below 1000 m. An extreme peak in frequency (839 days) is found in summer (Figure 5a) for the 4000 m to 4500 m category while all of the SMHs reach at least 1500 m by the end of the day. The autumn (Figure 6a) peak again falls to the 1500 m to 2000 m range and only 80 days reach SMHs of 4000 m or more. In winter (Figure 7a), the greatest number of daily SMHs (532) fall into the 1000 m to 1500 m category and only one day reaches more than 4000 m. SMHs from 500 m to 1000 m occur on 467 days, yet only six days have SMHs less than 500 m deep.

In Figure 8a, spring SMHs at Denver show a peak between 2500 m and 3000 m while 152 days reach over 4000 m and only one was below 500 m. SMHs generally increase in the summer (Figure 9a) with the peak frequency occurring in the 4000 m to 4500 m category. Autumn SMHs (Figure 10a) fall again to levels even lower than the spring SMHs. The greatest number of days in this season have SMHs 1500 m to 2000 m high and only 44 days are over 4000 m. By winter (Figure 11a), none of the SMHs reach 4000 m and 20 are below 500 m. The peak is from 1500 m to 2000 m but almost as many days have SMHs from 1000 m to 1500 m deep.

Comparing between the two regions, it can be seen that higher SMHs are more frequent in western Colorado, except in winter when the SMHs tend to be higher in the eastern region. The lower SMHs in winter imply a typically more stable temperature profile than Denver during these months. The greater frequency of more stable profiles is in agreement with some of Holzworth and Fisher's (1979) findings. They present a greater percentage of days with surface based inversions and, in particular, a greater frequency of deeper inversions (500 m or more) in the winter season in Grand Junction as compared to Denver. This phenomenon is probably due to the differences in terrain between the two regions and the orientation of the terrain to the mean westerly flow. The nighttime cool air near Grand Junction is more likely to pool while the westerlies flow over the top, instead of draining to the west. At the same time, the slope and orientation of the terrain in the Denver region are more conducive to cool air draining to the east and in the same direction as the westerlies.

The average wind speed from the surface to the final SMH also varies seasonally, but less noticeably and in the opposite sense. Wind speed is strongest under the influence of the westerlies and traveling storms which are characteristic of the winter months. Summer is the season with the most days with low wind speed.

Figure 4b shows that in Grand Junction in the spring the greatest number of days have average wind speeds through the mixing depth of 4 m/s to 6 m/s. Wind speeds of 2 m/s occur on 58 days and speeds of greater than 18 m/s on 34 days. The summertime frequency peak (Figure 5b) also happens in the 4 m/s to 6 m/s class but it is a much stronger peak (652 days). Wind speeds of 2 m/s exist for 64 days and days with winds greater than 18 m/s number only six. The frequency distribution for fall (Figure 6b) also has a peak at 4 m/s to 6 m/s but the peak is smaller and the distribution somewhat "flatter". In general, the winter frequencies (Figure 7b) indicate a shift to slightly higher wind speeds. The peak frequency, 375 days, is now in the 6 m/s to 8 m/s category while the 4 m/s to 6 m/s range still has 355 days.

The frequency distribution of average wind speed through the final mixing depth is given in Figure 8b for springtime Denver. A peak of 372 days occurs at winds between 4 m/s and 6 m/s. Wind speeds of greater than 18 m/s occur on 62 days. Only 3 summer days (Figure 9b) reach more than 18 m/s while 121 days have 2 m/s winds. In the 2 m/s to 4 m/s range, there are 556 days. The most number of days in the fall season (Figure 10b) also falls in the 2 m/s to 4 m/s range but there are more days at higher wind speeds than in summer. For instance, 40 days have wind speeds greater than 18 m/s. By winter (Figure 11b), the frequency peak has returned to the 4 m/s to 6 m/s category and wind speeds of greater than 18 m/s occurred 101 times.

In both regions, the frequency distributions of wind speeds are basically similar. However, the Grand Junction area shows slightly lower wind speeds in winter and spring and slightly greater wind speeds in the fall.

Because the SMA calculation is a product of the SMH and transport wind, it also changes through the year. However, because the SMH is more variable, the seasonal changes in SMA tend to reflect those of the SMH.

Figure 4c shows the greatest number of days (273) have final daily sums of SMAs greater than $14*10^8$ m^2 in Grand Junction in spring. There is also a second peak in frequency, with 199 days, in the $3*10^8$ m^2 to $4*10^8$ m^2 range. The summer frequency distribution (Figure 5c) shows more days with greater SMAs and a peak between $4*10^8$ m^2 and $5*10^8$ m^2. Autumn's peak frequency (Figure 6c) of 347 days has fallen all the way to the $1*10^8$ m^2 to $2*10^8$ m^2 category and only 41 days obtain greater SMAs than $14*10^8$ m^2. The winter frequency distribution (Figure 7c) also has a peak between $1*10^8$ m^2 and $2*10^8$ m^2 but it has been enhanced to 588 days at the expense of the categories with larger SMAs.

Figure 8c gives the final daily sum of SMAs for Denver in the spring. The peak frequency of 230 days occurs in the $4*10^8$ m^2 to $5*10^8$

m^2 range and 159 days have SMAs greater than $14*10^8$ m^2. The frequency distribution for summer, Figure 9c, also has a peak at $4*10^8$ m^2 to $5*10^8$ m^2 but the number of days with smaller SMAs have increased and the number of days with greater SMAs have decreased. The trend continues as you move into the fall season (Figure 10c). Here the peak frequency (369 days) has dropped to the $1*10^8$ m^2 to $2*10^8$ m^2 category with only 19 days greater than $14*10^8$ m^2. By winter (Figure 11c), the peak at $1*10^8$ m^2 to $2*10^8$ m^2 has increased to 415 days.

In both regions, the days with small SMAs are far more numerous in the fall and especially in the winter season. In the winter, the influence of the much lower SMHs overwhelms the effect of higher wind speeds. Wind speed and SMH at that time are both lower in the Grand Junction region than in the Denver region, giving it even more poorly ventilated days.

The spring and fall seasons show approximately the same number of small SMA days. Slightly fewer occur in the Grand Junction area where SMHs are greater. The small differences in winds between the two regions has only a small effect on their differences in SMAs.

The large number of days with high SMHs make the summer season one with very few poorly ventilated days. This is especially true in the area surrounding Grand Junction where a high percentage of SMHs reach 4000 m to 4500 m.

The monthly mean number of potentially bad air quality days, bad air quality days which are also undisturbed days, and bad air quality days which are also non-precipitation days are given in Table I. Also given are the mean monthly number of marginal days, undisturbed marginal

TABLE I.

Mean Monthly Number of Good, Marginal and Bad Air Quality Days for the Grand Junction and Denver regions.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Grand Junction												
Bad Air Quality Days	22.90	13.70	5.90	2.95	1.80	1.25	2.40	3.45	7.00	14.15	18.60	24.05
Undisturbed Bad Days	18.80	12.05	5.05	2.60	1.30	0.95	1.65	2.45	6.00	12.80	16.70	19.70
Non-precipitation Bad Days	16.20	10.90	4.60	2.30	1.20	0.85	1.45	2.15	5.70	12.25	15.70	17.20
Marginal Air Quality Days	5.50	9.25	11.75	9.60	7.75	7.40	12.20	14.30	11.85	10.95	8.15	5.25
Undisturbed Marginal Days	3.80	7.25	9.65	7.95	6.00	6.20	8.65	10.80	9.05	8.80	6.10	3.40
Non-precipitation Marginal Days	2.85	5.50	8.30	6.95	5.05	5.35	7.15	9.05	8.20	7.95	4.95	2.60
Good Air Quality Days	0.60	2.25	7.40	10.20	14.25	15.15	10.20	7.85	6.20	3.05	1.40	0.50
Denver												
Bad Air Quality Days	17.95	10.65	6.85	2.85	3.05	3.00	5.20	7.95	10.25	14.65	17.50	19.60
Undisturbed Bad Days	14.35	7.95	4.50	1.70	1.65	1.30	2.50	5.35	7.70	12.45	14.70	15.95
Non-precipitation Bad Days	12.20	6.45	3.65	1.55	1.20	1.10	1.75	3.55	6.70	11.40	13.20	14.05
Marginal Air Quality Days	8.50	9.55	10.45	10.20	9.55	9.80	12.70	12.35	12.25	10.85	8.00	7.35
Undisturbed Marginal Days	7.40	7.40	7.15	7.30	5.40	5.25	6.90	8.10	8.70	9.35	6.65	6.45
Non-precipitation Marginal Days	6.70	6.50	6.10	5.90	3.85	4.15	4.80	6.25	7.00	8.05	5.70	5.60
Good Air Quality Days	3.85	7.70	12.95	16.15	17.85	16.80	12.95	10.35	7.20	4.90	3.65	3.55

days, non-precipitation marginal days, and calculated potentially good air quality days (not including disturbed bad and marginal days).

Table I again demonstrates the dissimilarity between seasons; the average number of potentially bad air quality days is far greater in the winter months. Undisturbed bad days occur most often in December, nearly 20 days in Grand Junction and nearly 16 days in Denver. They occur least often in the month of June, an average of about one day per year for both regions. The highest percentage of potentially good air quality days computed by the method are found in May.

The pattern of the mean monthly number of potentially bad, undisturbed days in Denver is consistent with the mean monthly number of days when the eight-hour carbon monoxide standard of 9 ppm was exceeded as given in Figure 12. Thus, the number of potentially bad air quality days calculated may seem large in the fall and winter, but they do appear to be realistic.

B. Episodes

Not only the absolute number of potentially bad air quality days but the frequency and duration of consecutive days with potentially bad air quality are important in studying the air pollution potential of a region. Episodes of several consecutive days with poor ventilation mean that pollutants which are released within the region are not dispersed and continue to accumulate within the region for the duration of the episode. Figures 13-16 give the average frequency of these episodes which occurred for various durations each season.

Because the absolute number of bad air quality days is small in the spring and summer season, episodes during those times are short and

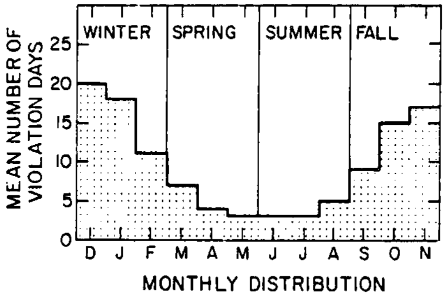


Figure 12. Monthly distribution of the mean number of days per month when the eight-hour carbon monoxide standard of 9 ppm was exceeded at a monitoring station near the center of the Denver metropolitan area for the period 1968-1975 (after Air Pollution Control Division 1976). From Haagenson (1979).

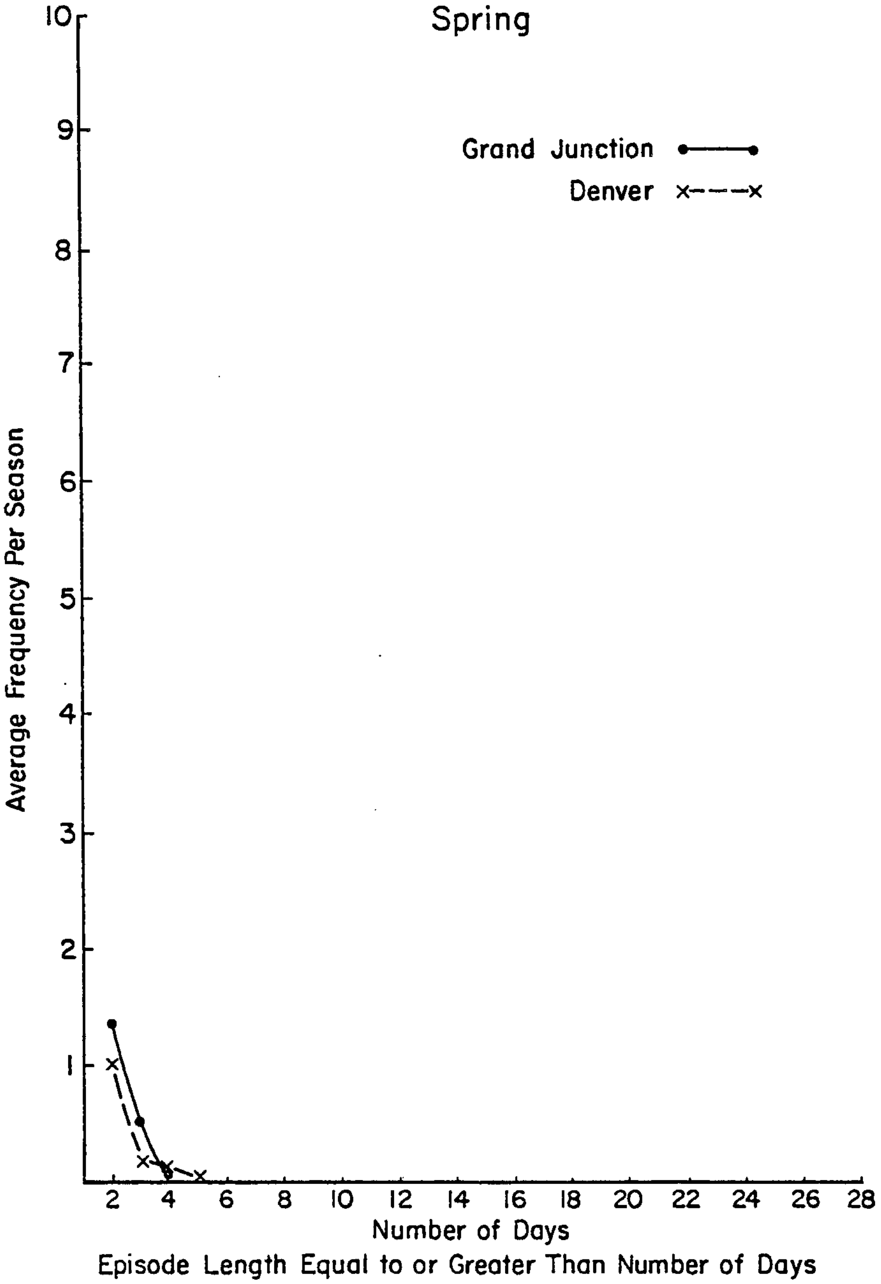


Figure 13. Average number of bad air quality episodes which occur in the Grand Junction and Denver regions in the months of March, April, and May.

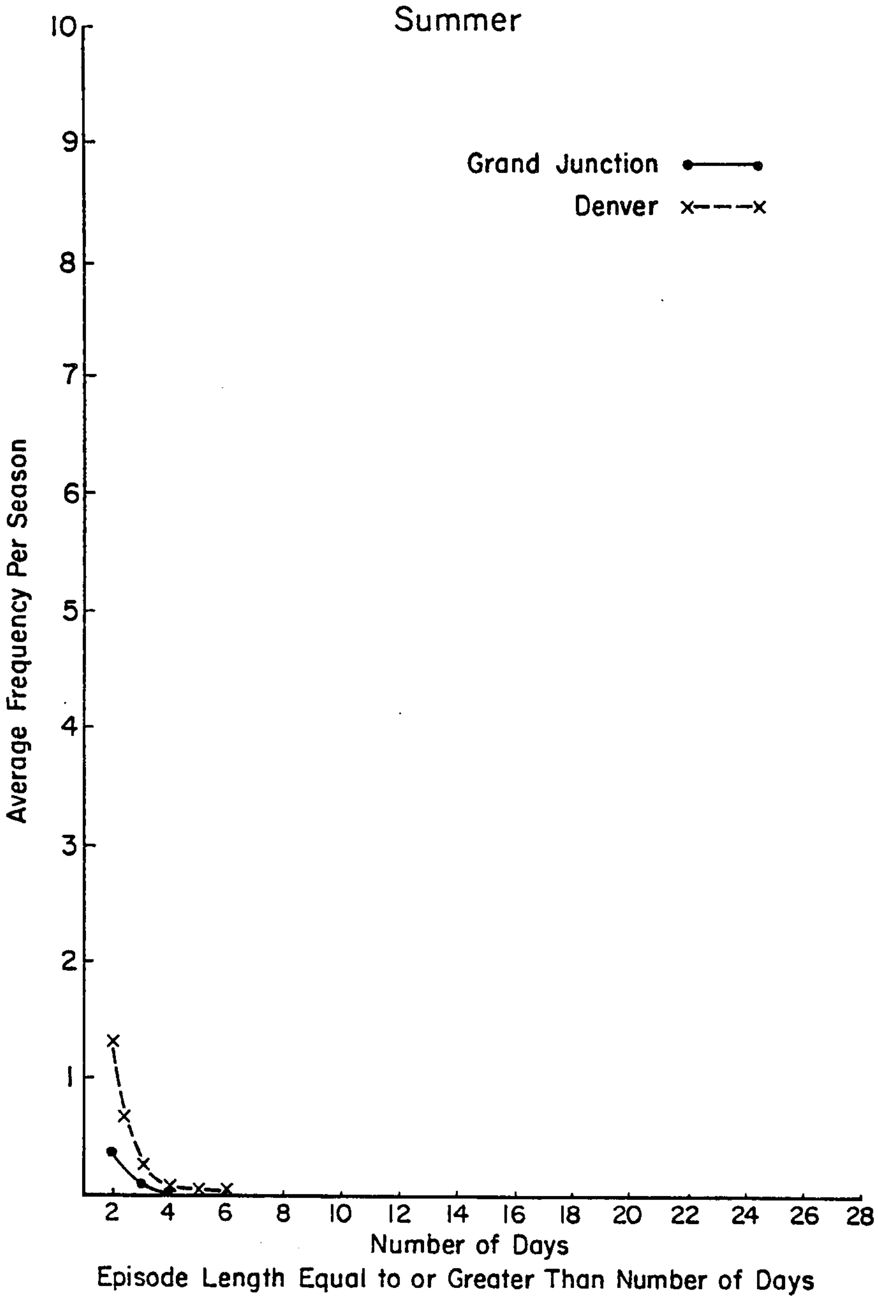


Figure 14. Same as Figure 13 but for the months of June, July, and August.

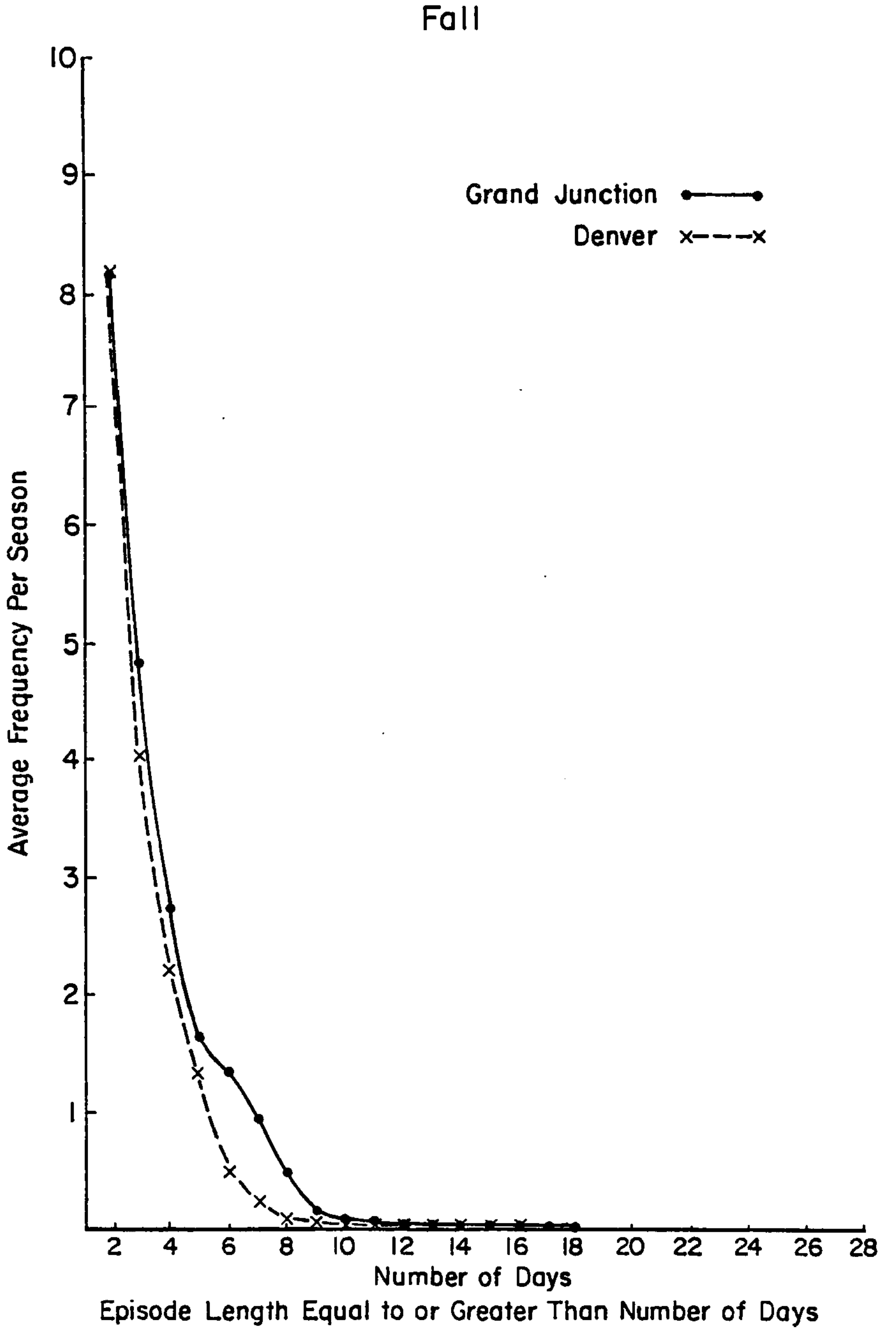


Figure 15. Same as Figure 13 but for the months of September, October, and November.

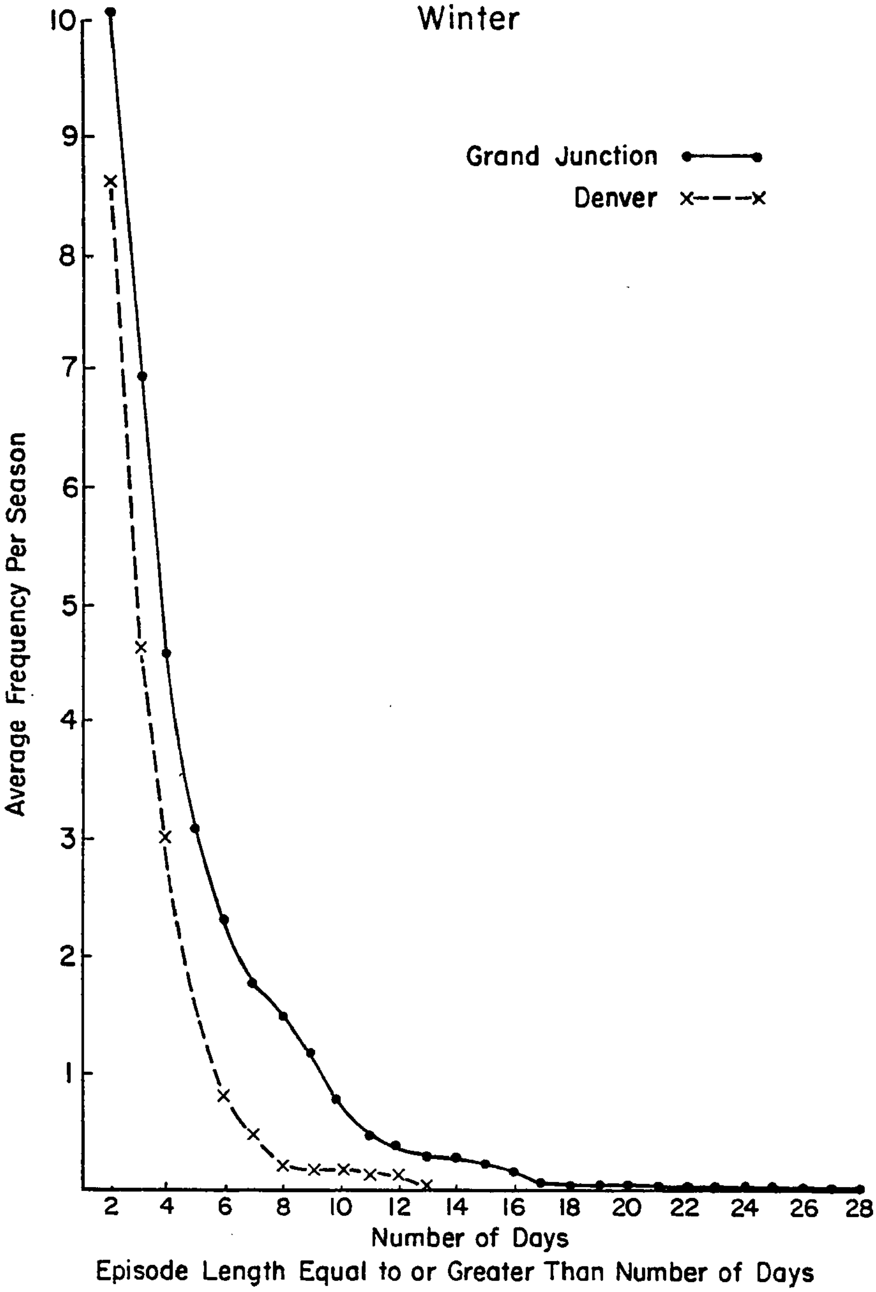


Figure 16. Same as Figure 13 but for the months of December, January, and February.

relatively infrequent. Grand Junction in the spring (Figure 13) showed 1.4 potentially bad air quality episodes per spring season, 10 of those spring episodes lasted three days or longer. Similarly, Denver in the spring has had only 1.0 potentially bad air quality episodes per spring season, 17 of those spring episodes were only two days long. Only seven episodes in the years 1959-1978 happened in Grand Junction in the summer (Figure 14), with only one three day episode and one four day episode. Figure 14 gives the average number of two day episodes in Denver in the summer as 1.1. Total three day episodes for the twenty years numbered only five with one six day episode.

However, as one moves into the fall season, the number of these episodes increases greatly. Figure 15 shows that Grand Junction experienced an average of 8.2 episodes per Autumn with 4.9 episodes lasting more than two days. Figure 15 shows nearly the same number of total episodes in the Denver region, but an average of 4.2 were only two days long. Although many of the episodes are only two days long, episodes of three days or longer are beginning to occur at a rate of nearly five (near Grand Junction) or four (near Denver) per fall season.

In the winter season (Figure 16), the number of two and three day episodes are approximately the same as in fall but the longer episodes continue to increase, particularly in the Grand Junction region where the total number of potentially bad air quality days is the greatest. During the months of December, January, and February, episodes of three days or longer have occurred at a rate of nearly seven per year near Grand Junction and five per year around Denver. One episode even lasted 28 days in the Grand Junction region in December 1976 and January 1977.

Tables II and III also show the differences between the number of episodes taking place in Grand Junction and Denver. Table II gives the percent probability that a particular number of episodes will occur in a given year in the Grand Junction region. Episodes of various lengths are included in the table. From Table II, it can be seen that there is a 95 percent probability that 14 episodes of two days or longer will take place in a given year. Likewise, there is a 70 percent probability that episodes of six days or longer will happen three times in the year. The probability of one episode of ten days or longer in a given year is 60 percent.

Table III gives the same information for the Denver region. In the Denver area, there is a 95 percent probability that 15 episodes of two days or longer will take place in a particular year. The probability of three episodes of six days or longer is only 20 percent and the probability of one episode of ten days or longer in a given year is 20 percent.

Tables II and III also demonstrate the year to year variability of episodes during the period of study. For instance, Grand Junction episodes of two days or longer vary from 13 occurrences in one year to 28 in another. Grand Junction episodes of six days or longer are less variable, from two occurrences a year to seven. A decrease in variability with increasing episode length is also present in the Denver region.

TABLE II.

Percent Probability of the Number of Occurrences of Episodes in the Grand Junction Region.

Episode Length Equal To or Greater Than Number of Days

Number of Occurrences in a Year	Number of days																		
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1						95	85	70	60	40	35	25	25	25	20	10	10	10	10
2						80	60	50	30	25	15	10	10	5	5	5	5		
3				90	70	60	35	15											
4				85	70	35	5												
5			95	70	30	15													
6			80	40	5														
7			70	15	5														
8			45	5															
9		95	30	5															
10		95	20																
11		75	5																
12		50	5																
13		35	5																
14	95	25																	
15	90	15																	
16	90	10																	
17	80	5																	
18	80	5																	
19	55	5																	
20	40	5																	
21	35																		
22	30																		
23	20																		
24	15																		
25	15																		
26	10																		
27	10																		
28	5																		

TABLE III.

Percent Probability of the Number of Occurrences of Episodes in the Denver Region.

Episode Length Equal To or Greater Than Number of Days

Number of Occurrences in a Year	Number of days																		
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1				95	75	60	30	25	20	20	20	10	5	5	5				
2				85	40	20	10	5	5										
3			90	85	20	5													
4			75	40	5														
5		95	70	10															
6		95	55	5															
7		95	20																
8		75	15																
9		55	5																
10		50	5																
11		25																	
12		15																	
13		10																	
14																			
15	95																		
16	90																		
17	65																		
18	65																		
19	50																		
20	40																		
21	40																		
22	30																		
23	15																		
24	10																		
25	10																		
26																			
27																			
28																			

CHAPTER V

CONCLUDING REMARKS

A. Suggestions for Further Study

In developing the method of determining potentially good and bad air quality days, several assumptions were made. A refinement of these assumptions could make the method more accurate, especially when it is to be applied to a particular locality.

For example, the percentage of solar energy which theoretically heats the boundary layer and determines the SMH for the calculations used in this study is estimated and treated as a constant. Thirty percent of the incoming solar radiation at the top of the atmosphere is probably an overestimate in some cases. These cases could be cloudy days when less of the direct sunshine reaches the earth's surface or days with snow cover on the ground reflecting much of the solar energy. Also, a significant amount of moisture available for evaporation means that less of the energy reaching the surface actually goes towards heating of the boundary layer. As a result, the method employed in this study tends to over predict SMHs (and therefore SMAs) particularly in the winter season. Thus, the method gives a conservative estimate of the number of potentially bad air quality days.

Further work could be done to take into account the effects of cloud cover, surface reflectivity, and moisture including the seasonal variations of these factors. This could be accomplished by including a factor derived from climatological means of cloud cover, snow cover, and moisture. Another approach would be to directly modify the input energy in each daily calculation of mixing area according to actual observations of these parameters. An example of modifying the input energy is given by Holtslag and VanUlden (1983).

Another possibility for further study is to apply the method of determining the potential for good and bad air quality to other regions in the west along with other regions in the United States. It would be interesting to compare the results of these studies to find the similarities and contrasts which exist both within and between climatic regimes.

B. Conclusions

A method to estimate regional potential for bad air quality days has been developed. The solar mixing area appears to be useful in separating potentially good air quality days from potentially bad air quality days for a region in general agreement with what would be expected from inspection of daily synoptic maps. Days which are calculated to have small mixing areas are typically found to be days when the synoptic pattern shows the influence of high pressure at the surface with a ridge of high pressure aloft and low wind speeds. In addition, the monthly variation of the mean number of bad air quality days determined for the Denver region is very similar to the monthly variation of the mean number of days which violate the eight-hour carbon monoxide standard in Denver.

When applied to the regions near Grand Junction and Denver, Colorado, the method showed a distinct seasonal variation in the average number of potentially bad air quality days. The fall and winter seasons demonstrated a much higher tendency for poorly ventilated days and more frequent and longer episodes of consecutive days with poor ventilation. This seasonal variation is particularly pronounced in the area around Grand Junction. Episodes of three days or longer averaged far less than one per season in both the spring and summer. However, in the fall and winter seasons, episodes of three days or longer occurred at a rate of nearly five and nearly seven times per season respectively.

The Grand Junction region has also demonstrated the possibility for the occurrence of very long episodes especially in winter. Episodes of six days or longer have a 70 percent probability of happening three times a year. In one winter case, poor ventilating conditions continued for 28 straight days.

A similar pattern occurred in the Denver region with the exception of the winter time episodes of consecutive days with poor ventilation. The Denver episodes are generally shorter and somewhat less frequent. The fact that potentially bad air quality days are more frequent in the Grand Junction region in the winter is due to the lower SMHs and lower wind speeds which occur more often there than in the Denver region. These differences are probably due to the influence of different terrain and the orientation of that terrain to the upper level flow.

It is important to observe that, in the front range region and particularly in the western slope region, days with small atmospheric mixing volumes can occur quite frequently and consecutively in episodes during the fall and winter seasons. This is a phenomenon which should not be overlooked in planning for the development of these areas where good air quality is so desirable.

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ABSTRACT

A climatological analysis of regionally potentially bad air quality days near Denver and Grand Junction, Colorado has been prepared. These bad air quality days are defined as days which have a small volume of atmosphere available for the dilution of contaminants released within the region. The atmospheric volume is represented by the product of a solar mixing height and average wind speed which leads to an hourly solar mixing area accumulated throughout the day to form a daily solar mixing area. Solar mixing height is calculated by a simple thermodynamic model using a percentage of the incoming solar energy (at the top of the atmosphere) and the morning rawinsonde temperature sounding. Wind speed is assumed to vary logarithmically with height and is fitted to the surface and 700 mb winds from the morning sounding. The average of the wind speed between the surface and the solar mixing height is multiplied by time to give the horizontal movement. The horizontal movement times the solar mixing height gives a solar mixing area. This value of solar mixing area is assumed to represent the mixing volume available for the dispersion of regionally released air pollution.

Twenty years (1959-1978) of rawinsonde soundings from Grand Junction and Denver, Colorado were used to perform the climatology. Disturbed days are defined to be good air quality days and are determined separately from climatological data. The results are the average monthly frequency of potentially bad air pollution days and the frequency and length of potential air pollution episodes on a seasonal basis.

In the Grand Junction region, the greatest number of potentially bad air pollution days and episodes exists in the fall and winter seasons, with very few potentially bad days in the spring and summer. Episodes of three days or longer occurred in the Grand Junction region an average of less than one time per spring and summer season, nearly five per fall season and nearly seven per winter season. Thus, these three day or longer episodes averaged 12.4 episodes per year. Very long episodes of potentially bad air quality are possible as illustrated by the 28 day episode of December 1976 and January 1977.

By comparing the western Colorado region around Grand Junction to the eastern Colorado region around Denver, a similar seasonal pattern can be found between the regions. However, the Denver region's episodes of three days or longer averaged four per fall season and five per winter season. Both the number and duration of potentially bad air quality episodes in fall and winter are greater in the area around Grand Junction.