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DIFFUSE IRRADIANCE IN THE ROCKY MOUNTAINS

AT 40° LATITUDE

by

Brock Allen LeBaron

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soil Science and Biometeorology

with emphasis in

Biometeorology

UTAH STATE UNIVERSITY

Logan, Utah

1979

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Brock Allen LeBaron

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ABSTRACT

Diffuse Solar Irradiance in Mountainous Terrain

At 40° Latitude

by

Brock Allen LeBaron, Master of Science

Utah State University, 1979

Major Professor: Dr. Inge Dirmhirn
Department: Soil Science and Biometeorology

A study of the parameters effecting diffuse irradiance in mountainous terrain was made. Ground/location parameters of site elevation, ground albedo, elevated horizon and surface tilt were examined under the pertinent atmospheric conditions of clear, polluted, overcast, and cloudy. Measured diffuse irradiance data used for comparisons were taken from fall 1977-spring 1979 at four sites located in northern Utah.

Diffuse irradiance varied with elevation according to the existing atmospheric conditions. For clear sky, diffuse irradiance decreased with elevation due to the shorter optical pathlength, thus less scatter of the direct beam. However, with completely overcast sky, diffuse irradiance increased with elevation. The thinner cloud cover associated with higher elevations causes less adsorption of the diffuse irradiance. For partially cloudy conditions a correlation of diffuse irradiance with duration of sunshine showed curved relationships with maximum diffuse irradiance at 70 percent cloud cover. At high elevation, the curves were much steeper than at low elevation, becoming almost linear.

Climatic changes in ground albedo were found to modify diffuse irradiance considerably. This occurred mainly through multiple reflection between ground and atmosphere with maximum enhancement for snow covered ground and overcast sky. Even for clear days snow cover shifted the maximum in the annual cycle of diffuse irradiance day totals towards the spring months. A comparison of March (snow cover) and September (bare ground) diffuse irradiance values for various amounts of cloud cover showed that diffuse enhancement increased steadily with cloud amount to a maximum at overcast conditions.

The effects of elevated horizon such as might be found in a mountain valley were examined through validation of a physical model describing a V-shaped valley. Comparisons between calculated and measured diffuse irradiance showed excellent results for clear days during winter, spring, and summer.

The ratio of measured diffuse irradiance on a south facing 50° tilt to that on the horizontal was plotted against duration of sunshine for different seasons. For clear days the 50° tilt enhanced diffuse irradiance values as much as two times the horizontal values during winter while during summer 50° values dropped to .8 of the horizontal values. For overcast days the ratio varied from 1.0-0.3 for winter and summer, respectively.

A model predicting diffuse irradiance on a tilted surface for clear day was developed and validated using measured data. A good comparison is shown for spring and fall days using high and low elevation data.

INTRODUCTION

With the advent of the so called "energy crunch," there has been a drive to diversify the United States energy supply by utilizing alternative sources of energy, particularly solar. Solar energy has generated this recent interest due to its inexhaustible, pollution free nature. It is also a wide spread source. Having a power input of 170 billion megawatts, the sun is already the basic driving force for the earth's natural systems and exceeds in power all of man's currently used sources of energy approximately 20,000 times (Kodratyev, 1977).

However, while solar energy is a widespread source, it is not an evenly spread source. It's availability varies according to geographic, atmospheric and terrain conditions. Thus, when evaluating a locale as a potential collection site, a unique set of parameters must be considered. In many cases this can only be done through meticulous on-site data collection and analysis. This is particularly true of mountainous terrain where topographic characteristics are manifested in reflection processes, orographic clouds, temperature inversions, extended snow cover, etc.

Background of the Problem

The solar energy arriving at any given place is composed of several parts; the direct beam, that scattered from sky and clouds, plus that reflected from the earth. The contribution of each of these parts is increased or decreased depending on the terrain, surface albedo, and atmospheric conditions.

While focusing devices concentrate only the direct component, flat plate collectors can utilize all radiation incident to the surface. Thus, for these types of collectors an investigation of the parameters affecting scattered or diffuse irradiance is important. Furthermore, since in most cases a flat plate collector will have a fixed orientation, the effect of tilting the collector is needed to maximize energy collection.

Previously, except for a few investigations (Bishop et al., 1966; Dirmhirn, 1951; Eisenstedt, 1961) radiation studies have been isolated to flat terrain. Based on duration of sunshine, Angstrom (1924) obtained the daily radiation-income Q_s to a horizontal surface. However, no means is provided for dividing it into a direct and diffuse component. Later, Liu and Jordan (1960) presented relationships from which instantaneous clear day values of diffuse irradiance on a horizontal surface could be determined. Relationships for the average hourly and daily diffuse radiation for cloudy days are also given.

Many methods to transpose these horizontal values to a tilted surface have been developed. Isotropic methods (Liu and Jordan, 1961; Kondratyev, 1977) based on the assumption that diffuse irradiance arrives equally from all parts of the sky have generally proved to be more accurate. However, recently anisotropic models (Hay, 1978) have shown considerable improvement.

Little literature has been found which deals with diffuse irradiance in mountainous terrain through on-site data collection; nor have any available models for flat terrain been tested using actual measured data from mountainous sites to determine their applicability.

Purpose and Objective of the Study

Main objective. The purpose of this study is to evaluate the parameters effecting the diffuse irradiance availability in the Rocky Mountains using on-site measurements. Together with information on direct irradiance availability, a practical assessment of flat plate collector efficiency will then be possible. Secondly, to examine applicable irradiance models to determine their accuracy for mountainous terrain.

Specific objectives.

1. To determine the effect of elevation on diffuse irradiance with varying amounts of cloudiness.
2. To determine the effect of ground albedo on diffuse irradiance under overcast and cloudy conditions (multiple reflection).
3. To determine the effect of direct reflection in mountain valleys, correlating the results to a previously developed model.
4. To examine the enhancement of diffuse irradiance by tilting the collector surface.

Parameter Interrelationships

The pertinent parameters affecting diffuse radiation in the mountains can be broken down into two groups--ground/location and atmospheric. The ground/location parameters considered are elevation, ground reflectance (albedo), horizon blockage, and tilt effects. These will be examined in conjunction with the atmospheric conditions of clear, polluted, overcast, and cloudy skies. Due to their complex interrelationships, these parameters are best organized in the form of a matrix (Fig. 1).

		ATMOSPHERE			
		CLEAR / CLEAR	CLEAR / POLLUTED	OVERCAST	CLOUDY
GROUND & LOCATION	ELEVATION	+	+	+	+
	ALBEDO (GROUND)	+		+	+
	HORIZON (VALLEY)	+		+	+
	HORIZONTAL / TILTED	+	+	+	+

Fig. 1. Matrix used to organize parameters affecting diffuse irradiance in mountainous terrain. +s in the matrix body indicate areas where effects were examined.

Elevation. Due to a decrease in turbidity (shorter pathlength of the solar irradiance) total radiation increases with height in the atmosphere. For the same reasons diffuse or scattered irradiance diminishes with height but only for clear sky conditions. Under cloudy conditions the thinner cloud cover associated with high elevations as well as orographic effects tend to increase the scattered radiative flux considerably, offsetting the reduction due to a clear sky (Dirnhirn, 1976).

Albedo. The extended snow cover found in mountainous areas can contribute substantial amounts of diffuse irradiance values. This is

especially true with cloud cover when the reflection process between snow and cloud can be greatly extended. Holmgren and Weller (1973) noted that in the Arctic, with its high latitudes and unique cloud conditions the incoming radiation does not decrease very much (15%) when a cloud cover forms over an extensive snow field.

Horizon. Due to the topography inherent to mountainous terrain, many locations have truncated day lengths. Steep valley walls not only block direct irradiance at low sun angles but cut out a portion of the diffuse irradiance throughout the day. However, with snow cover, these same valley walls can act as direct reflectors to focus large amounts of radiation. The effect is maximized with clear skies and proper slope orientation. Both Angstrom (1965) and Dirmhirm (1978) have observed this direct reflection enhancement in the Himalayas and Alps, respectively.

Tilt/horizontal. Maximum diffuse irradiance values can be obtained by tracking the sun throughout the day. Since this is not feasible for a fixed flat plate collector, an optimum orientation must be determined. Ground reflection, latitude, and energy requirement are important considerations. The snow cover and general clear skies associated with winter in the Rocky Mountains could provide enhanced energy collection with a proper surface tilt, when it is needed most.

Assumption

In terms of diffuse radiation, mountainous areas with their high elevation, extended snow cover, and steep terrain may offer excellent solar potential.

REVIEW OF LITERATURE

The available literature is reviewed in accordance with the organizational matrix developed and illustrated (Figure 1) in the Introduction section.

Elevation

The variation of diffuse irradiance with elevation is a function of the associated atmospheric turbidity, cloudiness, and ground reflectance. Literature pertaining to scattering by a clear atmosphere will be presented first.

Clear. The molecular scattering effect of pure "clean" atmosphere on solar irradiance is described by the Rayleigh relationship:

$$I_s \propto \frac{I_o}{\lambda^4} (1 + \cos^2 \theta)$$

where I_o = incident intensity, λ = incident wavelength, and θ = scattering angle. The result is that 10 to 30% of the solar irradiance incident on the atmosphere is scattered from the direct beam, about one half of which is scattered down to the earth's surface.

Polluted. For a polluted or "dirty" atmosphere the scattering of radiation by specific particulates, whose size is comparable to the wave lengths of the radiation, is very complex. Mie theory can be used to calculate the scattering of large spherical particles of a known size distribution. Sheppard (1958) suggests that due to the complexities of the problem it is natural to attempt to infer the effects of pollution on solar irradiance by direct measurements of the solar beam and

of the proportion scattered from it in atmospheres with varying degrees of pollution. His measurements at Kew Observatory show an inverse correlation between global irradiance and particulate concentration of the surface air.

The change in the turbidity factor with elevation is a useful tool when examining the effects of elevation on diffuse irradiance. Robinson (1966) discusses the decrease in the turbidity factor T with elevation derived by Steinhauser from measurements in Central Europe.

Bishop et al. (1966), during a solar irradiance study in the high Himalayas, noted problems in determining elevation effects arising from the fact that their observing sites were essentially high valleys and not isolated mountain peaks. As the particle content of the atmosphere originated from the solid surface of the earth, the observations on isolated mountains showed a more transparent atmosphere than that above a valley at the same elevation. Thus, the location for solar irradiance data collection is of importance.

Overcast. The effect of elevation with various amounts of cloudiness on diffuse irradiance has been examined extensively by Dirmhirn (1951) in the Alps. For clear sky conditions, diffuse irradiance was found to decrease with elevation due to a reduced optical pathlength. An opposite effect was observed for completely overcast conditions where thicker cloud layers reduced diffuse irradiance at lower elevations.

Cloudy. Clouds by their various forms are a hard parameter to define. Angstrom (1919) noted that the cloud forms are innumerable and the influence of different clouds exhibits great variations. From

measurements taken in Washington and Upsala he found that with increasing density of a cloud sheet the diffuse irradiance first increases in order to reach a maximum after which it decreases with increased thickness of the clouds. The amount of diffuse irradiance can also be altered considerably depending on the clouds' position relative to the sun. In general, partially cloudy conditions give the highest amounts of diffuse irradiance.

Kasten (1977) observed that diffuse irradiance increases with increasing cloud amount by a factor of about 1.4 to 1.6 at 6/8 cloudiness compared to clear sky values; then the curve sharply drops to between 0.5 and 0.8 at 8/8 cloudiness (overcast).

Dirmhirn (1951) found maximum diffuse irradiance values at .7 cloud cover in lower alpine valleys. However, at higher mountain elevations, the maximum was at 1.0 cloud cover. This is apparently due to the thinner clouds associated with high elevation.

A physical explanation of why maximum diffuse irradiance occurs under partially cloudy conditions and not overcast can be attributed to the screening of the brilliant cloud tops in the background by the dark base of clouds in the foreground (Robinson, 1966).

Models. Due to the high cost and maintenance requirements of radiation instruments, total or global short wave insolation on a horizontal surface is all that is normally recorded. Therefore, many models have been developed to estimate the direct and diffuse components through physical relationships with other atmospheric parameters. Once these components are known on the horizontal surface, they can be transposed to tilted surface values.

J. L. Threlkeld (1962) presented an analytical method for deriving diffuse irradiance on various surfaces which included ground reflectance. However, it was useful only for clear days.

Liu and Jordan (1960) used a relation between the ratio of daily diffuse to daily total irradiance on a horizontal surface, D/H_0 and the cloudiness index $K_T = H/H_0$.

Orgill and Hollands (1976) used hourly irradiance on a horizontal surface to revise Liu and Jordan's K_D , K_T correlation and recommended an equation to determine the hourly ratio of diffuse to total irradiance received on a horizontal surface.

A simpler method was developed by Iqbal (1977) to determine monthly averages of diffuse irradiance on horizontal surfaces to satisfy more general inputs required by some of the newer design methods of solar heating of buildings. However, these long term averages are not adequate for examining short term parameter effects.

In many cases where no radiation data is available, surface weather observations have been used to develop statistical relations for estimating diffuse irradiance. Angstrom (1924) suggested the use of percent possible sunshine hours as a parameter to predict radiation in his pioneering equation

$$Q_s = Q_o (0.25 + 0.75 \times S)$$

where Q_o = clear day radiation income, and S = percent possible sunshine.

Lund (1968) correlated 9 years of daily insolation, snow cover, wind, sunshine, sky cover, pressure, and precipitation. He found that

sunshine observations gave the best correlation with sky cover providing the second best for most months of the year.

Norris (1968) examined the correlation between solar radiation and cloud cover. After using several methods of cloud classification, he reported poor correlations and concluded that it is probably impossible to predict solar irradiance from this parameter.

Bennett (1969) established the usefulness of opaque sky cover when correlating with insolation. This allowed for distinctions to be made between different cloud types and accounted for cloud reflection to obtain a more "irradiance specific" observation.

It should be noted that these relationships have been derived through regression analysis of observations at a single location and may not be adequate for prediction of irradiance at other locations. Further verification at high elevations would be advantageous.

Albedo

The reflective properties of ground and atmosphere ensure that a proportion of incoming solar irradiance will be reflected back and forth between the two (Catchpole and Moodie, 1971). This process is referred to as multiple reflection.

Clear. Deirmendjian and Sekera (1954) found that in the case of a clear sky atmosphere and with scattering, according to Rayleigh's Law, the increase of diffuse irradiance ranges from 10-140%.

Overcast. In the presence of snow covered ground under cloudy conditions, multiple reflection between ground surface and cloud bases can have a dramatic effect on diffuse irradiance values.

Using a series of measurements of incoming irradiance (diffuse) for a dense overcast sky over a snow covered coastline with an albedo variation of 7-50%, Möller (1965) found an increase of 67% in diffuse irradiance. He further attempted to derive coefficients of back scattering for both clear and overcast sky.

Catchpole and Moodie (1971) found that illumination beneath the stratocumulus, cumulus stratus, and nimbostratus clouds was increased by at least 50% when snow-free ground was replaced by snow-covered ground. They also reported several visible effects of multiple reflection such as the "white out" where the upward and downward fluxes of light are almost identical and no horizon can be detected.

Several investigators have attributed the annual variation in diffuse radiation to multiple reflection.

An analysis of the 10-year winter data from five stations in the western United States shows that snow cover apparently produced an increase in the daily insolation of 1.5% for clear sky and 29.0% with overcast sky (Bennett, 1965).

Dirmhirn (1951), in a study of the radiation climate of the eastern Alps, found that the annual curve of overcast days was strongly skewed towards winter and early spring. The curve dropped dramatically during the spring snow melt and rose again at the advent of snow.

Baldazo (1970) stated that diffuse radiation during cloud-covered sky due to multiple reflection effect is very prominent with the highest values when there was snow on the ground in late winter and early spring.

Several investigators have tried to determine the albedo or back scattering of various cloud types and ground cover.

Using a Nimbus radiometer and pyranometers, Salomonson and Marlatt (1968) measured the anisotropic reflectance over stratus clouds, snow and white sand. The reflection from snow and white sand was not observed to be as anisotropic as the scattering from stratus clouds. It was also observed in the study that the underlying surface has an influence on the magnitude of the reflectance from stratus clouds observed by pyranometers and radiometers.

Models. Angstrom (1931) first described the multiple reflection process. The radiation reflected by the earth's surface is partially reflected back down through back scattering from the atmosphere and clouds, thus increasing the diffuse irradiance. This process is repeated an infinite number of times. A model based on the equation

$$G_r = G_o (1 - rd)^{-1}$$

was developed by Angstrom (Moller, 1965; Catchpole and Moodie, 1971) where G_o is the global radiation before any reflection, r is the albedo of the surface and d is the backscattering of the clouds.

Loewe (1961, 1963) added an absorption term to account for the loss due to absorption by the atmosphere.

Vowinkel and Orvig (1962) examined the magnitude of ground albedo, albedo of cloud tops and the effect of composite cloud typed in the Arctic to develop radiation tables using Angstrom's equation.

Diniz (1978) compared computed values from Angstrom's equation and measured values from a simulation model for overcast conditions to show good coincidence. She found that changes in cloud density under overcast conditions affect only the transmissivity, but have little effect on the contribution due to multiple reflection.

However, no verification of the models with actual values especially from mountainous areas are available. The Rocky Mountains with their extended snow cover provide an excellent source of irradiation data for verification.

Horizon

In mountainous terrain the diffuse irradiation from the sky can be increased not only by multiple reflection effects but by direct reflection processes from slopes above the horizon as well. In the presence of valley slopes or adjacent mountain peaks, diffuse values can be enhanced depending on ground albedo and atmospheric conditions. The process is most effective during clear sky periods and with snow covered ground.

Clear. After studying the radiation regime of Cache Valley, Baldazo (1970) attributed the higher clear sky diffuse values of the spring months to the closeness of the mountains and the reflection from the slopes. During the spring months when the mountains are still snow covered, the additional reflection increases the scattered irradiance more than during the fall months.

Solar irradiance measurements made in the high Himalayas (Bishop et al., 1966) show that in the neighborhood of snow covered mountains the sky irradiance is to a considerable extent made up of solar radiation reflected from the surrounding mountain slopes.

Dirmhirn (1978), in a comparison of irradiance in the Alps and the Rocky Mountains, stated that the terrain not only influences the irradiance by enhancement through reflection processes, but by blocking

the direct beam at low sun angles. Thus, while the diffuse irradiance may be enhanced through reflection, the blockage of the direct beam leaves the actual enhancement of the total or global irradiance in question. Of great importance is the time of year being examined. In the winter season, snow covered ground greatly increases reflected irradiance, however the low solar elevation also increases horizon blockage, truncating the normal day length.

Models. Due to the complexities of mountainous terrain, investigators (Eisenstadt, 1961; Diniz, 1978) have used simulation models to develop and verify the reflection process within valleys of a uniform "V" shape.

Eisenstadt (1961) examined the scattered radiation income to a differently oriented pyranometer using a special model of a mountain valley. Direct radiation was eliminated by means of a black shadow disk. The measurements showed that the diffuse irradiance of a surface was strongly influenced by orientation to an anisotropic sky.

In a similar way Diniz (1978) used a portable simulation model to test a mathematical model derived by Peterson (1978). Observed and computed values were compared, using different altitudes of the sensor within the model, slope angles and albedos. She found that clear sky irradiance decreased with increasing altitude and decreasing slope angle. For overcast days an opposite relationship was noted.

While the preceding investigators used simulation models to test valley models, no comparisons with actual measurements in a mountain valley have been made so far.

Tilt/Horizontal

In most cases a solar collector of the flat plate design will be mounted in a fixed position, possibly even being an integral part of a building structure. Thus, it is desirable to maximize the solar radiation incident on the collection surface by orienting (tilt and azimuth) the collector in some optimum fashion.

Intuitively a south facing surface (north facing for the southern hemisphere) would collect the most energy around solar noon when the sun is the highest. However, Felske (1976), while studying the effect of off south orientation on the performance of flat plate solar collectors, found that the average yearly energy collection for a given collector tilt is insensitive to azimuthal angle variations of less than 10 degrees.

More important than the azimuth angle is the tilt angle of the collection surface from the horizontal. Ideally, this surface should always be normal to the noon time solar rays (Kern and Harris, 1974) but this is impossible with a fixed installation due to the annual variation of the solar declination. This fact has led to numerous measurements and models to determine an optimum collector tilt.

Most authors report that optimum tilts are a function of latitude only with no consideration given to the local environment or energy demand of the collector.

It was shown by Kern and Harris (1974) that the energy demand should have a strong influence on collector tilt. If maximum output is required year round, the angle will be different than for a weather dependent demand.

Ground reflection can also contribute significant amounts of radiation to a tilted surface. This is especially true in mountainous areas and northern latitudes where extended snow cover is found. In a paper by Willcut et al. (1975), it is shown that ground reflectivity can enhance the average usable energy by 8% in Canadian cities.

Hunn and Calafell (1975) pointed out the need for accurate estimates of ground reflectivity as seen by a tilted surface to improve calculations from tilt models. They suggest a photographic method to determine average ground reflectances for comparison with those given in the simple Liu and Jordan Model (0.2 when the ground is covered with less than 1 inch of snow and 0.7 when snow is more than 1 inch thick). Using this method, they found that 0.6-0.7 reflectivity, similar to that used by Liu and Jordan, is accurate for most rural landscapes in winter where snow cover is predominant. However, the range of ground reflectivity for urban areas in winter is 0.16-0.49, considerably lower than that used by Liu and Jordan.

Models. Many investigators have put forth models to calculate the radiation received by an inclined surface. Most are expansions of horizontal surface models to include terms for transposing the direct and diffuse components to different tilts.

The technique for calculating direct solar irradiance fluxes to inclined surfaces has been adequately described by Kondratyev (1969) according to the equation

$$S_s = S_m \cos I$$

where S_m is the direct solar irradiance flux to a surface normal to the beam and I is the incident angle of the beam to the given slope.

The variation in the models arises with the methods used for transposing the diffuse component (from sky and ground). This is due to computational problems involved with the anisotropic nature of the scattered and reflected radiation fluxes.

Most models incorporate the assumption that the diffuse irradiance from sky and ground is isotropic to simplify calculations. Liu and Jordan (1961) proposed that the ratio (R_d) of the diffuse sky irradiance incidence on a tilted surface to that incident on the horizontal surface is given by the equation:

$$R_d = 1/2 (1 + \cos \beta).$$

To account for the diffuse irradiance contributed by ground reflectance (R_p), they suggest the equation:

$$R_p = \left(\frac{1 - \cos \beta}{2} \right) \rho$$

where β = tilt angle and ρ = surface albedo.

Kondratyev (1977) derived isotropic equations similar to those of Liu and Jordan to transpose the diffuse fluxes.

Heywood (1966) developed a "radiative characteristic line" by plotting the ratio of the direct irradiance multiplied by the cosine of the incident angle to the direct irradiance multiplied by the cosine of the solar zenith angle against parameters determined experimentally for a given locality. Then incorporating the isotropic equation for diffuse sky irradiance, he calculated the total radiation flux received by a surface of any orientation. Diffuse ground reflection was ignored in the calculations.

The isotropic assumption was also used by Garnier and Ohmura (1970) in their formulae to evaluate the global radiation flux on surfaces of any inclination or azimuth.

Bugler (1977) developed a method in which the diffuse irradiance is calculated from the global horizontal irradiance using three different relationships. The appropriate relationship is selected according to the ratio of actual global irradiance to global irradiance for clear days. Then the isotropic equations were used to transpose the values to an inclined plane.

Using experimental data, Klein (1976) verified Liu and Jordan's isotropic model and expanded it to include not only surfaces facing directly towards the equator but towards various azimuth angles as well.

Each of the previously mentioned models has ultimately relied on the isotropic assumption in describing diffuse irradiances. Further, they have utilized the equations originally proposed by Liu and Jordan to transpose calculated diffuse values from the horizontal plane to inclined orientations.

Kondratyev and Manolova (1960) examined the effects of the diffuse isotropic assumption for sky and ground reflection and tried to determine in what cases and with what accuracy this approximation is valid. They conclude, that for clear skies, an isotropic assumption for ground reflection gives negligible error for slopes less than 30° , when the portion contributed to the scattered radiation flux by reflection is small (<10 percent). The anisotropy of sky irradiance should be taken into account where the solar zenith angle is greater than 75° , when diffuse sky radiation constitutes a considerable portion of the

total radiation. These tilt angles necessary for significant ground reflection have been verified by Dirmhirn (1964).

For overcast sky, diffuse irradiance depends on the inclination of the slope but not on the azimuth and thus the isotropic approximation is satisfactory. However, when the overcast is not uniform or is partially transparent (cloudy) the isotropic approximation again fails.

In view of this fact many investigators have attempted to develop anisotropic models for transposing horizontal diffuse values to an inclined surface.

Morse and Czornecki (1958) used the assumption that the diffuse irradiance (E) is not uniformly distributed over the whole sky but is largely concentrated around the sun according to the equation:

$$E = X \sin B + Y \cos B$$

where the ratio X/Y is a function of zenith angle and B is the surface tilt angle.

However, when Norris (1966) compared calculated values with measured values, individual errors up to 30% were found (high cloudiness) with a mean error of 8%.

Using the standard isotropic equations (Liu and Jordan, Kondratyev, Robinson) Temps and Coulson (1976) compared calculated values to measured values to develop empirical correction terms for the anisotropy of diffuse sky and reflected irradiance.

Hay (1978) tested four approaches to calculating diffuse irradiance incident on an inclined surface. One isotropic and two anisotropic models were taken from previously published literature. A fourth

anisotropic model was developed by parameterizing the ratio of circumsolar to isotropically distributed radiation. This ratio of circumsolar to isotropic diffuse irradiance (hence the degree of anisotropy) varies according to changes in amount, distribution, and other characteristics of cloud cover.

It would appear from the literature that there are many adequate tilt models to choose from, both isotropic and anisotropic. However, most were developed for one locality with limited measured data verification.

In a report funded by the U.S. Department of Energy (Carter and Pate, 1978) 24 methods of calculating solar irradiance on inclined surfaces were evaluated. After converting the various methods to a common nomenclature, only the Liu and Jordan method and the Temps and Coulson method were compared. All the other methods were based on isotropic approximations similar to Liu and Jordan and would not offer significant variation. The results showed that the Liu and Jordan method provides the most satisfactory results of hourly calculations. The highest degree of error for the Temps and Coulson method occurred when the diffuse irradiance was greater than half the global irradiance. However, the accuracy of any of the models depends largely on the accuracy of the data used for development.

METHODOLOGY

Site Location, Set Up, and Duration

The data used in this study were recorded at three permanent sites established approximately 41° north latitude in the Rocky Mountains and were situated so as to be within 20 miles of one another. A fourth radiation site was located on top of the Natural Resources Building at Utah State University and was used only for short-term studies, primary instrument calibration, etc. The exact location of each site can be found in Fig. 2 and general site characteristics are given in Table 1.

Table 1. General site characteristics

Site	Characteristic	Elevation (m)
Salt Lake City Airport	Open valley	1,290
Snowbird, Hidden Peak	Mountain top	3,350
Snowbird, Cliff Inn	V-shaped valley	2,510
Logan, U.S.U.	Short-term studies	1,356

These recording sites are part of a larger network being used to examine solar energy potential in the Rocky Mountains through a grant from the United States Department of Energy.

Each recording station consists of a stand supporting three star pyranometers which detect horizontal, global, and diffuse irradiance

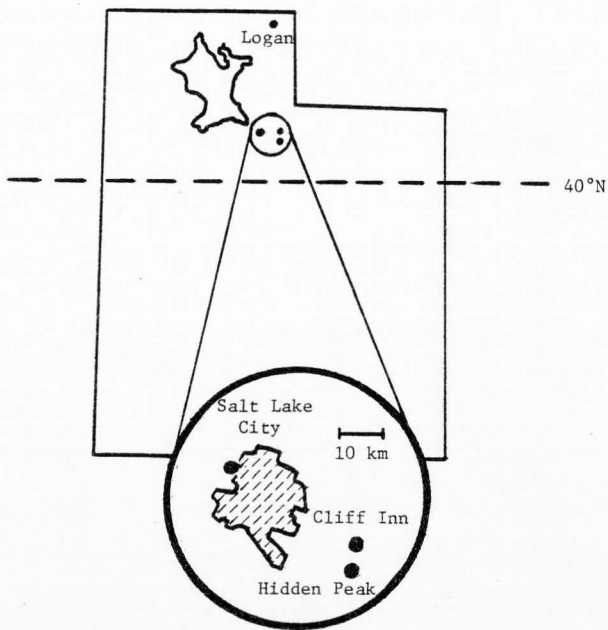


Fig. 2. Map of Utah indicating the locations of sites recording diffuse irradiance used in the study.

along with global irradiance on a 50-degree tilt and their recording apparatus. The stand is spray painted with 3-M flat gray and oriented true north-south. There are four adjustable legs for elevating the stand during extended snow cover.

A shadow band is provided for measurement of horizontal diffuse irradiance. It is similar to Drummond's (1956) axial design except for a greater width and radius of the band required to shade the pyranometer. It is tilted at an angle equal to the latitude and has adjustments for solar declination. With proper adjustment the pyranometer will remain shaded for 2-3 days.

Salt Lake City Airport. Located centrally in a wide open valley, this site will provide a low (Utah) elevation (1,290 m) flat land situation. Horizon blockage is less than 7 degrees in the east and west direction. The site will be subject to the high turbidity generated by the industry and transportation of nearby Salt Lake City. This is increasingly important during the predominant valley inversion in the winter season. The stand and radiation instruments are installed on top of the executive terminal building with easy access.

Snowbird, Hidden Peak. This site, at 3,350 meters, is the location of high elevation radiation data. Situated on Hidden Peak, it has essentially free horizon blockage in every direction. High winds, extreme temperatures, and lightning are problems inherent to this site requiring constant maintenance. The stand and radiation instruments are located on the ski patrol shack with access to the top of the mountain by aerial tram.

Snowbird, Cliff Inn. The V-shaped mountain valley situation will be represented by this site. Still at a relatively high elevation (2,510 m), the site is protected from the extreme conditions of Hidden Peak. The valley runs approximately east-west with a high degree of horizontal blockage by the north and south sides (Fig. 3). The stand and radiation instruments are located on the roof of the nine-level Cliff Inn.

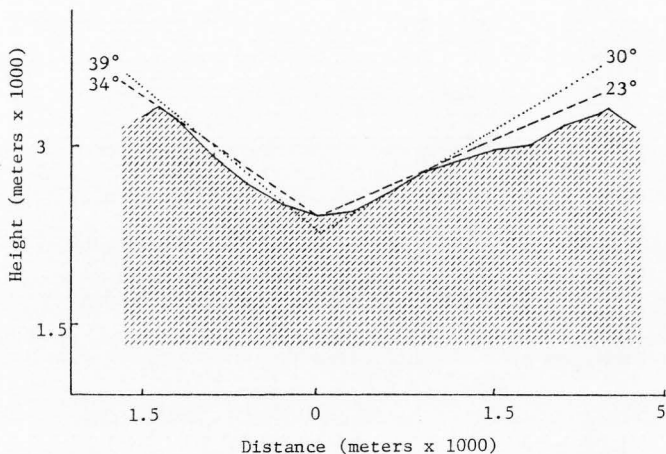


Fig. 3. North-south cross section of the Cliff Inn site indicating the various possible angles of horizontal blockage.

All three permanent sites utilized local personnel for routine site maintenance. They were responsible for shadowband adjustment, keeping radiation instruments clean and free of snow, and mailing recorded data to Utah State University.

The period of measurement varied from site to site depending on installation and access availability. In general however, horizontal global and diffuse plus 50 degree global irradiance were recorded from fall 1977 through summer 1979.

Several short-term studies were made at a fourth site (Utah State University) where a more controlled and carefully watched environment could be maintained.

Supporting Studies

An in-depth study into the effects of a shadowband on diffuse radiation measurements was undertaken. It was primarily concerned with the shadowband correction factor and the possibilities of direct reflection off the band's interior at low sun elevations. A physical model was developed from which a shadowband correction is obtained for specific zenith and azimuth angles (LeBaron et al., 1978).

A second study used a photographic technique to make a visual, qualitative investigation into the effects of clouds on diffuse irradiance values. Using a 160° fish eye lens, all-sky photographs could be made by exposing the camera in a vertical position. A timing device was incorporated to take sequence exposures at 15-minute intervals throughout the day (Fig. 4).

Simultaneously, a star pyranometer in conjunction with a shadowband was used to detect diffuse irradiance. The output was recorded by a Honeywell strip chart recorder.

The cloud cover in the sky photographs could then be correlated to specific time intervals and diffuse irradiance values on the strip chart recording. The results of this study are included in Chapter 4.

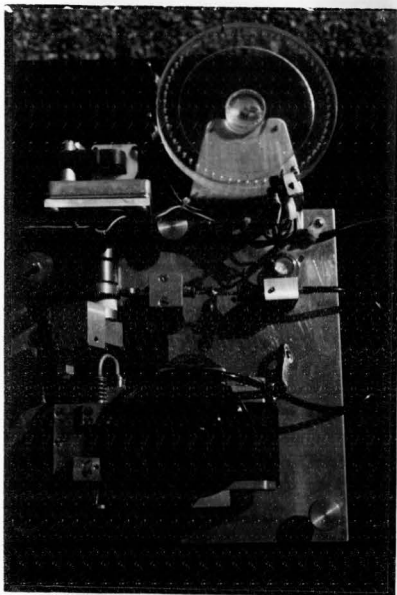


Fig. 4. Timing device incorporating a camera and fish eye lens to make all-sky photographs at specific intervals.

Radiation Sensor and Recording Instruments

The instrumentation at each radiation site was designed to withstand harsh environmental conditions. The pyranometers were attached to a rigid frame so as to withstand high winds (Fig. 5). Desiccant was placed in each pyranometer to inhibit condensation.

The recording system was designed to operate under a temperature range of $\pm 50^{\circ}\text{C}$ (Fig. 6). It had the capability of utilizing either a 12-volt D.C. or 110 A.C. power source depending on availability. At all sites the recording instruments were housed in some type of protective shelter, usually heated.

The instrument package at each site consisted of:

Sensors: 1 star pyranometer (Global)
 1 star pyranometer (Diffuse)
 1 star pyranometer (50°)

Recorders: 1 integrator + cassette recorder
 1 strip chart recorder (Global)
 1 strip chart recorder (Diffuse)
 1 strip chart recorder (50°)

Pyranometers. The pyranometers (Fig. 7) were produced by Schenk, Austria, and are of a black and white thermopile (copper-constantan) design. They have a response time of 20 seconds to reach 99 percent output millivolts. For details of the development, construction, and operation of the star pyranometer see Dirmhirm (1958).

Tests for temperature effect, linearity, and cosine response were made on newly purchased pyranometers to determine individual characteristics (Mohr, Dahlberg, and Dirmhirm, 1979). The tests helped in the

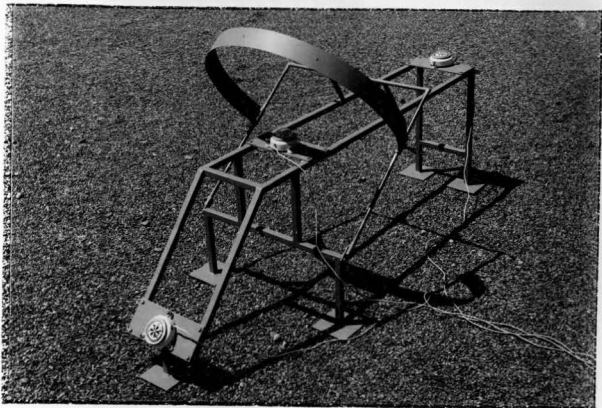


Fig. 5. Stand used at each site to support the sensors measuring horizontal diffuse, and 50° tilt global irradiance. Diffuse irradiance was measured using a shadowband.



Fig. 6. Recording system comprised of a datalogger and cassette recorder with strip chart recorders for back-up.



Fig. 7. Black and white star pyranometer used throughout the study.

placement of pyranometers in the field. For example, a pyranometer with a poor cosine response would be used only for measuring diffuse irradiance.

Subsequent to the field placement the pyranometers were periodically calibrated against a secondary standard which could be transported to each site. The secondary standard itself was frequently calibrated using a Kendall absolute net pyraheliometer. These calibrations provided a constant by which the millivolt output of the pyranometer could be equated to an irradiance ($w\text{ cm}^{-2}$).

Recorders. The primary recording system was a datalogger designed and developed by Campbell Scientific of Logan, Utah. It was set up to integrate millivolt inputs of radiation over 5-minute intervals. After each interval the datalogger would activate a small cassette recorder and the integration was recorded on magnetic tape along with the

corresponding date, hour, and minute. Each cassette tape could hold approximately seven days of data (both sides).

A secondary system utilizing strip chart recorders was incorporated as a back-up for each pyranometer. These small but accurate recorders were purchased from Datamart. The chart paper was changed at the same time as the tapes to avoid errors in maintenance.

Approximately every two weeks the cassette tapes and strip charts from each site were mailed to Utah State University for analysis.

Data Editing and Reduction

All data reduction and analysis was performed at Utah State University in Logan, Utah.

Strip chart data was filed chronologically for back-up reference. A qualitative inventory was made to determine data gaps, strip chart malfunctions, misadjustment of the shadowband, etc.

Raw (millivolt) data recorded on cassette tapes was interfaced with the Burroughs 6700 computer using a computer remote terminal (CRT). It was then stored on computer disk pack in numeric files holding 2-3 days.

These files were subjected to several computer checks to determine the quality of the data. A program, CHECK, made certain numeric value substitutions and looked for improper alpha characters in the data. Another program, MISS, examined the file for data gaps and time channel malfunctions.

Once the data gaps were accounted for and the times corrected a working program, CALPRINT, could be used. This program performed the following functions:

1. Identified the data to pyranometer, assigned cosine corrections (global), shadowband corrections (diffuse), and calibration constants ($W \text{ cm}^{-2}$).

2. Calculated the direct irradiance $(\frac{G - R_s}{\cos \theta})$ normal to the sun (R_L), the direct irradiance on a 50° tilt and the diffuse irradiance on a 50° tilt.

3. Converted $W \text{ cm}^{-2}$ to langleys (Delinger, 1976) and tested the 5-minute direct normal irradiance value against a threshold of 0.3 langleys to determine duration of sunshine.

4. Summed the values of horizontal, global, and diffuse, 50 degree global and diffuse, and direct normal irradiance plus duration of sunshine for hourly and daily periods.

Duration of sunshine is used here as an estimator of cloudiness for correlation with parameters affecting diffuse irradiance in the mountains. The threshold value of $21 \text{ m } W \text{ cm}^{-2}$ (0.3 langleys) has been established by the World Meteorological Association as the cut-off for duration of sunshine.

Once the data was in its final form, careful cross checking with the corresponding strip chart recordings was undertaken to remove erroneous data. Approximately 25% of the edited data was not used due to poor on-site maintenance.

Examination of Parameters

In order to examine the effects of the various mountain parameters, the organizational matrix presented in Chapter I was followed. The procedure was to examine the ground-location parameters for the atmospheric conditions noted (X) through inter- and intra-site comparisons.

Elevation. The effect of elevation on diffuse irradiance was developed through comparisons between Salt Lake City and Hidden Peak. Both have small horizon blockage (<5 degrees) and are essentially "flat" terrain sites. Thus the only different parameter is the elevation (6500 ft.) and phenomena associated with it.

Horizontal hourly diffuse irradiance data (langleys) for both sites were plotted against duration of sunshine (cloudiness) for specific months. Where the change in declination was small, months were plotted together. Two months from each season were used: January-February, March-April, June-July, and September-October. The months were chosen on a basis of similar solar declination and ground reflectance. Curves were then drawn through each set of points to represent the effect of various amounts of cloudiness, from clear to overcast, on diffuse irradiance values.

A mathematical relationship for the elevation effect was developed for clear and overcast sky conditions during each of the four seasons. Graphs of the seasonal averages were plotted against their respective site elevation. From these points an equation was derived relating elevation to diffuse irradiance.

An evaluation of the widely used Liu and Jordan method for determining horizontal daily diffuse irradiance was made through comparison with measured data from Salt Lake City and Hidden Peak.

Albedo. The effect of surface albedo on horizontal diffuse irradiance values was shown through intra-site data comparisons. Since this effect is primarily due to enhancement by multiple reflection, only overcast days were examined. The Salt Lake City and Hidden Peak

sites were used because their low horizons would eliminate the possibility of direct reflection to the sensor.

Overcast day totals (langleys) throughout the entire period of measurement were plotted against their corresponding measurement date. Graphs were made for both Salt Lake City and Hidden Peak. The effects of snow covered ground (spring) and bare ground (fall), at equal solar declinations, on irradiance values can be shown.

By plotting the ratio of diffuse values with snow cover to those without, at equal solar declinations, against ground albedo, a simple relationship was developed.

Horizon. A mathematical model describing a V-shaped valley typical for mountainous terrain was verified to determine the effects of elevated horizon. Instantaneous measured diffuse irradiance data from Cliff Inn, representing a valley situation, were compared to those from a computer simulator program based on the model developed by Peterson, Hurst, and Dirmhirn (in preparation). The model incorporates inputs of sensor height within the valley, slope angles, and albedo of the valley walls, and the azimuthal orientation of the valley.

The absolute computed and measured values were plotted against solar time for each day to determine the model's accuracy. Only clear days were used since this is when direct reflection can have its most dramatic effect, while multiple reflection is negligible. Days from winter, spring, and summer having various slope albedos and day lengths were examined.

Tilt/Horizontal. The effect of tilting the sensor surface towards the sun was examined for a 50 degree tilt angle at Salt Lake City and

Hidden Peak. Using 50 degree diffuse values relative to horizontal diffuse values, daily totals were plotted against duration of sunshine. Periods of similar declination were used; January/February, March/April, June/July, and September/October at both Salt Lake City and Hidden Peak. From these graphs the dependence of the 50 degree tilt values on the annual variation in surface albedo and with different amounts of cloudiness is shown.

A computer simulator program based on a mathematical tilt model using the isotropic assumption (LeBaron and Peterson, 1978) was compared to instantaneous measured data for clear and overcast days.

Graphs of computed 50 degree values and measured 50 degree values were plotted against solar time for days with and without snow cover to determine the model's accuracy.

RESULTS AND DISCUSSION

The matrix used to organize the interrelationship of mountainous irradiance parameters in the Introduction will be followed for the results and discussion. The ground and location parameters are given as the major section headings and in each case are examined for the pertinent atmospheric conditions. In describing the results and discussion, first the effects of a clear atmosphere will be established. After this the effects of the overcast and more complex cloudy conditions are developed. Finally, comparisons with available literature are made.

The data base of hourly diffuse irradiance (langleys) used for analysis was broken down into seasons of similar solar declination and ground reflectance (Table 2). The same seasonal months were used for each radiation site to allow inter-site comparisons.

Table 2. Months comprising the seasonal data base and the corresponding reflectance

Season	Months	Reflectance
Winter	January February	.6
Spring	March April	.6-.1
Summer	June July	.1
Fall	September October	.1

Elevation

The relationship between diffuse irradiance and elevation is strongly dependent on cloud amount. The case of a clear atmosphere will be discussed first.

Clear. The effects of elevation on clear days for hourly diffuse irradiance is shown in Fig. 8. For all four seasons, diffuse irradiance decreased with elevation from Salt Lake City to Hidden Peak. This is due to reduced scattering associated with the shorter optical path length at Hidden Peak.

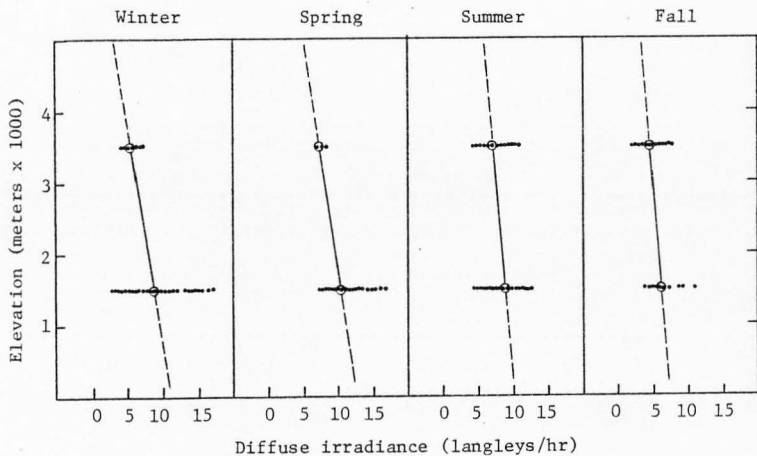


Fig. 8. Relationships for seasonal averages of hourly diffuse irradiance with elevation for clear sky between Salt Lake City and Hidden Peak during winter, spring, summer, and fall.

The seasonal averages of hourly diffuse irradiance were made by averaging all the hours with corresponding duration of sunshine equal to 10/10 (clear) for that season. A line has been drawn through these seasonal clear hour averages (langelys) to represent a linear dependence of diffuse irradiance on elevation, between Salt Lake City and Hidden Peak. Mathematical equations for this dependence during each season are given in Table 3.

Table 3. Seasonal averages of hourly diffuse irradiance at clear sky conditions, percentage decrease with elevation from Salt Lake City to Hidden Peak and linear mathematical expressions for diffuse irradiance with elevation for clear sky

Season	Salt Lake City	Hidden Peak	Percentage	Expression
Winter	8.8	5.5	37	$y = 6800 - 610x$
Spring	10.6	7.2	32	$y = 7700 - 590x$
Summer	8.7	6.9	21	$y = 1100 - 110x$
Fall	5.9	4.5	24	$y = 9900 - 140x$

The linear relationship from the change in diffuse irradiance with elevation is suggested only as a first approximation. The type of relationship is primarily dependent on the variation in atmospheric pressure, water vapor, and ozone concentration. If it is assumed that the variation in irradiance absorption due to the last two is negligible between Salt Lake City and Hidden Peak then scattering is directly related to atmospheric pressure. Thus a linear relationship was used for the change in diffuse irradiance with elevation, since

the change in pressure with elevation is nearly linear between 1,300 and 3,400 meters.

By examining Table 2 and Fig. 8, it can be seen that the fall season had the lowest hourly diffuse irradiance. In addition, Fig. 8 shows that there was little spread in the hourly diffuse values (6 langleys). Together these two facts indicate that during fall the clear days have consistent low turbidity with little scattering of the direct beam.

The summer values of hourly diffuse irradiance are higher than fall, as would be expected. Winter and spring values, however, are consistently higher. The known annual wave of clear day diffuse irradiance is, thus, interrupted and for winter and spring dominated by another process. There is a relatively large enhancement of the clear sky values due to multiple reflection occurring between the atmosphere and the snow covered ground. Though the winter clear sky diffuse irradiance on the mountain station is slightly lower than in summer (due to the extremely clear atmosphere and consequently low scattering) it still is higher than in fall. Apparently the presence of snow cover in the winter and spring seasons causes a positive shift in the annual variation of diffuse irradiance.

A second effect was found to distinguish the spring and winter from other seasons. Strong temperature inversions can develop in the Salt Lake Valley and, during the colder winter and spring seasons, may persist for several days. The high atmospheric turbidity of these periods is denoted by the high diffuse irradiance values. Since Hidden Peak is located above this inversion layer and not subject to turbidity,

a strong gradient is found between the two sites (Fig. 9).

This reduction gradient is evident in Table 3 where the decrease in hourly diffuse radiance from Salt Lake City to Hidden Peak during the winter and spring seasons is 37 and 32%. In the warmer summer and fall seasons when temperature inversions at Salt Lake City do not persist long enough to build up high amounts of pollution, the reduction gradient is only 21 and 24%.

Polluted. The effects of the summer and winter temperature inversion periods are shown by plotting hourly diffuse irradiance on clear days against a turbidity indicator $\frac{R_D}{R_I}$, where

$$\frac{R_D}{R_I} = \frac{\text{hourly horizontal diffuse irradiance}}{\text{hourly normal direct irradiance}}$$

Small values of $\frac{R_D}{R_I}$ indicate low atmospheric scattering and thus low turbidity levels. Larger values of this ratio correspond to increased scattering due to pollution build up.

Figs. 10 and 11 show this relationship for two winter months, January and February, and two summer months, June and July at Salt Lake Airport.

The relationships for June and July, when temperature inversions do not persist, are strictly linear.

In January and February the relationships have more scatter due to very turbid periods resulting from extended temperature inversions. However, when storm fronts move through, strong winds break up the inversions, cleansing the atmosphere. The resulting group of very clear periods exhibit even less turbidity than the clear summer periods.



Fig. 9. Photograph taken from Hidden Peak (Snowbird tram) showing a typical winter temperature inversion in the Salt Lake Valley.

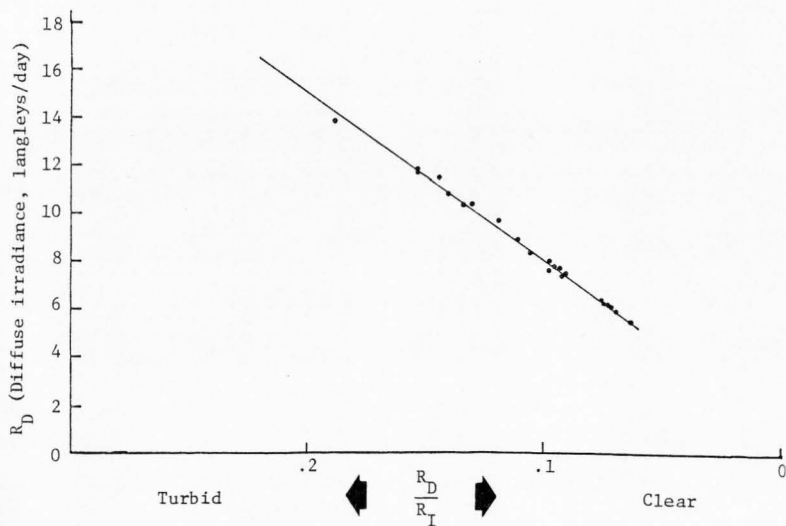
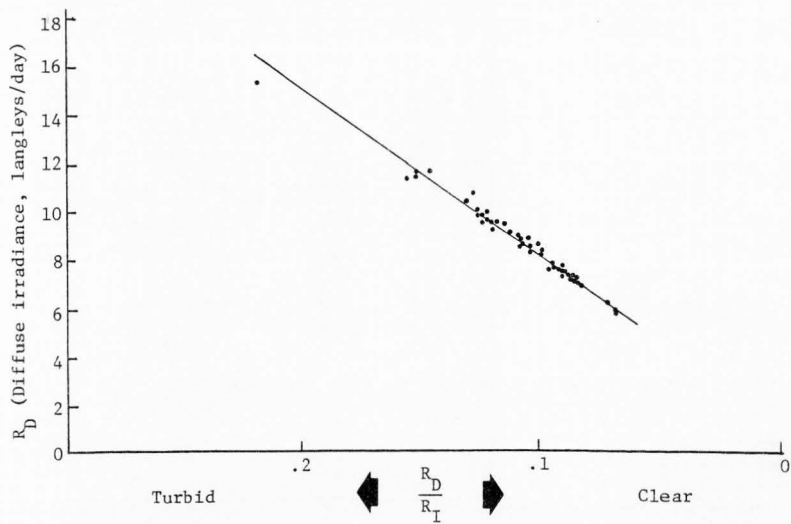


Fig. 10. Relationship between daily diffuse irradiance and a turbidity indicator, R_D/R_I , for two summer months at Salt Lake City.

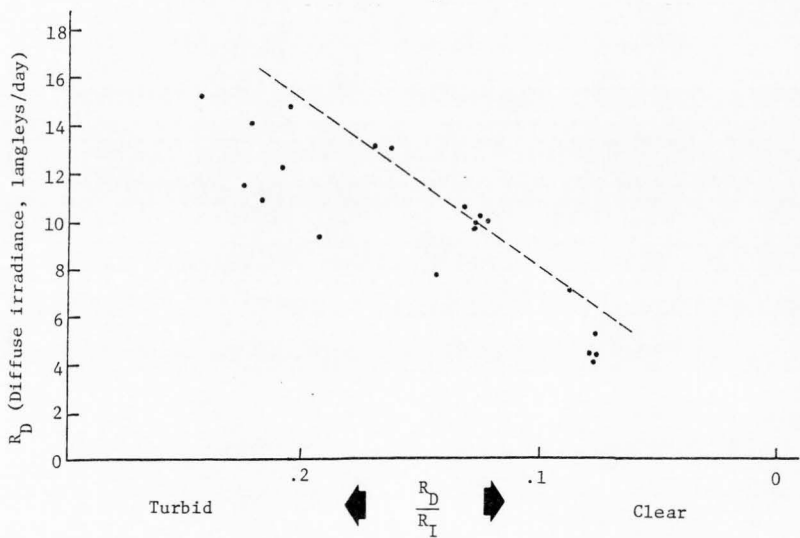
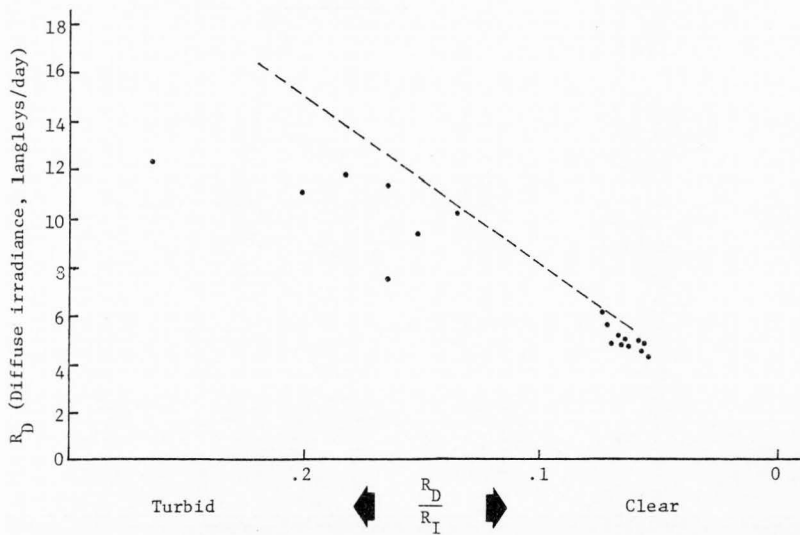


Fig. 11. Relationship between diffuse irradiance and a turbidity indicator, R_D/R_I , for two winter months at Salt Lake City.

The dashed line indicates the relative position of the summer relationship.

It is interesting to note that although Salt Lake City exhibits this very different turbidity pattern between the summer and winter months, the clear hour averages for the summer and winter seasons are the same, 8.7 langley's and 8.8 langley's, respectively.

Overcast. Fig. 12 shows the effects of elevation on overcast hourly diffuse irradiance values. In a fashion similar to the clear hourly data, lines were drawn through the seasonal irradiance on elevation.

An opposite effect to the clear sky condition is found for the overcast sky condition. In every season, except in summer, there is a strong increase in diffuse irradiance with elevation. Table 4 lists the seasonal averages (langley's) of hourly overcast values for Salt Lake City and Hidden Peak, the percentage increase with elevation, and the linear seasonal models describing the diffuse irradiance enhancement with elevation.

Table 4. Seasonal averages of hourly diffuse irradiance at overcast sky conditions, percentage increase with elevation from Salt Lake City to Hidden Peak, and linear mathematical expressions for diffuse irradiance with elevation for overcast sky

Season	Salt Lake City	Hidden Peak	Percentage increase	Expression
Winter	12.9	22.4	174	$y = 210x - 1200$
Spring	25.7	39.9	155	$y = 140x - 4100$
*Summer	22.2	12.5	56	$y = 6100 - 210x$
Fall	13.2	8.0	136	$y = 420x - 4000$

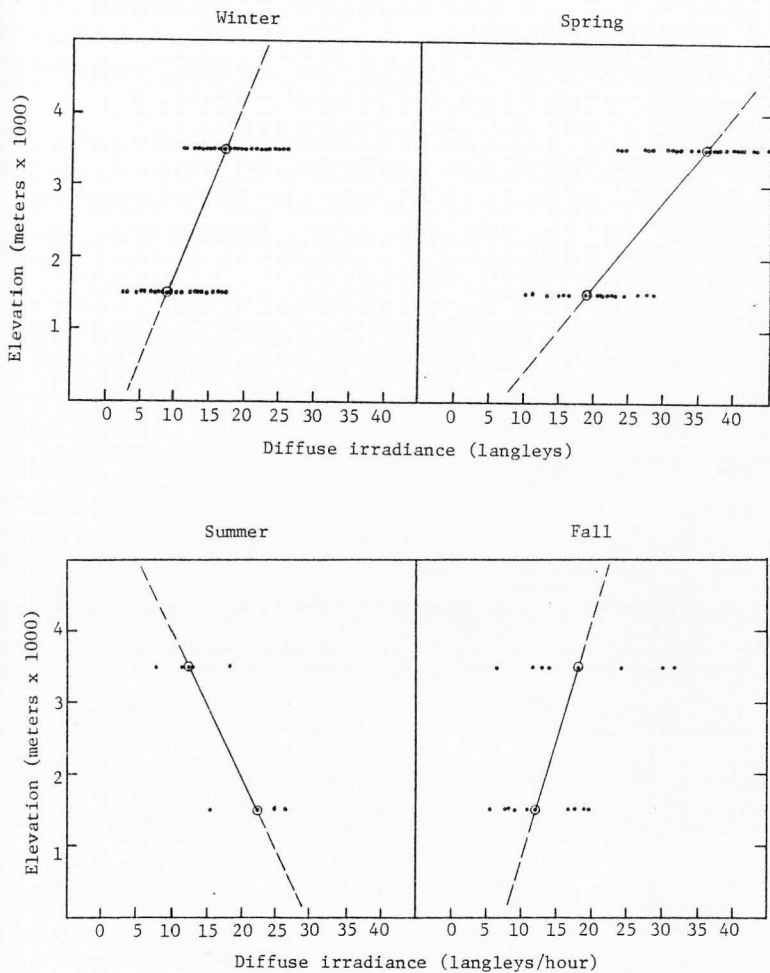


Fig. 12. Relationships for seasonal averages of hourly diffuse irradiance with elevation for overcast sky between Salt Lake City and Hidden Peak during winter, spring, summer, and fall.

The increase in diffuse irradiance for overcast periods with elevation is the result of the thinner cloud cover found at high elevations. The thicker cloud cover at Salt Lake City greatly suppresses the diffuse irradiance while at Hidden Peak the cloud cover is generally thinner resulting in less absorption.

The exception of the summer season may, in part, be due to the lack of overcast periods from which to draw a reliable average. However, for the few overcast cases available (Fig. 12) a decrease in diffuse irradiance with elevation can be attributed to the orographic clouds associated with mountain tops. These clouds exhibit a thick cumulus nature during the summer which greatly reduces diffuse irradiance at Hidden Peak. Thus the * expression derived from summer data, while differing from the other seasons, may be valid.

From the seasonal averages in Table 4, it can be seen that during the seasons with snow cover there is a significant increase in diffuse irradiance due to enhancement by multiple reflection between the clouds and snow. This is especially evident in the Hidden Peak values where the normally low diffuse irradiance of winter is much higher than summer diffuse irradiance. The spring values rise above even the winter values. Thus, there is a shift in the expected annual cycle of overcast diffuse irradiance similar to the clear sky situation except to a greater order of magnitude.

An in depth examination of the effects of ground albedo on diffuse irradiance is made in the following section.

Cloudy. The effect of elevation with various amounts of cloudiness at both Salt Lake City and Hidden Peak is shown in Figs. 13 through 19.

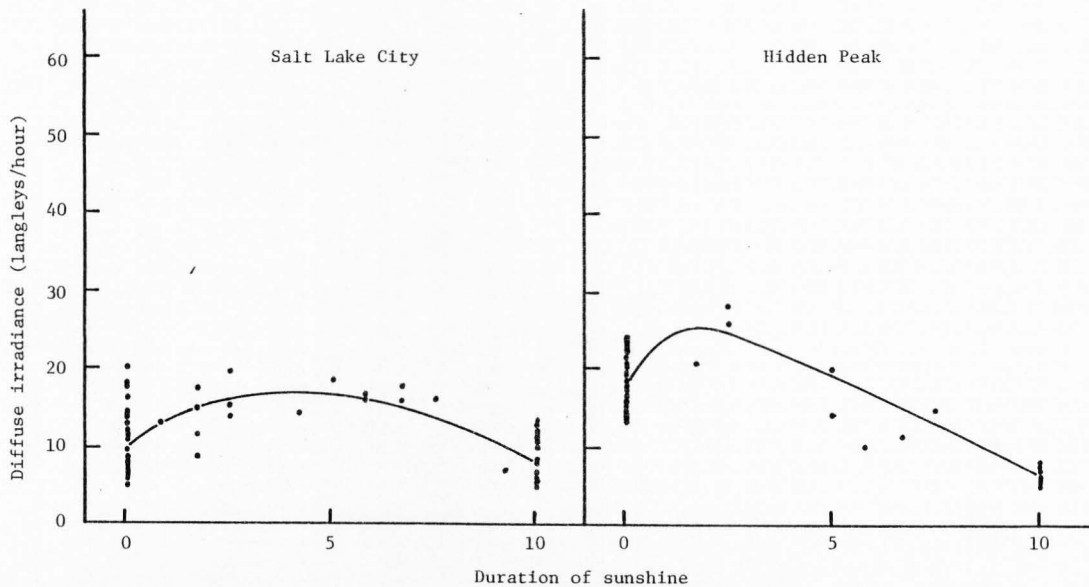


Fig. 13. Relationship between hourly values of diffuse irradiance and duration of sunshine (tenths/hour) during January at Salt Lake City and Hidden Peak.

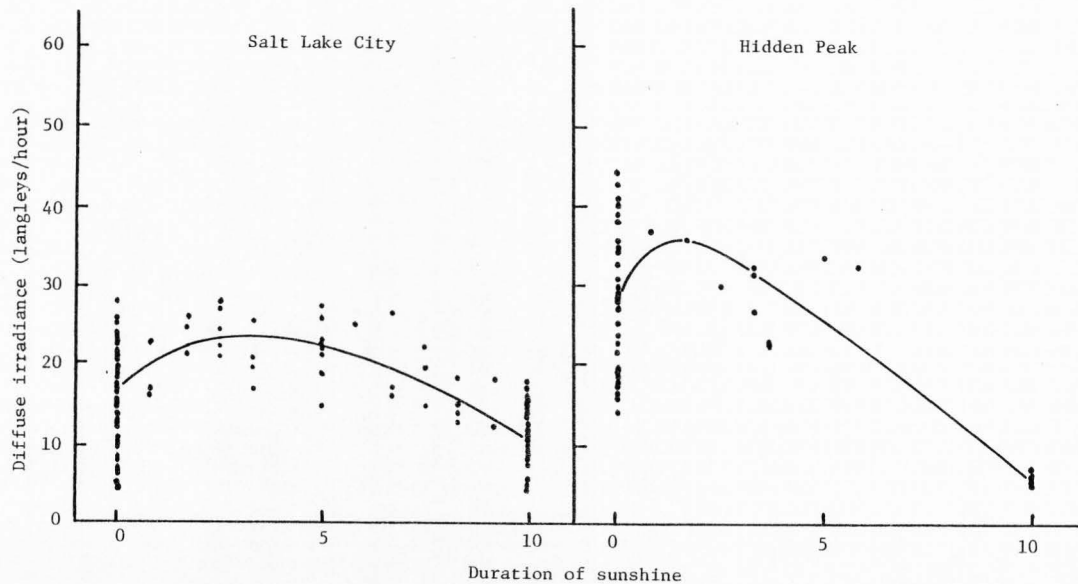


Fig. 14. Relationship between hourly values of diffuse irradiance and duration of sunshine (tenths/hour) during February at Salt Lake City and Hidden Peak.

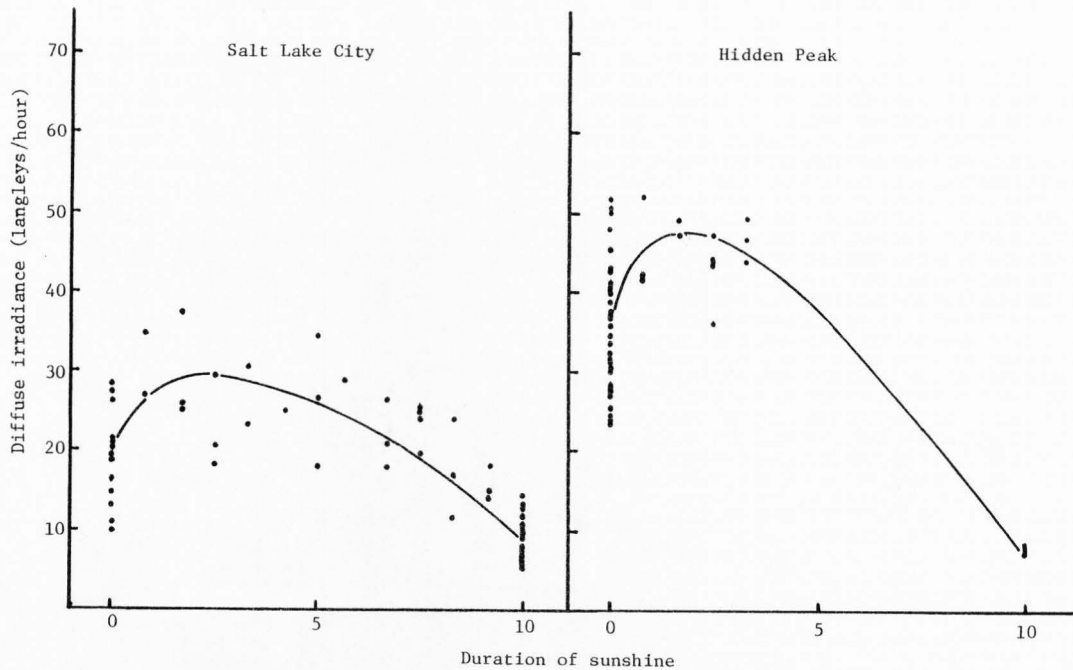


Fig. 15. Relationship between hourly values of diffuse irradiance and duration of sunshine (tenths/hour) during March at Salt Lake City and Hidden Peak.

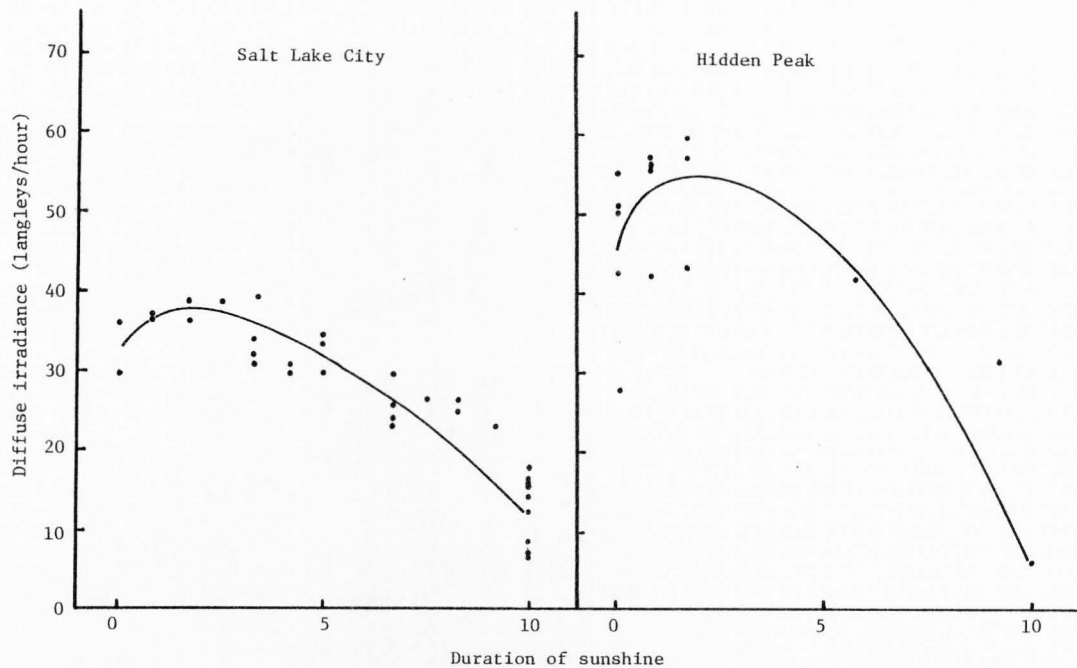


Fig. 16. Relationship between hourly values of diffuse irradiance and duration of sunshine (tenths/hour) during April at Salt Lake City and Hidden Peak.

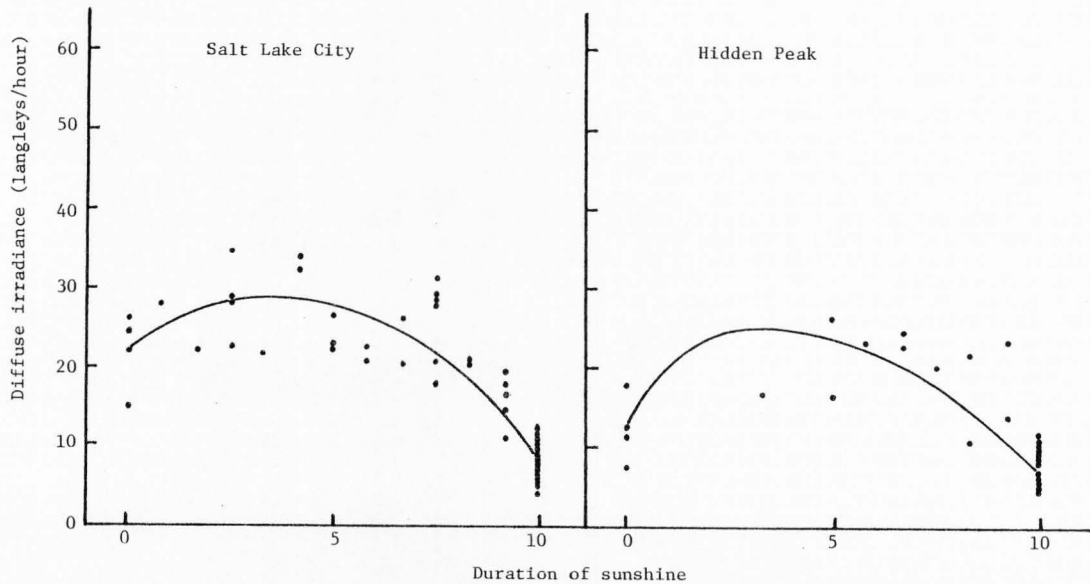


Fig. 17. Relationship between hourly values of diffuse irradiance and duration of sunshine (tenths/hour) during June-July at Salt Lake City and Hidden Peak.

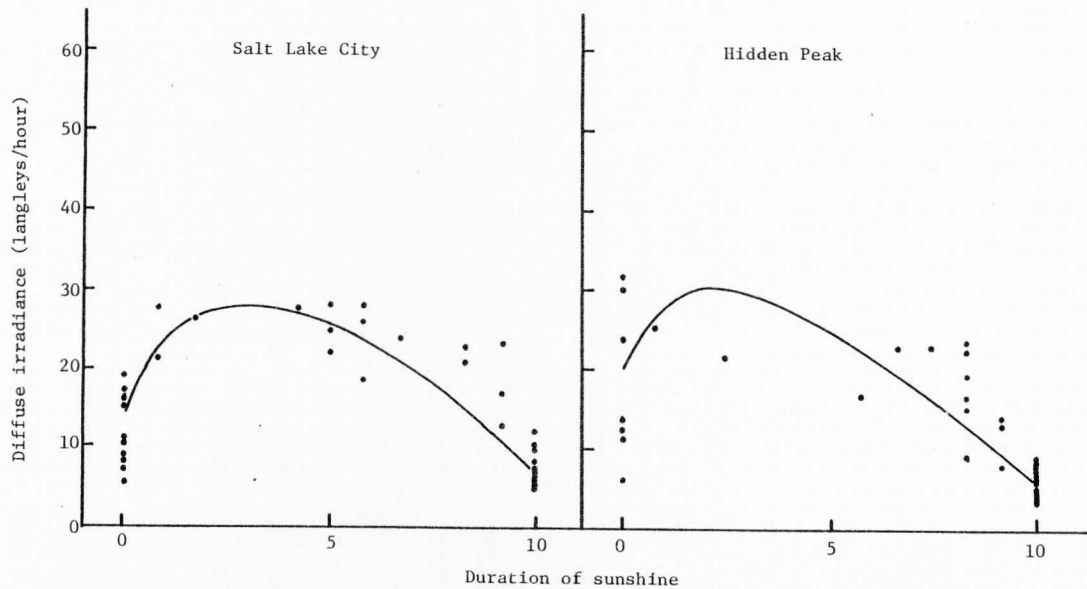


Fig. 18. Relationship between hourly values of diffuse irradiance and duration of sunshine (tenths/hour) during September at Salt Lake City and Hidden Peak.

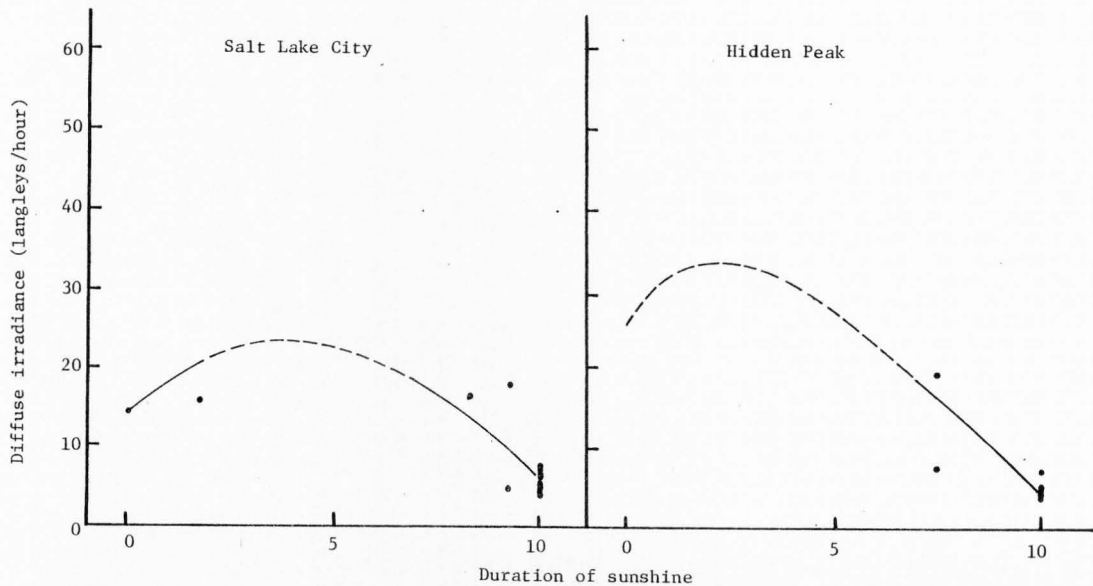


Fig. 19. Relationship between hourly values of diffuse irradiance and duration of sunshine (tenths/hour) during October at Salt Lake City at Hidden Peak.

Cloudiness conditions from overcast to completely clear are represented by 0 to 10 tenths duration of sunshine (hourly), respectively. The close relationship between these two quantities has been widely corroborated. From Angstrom (1924) on, many researchers have suggested and used this relationship as a cloudiness indicator. Recently Mohr (1979) gave a detailed description of its application.

From these curves of diffuse irradiance with various amounts of cloudiness, a number of effects are evident.

1. The hourly values of diffuse irradiance in all cases denote a curved relationship with a maximum around three-tenths duration of sunshine (70 percent cloudiness). This would verify similar findings by Angstrom (1919), Dirmhirn (1951), Robinson (1966), and Kasten (1977).

2. The curves for Hidden Peak were steeper than for the corresponding Salt Lake City curves. That is, they had a larger irradiance gradient from clear to overcast sky conditions almost eliminating the three-tenths maximum. This is the result of low atmospheric turbidity during the clear periods and a thinner cloud cover during the cloudy periods. Salt Lake City, by comparison, had higher clear period irradiance due to the longer optical pathlength (increased scattering) and lower cloudy period irradiance because of the increased thickness of the cloud layers thus resulting in a flatter curve.

3. The curves for both Salt Lake City and Hidden Peak have their most pronounced shape and highest diffuse irradiance values during the spring. Fig. 20 illustrates the progression from winter to spring at both sites. While the clearest periods remain relatively the same, the cloudy periods in conjunction with the snow cover produce a significant

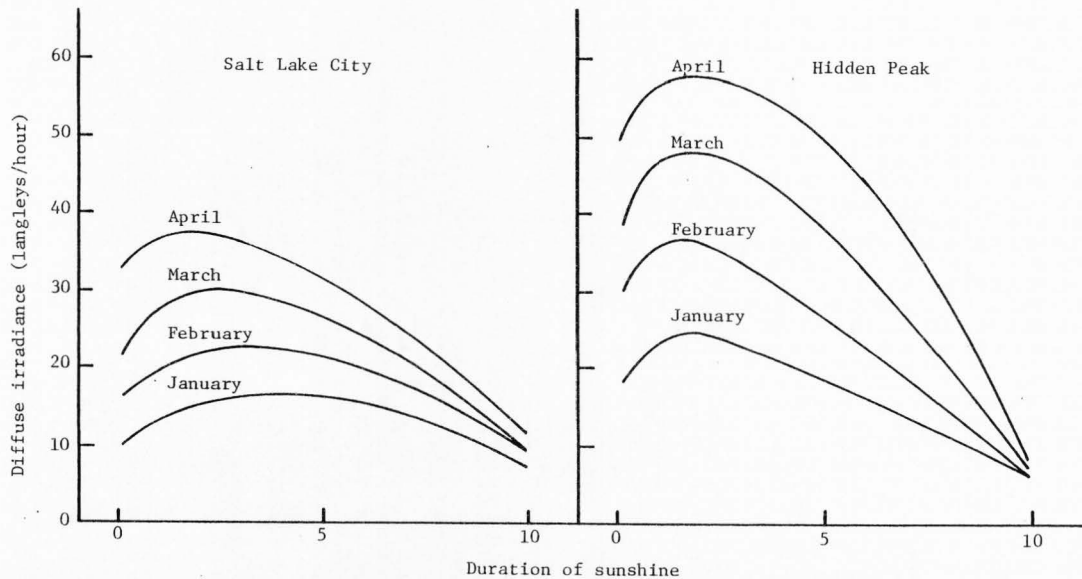


Fig. 20. Composite of monthly relationships: January, February, March, and April, from winter to spring at Salt Lake City and Hidden Peak showing effect of solar elevation on enhancement by multiple reflection between snow and cloud cover.

enhancement by multiple reflection. The importance of solar elevation to this process can easily be seen.

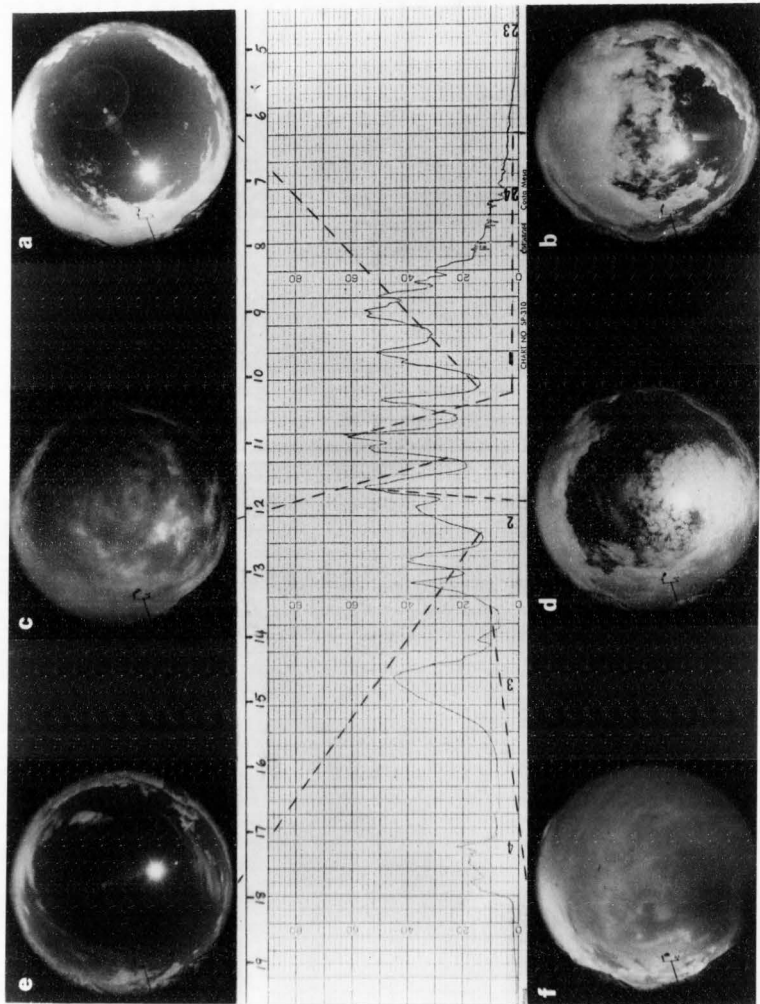
4. There is a large scatter in diffuse radiation for the cloudy periods, especially at the Hidden Peak site. This would be expected considering the sensitivity of diffuse irradiance to sun/cloud positions, multiple reflection possibilities and the variability in the types of clouds themselves.

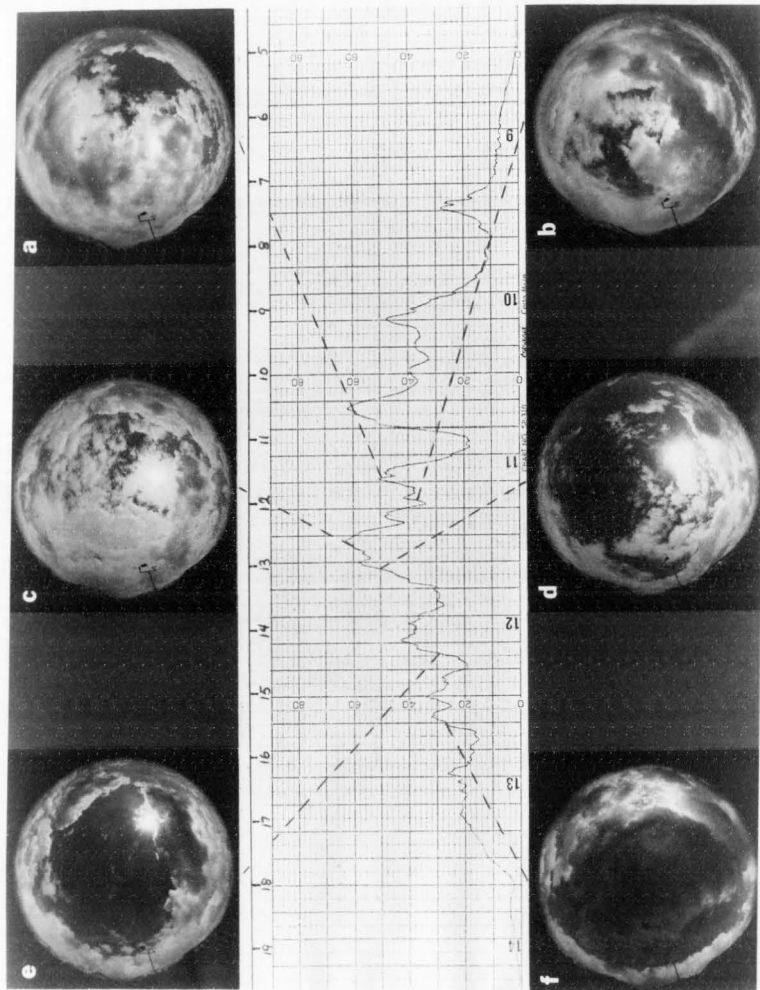
Supportive study. A photographic technique was used to obtain a qualitative appreciation of the cloud conditions responsible for various amounts of diffuse irradiance. Figs. 21, 22, and 23 show the conditions that were found on three consecutive days in May of 1979 at Logan, Utah. Six all-sky (160°) cloud pictures have been correlated to their respective diffuse irradiance on a strip chart recording. The solar time scale has been inset on the recording.

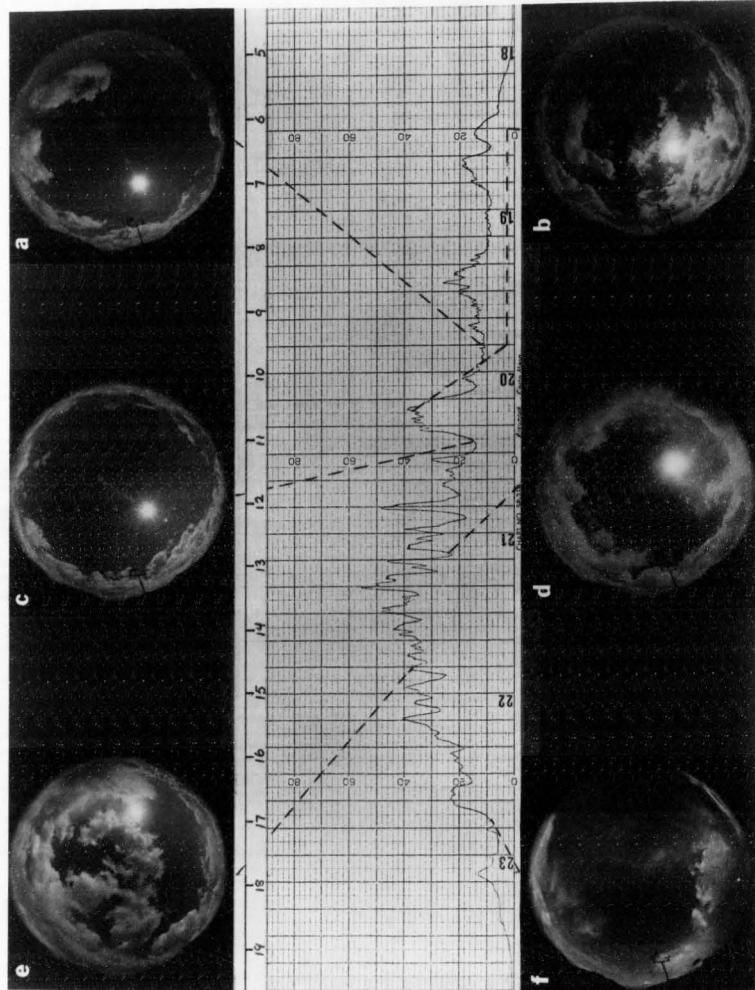
The correlation shows that the highest values of diffuse irradiance were found under partially ($\approx .7$) cloudy conditions, where the solar disk is obscured. When the sun is unobscured by clouds the diffuse irradiance drops radically due to the loss of irradiance from clouds scattering the direct beam.

In the case of an unobscured solar disk and proper sun-cloud positions (Fig 22e), enhancement by direct reflection off the cloud surface can take place. However, this enhancement does not compensate the diffuse irradiance attenuation lost when the solar beam is not scattered by clouds (solar disk is obscured) as seen in the strip chart recording.

During overcast conditions (Figs. 21f-23f) diffuse irradiance again drops to low values. Depending on the thickness of the overcast







cloud layer the values can sometimes even drop lower than values for clear periods.

Thus, it can be seen that clouds have a very dramatic but highly variable influence on diffuse irradiance which is dependent on:

(1) obscured/unobscured solar disk, (2) total cloud amount, (3) cloud layer thickness, (4) cloud distribution, and (5) sun-cloud positions.

Comparisons. Due to economic and maintenance problems in many situations, it is not feasible to measure both global and diffuse irradiance. Various methods have been developed in order to extract values of diffuse irradiance from measured global irradiance. One of the most widely used is the Liu and Jordan method for determining horizontal daily diffuse irradiance as a function of a cloudiness index, K_T . Their relationship was developed by plotting K_R against K_T where:

$$K_R = \frac{\text{Daily diffuse radiation on a horizontal surface}}{\text{Daily global radiation on a horizontal surface}}$$

$$K_T = \frac{\text{Daily global radiation on a horizontal surface}}{\text{Extraterrestrial daily insolation on a horizontal surface}}$$

From these points they derived a curve for estimating, to an average accuracy of $\pm 5\%$, the daily diffuse irradiance for localities where the daily global irradiance is known.

In a manner similar to Liu and Jordan, daily irradiance data from Salt Lake City and Hidden Peak were plotted. Days from all seasons and various amounts of cloudiness were used.

The extraterrestrial daily insolation received on a horizontal surface (H_0) was computed according to Liu and Jordan from the following equation:

$$H_o = \frac{24}{\pi} r I_{sc} (\cos L \cos \delta \sin w_s + w_s \sin L \sin \delta)$$

where r = ratio of solar radiation intensity at normal incidence outside the atmosphere of the earth to the solar constant; I_{sc} = solar constant; L = latitude, degrees; δ = solar declination, degrees; and w_s = sunset hour angle, radians.

Fig. 24 shows the fit of the Liu and Jordan relationship to the measured data from Salt Lake City and Hidden Peak.

The Salt Lake City data (Fig. 24) fit the model curve quite well, thus indicating that for this location with its relatively low elevations and its characteristic cloud and atmospheric conditions, the Liu and Jordan relationship could be used.

However, the Hidden Peak data (Fig. 24) exhibits strong deviations from Liu and Jordan's relationship. These deviations are especially apparent when the cloudiness index (K_T) is less than .5 connoting a high amount of cloudiness.

Upon examination of the methodology used by Liu and Jordan to derive the relationship, it was found that the supporting measured data was taken from a low elevation site (Blue Hill, Massachusetts). Furthermore, the variability in the data increased with cloudiness. They stated that in analyzing the data for Blue Hill, the relationship was supported by all points with $K_T < 0.75$, but not for the few points with $K_T > 0.75$.

Thus, the characteristic cloud regime of high elevations, as discussed previously and multiple and direct reflection processes (discussed in later sections) which are enhanced with high elevation

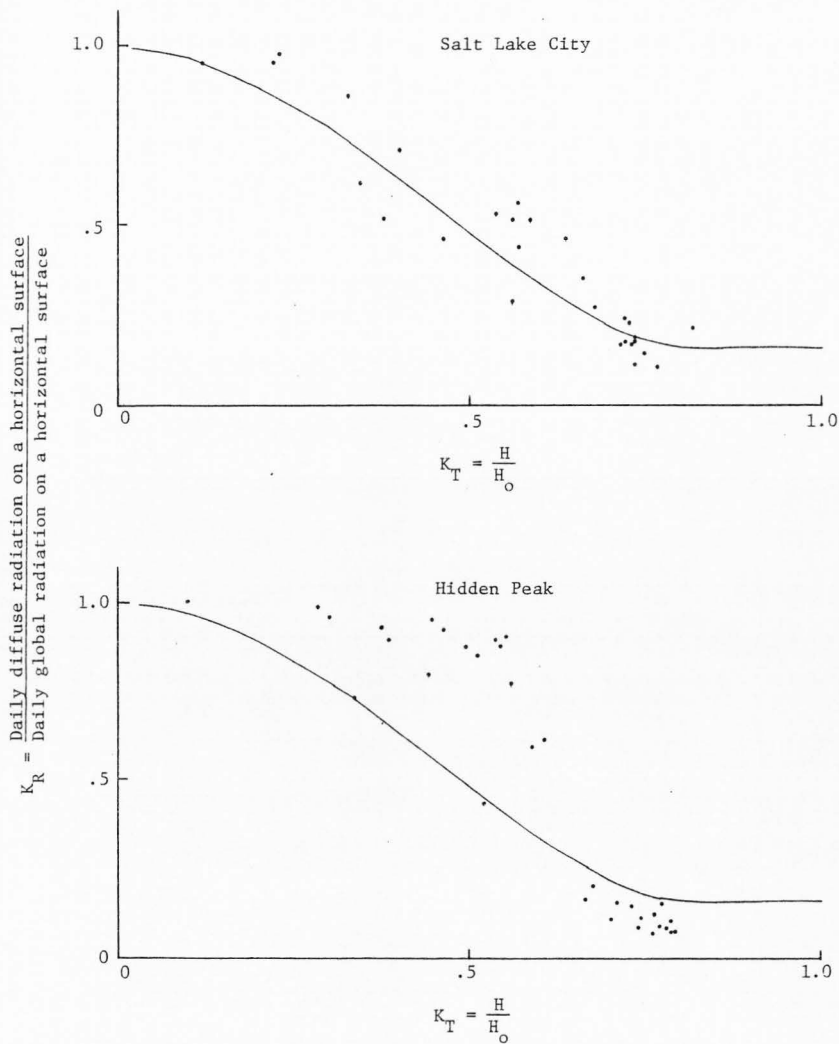


Fig. 24. Comparison of Liu and Jordan's relationship (solid line) for predicting diffuse irradiance for various amounts of cloudiness with measured irradiance data from Salt Lake City (low elevation) and Hidden Peak (high elevation).

and mountainous terrain, limit the Liu and Jordan relationship to low elevation irradiance predictions.

Albedo

Climatological changes of the albedo of the ground can modify the diffuse irradiance considerably. On a horizontal surface the enhancement by high surface albedo is brought about mainly through multiple reflection between ground and atmosphere. In addition, if the atmospheric backscatter, due to clouds or even turbidity, is high this multiple reflection process will be greatly extended, increasing diffuse irradiance even more. Thus, while multiple reflection does occur between ground with high albedo (snow) and "clear" sky, it has its most pronounced effect on diffuse irradiance with overcast and cloudy sky.

Clear. For clear days in the mountains during the regular and long lasting periods with snow cover (high albedo), diffuse irradiance is significantly increased. Fig. 25 shows the annual variation of diffuse irradiance for clear days at Hidden Peak (solid line).

The highest daily totals occur during the spring, the lowest during the fall. This is not the expected annual cycle where the variation in day length should produce maximum values in the summer and minimum values in the winter (dashed line). As was previously discussed in the section on elevation, there is a positive shift in the annual cycle of diffuse irradiance towards the spring and winter. The snow cover present during these two seasons results in an enhancement of the expected diffuse irradiance due to multiple reflection.

Overcast. With overcast conditions the backscattering from the sky is much greater than for clear sky conditions and the multiple reflection process is more effective.

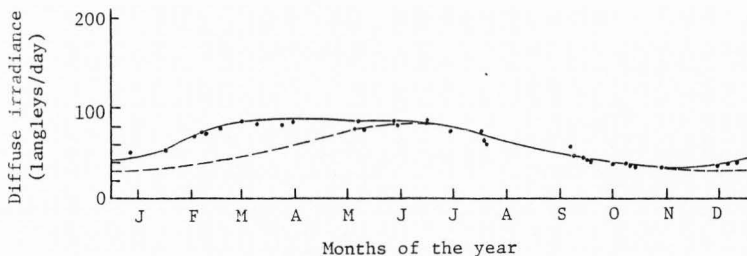


Fig. 25. Clear daily totals of diffuse irradiance at Hidden Peak throughout the year.

Figure 26 shows the annual variation in daily totals of diffuse irradiance for overcast days at Hidden Peak (during summer months, no overcast days were available). When compared to Fig. 25, it is evident that clouds have a pronounced effect on the multiple reflection process especially during spring with snow cover. However, values of the actual enhancement of diffuse irradiance by snow covered ground over bare ground are presently not available. The annual cycle without snow cover has still to be verified through longer periods of measurements.

The annual irradiance variation in Figs. 25 and 26 is also influenced by day length, thus when comparing irradiance values, it is important to use periods of similar declination. However, in general, diffuse irradiance was highest in late winter and spring when there was snow on the ground and lowest in summer and fall when the surface was bare ground, for clear conditions.

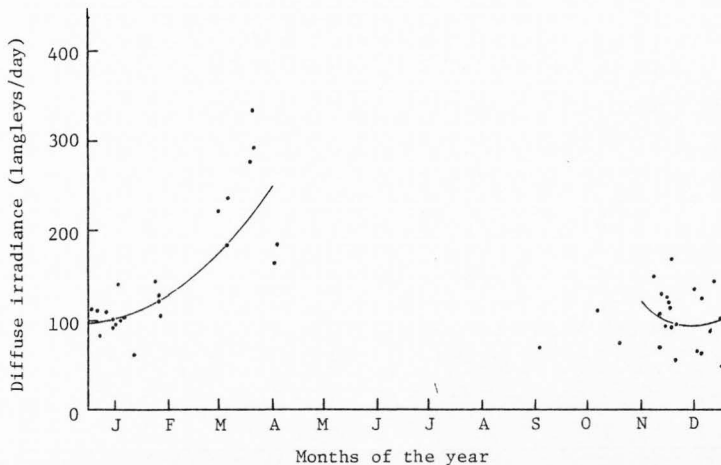


Fig. 26. Overcast daily totals of diffuse irradiance for Hidden Peak throughout the year.

Figure 27 shows the difference in hourly diffuse irradiance for bare and snow covered ground with various amounts of cloudiness at Salt Lake City and Hidden Peak. Months of similar declination (March and September) were used to eliminate the effects of solar elevation.

The curves were developed from hourly data in order to generate an adequate number of cloudy periods. These relatively short period integrations exhibit much more variability than that for longer periods (daily totals). However, the averaging inherent in the curve fitting eliminates serious error. A check on the deviation between calculations of diffuse irradiance enhancement for overcast skies at the equinoxia, using hourly and daily totals showed a 10% error.

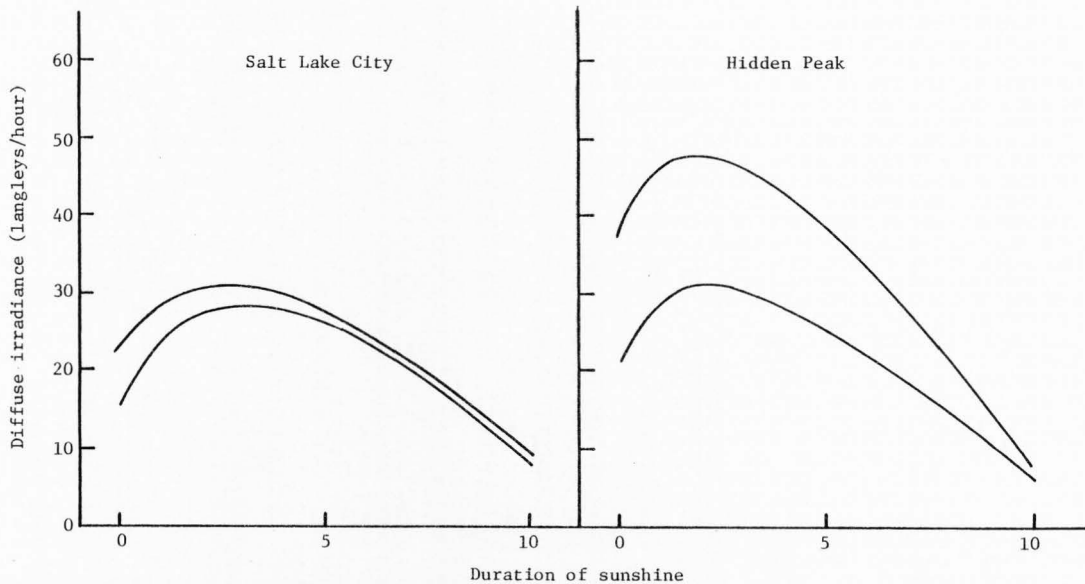


Fig. 27. Enhancement of diffuse irradiance by snow covered ground versus bare ground using curves from March and September for Salt Lake City and Hidden Peak.

At both Salt Lake City and Hidden Peak, maximum enhancement is achieved during completely overcast periods. At this maximum, snow cover is responsible for a 43% increase in diffuse irradiance over bare ground conditions at Salt Lake City and 69% increase in diffuse irradiance at Hidden Peak. These percentages are relative to the bare ground diffuse irradiance occurring for the respective sites. The increased effect at Hidden Peak is due to several factors:

1. The relatively larger amount of snow covered area.
2. The colder, dryer snow has a higher albedo.
3. The thinner cloud cover associated with the high elevation transmits relatively greater amounts of irradiance without a significant drop in cloud albedo.
4. The shorter pathlength between snow cover and cloud base decreases atmospheric attenuation.

Comparisons. Other investigators have published similar results of enhancement by surface albedo.

Moller (1965) reports two methods to determine the increase of diffuse irradiance over snow cover. By taking irradiance measurements over a snow covered coastline and open ocean under a dense overcast sky, an increase of 70% was found. This large increase is due to the initially low albedo (thus low diffuse irradiance) of water.

A second statistical method using hourly irradiance values under overcast conditions from Moosonee and Toronto indicated an increase of 53% and 44%, respectively, as a result of snow cover. This method is similar to the present study and gives comparable results, especially at Salt Lake City where the radiation regime would be the same.

Catchpole and Moodie (1971) proposed the equation:

$$G_r = G_o (1-rd)^{-1}$$

where G_o = global radiation over an ideally black earth surface, d = backscatterance of the sky, and r = reflectance (albedo) of the surface, as a model of the multiple reflection process.

Diniz (1978) verified the Catchpole and Moodie equation using a simulation model. She then established a curve (Fig. 28) showing the dependence of multiple reflection on surface albedo. This curve assumes a constant cloud albedo (backscatter) of .700.

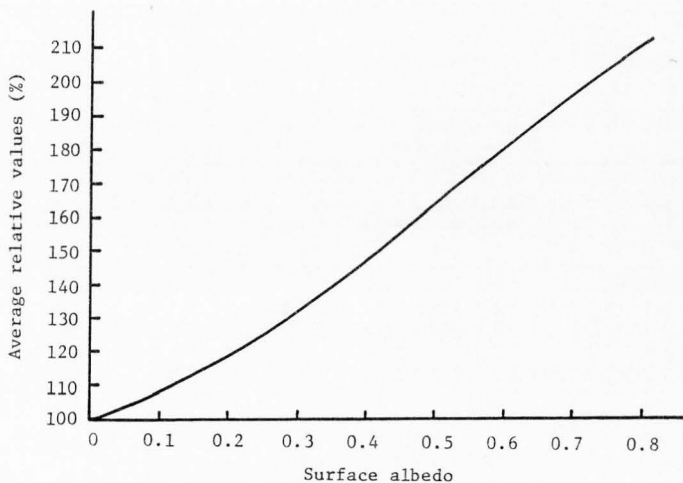


Fig. 28. Average increase in relative irradiance due to multiple reflection (cloud albedo 0.700) depending on surface albedo. (From Diniz, 1978)

Using this curve the average ground albedo of Salt Lake City is approximately .45 in the presence of snow cover. An albedo greater than .60 is found for Hidden Peak with snow cover.

These values agree well with those given in available literature. Using an analytical method to determine average ground reflectivity, Hunn and Calafell report albedos of 0.6-0.7 for snow covered rural landscapes. The albedo found for urban areas during winter was 0.16-0.49.

Horizon

In order to calculate the effects of an elevated horizon on clear sky diffuse irradiance, a mathematical model describing a V-shaped valley was developed by Peterson, Hurst, and Dirmhirn (in preparation).

The necessary inputs for the model are:

1. Julian date
2. Latitude of the valley
3. Orientation of the valley
4. Slope angles of the valley sides
5. Albedos of the valley sides
6. Height of the sensor in the valley
7. f ratio, where

$$f = \frac{\text{horizontal diffuse irradiance}}{\text{normal direct irradiance}}$$

The ratio, f, was identified from evidence that the relationship between the horizontal diffuse irradiance and the direct irradiance normal to the sun has a relatively constant daily value. Variations, depending on seasonal and atmospheric conditions, from .13 to .05 have been

measured for clear days. The derivation used the assumption that the diffuse sky irradiance is isotropic. Equations were developed to calculate the irradiance (relative units) contributed by the individual components of the global irradiance arriving at a specific elevation in the valley. The components the detector "sees" are the direct (D), reflected (r), and diffuse (S). The global (G) is therefore,

$$G = R + S + D.$$

Diniz (1978) compared calculated and measured values using a simulation model. She suggested that close agreement between measured and computed values demonstrates the accuracy of the model in predicting the percentage of global irradiance at a given altitude in V-shaped valleys to that on a flat unobstructed surface.

A comparison of calculated values from the mathematical model and actual measured values from Cliff Inn was made hourly, for clear sky to further verify the accuracy of the model.

The inputs to the model necessary to describe the Cliff Inn location are listed in Table 5.

Table 5. Inputs to the V-shaped valley model necessary to describe the Cliff Inn site location.

Day	Latitude	Orientation	Slope angles	Albedo	f ratio
13	40	90°	37°, 25°	.60	.057
83	40	90°	37°, 25°	.50	.085
178	40	90°	37°, 25°	.10	.066

Values from the model were transformed to absolute values by multiplication with measured global irradiance having no horizon blockage.

Fig. 29a-c shows the hourly comparison of calculated values and actual measured values of diffuse irradiance for clear days during the summer, spring, and winter seasons.

The results suggest that the model is accurate in predicting diffuse irradiance. There is a slight over estimation in the computed irradiance, especially during the spring. This error can be attributed to the anisotropy of the diffuse sky irradiance, which the model does not account for. The increased error during the spring season is due to the higher anisotropy of the sky resulting from enhancement by multiple reflection between snow and clear sky, as discussed previously in the section on albedo.

The results also show that for clear days at Cliff Inn, daily totals of diffuse irradiance are approximately the same in spring and summer. While the day length is greater during the summer, direct reflectance off snow covered slopes enhances overall irradiance. During the winter loss of direct reflection due to the low sun angle greatly reduces diffuse irradiance values.

Tilt/Horizontal

In the previous sections the effects of parameters affecting diffuse irradiance were concerned with horizontal collection surfaces. The diffuse irradiance can also be enhanced by tilting the collector towards the south (northern hemisphere) especially in the presence of a highly reflective foreground.

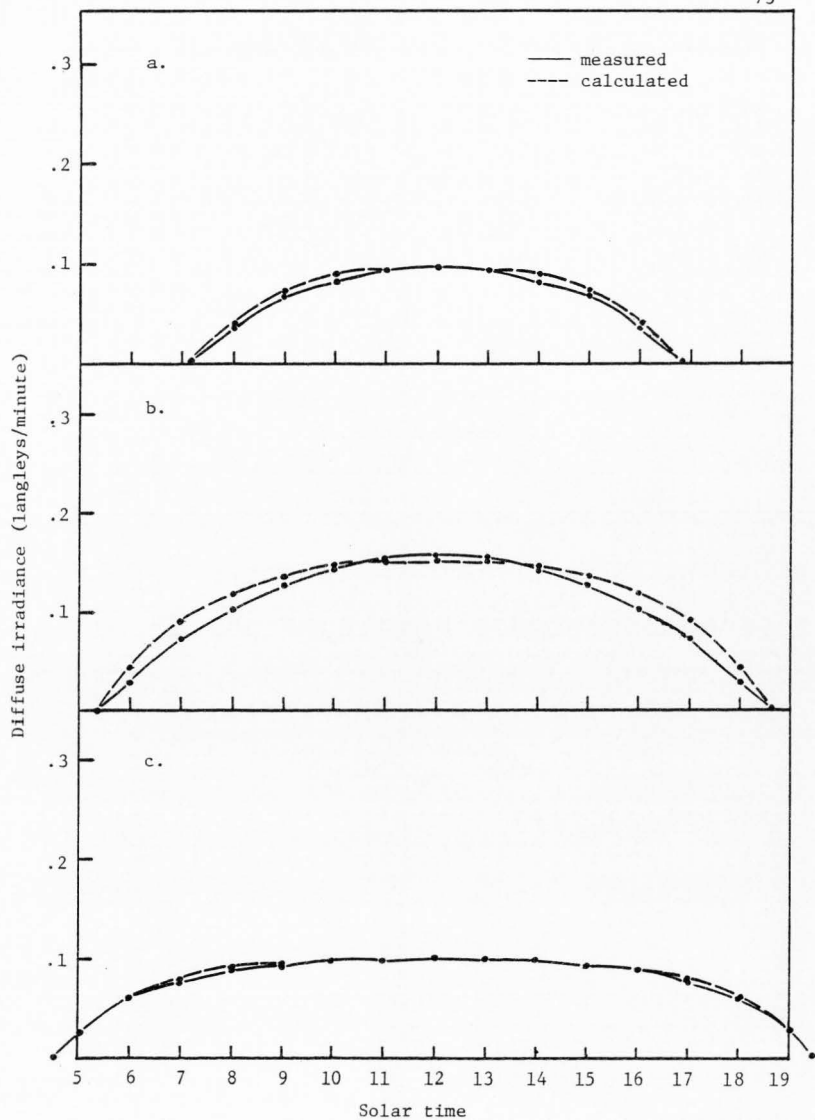


Fig. 29. Hourly comparisons of calculated and measured values of diffuse irradiance in langley/minute for an east-west V-shaped valley for clear days during winter, spring, and summer.

Measured daily totals of diffuse irradiance on a 50 degree tilt were determined relative to that on the horizontal plane. These relative 50 degree values were plotted against their corresponding cloudiness (duration of sunshine) for Salt Lake City and Hidden Peak in Figs. 30 and 31. The seasons, represented by two months each, were plotted separately since the ratio is dependent on solar declination. The dashed line represents unity of the ratio ($50^\circ/\text{Hor.}$) and indicates that no diffuse irradiance is lost due to tilting the collecting surface 50 degrees.

Clear. The clear daily ratios represented by duration of sunshine greater than 8-tenths, vary dramatically according to season. The ratios are highest during the winter and lowest during the summer. This is due primarily to three factors:

1. At clear sky the incidence angle of the direct solar irradiance is of importance due to the non-isotropy of the diffuse irradiance coming from the sky. Thus when the sun is low, as in winter (Figs. 30a and 31a), a surface tilted 50 degrees to the south will receive a higher portion of the bright area around the solar disk, known as the circumsolar region of the sky, enhancing the diffuse irradiance.

2. At clear sky conditions direct reflection from the foreground to a tilted surface is dependent on solar elevation and ground albedo. Thus, during the winter (Figs. 30a and 31a) both effects are maximized. The low sun elevation provides an incident angle conducive to direct reflection on a 50 degree tilted surface and the high albedo of the associated snow cover greatly enhances the reflection process.

3. The daily totals of horizontal clear sky diffuse irradiance, to which the ratios are relative, vary annually (Figure 25). As

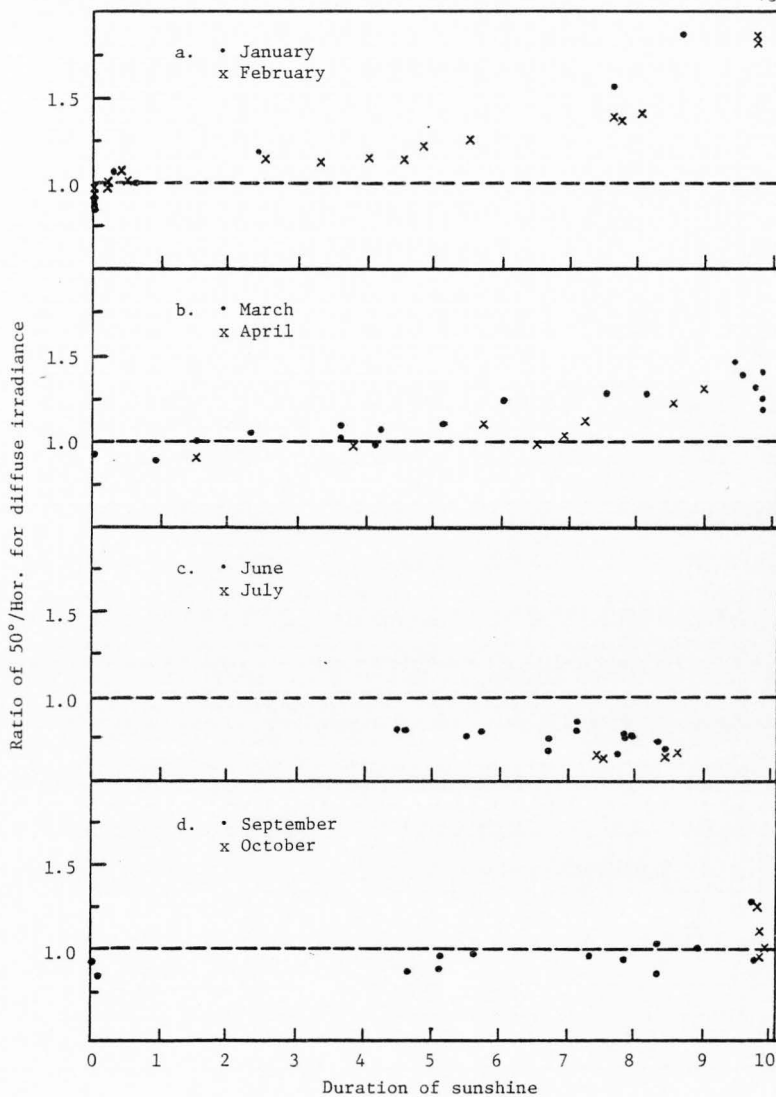


Fig. 30. Relationship between the ratio of daily diffuse irradiance on a 50° tilt to daily diffuse irradiance on a horizontal surface, and duration of sunshine in tenths/day at Salt Lake City.

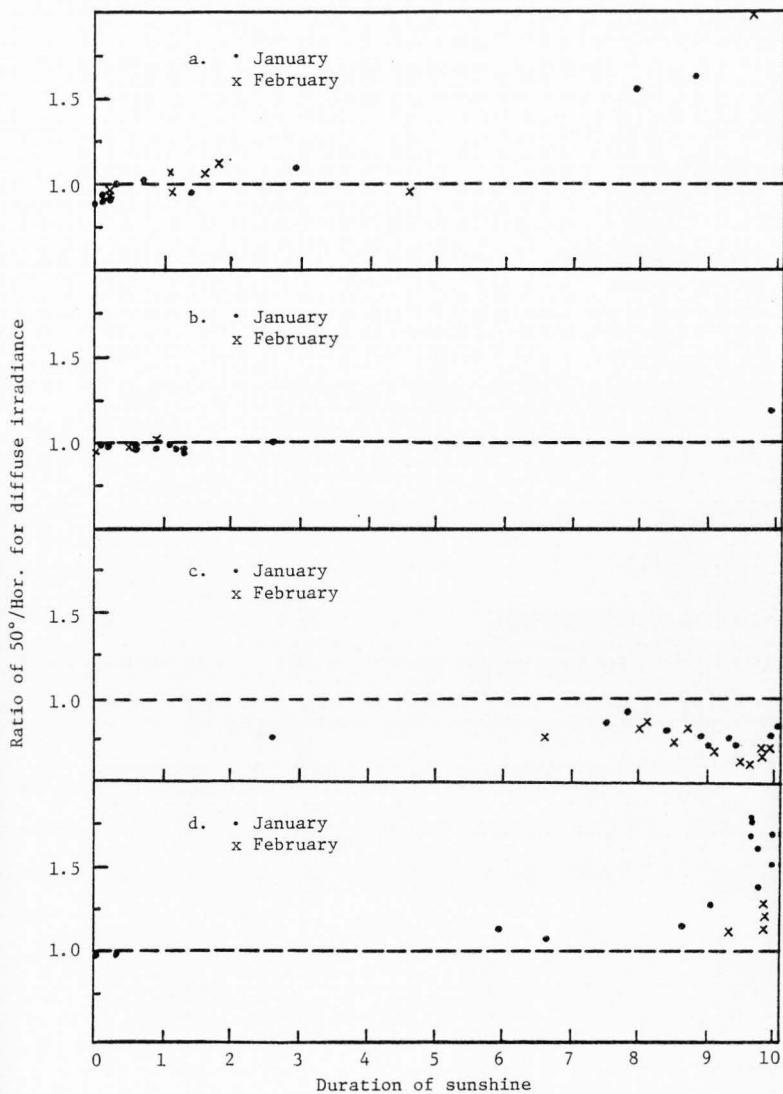


Fig. 31. Relationship between the ratio of daily diffuse irradiance on a 50° tilt to daily diffuse irradiance on a horizontal surface, and duration of sunshine in tenths/day at Hidden Peak.

discussed in the section on albedo, multiple reflection enhancement in conjunction with snow cover caused maximum values to occur during the fall. Thus, while the winter ratios are close to 2, exhibiting the enhancement by effects 1. and 2., the spring ratios (Figs. 30b and 31b) are overly reduced due to the high horizontal denominator. For fall (Figs. 30d and 31d), the opposite situation occurs. A small denominator produces ratios which are about the same as spring at Salt Lake City and higher than spring at Hidden Peak.

During the summer, according to 1., the high solar elevation would provide a greater relative enhancement to the horizontal surface, reducing the ratio. In addition the loss of foreground reflection, effect 2., reduces the diffuse irradiance on a 50 degree to what is received from the sky. In Figs. 30c and 31c, this is verified; during the summer the 50° tilted surface only receives about 80% of that received on a horizontal surface on clear days.

Overcast and cloudy. For overcast and cloudy conditions, there is only a small variation in diffuse ratios of daily total irradiance throughout the year. During snow covered periods with a relatively low solar angle (Figs. 30a and 31a) due to multiple reflection, irradiance values on a 50 degree tilt and on a horizontal surface are approximately the same ($50^\circ/\text{Hor.} = 1.0$). This situation constitutes what Catchpole and Moodie (1971) refer to as a "white out" where diffuse irradiance coming from ground and sky are the same and no horizon can be detected.

During times of no snow when the foreground has a low albedo, (Figs. 30c and 31c), multiple reflection is diminished and diffuse ratios reach their minimum value with 50 degree diffuse irradiance being

only 80 percent of the horizontal diffuse irradiance. This is about the percentage expected considering the 50 degree tilted surface is only receiving diffuse irradiance from that portion of the sky which it "sees".

Model development. In order to calculate the tilt effect for clear sky and because of the present controversy in available literature (Review of Literature section) over the correct methodology for calculating diffuse solar irradiance on an inclined surface, a new method was derived and validated. The premise was to establish an acceptable method of determining instantaneous diffuse irradiance on an inclined plane from data of global irradiance on the horizontal plane for the same time of year. The assumption that the sky illumination and foreground reflection is isotropically distributed was used due to the complication in calculating anisotropic fluxes. Such an isotropic approximation can only give approximate results, diffuse radiation being essentially nonisotropic.

The inputs to the model are:

1. Tilt angle of the receiving surface towards the south.
2. Zenith angle of the sun, which is dependent on latitude, date, and solar time.
3. Incident angle of the direct beam of the tilted surface, which is dependent on zenith angle and tilt angle.
4. Albedo of the foreground.
5. f ratio, such that:

$$f = \frac{\text{horizontal diffuse irradiance}}{\text{direct normal irradiance}}$$

This ratio is used as previously described in the V-shaped valley model (Peterson, Hurst, and Dirmhirn).

The global irradiance on a given tilt is determined through calculation of its individual components using the ratio (f).

Direct Beam (DB)

$$DB = \frac{\cos \psi}{\cos \beta + f}$$

Diffuse Sky (DS)

$$DS = \frac{f}{\cos \beta + f} \cos^2 \left(\frac{\Sigma}{2} \right)$$

Reflected Direct

$$RD = A \frac{\cos \psi}{\cos \beta + f} \sin^2 \left(\frac{\Sigma}{2} \right)$$

Reflected Diffuse (RS)

$$RS = A \frac{f}{\cos \beta + f} \sin^2 \left(\frac{\Sigma}{2} \right)$$

where β = zenith angle, ψ = incident angle, Σ = tilt angle, and A = albedo, such that

Global Radiation (RAD)

$$RAD = DB + DS + RD + RS$$

The individual components, and thus the tilted global irradiance, are relative to the horizontal irradiance.

The calculated diffuse sky, reflected direct and reflected diffuse components (50 degree tilt) were added for the total diffuse. This

relative value was converted to absolute units through multiplication with measured horizontal global irradiance.

Fig. 32 shows the comparison between computed 50 degree values and measured 50 degree values plotted against solar time. Clear days of similar solar declinations having bare and snow covered ground were used at both Salt Lake City and Hidden Peak. The increased diffuse irradiance due to snow cover is evident. The correlation between computed and measured values shows close agreement. Some deviation was found at midday in Fig. 32b, however this is due to the erroneous recordings of measured 50 degree values and not from the model itself.

Additional verification of the model was made by comparing measured (Fig. 33) and computed diffuse values for various tilt angles at solar noon. Measurements were taken on a clear day during October 1978. Computed relative values were changed to absolute values through multiplication by measured horizontal global irradiance. Fig. 34 shows the result.

A close comparison is seen between measured and computed irradiance at all angles except 0 and 90 degrees where there is a 7 percent deviation. This deviation can be accounted for by the anisotropy of the sky irradiance, which is not taken into account by the model.

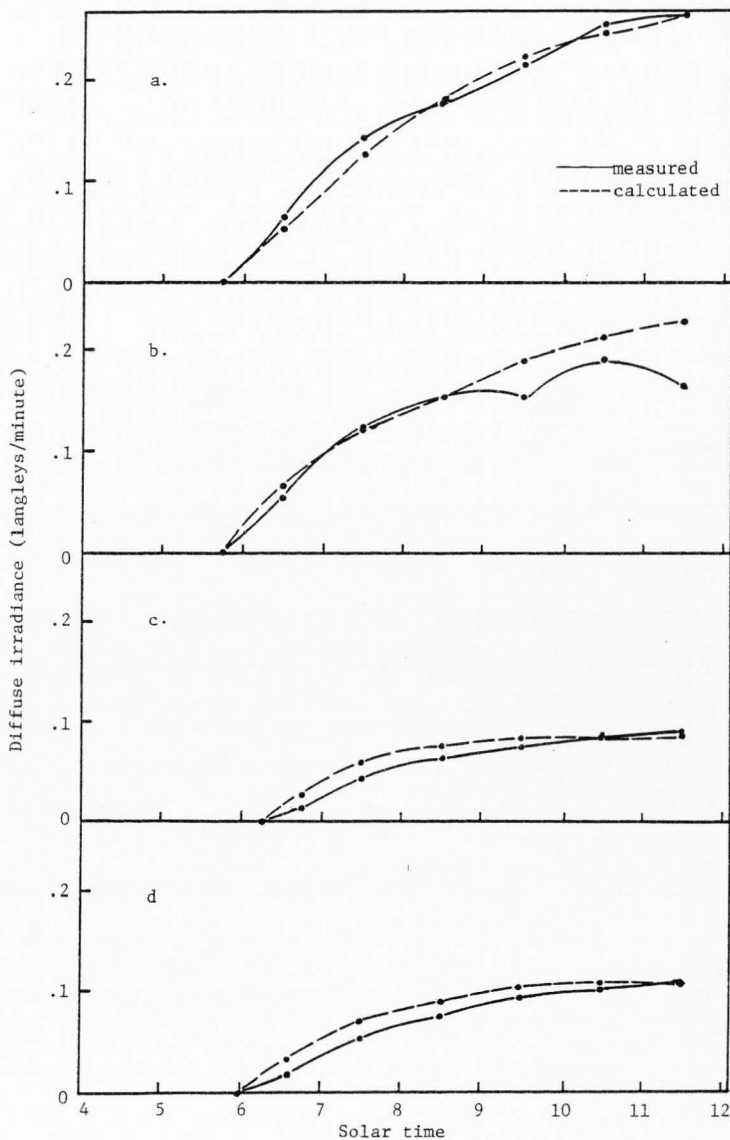


Fig. 32. Hourly comparison of calculated and measured values of diffuse irradiance in langley/minute on a surface tilted 50° to the south for clear days during spring and fall at Salt Lake City and Hidden Peak.



Fig. 33. Instrumentation used to measure diffuse irradiance on various tilted surfaces--digital voltmeter, tilt platform, and star pyranometer.

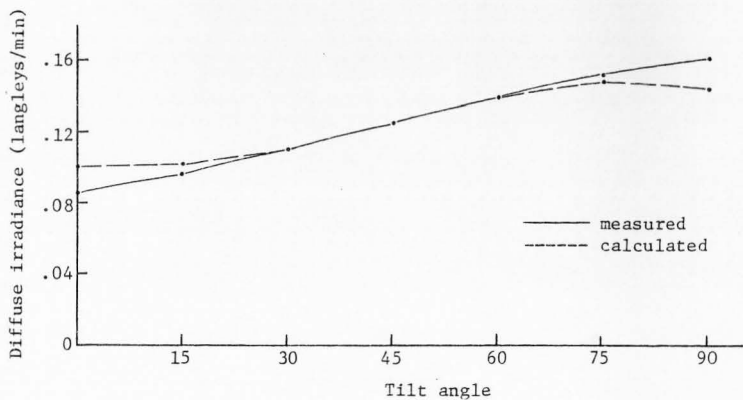


Fig 34. Comparison between calculated and measured values of diffuse irradiance in langleys/minute on surfaces tilted 0-90° to the south.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Investigations into the mountain parameters affecting diffuse irradiance suggest that high elevation locations would provide higher amounts of diffuse irradiance than that for flat terrain at low elevation. This is particularly true of winter and spring when the annual variation in duration of sunshine on the western slopes of the Rocky Mountains indicates a high amount of cloudiness. For these periods when energy requirement is greatest, high elevation collection sites can partially compensate the direct irradiance lost through enhancement of the diffuse irradiance. This is the result of less absorption of diffuse irradiance by the thinner cloud layer along with enhancement from direct and multiple reflections off of the extended snow cover.

It is widely known that tilting the collection surface toward the south can enhance collection efficiency due to the increase in direct radiation. Tilting the collection surface will also increase the diffuse irradiance during the fall, winter, and spring when it is needed most. The increase is achieved for clear sky when a low solar angle and snow cover are conducive to direct reflection. Additional enhancement is attributed to the tilted surface "seeing" the brightest part of the anisotropic sky. Even for overcast conditions little is lost in tilting the collector due to the high reflectivity of the snow covered foreground.

Recommendations

The following recommendations for further investigation are made based on the results:

1. Continue recordings of diffuse irradiance. While a general description of the parameters affecting diffuse irradiance can be made from this data base, a longer recording period could further validate findings.

2. A more extensive study of the correlation between diffuse irradiance and snow cover records be made since this study has shown that the annual variation in diffuse irradiance with all types of atmospheric conditions is strongly influenced by surface albedo.

3. Application of an anisotropic term to both the V-shaped valley model and the tilt model to improve their accuracy in predicting diffuse irradiance. This could be done by separating the circumsolar component.

4. Additional verification of the tilt model with measured irradiance data for tilted surfaces representing those which would be used to collect maximum energy during the summer where cooling is required.

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APPENDIX

Appendix AComputer Program for Calculating Irradiance on a Tilt

```

LIST TILT
#FILE (150022)TILT ON PACK
100 FILE 6(KIND=REMOTE,MAXRECSIZE=22)
200     PI=3.1416
300     PHI=60.0
400     A=.59
500     F=.08
600     DAY=355
700     WRITE(6,500)
800     500 FORMAT(10X,'TYPE IN DAY,F,ALBEDO,LAT. ')
900     READ(5,/)DAY,F,A,PHI
1000    PHI=PI*PHI/180.0
1100    SP=SIN(PHI)
1200    CP=COS(PHI)
1300    ARG=2.0*PI*(284.0+DAY)/365.0
1400    DEC=23.45*SIN(ARG)
1500    DEC=PI*DEC/180.0
1600    SD=SIN(DEC)
1700    CD=COS(DEC)
1800    WRITE(6,100)
1900    100 FORMAT('1',10X,'*NORM DIR*', 8X,'*REFL DIR*',8X,'*REFL SCAT*',7X,'
2000    *NORM SCAT*',7X,'*TOT DIFF*',7X,'**GLOBAL**')
2100    T=0.0
2200    N=7
2300    DO 10 I=1,N
2400    TI=180.0*T/PI
2500    WRITE(6,400) TI
2600    400  FORMAT(20X,'TILT = 'F6.2)
2700    O=0.0
2800    M=10
2900    DO 20 J=1,M
3000    CB=SD*SP+CD*CP*COS(O)
3100    PT=PHI-T
3200    CS=COS(PT)*CD*COS(O)+SIN(PT)*SD
3300    DN=CS/(CB+F)
3400    RD=A*CS*SIN(T/2)*SIN(T/2)/(CB+F)
3500    RS=A*F*SIN(T/2)*SIN(T/2)/(CB+F)
3600    IF (DN.LT.O)DN=0
3700    DS=F*COS(T/2)*COS(T/2)/(CB+F)
3800    IF (RD.LT.O)RD=0
3900    G=DN+RD=RS+DS
4000    TD=G-DN
4100    WRITE(6,300) DN,RD,RS,DS,TD,G
4200    300  FORMAT(3X,6E18.6)
4300    O=O+PI/12.0
4400    20  CONTINUE
4500    T=T+PI/12.0
4600    10  CONTINUE
4700    STOP
#      END

```


VITA

Brock Allen LeBaron

Home Address:

408 East 2nd South
 Logan, Utah 84321
 Phone: (801) 753-5738

Age: 26
 U.S. Citizen
 Health Excellent

EDUCATION

- M.S. BIOMETEOROLOGY, Utah State University, Logan, June 1980
 This program provided background in advanced meteorological concepts with specific studies in atmospheric radiation. Additional classwork was completed in air pollution meteorology. Thesis dealt with research into parameters affecting diffuse solar radiation in mountainous terrain. Enhancement of irradiance with collector tilt and location were extensively examined and modeled. Additional investigations into corrections for a shadowband were made.
- B.S. BIOLOGY, Utah State University, June 1975
 Major: Biology
 Minor: Chemistry

COURSE EXPERIENCE

METEOROLOGY	*PHYSICS & MATH*	
Physical Climatology	Differential Calculus	
Dynamic Meteorology	Integral Calculus	
Physical Meteorology	Computer Calculus	
Synoptic Meteorology	General Physics 1,2,3	
Environmental Remote Sensing	Optics Theory	
Air Pollution Meteorology	E-M Wave Theory	
Air Quality Management	Diffraction Theory	
BIOLOGY	*CHEMISTRY*	*MISCELLANEOUS*
General Biology 1-3	Inorganic	Fortran
Mammalogy	Chemistry 1-3	Statistical Methods
Ecology	Organic	Environ. Economics
Genetics	Chemistry 1,2	Directed Teaching
Aquatic Microbiology	Intern.	Spanish 1,2
Cell Physiology	Biochemistry	Electronics
		Geology

JOB EXPERIENCE

Meteorological Research Assistant, Utah State University, 1977-79

*Involved with Department of Energy grant to examine solar potential at five mountainous sites

- *Set up sites using a data logger to integrate 5-minute recordings of global horizontal, diffuse, and global 50° tilt radiation plus air temperature, wind (speed and direction), and time
- *Maintained and calibrated radiation instruments including black and white pyranometers, Lambda silicon cells and normal incidence and absolute cavity pyrheliometer
- *Performed tests to determine cosine corrections for pyranometer calibrations
- *Calibrated Schenk, Eppley, and Lambda Cell pyranometers on different tilts to determine effects on sensitivity.
- *Compiled, edited, and reduced radiation site data using project's remote computer terminal
- *Wrote Fortran programs to manipulate data into a usable data library
- *Wrote Fortran programs for tilt angle irradiance models
- *Familiar with CANDE operator language
- *Made extensive diffuse radiation measurements to develop and verify a model for shadowband corrections resulting in a publication
- *Maintained photographic records for all radiation sites and project events
- *Designed a device for making continuous photographic records of cloud cover at specified intervals using a fisheye lens

Entomological Field Technician, Plant Protection and Quarantine
USDA, 1973-75 (summer employment)

- *Personally responsible for weekly surveys of economic insect infestations in eastern Utah
- *Made initial contact with local farmers and ranchers for insect pest control programs
- *Helped organize and carry out aerial spray programs in heavily infested areas

Water Quality Technician, Utah Water Research Laboratory, 1973-75
(school year employment)

- *Performed quantitative water quality analysis on commercial, public, and private effluent samples
- *Experienced using gas chromatograph, nitrogen analyzer, flame photometer, spectrometer, carbon analyzer
- *Familiar with quantitative tests for:

Calcium	Biochemical Oxygen Demand	Phosphorus
Chlorophyll	Chemical Oxygen Demand	Potassium
Chloride	Iron	Sodium
Coliform	Nitrate and Nitrite	Sulfate
Dissolved Oxygen	Ammonia	Solids

Biological Research Assistant, Utah State Crop Pollination Lab
1972-74

- *Studied the use of bees as crop pollinators
- *Personally organized and recorded daily bee incubation data
- *Constructed bee nesting houses and maintained project greenhouses

PUBLICATIONS

Corrections for Diffuse Irradiance Measured with a Shadowband. (paper). First United States Department of Energy Environmental Resource Conference, February 1978

Preliminary Results of the Impact of Reflection on Irradiance in Mountainous Terrain. (publication). Third Conference of the American Meteorological Society on Atmospheric Radiation. April 1978

Shadowband Correction for Measurement of Diffuse Radiation. (under review by Solar Energy for publication)

Parameters Affecting Diffuse Irradiance in Mountainous Terrain. (paper). Department of Energy Division of Distributed Solar Technology Contractor's Review. April 1979

Diffuse Solar Irradiance in the Rocky Mountains at 40 Degrees Latitude. (Masters Thesis, 1979, Utah State University, Logan)

TRAVEL

Lived and traveled in Central and South America 1971-78. Knowledge of Spanish based on 10 hours of classroom study and actual usage.

Lived in Europe for 2 years.