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CLOUDINESS OVER THE SOUTHWESTERN UNITED STATES AND ITS RELATION TO ASTRONOMICAL OBSERVING

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ABSTRACT

A number of types of cloudiness statistics for Weather Bureau stations in the southwestern United States are analysed in terms of their implications for astronomical observatory site-selection. In all but one of the analyses, Yuma proves to be distinctly superior to other stations with respect to clearness of skies. Lack of nearby mountain peaks extending above haze and dust layers plus poor seeing due to inevitably high thermal instability throughout much of the year render the immediate vicinity of Yuma astronomically unattractive, however. Hence the difficult task of comparing the relative cloudiness of the region roughly concentric with Yuma is the practical problem confronting the astronomer seeking new observing sites.

Inherent limitations in available types of meteorological observations are discussed; but these limitations are not precisely defined, since they are not quantitatively known to the meteorologist at present. In view of these uncertain limitations in each individual type of data, the safest procedure becomes that of assembling all possible types of independently observed data and assessing the site problem in terms of the overall implications of all of these data. The present report consists chiefly in such an assembly and assessment of meteorological data. In addition, a review of past studies of the site-selection problem is given.

It is concluded that during the winter half-year (more significant to astronomical observing than the summer half-year for night-duration reasons), the area extending out about 200 miles northeast and east of Yuma is the best portion of Arizona for observing sites. Sites in this area will have clearer winter skies than those over coastal southern California, and will be somewhat superior to those north of the Mogollon Rim where more frequent migratory cyclonic storms increase the mean winter cloudiness to values higher than those found to the south. The southeastern corner of Arizona is unattractive in the summer rainy season (July-August) due to high frequency of thunderstorms, and equally undesirable in summer is the whole Mogollon Rim whose thunderstorm frequencies are nearly as high, on the average, as those of extreme southeastern Arizona. A rapid westward diminution of summer thunderstorm activity across southern Arizona (due to upper-level flow conditions governing moisture distribution over the Southwest) makes summer conditions increasingly more favorable from Tucson westward to Yuma; and in the winter the entire border area west of Tucson to and beyond Yuma is quite favorable.

Haze and dust tops average about 5000 to 6000 ft. msl. in winter and probably 8000 to 10,000 ft. msl. in summer in southern Arizona. Areas of agricultural cultivation, as the Salt River Valley area around Phoenix, have a locally severe transparency problem. The general altitude of the haze and dust layers plus other seeing difficulties leave only a few peaks in southwestern Arizona as feasible sites. A peak at 5672 ft. in the Harquahalas and Kitt Peak (6875 ft.) in the Quinlans seems to offer the

the meteorologically best possibilities in Arizona. Several California peaks considered by Irwin may be almost as favorable as those in southwestern Arizona, but no first-order Weather Bureau station data are available for those areas. However, the only peaks above 6000 ft. msl. in the area west of Yuma are those just south of San Jacinto Peak and these ranges undoubtedly have about as high a winter cloudiness as San Diego, which proves to be distinctly higher than either Tucson or Yuma.

I. INTRODUCTION.

The arid southwestern United States offers well-known advantages for astronomical work because of its generally low cloudiness. Eight major American observatories are located in this region at the present time, and an intensive search is currently in progress to find a suitable site for still another. This concentration of observing sites might reasonably be presumed to imply that a great deal is now known of the cloud climatology of the Southwest; but this, unfortunately, is very far from being true. Indeed, meteorologists are well aware that embarrassingly little is actually known about the details of cloud climatology for any localities within this or other countries of the world. In particular, the kind of questions that astronomers wish to have answered concerning cloud characteristics over prospective sites are very difficult to answer, except in general terms, on either cloud-physical or climatological basis. For all of these reasons, it should be evident that there is need for many more studies of the cloud climatology of the Southwest.

Institute activities touch on cloud climatology in many ways, and a growing stock of information about this subject is evolving from our current program. For example, by far the most intensive and extensive study of cloud climatology every conducted for any locality in the United States has just been completed by DesJardins (1958) for Tucson, Arizona. Based on a detailed analysis of some 25,000 observations during the period 1945-54, (performed manually at the expense of almost one full man-year, because

IBM punchcards do not permit full examination of many critical items of interest), DesJardins' study has revealed many interesting features of this one southwestern station's cloud climatology. In the present report, many of DesJardins' results will be drawn upon. For the areas of the Southwest outside of the Tucson area, no past Institute studies have yielded any very detailed cloud information. When, therefore, requests for such information were made to the Insitute in the course of current search for a large national observatory site, it seemed desirable to undertake at once a number of studies to fill the gaps in this important aspect of the regional climatology of the Southwest. Such studies were recognized as being of fundamental interest in our overall program since the derived statistics are very useful in hydrometeorological analyses of the region. Hence it was feasible to divert the effort of a number of staff members to this type of investigation when the recent need for cloud data arose.

The present report began chiefly as an effort to assemble into a single published document four or five tabulations that had been done within recent months (chiefly under the supervision of Mr. R. B. DesJardins) but which had not previously been summarized or been given meteorological interpretation due to Mr. DesJardins' departure to take a new position at another institution. In the course of assembling and reprocessing these existing tabulations I saw a number of opportunities for extension of the analyses in other directions, and hence the present report contains both these earlier unpublished Institute tabulations, and discussions thereon, and also additional analyses of other data. In addition, a brief review of previously published studies of Southwestern cloud climatology is presented.

The last point will be considered first. The astronomer can find some useful charts of sunshine and cloudiness in two standard climatological references: The 1941 Yearbook of Agriculture, Climate and Man (U.S. Dept. of Agriculture, Washington), and Visher's Climatic Atlas of the United States (Harvard Press, 1954). The first of these is based on data for about 200 first-order U. S. Weather Bureau stations for the forty-year period 1899-1938; but the total number of active stations in the sparsely populated Southwest during about the first half of this period renders the actual sample weaker than these figures might seem to imply. No list or map of station-records used for each chart is given. Thus it is not clear whether, say, clear-day statistics came chiefly from first-order station reports or chiefly from the less fully controlled cooperative stations reports. It is also impossible for a reader to determine the source of much of the data in Visher's atlas which strives chiefly to depict broad patterns on a scale too large to be very useful to either the astronomer seeking an observing site or to the cloud physicist seeking details of cloud patterns that may offer clues to physical processes involved. A still earlier publication, the Atlas of American Agriculture (U.S. Dept. of Agriculture, 1936) is probably considerably less reliable (at least for the Southwest) than the 1941 Yearbook, since the cloud-cover maps in it were actually compiled in 1928. It, too, fails to give the reader any information as to how many station records actually underlie each chart.

Turning from these general references (of which I would cite the 1941 Yearbook of Agriculture as probably the most useful and reliable for astronomers who may wish only a general orientation for a given broad region), it is possible quickly to summarize past studies of Southwestern cloud climatology conducted specifically for astronomical site-selection purposes. Dr. E. F. Carpenter, Director of the University Steward Observatory, has been in close touch with regional observatory work for several decades, yet he was able to call my attention[1] to only two such studies.

The need for a new site specially adapted to photoelectric photometry led Irwin (1952) to examine breifly some cloud-cover data for the Southwest and to consider their bearing on optimum location of a photoelectric observatory. It seems worth quoting, for the benefit of climatologists not aware of the stringent demands of photoelectric observing, Irwin's statement of the problem: "The astronomical photometrist requires, above all else, a clear sky; this is espeically true because his results may be discussed in terms of thousandths of a magnitude. One might ask: 'How clear a sky?' The answer is: 'Just as clear as possible -- *the best is none too good.*' The photocell can 'see' and respond to thin cirrus clouds long before they become apparent to the naked eye. Such clouds are worse than a nuisance; once they have intruded themselves into the observations their effects are subtly injurious to the scientific interpretation and are difficult to eradicate." (Irwin's italics).

Irwin was apparently unaware of the cloudiness data available in the 1941 *Yearbook of Agriculture*, for he drew such data as he examined solely from the much older and almost certainly less trustworthy *Atlas of Agriculture*. His Figure 1, showing isolines of total annual number of "clear" days (three tenths or less mean cloud-cover) appears to give generally *higher* numbers of clear days than do more recent tabulations. In Section VIII-D below Irwins's figures will be compared with those obtained here and in other studies. Here it is sufficient to note that the 1928 *Atlas of Agriculture* patterns of cloudiness appear to give generally too-high estimates of numbers of clear skies compared with more recently

[1]Private communication, February, 1958.

derived patterns, though Irwin's general conclusion that the Yuma area is the most cloud-free part of the country is surely not contradicted by any other studies, including the present one. Using an adjustment technique (which he recognizes to be quite approximate) based on known relations between cloudiness and observation records at Goethe Link Observatory in Indiana and McDonald Observatory in West Texas, Irwin estimates that 70-80 per cent of all nights in the Yuma area may be "photoelectrically observable" nights. He suggests that this high value may be about twice as large as that characteristic of "other existing American observatory sites". (The cirrus nuisance being what it is in photometry, and the nighttime cirrus observation being the imperfect technique that it is, I am disposed to doubt that the Yuma area is quite as superior to other southwestern areas as Irwin's 1928 data might seem to indicate.)

As Irwin notes, Yuma itself is at too low an altitude (about 200 ft msl) to provide good seeing, both for transparency and turbulence reasons. There are no very high peaks in the immediate vicinity of Yuma. Irwin has listed the available peaks in the winterland concentric with Yuma; but no discussion of the relative merits of the nine or ten sites he considers will be given here.

Apparently only a single meteorologist, Hess (1952), has previously commented on Irwin's study. Hess pointed out that to use clear-day statistics in an effort to predict clear-night patterns is hazardous in view of the quite different diurnal variability regimes of low-level convective clouds and of high-level cirriform clouds. Hess made the conjecture that if reliable nighttime data were at hand, the Yuma region would lose much of its apparent superiority, because, although it does have relative few convective clouds, it probably has about as much high cirrus as most other areas for some hundreds of miles in all directions. Hess's point has fairly high meteorological plausibility, but less so with respect to summer than to winter conditions in the area east of Yuma. During the peak of the summer rainy season (July-August) of Arizona and New Mexico, statistics on daytime convective cloud-cover are not irrelevant to nighttime observing, since anvil cirrus can persist for several hours, as Institute observations attest (espeically with respect to the apparently very intense stroms of the Bisbee-Douglas corner of the state). It may also be noted, that, for an observatory whose prospective program includes solar work, Irwin's approach is not in question on any other grounds than those of data quality and quantity (the latter being quite uncertain in assessing Irwin's chart taken from a thirty-year-old tabulation).

Jones (1952) concurs with Hess in putting only provisional weight on daytime cloud statistics as indicators of nighttime astronomical observability, citing experience in central England to support his views. The only point I would add is that one needs to know a good deal about the details of local climatology before he can feel free to carry over conclusions drawn for an area in England to, say, the Southwest. It is sad commentary on the general state of cloud climatology that a meteorologist has no reliable references to which he may turn in considering such questions. For example, one simply does not know whether nocturnally persistent anvil cirrus are nearly the problem in English summer work that they would be near, say Ft. Huachuca, Arizona (strongly influenced by the apparent maximum convective activity of the Bisbee-Douglas corner of the state of Arizona). Nevertheless, Jones' data are of some general interest: He compares coastal Herstmonceux with inland Greenwich and finds that whereas daytime sunshine recorded at the former site is greater by about 40 per cent that that recorded at the latter site, pole-star-camera records of nighttime cloudiness shows a Herstmonceux advantage of only about 6 per cent, the difference being explainable in terms of stronger midday convective action near Greenwich. This difference implies that the Greenwich cumuli do not typically send out nocturnally persistent anvils. Pole-star nighttime cloudiness-recorders, Jones points out, can be built for very low cost and enable observatory workers to obtain data on even such tenuous clouds as wispy cirrus. As a meteorologist well aware of the deficiencies in existing data on night cloudiness, I should like to second his proposal that devices be set up and routinely operated at many observatories to secure presently unavailable cloud information of both astronomical and meteorological value.

The most carefully executed study of cloudiness in the Southwest and its implications for astronomical observing of which I am aware was done by Smith and McCrosky (1953). This study has apparently never been formally published. (I am indebted to Dr. D. F. Carpenter for loaning me his multigraphed copy of Smith and McCrosky's report.) Their analysis was based upon cloud data read from about 3000 synoptic weather charts scattered through an 8-year period from 1939 to 1946. They used two map-times, 2330 and 0530 MST, and extracted data for twenty stations in the Southwest to obtain figures on average annual and monthly number of clear hours per night for each station. From various measures of internal consistency of the data, they estimate a probable error of only about five per cent in their resulting figures. By their definition, a "clear observation" was one either wholly free from clouds or having cirrus to the extent of no more than one-tenth sky coverage. Because the intertwilight nighttime duration varies from slightly under seven hours near the summer solstice to almost eleven hours near the winter solstice, Smith and McCrosky take this variation into account in estimating average number of clear hours. Roughly speaking, 50 per cent clear skies in December actually afford nearly twice the total telescope-time that 50 per cent clear skies in June afford, in the latitudes in question. Of their twenty stations, Yuma proved clearest with an annual average of 6.8 hours per night "clear". By way of comparison, the authors note that at Harvard's Agassiz Observatory in Massachusetts the same type of annual average is a mere 2.9 hours per night, and Mt. Wilson averages 5.5 hours per night. A reproduction of the Smith-McCrosky map for just the Arizona portion is shown below as Figure 10, for comparison with other charts in the present report.

Smith and McCrosky were able to compare their cloudiness estimates of average number of observing nights with actual observatory records at McDonald in west Texas. Their estimate from cloud data was 5.8 hours per night as an annual average, whereas a seven-year log at McDonald showed an average of 5.5 hours per night of actual telescope operating time. Since the latter figure will tend, probably, to be smaller than the average potentially observable time, the agreement is encouraging evidence that careful use of nighttime cloudiness figures can yield results of real meaning for astronomical purposes. The authors also cite evidence supporting their map in the Flagstaff area (Öpik meteor-expedition experience), in the White Sands area (Proving Ground cloud observations at time of radiosonde releases), and near Sacramento Peak (pole-star camera data at the Upper Atmospheric Station). From these several sources and from internal consistency checks, they infer a probable error of only about 0.3 hours in their estimates of annual averages of clear nights. They observe that their estimates must be cut down by perhaps 10 to 20 per cent if one seeks an estimate of the amount of time that photometric observing can be done; but this appears to be a quite rough guess that must not yet be taken as reliable even to the rough limits of their suggested correction.

II. MEAN MONTHLY AND ANNUAL TUCSON CLOUDINESS.

The first cloudiness data extracted for the use of the AURA site-survey group were those pertaining to Tucson itself. The data came from the extensive tabulation which DesJardins (1958) made from the original station-records of the Tucson Weather Bureau office for the period 1 July, 1945 to 31 August, 1954. In Table 1, monthly and annual average percentages of clear and cloudy skies are shown for Tucson for this period. Here a day is termed "clear" only when there was less than one-tenth of sky cover reported at each and all of eight equally spaced observation times throughout the 24-hour day. If a single one (or more) of the eight observations had coverage equal to or in excess of one-tenth, that day went into the "cloudy" category. Of the total of 3347 observations underlying Table 1, it will be seen that, on an annual average, only about 23 per cent were in the "clear" category, as defined on this stringent basis.

The cloudiest period of the year according to Table 1 comes during the summer rainy season, July and August, when only 3 per cent and 7 per cent, respectively, of all days yield eight consecutive "cloud-free" observations. In interpreting Table 1 for astronomical purposes, it must be realized that the presence of an active thunderstorm over a hundred miles away from the Tucson Weather Bureau station (as, for example, in the region of intense thunderstorm activity in the Huachuca-Douglas sector) at even a single one of the eight observation times on a given July or August day can serve to shift an otherwise "clear" day into the "cloudy" category. This is a situation that is not uncommon during the beginning and ending of the rainy season. It should also be noted that, although summer thunderstorm activity does persist into the evening in southeastern Arizona, its strongly defined maximum occurs just prior to sunset, so that, unlike other times of the year, the average summer cloudiness tends to be rather heavily weighted by phenomena that often pose no nighttime seeing problem. This weighting is not entirely unreal, however, since cirrus clouds of the anvile type spread out from afternoon and evening cumulo-nimbi and may last for several hours.

Table 1

Monthly and annual percentages of clear[1] and cloudy days as reported at the Tucson Weather Bureau office during the period 1945-54. Basic data from DesJardins (1958).

Month	N[2]	Per Cent Clear	Per Cent Cloudy
January	279	23	77
February	255	29	71
March	279	16	84
April	270	22	78
May	279	32	68
June	270	44	56
July	310	3	97
August	310	7	93
September	270	27	73
October	279	30	70
November	270	31	69
December	279	21	79
Annual	3347	23	77

[1]A "clear" day for purposes of this Table was one on which every one of eight equally spaced observations reported less than one-tenth cloud-cover. All other days were regarded as "cloudy."

[2]N is the total number of observations used in obtaining each percentage.

I have recently asked Tucson Weather Bureau personnel (R. L. King, Meteorologist-in-Charge, and E. T. Hawkinson) who have observed here for many years what their general impression is with regard to east-west differences near Tucson. They were emphastic in saying that the observable thunderstorm activity to the west of Tucson (i.e., to the observable limits of roughly 100-150 miles to the west) systematically tends to die out much earlier in the evening than does the activity to the east and southeast of Tucson. I have the same impression from my own less extensive observations (four summers) in the area. Such a pattern is quite reasonable on meteorological grounds inasmuch as Arizona summer thunderstorms are chiefly orographic in origin, and the fraction of terrain above, say, 5000 ft msl southeast of Tucson is very much larger than the same fraction to the southwest and west of Tucson. All of these considerations are of astronomical interest in that Kitt Peak, in the Quinlan Mountains about 45 miles southwest of Tucson, is one observatory site which is now under scrutiny by the AURA team. It is quite important to keep in mind that Tucson Weather Bureau cloud observations of summer thunderstorms are weighted upwards by ease of observability of anvils and nighttime lightning associated with the intense convective activity of the southeastern corner of Arizona. As will be noted below in the discussion of Arizona data on days with more than 0.01 inch of rain in July and August, the Sells records (just west of Kitt Peak) show only about half as many rain days as do records for stations near the Huachuca, Chiricahua, and Mule Mountains, a hundred-odd miles southeast of Tucson.

One of the meteorologically most interesting features of Table 1 is the abrupt drop in the percentage of clear skies between June and July. Indeed, while June is the month with the annual maximum of clear-sky percentage, July is the month with annual minimum of clear skies, when the present criterion is employed. This sudden change is a consequence of the peculiar monsoon tendencies of the summer circulation over the Southwest (see, for example, Bryson and Lowry, 1955). The effects of the arrival of the southeasterly monsoonal flow is so interestingly displayed by the mean daily cloud-cover values from which Table 1 was prepared that they have been graphed below for a period of twenty days centered on July. Since only 9 years of June observations were available, while 10 years of July data were used, the values have here been converted to percentages to permit direct comparison. During the past nine or ten years, the mean date of arrival of the monsoon, if judged simply by rise in total cloud-cover, would seem to have been June 30.

III. MEAN TUCSON NOCTURNAL CLOUDINESS.

The next Tucson cloud-cover analysis carried out for AURA was limited to three nighttime observations -- those made at 2030, 2330, and 0230 MST, since this is the period of critical importance in most astronomical work. It is essential to recognize that nighttime cloud-observing, as carried out by typical observers, is less than perfect. For example, the phase of the moon is known (Baer, 1956; and Appendix A of present report) to be strongly correlated with nighttime cloud frequencies because of the marked effect of illumination upon probability of cloud detection.

The data on nighttime cloud frequencies were drawn from the same study by DesJardins (1958) that yielded the frequencies of Table 1. The results are shown in Table 2 in the form of percentages of all observations in each time and month category that fall into each of four categories of cloudiness near the zero end of the cloudiness scale. The percentages do not add to 100 per cent in each category, of course, since the categories are not exhaustive. There are 3350 observations summarized in each time-category, distributed about equally over the twelve months. In the table, N gives the number of observations used in computing each indivdual month's percentages. The column-heading

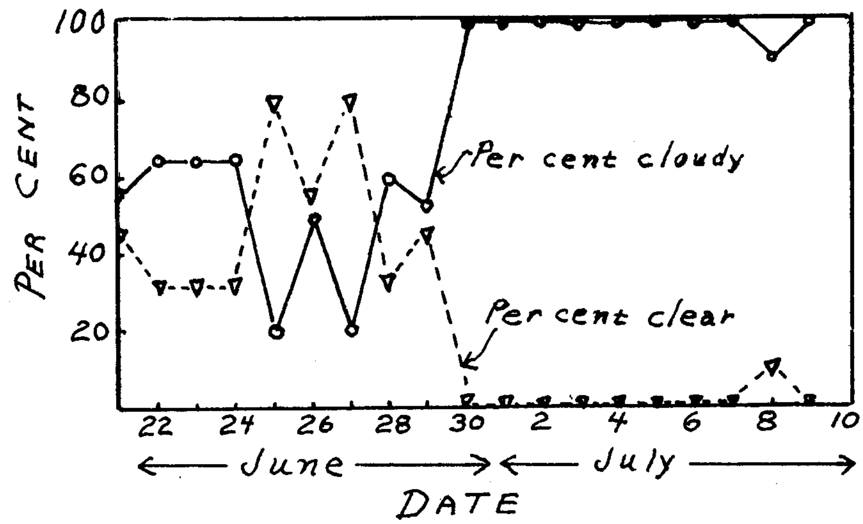

Figure 1. Sequence of mean daily percentages of clear and cloudy days near the mean date of arrival of the southeasterly monsoon at Tucson (1945-54). See text for explanation of terms.

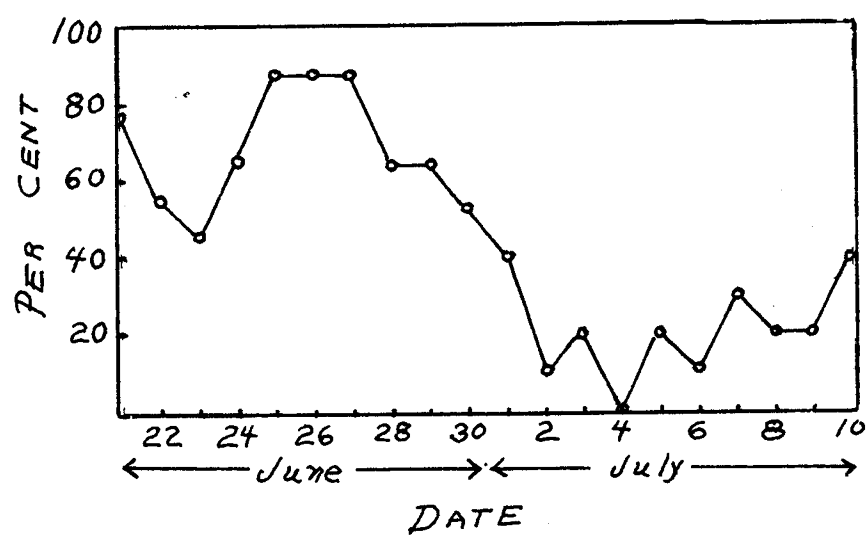

Figure 2. Sequence of mean daily percentage of 2030 MST observations at Tucson reporting less than one-tenth cloud-cover (1945-54).

Table 2

Mean cloudiness at Tucson for three nighttime observational periods during 1945-54. Basic data from DesJardins (1958). Figures in the body of the table are percentages of all cases falling into each category of cloudiness.

Month	N	2030 Cl[1]	2030 0+	2030 0.1	2030 0.2	2330 Cl	2330 0+	2330 0.1	2330 0.2	0230 Cl	0230 0+	0230 0.1	0230 0.2	2030-0230 Cl
January	279	37	16	2	3	52	6	1	4	52	7	1	3	26
February	255	45	12	2	3	51	9	3	4	53	8	3	3	26
March	279	34	12	5	3	47	9	3	3	47	9	2	3	22
April	270	33	20	4	4	57	8	4	2	56	10	2	3	23
May	279	38	27	3	2	65	8	2	3	66	11	2	3	28
June	270	37	31	4	3	62	14	2	3	64	15	1	3	30
July	310	5	10	3	3	14	9	3	4	15	12	4	3	2
August	310	10	16	3	4	21	12	4	5	25	13	5	4	6
September	270	36	21	4	3	53	15	6	2	57	12	3	4	30
October	279	49	12	2	4	57	13	3	3	57	11	3	4	33
November	270	49	13	4	3	56	10	3	3	57	11	1	3	32
December	279	40	11	1	3	46	9	2	3	49	8	2	2	25
Annual	3350	31	17	3	3	48	10	3	3	49	11	2	3	23

[1]In this Table, "Cl" means "clear," and here carries the meaning that no cloudiness in any amount was observed at the given observation time. "0+" means less than one-tenth, while "0.1" and "0.2" mean one-tenth and two-tenths sky-coverage, respectively.

"Cl" means "clear", and in this case has the more stringent implication that no cloud in any amount was observed. The amount labeled "0+" means "less than one-tenth but more than zero". The last column of Table 2 headed "2030-0230" shows the mean percentage of occurrences, within each month, when completely clear skies were reported for all three observations (2030, 2330, and 0230), so it is evident why these percentages are systematically lower than those under the heading "Cl" at the three individual observational times.

In general, the annual course of Tucson nighttime cloudiness appears to follow the pattern of the daily-mean cloudiness summarized in Table 1. The only exception is found in the case of the May and June 2030 MST observations. At these times, the percentage of clear skies is noticeably lower than in the late fall and early winter for that same hour; while at 2330 and 0230, May and June exhibit the year's highest percentages of clear skies (in agreement with the cruder day-long data of Table 1). One possible explanation of this anomaly that seems plausible is the following: 2030 is only slightly later than the 1800-1900 time of maximum summer thunderstorm activity in most parts of the Southwest. By about mid-June, the stronger thunderstorms in northern Sonora begin to be visible from Tucson at night via lightning observations. It is possible that until about 2030 on evenings in the latter half of June these distant storms are still electrically active enough to be observable to the south of Tucson, thereby depressing the reported frequency of "clear" skies; while, already by 2330 in late June, the chances of spotting such Mexican storms is diminished by virtue of the normal diurnal cycle of thunderstorm activity. This diurnal variation, it is to be noted, is clearly revealed in Table 2 by the almost threefold increase in frequency of clear skies between 2030 and 2330 in July and twofold increase for the same time interval in August.

Note that even during the parts of the year that do not fall within the July-August thunderstorm season, there is a distinct trend towards greater mean frequencies of "clear" reports as the night progresses. Now it is known that Tucson's wintertime precipitation exhibits nearly negligible diurnal variation (McDonald, 1956), and this should be a fairly reliable indication that there is also no strong diurnal cloudiness variation in winter at Tucson. Yet the mean percentages of reported "clear" skies at Tucson for the three winter months of December, January, and February are 41 per cent at 2030, 50 per cent at 2330, and 51 per cent at 0230. Even though 2030 is past sunset-time in winter, it seems almost certain that most of this apparent nocturnal rise in frequency of clear skies in winter is due to sheer difficulty in seeing clouds (except near full moon) at night. There is a well-known inertial tendency for observers to "carry cloud reports along" for a short time after sunset even when not discernible, and this could easily account for the fact that 2030, though after sunset, is still a time of relatively low frequency of wintertime "clear" reports. In summer, on the other hand, there is a real and, in fact, extremely strong diurnal variation in cloud-cover so considerabley greater trust may be placed in the reality of the diurnal progression of frequencies of clear skies in Table 2 for July and August, and to some extent for June and September, too.

Note that when all three nighttime observations of Table 2 are lumped, as in the last column, July comes out with only 2 per cent of all days exhibiting completely clear skies from 2030 to 0230. Anyone familiar with the summer orographic thunderstorm distribution of southern Arizona will not be greatly surprised by this, since, as has been noted above, a single nocturnal storm developing over a hundred miles away and producing lighting activity for only ten or fifteen minutes can spoil a "clear" record in the sense of the last column of Table 2.

For photometric observations demanding six continuous hours completely free from clouds, it would appear from the last column of Table 2 that there is an empirical probability of about 0.3 of favorable observing near Tucson during all months of the year except July and August. As has already been noted, however, some downward adjustment for the imperfection of nighttime cloud observation is almost certainly needed, though the magnitude of this correction is not known. For photometric or other astronomical work that could be successfully carried out in only about one hour, the 2030 observations (less suspect on grounds of nighttime observational difficulties) suggest an empirical probability of about 0.4 for months not including the summer thunderstorm season. Although it is obviously desirable to be able to make firmer statements than the preceding, it is not possible within the limits of the avilable type of observations.

The original analysis underlying Table 2 yielded individual daily mean frequencies at each of the three nighttime observation periods. Using just the more trustworthy 2030 observations, I have plotted in Figure 2 the decline of percentage occurrence of completely clear skies during late June and early July. The date of June 30 suggested by Figure 1 for the arrival of monsoonal cloudiness in the Tucson area also seems to serve quite well to identify the mean time of monsoon arrival as depicted in Figure 2. Only very active convective clouds can persist to the 2030 period (about one hour past Tucson sunset near 1 July), and it is the almost discontinuous arrival of air mass conditions favoring generation of such clouds near the end of June that leads to a rapid deterioration of the clear-sky nocturnal conditions that prevail in the dry foresummer period in southeastern Arizona. If it were not for dilution by observations of distant thunderstorms over northern Mexico in late June, this break in the 2030 Tucson cloudiness would almost certainly be even more abrupt.

IV. FOURTEEN-YEAR MEAN MONTHLY AND ANNUAL NOCTURNAL CLOUDINESS AT TUCSON, YUMA, LOS ANGELES, AND SAN DIEGO.

The next type of study carried out was designed to compare cloudiness in southern Arizona with that of coastal southern California. The only relevant cloud-cover data immediately accessible at the time this study was begun were those contained in the daily weather observations reported on the U. S. Weather Bureau's Washington, Daily Weather Maps. Inasmuch as these maps are based upon synoptic reports for 2330 MST, these data do fortunately concern the nighttime period of prime astronomical interest, so the Institute's files for the 1943-57 period were utilized to extract a large amount of simple comparison data. Approximately 5000 daily maps were used in this tabulation, and the cloud reports extracted therefrom were punched on IBM cards for convenience of analysis.

As one type of comparison, the mean monthly frequencies of clear and cloudy skies were computed for the 1943-57 period for Tucson and Yuma in southern Arizona and for Los Angeles and San Diego in coastal southern California. In Table 3, these averages are summarized in the form of percentages of all observations falling into each of two cloudiness categories, "clear" and "cloudy". "Clear" sky in Table 3 means less than one-tenth coverage (not, therefore, completely cloud-free sky); and "cloudy" means one-tenth or greater coverage. (The difference in the "clear" criterion between Table 2 and Table 3 was necessitated by virtue of the code according to which cloud-cover is plotted on synoptic charts of the type used in obtaining the data of Table 3. Table 2 is based on the very much more detailed analysis of the original Tucson records carried out by DesJardins (1958).)

First, examining just the annual averages as crude overall measures of cloudiness, it will be seen that the order of stations with decreasing frequency of "clear" skies is Yuma, Tucson, Los Angeles, San Diego, the range

Table 3

Mean monthly and annual percentages of clear versus cloudy skies during the 14-year period 1943-57. Data read from approximately 4800 Washington Daily Weather Maps.

Month	N[1]	Tucson		Yuma		Los Angeles		San Diego	
		Clear[2]	Cloudy	Clear	Cloudy	Clear	Cloudy	Clear	Cloudy
January	392	49	51	57	43	47	53	43	57
February	394	53	47	66	34	47	53	41	59
March	390	48	52	64	36	42	58	33	67
April	407	61	39	71	29	39	61	24	76
May	394	66	34	78	22	39	61	17	83
June	382	64	36	84	16	52	48	16	84
July	392	18	82	62	38	56	44	14	86
August	424	19	81	68	32	58	43	21	79
September	412	56	44	79	21	59	41	33	67
October	425	60	40	74	26	50	50	31	69
November	404	62	38	73	27	58	42	48	52
December	417	48	52	59	41	46	54	41	59
Annual	4833	50	50	70	30	49	51	30	70

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[1]N is total number of 2330 MST reports used in obtaining each set of monthly (or annual) percentages. Missing cases have here simply been excluded from the computation of percentages.

[2]"Clear" means sky-cover of <u>less than</u> 0.1 in this Table. See text concerning necessity of using this criterion in the above tabulation.

extending from 70 per cent clear skies at Yuma to 30 per cent at San Diego for the 14 years of 2330 MST observations.

Next, inspection of the monthly means of Table 3 reveals that San Diego's low annual average is strongly influenced by the very low percentage of clear skies during summer, particularly during May-July. This is chiefly due to prevalence of low stratus, which poses no observing problem to a mountaintop observatory at altitudes in excess of only a few thousand feet. On the other hand, the almost equally low percentage of "clear" skies reported at Tucson in July and August, during the height of the summer monsoonal flow, is due to chiefly to deep convective storms which do pose a real observing problem when they occur within a few tens of miles of a given station. Hence, the comparative annual and summer statistics of Table 3 cannot be applied in very direct fashion to the observatory site-selection problem. It is unfortunate that no mountaintop observations from southern California are immediately available, since these would permit more direct comparison with the Arizona data. Even inland observations would be more relevant to the problem, but none were accessible when this study was being carried out.

The data of Table 3 are, it should next be noted, fairly unbiased indicators of the degree of sky-cover above mountaintop altitudes in these four California and Arizona localities in the winter half-year, since in that time of year neither a predominance of coastal stratus along the Pacific coast nor locally peculiar observability of remote cumulo-nimbi in southeastern Arizona enter to distort the astronomical implications. It is, then, of interest to note that a simple averaging of the six monthly percentages for November through April yields the following 14-year mean percentages of "clear" skies at these four stations at 2330 MST.

Yuma	65 per cent
Tucson	53
Los Angeles	46
San Diego	38

Apparently the Yuma-Tucson belt is superior to the coastal California belt in winter as regards nocturnal sky observability. Since the duration of the nighttime intertwilight period in winter is substantially larger than that for summer at 30°-35°N latitude, this winter cloudiness advantage would seem to be considerably more important than the summer disadvantage of the Yuma-Tucson belt (or, more accurately, the summer disadvantage of the area from Tucson east and southeast, since Yuma's summer skies are very clear). The question of whether stratus is an important factor in the latter half of the winter is one I am unable to answer conclusively on the basis of personal knowledge or on the basis of information in the literature. Probably the persons best qualified to speak on this point are the Palomar and Wilson astronomers who have the unique advantage of looking down on shallow stratus decks from above. My supposition here is that most of the Los Angeles and San Diego winter half-year cloudiness is due to passing cyclonic systems that will also affect mountaintop sites. If this is contradictory to the Palomar-Wilson experience, the latter must be accepted as the more reliable for site-selection purposes.

It is not difficult to understand (in rainshadow terms) the lower cloud frequencies in Yuma than in coastal southern California in winter; but it is less obvious why Tucson, still further from Pacific moisture sources, should exceed Yuma in winter cloudiness. Two factors must be chiefly responsible, though it is not now possible to evaluate their relative importance: First, Tucson lies about 1500 ft. higher than Yuma and hence a slow ascent of air in the prevailingly westerly flow of winter is topographically induced, especially when an extratropical Pacific cyclone moves through the Southwest. This topographic lifting must bias Tucson's climate towards mean cloudiness slightly greater than at Yuma. Second, Yuma is not surrounded by any mountain ranges high enough to force winter air masses to their lifting condensation level, while Tucson Weather Bureau observers look out upon several major ranges with summits near 9,000 ft., several thousand feet above typical LCL's (lifting condensation levels) during passage of winter cyclonic storms. (In a study now in progress, I find that winter LCL's average about 6000 ft. near Tucson when lows are moving through).

Kitt Peak at 6875 ft. (one site currently under consideration in Arizona) is almost certainly high enough to raise air in southwesterly cyclonic flow to the local LCL, though Kitt lies close enough to the north end of the Quinlan and Baboquivari Ranges that flow-around may act to reduce the local intensity of the lifting condensation. It seems likely from LCL statistics that a mountain about two thousand feet lower would produce substantially less <u>local</u> orographic winter cloudiness. (The Tucson Mountains are a good example: With crests near 4000 ft., the Tucsons are not infrequently cloudless even when the Santa Catalinas twenty miles northeast are cloud-covered, especially near the beginning or ending of a major storm-passage.) At the same time, a range even a few tens of miles farther west than the Quinlans might be expected to be significantly less under the influence of the summer monsoonal effects, since there is good evidence that the monsoonal current exhibits a very strong mean precipitable-water-vapor-content decrease toward the west in the general vicinity of Tucson. (In an unpublished study of mean upper-air mixing ratios, I have found, for example, that the August 700-mb mixing ratio has, during the decade 1946-55, averaged 6.6 g/kg over Tucson but only about 4.5 g/kg over Yuma; whereas, moving eastward from Tucson, one finds only a very gentle increase to a maximum of merely 7.2 g/kg, at Tucson's latitude, roughly over Alomogordo, N. M.). For these two reasons, then, it might seem that some range such as the Quijotoa Range, with summits under 4000 ft. and lying about 30 miles west-northwest of the Baboquivaris and the Quinlans could offer somewhat better observing from the viewpoint of mere cloud conditions. However, the advantage gained during the roughly two-month-long summer thunderstorm period would probably not be very great, due to the nature of the winds at high altitudes over southern Arizona in summer. When a cumulo-nimbus rises to near the tropopause (mean altitude in summer about 50,000 ft. over most of the Southwest), the typical ice-crystal anvil structure spreads laterally due to the thermal stability characteristic of the base of the stratosphere. As a result, anvil cirri drift with the winds that prevail near the tropopause, and may spread out for several tens of miles downwind. The long lifetimes of cirrus crystals can thereby impose a temporary obscuration over a mountaintop twenty to forty miles downwind of the original site of the convective storm for an hour or two after decay of the generating thunderstorm.

To estimate how tropopause-level winds might influence observatory site characteristics in southern Arizona, I have obtained mean tropopause-level wind data for July for three successive years, 1955, 1956, and 1957 for Tucson. Out of a total of 91 daily July observations, it appears that the mean wind at the tropopause has a speed of about 15 mph, with quite variable direction: About 33 per cent of all the July tropopause winds analysed blew from compass points in the interval 0-90°, about 30 per cent from 100-180°, about 31 per cent from 190-270°, and about 6 per cent from 280-360°. An observatory on, say, Quijotoa Mountain would thus be under the influence of anvil cirrus from the Baboquivari-Quinlan area in something like 25-30 per cent of the times that thunderstorms formed in that area, which would tend to cancel the advantage gained by going as far northwest as Quijotoa. By the same argument, the above wind-direction distribution suggests that anvils from thunderheads over Baboquivari Peak may drift over Kitt Peak in about 20-25 per cent of all such cases, while the Sierritas may send anvils to Kitt in about 25-30 per cent of all Sierrita storms.[1] Since the Comobabis also generate orographic cumulo-nimbi to some extent, the Quijotoas would probably be influenced by Comobabi anvil cirrus in about the same fraction of all cases as Kitt will be influenced by Sierrita anvils, although the absolute frequency of thunderstorm activity over the Comobabis is certainly less than that over the Sierritas. In all, it would seem that an observatory site on the Quijotoas would be better than one on Kitt in July and August, but probably only slightly better. And in winter, though a Quijotoa site would not often be overlain by Quijotoa-created clouds at the LCL, probably well over half of the loss of observing in winter at <u>any</u> site in this general locale results from transient <u>overcasts</u> due to passing cyclones. Hence the advantage of a lower range, even in winter, is not so important as might be inferred from LCL arguments alone. Since there are many other considerations dictating site-selection at altitudes rather greater than those available in the Quijotoa area, it would appear that the meteorological advantages of a site in the Quijotoas are unimpressive when compared with Kitt Peak advantages.

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[1] These several percentages are <u>not</u> additive, and the basic frequencies of storm activities are not obviously the same for these ranges. My own impression is that cumulo-nimbi form over the Sierritas significantly more frequently than over the Baboquivari-Quinlan barrier. The Sierritas' geometry is quite different from that of the long, narrow Baboquivari-Quinlan Range and it is meteorologically reasonable that this marked difference in geometry favors greater convection over the Sierritas. Unfortunately, the theory of orographic effects on convection is in much too primitive a state to permit more than rough conjecture to support these limitive personal observations.

Broadly speaking, the Tucson and Yuma data of Table 3 warrant an interpolation to arrive at a rough estimate of conditions at a point such as Kitt Peak. Such an interpolation, if made in simple linear fashion, suggests that Kitt will resemble Tucson rather more than it resembles Yuma, and this implication seems meteorologically plausible. More than that cannot now be said on the basis of the type of data at hand. (See however Appendix B, concerning available information on haze and dust layers.)

V. COMPARISONS OF CONCURRENT NOCTURNAL CLOUD-COVER OVER COASTAL SOUTHERN CALIFORNIA AND SOUTHERN ARIZONA.

It was relevant to the AURA site study to determine, at least approximately, how the cloudiness in southern California was temporally related to that in southern Arizona. Hence the IBM punching of 2330 MST cloud-conditions that led to Table 3 was planned in such a way that the punchcards could be processed to yield information on concurrent conditions in California and Arizona. A variety of possible modes of getting at temporal phase relations was possible, but only one method has been used. All of the cards were first sorted into two sets comprising those for which the Los Angeles entry showed, respectively, clear or cloudy skies. Then each one of these two categories was, in turn, so sorted as to yield the number of cases where Yuma was clear or cloudy and then sorted to yield the number of cases where Tucson was clear or cloudy. Then the whole deck was resorted on the basis of San Diego cloudiness and a similar analysis was then made.

The resulting data are presented for Los Angeles in Table 4 and for San Diego in Table 5. Since slightly over 4800 observations at each stations were processed these data may be expected to be statistically fairly representative of the 1943-57 period. (This statistical stability does not, of course, improve the basic caliber of the cloud reports themselves, or remove

Table 4

Concurrent state of the night sky over Yuma and Tucson for cases where Los Angeles was respectively clear and cloudy. For explanation see text. Based on approximately 4800 2330 MST Weather Bureau observations for the period 1943-57. "Clear" means less than one-tenth sky cover here.

	Los Angeles Clear (2328 Cases)				Los Angeles Cloudy (2508 Cases)			
	Yuma Clear	Yuma Cloudy	Tucson Clear	Tucson Cloudy	Yuma Clear	Yuma Cloudy	Tucson Clear	Tucson Cloudy
January	74	26	58	42	42	58	41	59
February	82	18	62	38	52	48	43	57
March	84	16	59	41	49	51	40	60
April	82	18	76	24	64	36	52	48
May	82	18	75	25	75	25	61	39
June	88	12	66	34	78	22	61	39
July	68	32	20	80	55	45	16	84
August	74	26	22	78	58	42	15	85
September	81	19	56	44	77	23	57	43
October	80	20	64	36	68	32	55	45
November	86	14	70	30	55	45	51	49
December	80	20	59	41	41	59	39	61
Annual	80	20	55	45	60	40	45	56

Table 5

Concurrent state of the night sky over Yuma and Tucson for cases where San Diego was respectively clear and cloudy. For explanation see text. Based on approximately 4800 2330 MST Weather Bureau observations for the period 1943-57. "Clear" means less than one-tenth sky cover here.

	San Diego Clear (1471 Cases)				San Diego Cloudy (3393 Cases)			
	Yuma Clear	Yuma Cloudy	Tucson Clear	Tucson Cloudy	Yuma Clear	Yuma Cloudy	Tucson Clear	Tucson Cloudy
January	75	25	64	36	43	57	38	62
February	82	18	65	35	55	45	43	57
March	86	14	68	32	53	47	39	61
April	83	17	76	24	68	32	56	44
May	86	14	83	17	76	24	62	38
June	86	14	65	35	83	17	63	37
July	63	37	21	79	62	38	17	83
August	78	22	29	71	65	35	17	83
September	87	13	61	39	76	24	53	47
October	85	15	71	29	69	31	54	46
November	92	8	77	23	56	44	48	52
December	85	15	68	32	40	60	33	67
Annual	83	17	65	35	64	36	43	57

difficulties due to obscuration of truly bothersome high clouds as a result of presence of low clouds which may themselves pose no seeing problem.)

Considering Table 4 first, one sees that on all those 2328 occasions when Los Angeles reported clear (i.e., less than one-tenth sky-coverage) at 2330 MST, Yuma was concurrently clear in 80 per cent of the cases and Tucson was concurrently clear 55 per cent of those same times (annual average percentages). It may be noted, by way of further clarification of the meaning of Table 4, that these instances of clear skies at Los Angeles constitute, according to the last line of Table 3, 49 per cent of all Los Angeles 2330 MST observations in the 1943-57 period. Since Table 3 reveals that Yuma's annual average percentage of clear skies for this same period was 70 per cent, these several figures suggest a non-random relation of clear conditions between Los Angeles and Yuma (see also below, Section VI). The other implications of Table 4 are self-evident and need no discussion here.

Table 5 shows the corresponding joint frequency distributions for San Diego *versus* Yuma and Tucson. Of the 30 per cent of all days (1471 days) throughout the year at which San Diego reported clear at 2330 MST (see Table), Yuma concurrently reported clear 83 per cent of those times, while Tucson concurrently reported clear 65 per cent of those times. Note that during the mid-summer, San Diego is so frequently cloudy (due to low coastal stratus) that the degree of correlation between its reports and those in Arizona, especially Yuma, goes very low. Thus, in June (when about 84 per cent of all 2330 MST San Diego's skies are cloudy (Table 3), Yuma reports clear in 83 per cent of the cloudy-San Diego cases and even Tucson reports clear in 63 per cent of those instances (and the latter despite the summer convective cloud-cover observable from Tucson). The San Diego stratus usually have tops under 3000 ft. msl., however; so again it must be emphasized that these relationships are not directly interpretable in terms of astronomical observing opportunities for mountaintop sites in California.

VI. SOME ARIZONA-CALIFORNIA CORRELATIONS.

In a general way, mere inspection of Tables 4 and 5 reveals the degree of correlation between the reports from southern California and southern Arizona. It is next of interest to ask whether a statistically significant relationship exists and to obtain some measure of the degree of correlation for selected parts of the year.

With respect to the first of these questions, we may consider as an example the Los Angeles-Yuma relationship, averaged over the whole year. Table 3 shows that Yuma's annual average per cent of clear skies is 70. Hence, if there were only random relation between Yuma and Los Angeles cloud conditions, we would expect just 70 per cent of all clear-Los Angeles cases to be clear-Yuma cases, and also 70 per cent of all cloudy-Los Angeles cases to be clear-Yuma cases. Instead, Table 4 shows, respectively, 80 and 55 per cent, or 10-15 percentage units respectively above and below the expectation values. Are these departures statistically significant? Highly. Application of the Chi-square test to the original frequencies from which Table 4 was computed, yielded a value of Chi-square of 228 with one degree of freedom, or about twenty times greater than the value of Chi-square significant at the 0.1 per cent level. Clearly, the relation is not just a random effect, but must in fact result from large-scale synoptic controls that tend to govern cloudiness at both stations.

Having established, for a single representative case, the statistical reality of some degree of relationship, it is next of interest to compute, as a simple but here adequate measure of correlation, the tetrachoric correlation coefficients between some of these California and Arizona frequencies. I have computed twelve of the more interesting tetrachoric coefficients out of the many possible correlations that could be formed from the original data. These twelve are presented in Table 6. The Los Angeles-Yuma annual correlation is

Table 6

Tetrachoric correlation coefficients r_t for the sky-condition frequencies at two California and two Arizona stations (1943-57).

Station-pair	Annual r_t	Jan-Feb r_t	July-Aug r_t
Los Angeles-Yuma	.87	.81	.25
Los Angeles-Tucson	.15	.51	.14
San Diego-Yuma	.39	.52	.15
San Diego-Tucson	.33	.64	.21

seen to be quite high, 0.87, yet the Los Angeles-Tucson annual correlation is low, 0.15, due chiefly to summer effects. San Diego is only weakly correlated with Yuma and Tucson on an annual basis, the San Diego-Arizona coefficients lying between 0.3 and 0.4. To see how the winter and summer periods might be contributing to these annual trends I obtained the tetrachoric coefficients from the original raw frequencies summed first over January-plus-February to indicate "winter" conditions and then summed over July-plus-August to indicate "summer" conditions. Table 6 shows that the degree of Los Angeles-Yuma correlation is quite high in winter (0.81), but negligible in summer (0.25). That these two pairs of months cannot be taken to represent the winter and summer <u>half-years</u> is clearly indicated by the fact that the <u>annual</u> coefficient for Los Angeles-Yuma is even higher than either the January-February or the July-August value; other months boost the annual correlation even above the high January-February value. Los Angeles and Tucson exhibit only moderate correlation in the January-February period ($r_t = 0.51$), but entirely negligible correlation in July and August ($r_t = 0.14$). Curiously, San Diego and Yuma appear to be only about as well correlated in January and February as are Los Angeles and Tucson, despite the fact that the interstation distance is about three times greater for the latter station-pair than for the former pair.

Most surprising of all, however, is the indication that San Diego is better correlated with Tucson in January and February ($r_t = 0.64$) than it is with Yuma ($r_t = 0.52$)! Can this be a consequence of the fact that both San Diego and Tucson have orographic barriers immediately downwind (to the east) while Yuma has none? This would tend, during passage of cyclones and troughs, to give rather similar orographic cloud-cover as viewed by Weather Bureau observers at the San Diego and Tucson stations, while Yuma observers are not in viewing distance of any high and extensive ranges that can yield appreciable orographic effects in winter.

The last column of Table 6 reveals, as would be expected from general meteorological considerations, that the July-August cloud-cover in coastal southern California is almost entirely unrelated to that of southern Arizona. To me, it seems almost surprising that no negative coefficients appear among the four values in this last column of Table 6. Perhaps the rare instances wherein moisture from the Gulf of Mexico extends all of the way to the coast (e.g., July-August, 1955) serve to hold these correlations to above-zero values despite the coastal stratus effects that should tend to yield negative correlation, at least between San Diego and Yuma.

It may be well to note, for the benefit of any reader not familiar with the properties of the tetrachoric correlation coefficient, that r_t is only a moderately reliable estimator of correlation, inferior in most contexts to the produce-moment correlation coefficient. However, the latter cannot even be used in principle with the type of tabulational data at hand; and also, experience does show (McDonald, 1957) that r_t is usually within about one standard error of the product-moment correlation coefficient in instances where both can be computed. Hence the values of Table 6 may be taken as tolerably reliable indicators of the degree of correlation between the cloudiness frequencies of the two geographic areas involved.

VII. PHASE RELATIONS BETWEEN 2330 MST CLOUDINESS OVER TUCSON AND LOS ANGELES.

As one additional approach to the problem of the relative cloudiness in southern Arizona and southern California, two years of Washington Daily Weather Maps (1955-56) were used by Mr. Robert Rombaugh of the Institute staff to tally the concurrent cloud-cover conditions at Los Angeles and Tucson. A total of 727 maps were examined to obtain the following percentage frequency distribution according to eight types of concurrent conditions at Los Angeles (LAX) and Tucson (TUS):

1) Clear at both LAX and TUS - 27% (of all cases)
2) Middle or high cloud at TUS, no middle or high cloud LAX (but possibly scattered or low at LAX) - 21%
3) Low overcast LAX, clear TUS - 13%
4) Low scattered or broken LAX, clear TUS - 10%
5) Low overcast LAX, high or middle TUS - 8%
6) Middle or high cloud LAX, none TUS - 9%
7) Middle or high cloud both LAX and TUS - 8%
8) Miscellaneous - 4%.

In Types 3 and 5 above, with low overcast prevailing at Los Angeles, it was, of course, not possible to ascertain presence of absence of middle or high clouds for simple obscuration reasons. If, then, we merely assume for lack of better information, that just 50 per cent of these cases did have middle or high clouds above the low overcast at Los Angeles, then half of each of the Type 3 cases were instances of better sky visibility at Tucson than at Los Angeles, while the other half were instances where mountaintop seeing would have been just as good at Los Angeles (despite a low overcast) as at clear Tucson. Similarly, of the Type 5 cases, half would then be favorable to Los Angeles, the other half equally poor at both localities. Making this crude guess in these indeterminate cases we see that Tucson had astronomically better observing conditions than Los Angeles in 15-1/2 per cent of the cases (namely, 6-1/2 per cent in Type 3 plus 9% in Type 6, while Los Angeles had better seeing than Tucson in 21% of all cases (namely, the 21 per cent falling in Type 1 plus 4 per cent of Type 5).

On the other hand, if every time Los Angeles had a low overcast, there actually had been a high overcast above it, 22% (Type 3 and 6) would be favorable to Tucson seeing but only 21% would be favorable to Los Angeles seeing. And, at the other extreme possibility where each low overcast at Los Angeles might be accompanied by totally clear skies at high altitudes, only 9 per cent would be favorable to Tucson (Type 6 only) but 29 per cent (Types 2 and 5) would be favorable to Los Angeles.

In all, it seems probable that these two years' data must be taken to imply generally clearer skies above mountaintop altitudes in the Los Angeles vicinity than in the Tucson vicinity on a year-round average basis, but only slightly better. To see this, we may return to the hypothesis having highest *a priori* probability, namely that which assumes exactly half of all cases of low overcasts at Los Angeles were accompanied by middle or high clouds that would have interfered with mountaintop seeing. Totalling all cases where mountaintop observing would have been possible at each station yields the estimates of 68-1/2 per cent for Los Angeles, and 59 per cent for Tucson, a small difference in favor of Los Angeles.

As was noted earlier, Tucson's winter skies are, however, clearer than Los Angeles', and the long winter nights give this winter advantage a roughly twofold weight-factor as contrasted with summer disadvantages.

VIII. LARGER-SCALE PATTERNS OF CLOUDINESS OVER THE SOUTHWEST.

The preceding analyses have revealed a number of characteristics of cloud conditions at four localities in the two states of California and Arizona. It is of both climatological and astronomical interest to consider next how these four localities fit into broader patterns of cloud-cover over the entire Southwest.

One source of cloudiness data that is immediately accessible without elaborate tabulations of original observations is the Weather Bureau's serial publication, Local Climatological Data. In the annual summary issues of this publication, full-record means of several types of cloud statistics are published. Unfortunately, the record-lengths vary from one station to another, and this can introduce some heterogeneity into the data as a consequence of possible secular trends. However, since initial analysis revealed highly consistent patterns over large areas, these published averages have been used to carry out a number of analyses of regional cloudiness patterns. In all cases, the means are those for the total available period of record ending with December, 1956. Record-lengths will be listed, for reference, in each tabulation.

A. Mean per cent of possible sunshine. In the geographic region of interest in the present study, a total of twenty-two Weather Bureau stations make daily sunshine-duration measurements. Inasmuch as these are not subjective estimates (as are all Weather Bureau reports of sky-cover), it is immediately tempting to regard the sunshine-duration figures as distinctly superior to the sky-cover figures in evaluating relative cloudiness at stations in different areas. In general, this superiority probably does exist, but it is well to note several inherent weaknesses in this type of data, especially for the information of astronomers reading this report.

For about the past five years, the Weather Bureau has been replacing the previously used Marvin sunshine-duration-records with a new photoelectric duration-records; so the 1956 cumulative means employed here will represent results obtained, in general, with both types of devices. Nevertheless, for most stations, it is chiefly observations obtained with the Marvin device that dominate the cumulative means (see Table 7 for record lengths).

For a description of the Marvin recorder see Middleton and Spilhaus (1953, p. 221) and for a detailed discussion of certain of its performance characteristics see Brooks and Brooks (1947). This device is essentially a differential air thermometer in which mercury is forced from a lower blackened bulb upwards into a constriction containing an electrical contact. Another contact is sealed into the mercury bulb and these are externally connected to a duration-recording device in the Weather Bureau office. When sunlight warms the blackened bulb to such an extent that the mercury expands far enough to make contact with the electrode in the stem, the duration-recorder is activated. The daily record on a day with broken clouds is thus a series of intermittent duration-counts, the sum of which yields the total daily sunshine duration. The quotient of this sum divided by the astronomically determined time-period between sunrise and sunset is defined by the Weather Bureau as the "per cent of possible sunshine" for the given day.

The principal weakness of the Marvin recorder was that it was not readily adjusted to a truly uniform threshold of response. The Weather Bureau instructions to observers stipulated that the device should, from time to time, be tilted just far enough off vertical that the mercury column barely closed the circuit at times when the disk of the sun was barely discernible through the clouds, as with thick cirrostratus. (Brooks and Brooks (1947) found by comparisons with pyrheliometric observations, that a well-adjusted Marvin has a threshold of about 0.37 langleys per minute.) There is little doubt that the calibration procedure must have resulted in appreciable differences between thresholds at various stations. In addition, the Marvin recorder was sensitive to both direct and diffuse sunshine, and since it is known that reflection from sides of clouds of vertical development can be quite large, one cannot say that a Marvin record was truly a record of the time the sun's disc was more than barely discernible, even with a nicely calibrated instrument.

The newer photoelectric sunshine duration recorder, in principle, is free from the two main difficulties of the older Marvin device. Two photocells, uniformly exposed to the diffuse radiation from the sky, but with one shaded from direct sunlight by an occulting ring (adjustable, to follow the declination of the sun), are electrically opposed. Their net voltage, controlled only by direct solar radiation, must rise above a standard value to actuate a relay that in turn actuates the remote duration-recorder in the Weather Bureau office. I am unaware of any published reports on the operating characteristics of this new device. That it may not yet afford a fully satisfactory answer to the short-comings of the Marvin recorder is suggested by the fact that the Tucson Weather Bureau airport office has had to replace the sensing element in its photoelectric device some twelve times since its installation in 1953. Reportedly, the Phoenix office has had similar difficulties, but whether this is in some way a regional peculiarity associated with very high insolation rates or is a basic design weakness, is not known to me.

There is an important difference between per cent of possible sunshine and per cent sky-cover as estimated by Weather Bureau observers. Observers are instructed to report as the fractional sky-cover the fraction of solid angle of the celestial hemisphere that is subtended by bases or sides of clouds. With, say, even only a few tenths of cumulus clouds as measured in terms of vertically projected coverage (basal-area coverage), a given observer can see blue sky only within a limited vertical cone above his position, since the sides of clouds at low altitude-angles completely fill the "sky" in the solid angle sense, and he may thence report five or six tenths coverage, depending on cloud geometry. This is often called the "echelon effect" of distant clouds. (Actually, my own experience has been rather distrubing on this point in that I have found many persons who have done cloud observing of one sort or another who have had the misimpression that an observer is to estimate the vertically projected area (basal area) of clouds and report this as the fractional sky-cover. Weather Bureau instructions seem unnecessarily vague on this point and one must interpret sky-cover percentages with these difficulties well in mind.)

Now the sunshine-duration recorders give a measure of sky-cover that is somewhat similar to that which the well-trained observer is supposed to give, but only for a strip of sky along the sun's diurnal path. On an imaginary day with uniform cloud cover at all times and over an area of a hundred or so miles in radius (area of observability of clouds), a sunshine-duration recorder should give a per cent of possible sunshine that is identical with the observer's reported sky-cover if the sun crosses the meridian at zenith. But if the noon solar altitude is quite low, the duration-recorder sees a strong echelon effect that will tend to suppress the computed per cent of possible sunshine to a value below that reported by the well-trained observer. Hence, it should be clear that many obstacles stand in the way of clear-cut interpretation of available sunshine and sky-cover figures (and there are a number still not cited here). Viewing the matter astronomically, one sees that if daytime cloud characteristics were to persist regularly into the night, then the sunshine-duration recorder probably gives the most realistic estimate of available observing time (for celestial objects whose declination happens to be close to that of the sun). But of course, many cloud types (notably cumuliform types) have strong diurnal variability, and one is confronted with a basic meteorological difficulty in drawing inferences concerning astronomical observability from data on per cent possible sunshine. For one class of astronomical work, solar studies, the latter difficulty does not enter, but for nighttime work, sunshine statistics can only be regarded as useful supplementary data on cloud climatology.

Despite the evident difficulties in drawing firm conclusions from data based on past and present sunshine-duration observations, these data are, in principle, "objective" in nature. Hence the monthly and annual 1956 cumulative means for twenty-two southwestern stations have been summarized in Table 7, grouped by states. The length of record in year, N, is listed for each station.

Table 7

Mean monthly and annual percentage of possible sunshine for twenty-two southwestern Weather Bureau stations. All values are cumulative means effective December, 1956. The record length N is given in years.

Station	N	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Arizona														
Phoenix	61	76	78	82	88	93	94	83	84	89	88	84	76	85
Prescott	10	69	76	80	82	89	91	72	74	85	86	83	72	80
Tucson	9	78	85	85	90	93	93	74	82	91	92	91	82	86
Yuma	6	84	93	92	94	97	98	90	93	97	96	91	85	93
California														
Eureka	46	39	44	50	53	54	56	52	46	51	48	42	38	48
Fresno	17	49	66	76	82	89	96	98	98	96	88	71	44	82
Los Angeles	16	71	74	74	65	67	67	80	82	81	74	79	70	74
Red Bluff	37	48	59	65	73	80	86	95	95	88	77	61	49	75
Sacramento	8	39	61	68	72	81	88	96	94	92	84	59	40	75
San Diego	16	67	72	71	59	59	58	65	67	68	64	76	68	66
San Francisco	20	53	61	66	68	71	73	64	62	71	70	63	51	65
Colorado														
Denver	7	67	72	72	64	65	72	70	71	77	77	65	65	70
Grand Junction	10	53	63	63	68	70	78	76	72	81	77	65	58	69
Pueblo	16	71	72	71	67	67	76	76	75	79	77	73	71	73
New Mexico														
Albuquerque	17	69	74	73	76	79	84	76	76	82	80	79	69	76
Nevada														
Ely	18	61	65	68	64	65	77	78	81	81	73	65	60	70
Las Vegas	16	75	78	79	80	86	92	85	86	92	84	82	73	83
Reno	14	64	70	68	73	75	80	91	92	90	78	69	57	77
Winnemucca	50	53	57	64	70	75	83	90	90	86	75	63	53	73
Texas														
Amarillo	16	65	66	72	71	69	75	75	77	76	74	76	67	72
El Paso	14	75	80	80	85	88	88	77	81	82	85	86	76	82
Utah														
Salt Lake City	19	46	53	61	68	72	77	82	82	84	72	55	44	68

Taking 1953 as the approximate data of conversion to photoelectric recorders (some still have not been converted, I understand), it will be seen that the bulk of the underlying observations were made with the older Marvin-type device.

To facilitate discussion of general trends, Figures 3, 4 and 5 have been plotted. In Figure 3 all of the values of annual mean per cent possible sunshine are shown. From a regional high of slightly over 90 per cent near Yuma, the annual means decrease rapidly westward to the coast of southern California (a gradient strongly influenced by coastal stratus), but more slowly in all other directions. A ridge of high percentage sunshine extends northwestward up the California-Nevada line, with values near 75 per cent in the vicinity of Sacramento, Red Bluff and Reno. Westward from the Red Bluff-Sacramento area, there is a decline towards the coast due both to orographic and coastal effects, with Eureka averaging slightly under 50 per cent of possible sunshine for the year. Within Arizona, Yuma's high of 93 per cent is followed by Tucson's 86, then Phoenix's 85 and Prescott's 80 per cent. The general trend towards decreasing values to the north through Arizona and Utah as well as through New Mexico and Colorado is meteorologically reasonable both because of increasing elevation of terrain and because of increasing frequency of winter-season cyclonic storms at higher latitudes in this part of North America.

A general note on this and subsequently discussed figures needs to be made. The isoline patterns have been drawn <u>without</u> any systematic attempt being made to interpolate between plotted observations on the basis of <u>indirect</u> meteorological arguments. Terrain variations can impose marked convolutions on the actual cloudiness or sunshine isolines, of course; but to try to deduce those sinuosities seems hazardous. The isolines that do appear, are to be regarded chiefly as aids in grasping overall patterns and not as fully adequate

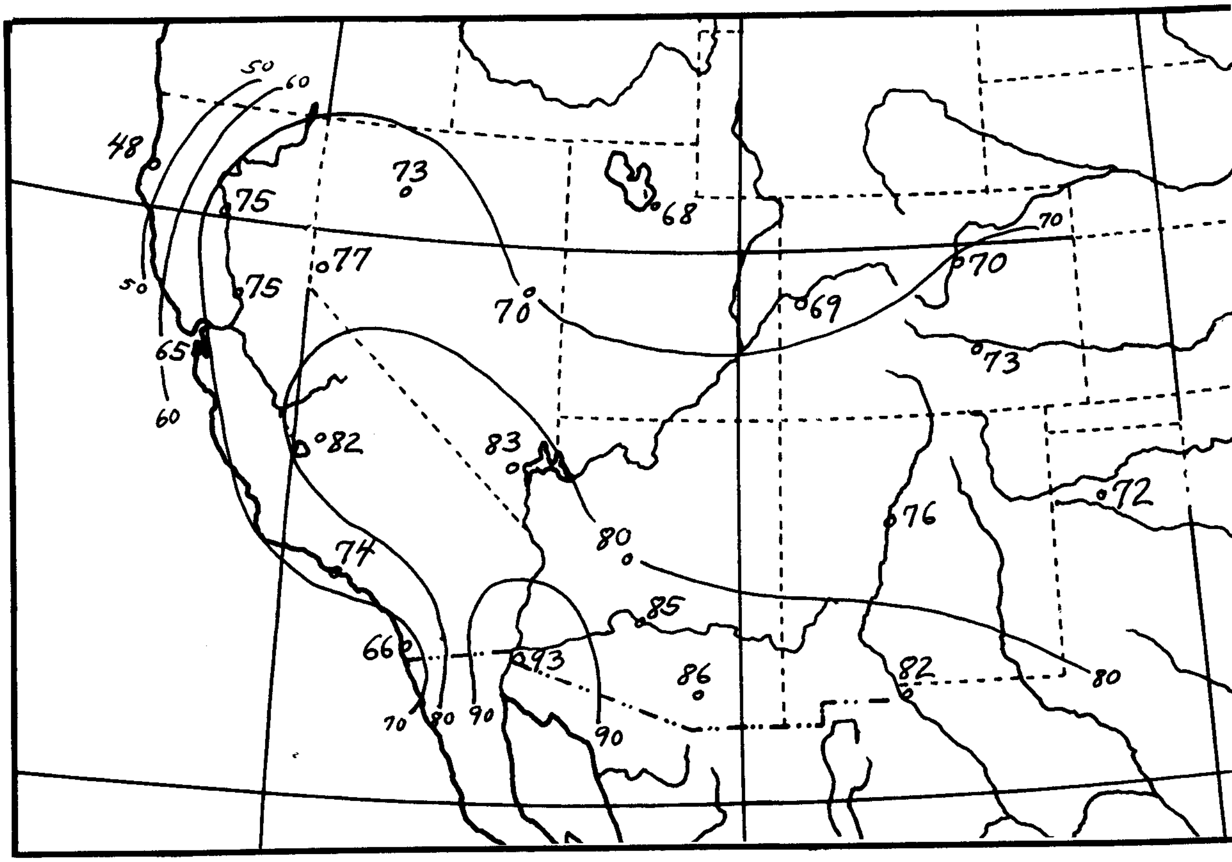


Figure 3. Mean annual per cent possible sunshine for twenty-two southwestern Weather Bureau stations. For lengths of record (variable) see Table 7.

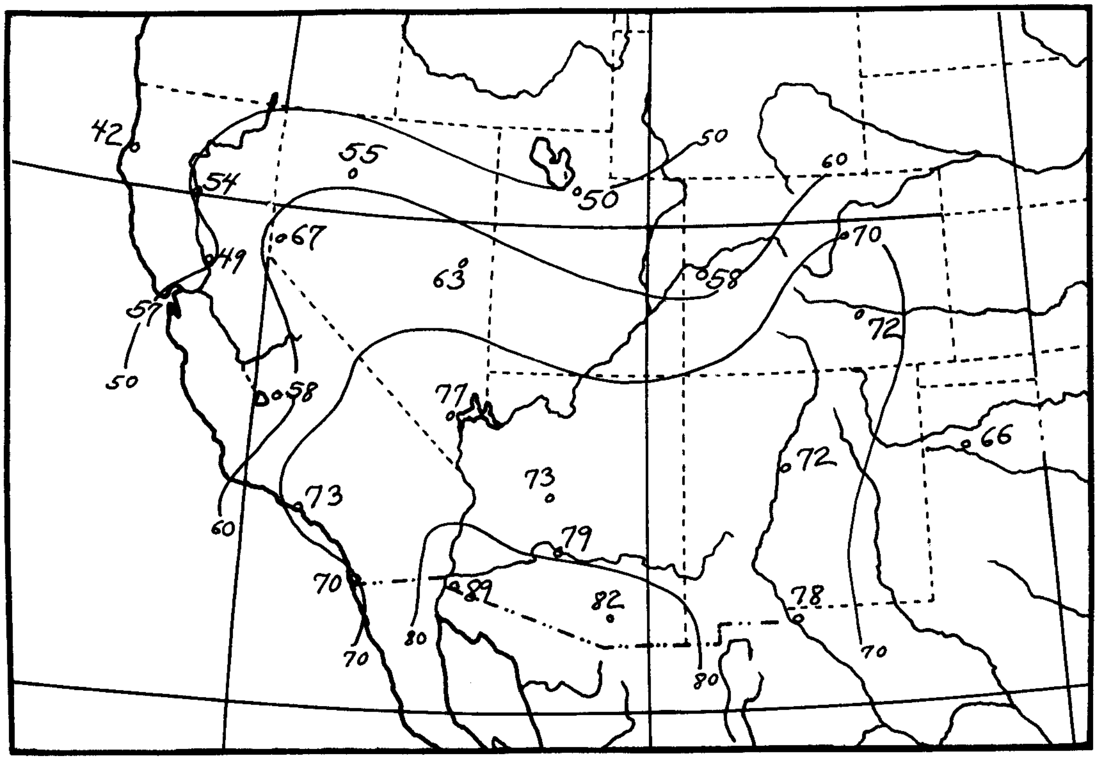


Figure 4. Mean per cent possible sunshine for January plus February at twenty-two southwestern Weather Bureau stations.

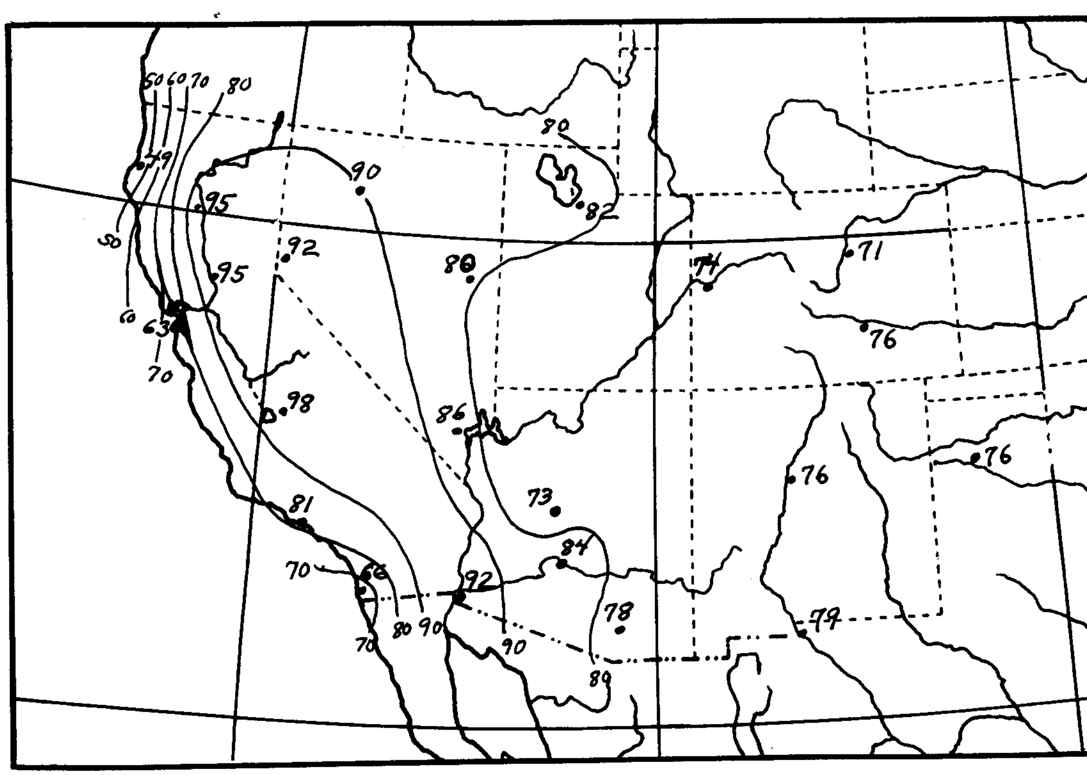


Figure 5. Mean per cent possible sunshine for July plus August at twenty-two southwestern Weather Bureau stations.

keys to the detailed distributions. For example, it seems meteorologically inevitable that a strip of lower per cent possible sunshine must lie along the Sierra Nevada nearly in the middle of the indicated ridge of high per cent. It has seemed wiser here to let the reader draw his own inferences as to detailed patterns between scattered reporting stations than to impose them on the isoline analysis myself. All too little is known about orographic effects and cloud climatology in the Southwest to permit reliable guesses as to finer details of cloudiness patterns.

Because the Southwest is a region of climatically unique seasonal regimes of rainfall, and hence, presumably of cloud-cover, it is of interest to give separate consideration to summer and the winter patterns of sunshine percentage. In Figure 4 I have plotted the average of the January and the February Weather Bureau sunshine percentages. By way of explantion of Figure 4, note that Table 7 shows that Tucson has averaged, during its nine years of record ending with 1956, 78 per cent of possible January sunshine and 85 per cent of possible February sunshine. The average of these two averages, rounded off to an integral per cent, is 82 per cent, the value plotted for Tucson in Figure 4.

The prominent ridge of high <u>annual</u> percentage sunshine extending from Yuma northwestward up the Central Valley of California in Figure 3 is not found in the <u>winter</u> pattern of Figure 4. Thus, while Tucson's annual average per cent of possible sunshine is only 4 units higher than that for Fresno, Tucson's January-February per cent possible sunshine is 24 units higher than Fresno's. On the other hand, the January-February pattern of Figure 4 exhibits another ridge of high sunshine that is not to be found in the annual pattern, namely that trending north-south along the east side of the Rockies. Downslope heating effects in the predominantly westerly flow of winter is the probable explanation of this band of winter-clear skies. The isolines of sunshine trend nearly zonally from northern California into central Colorado, reflecting the mean increase in numbers of migratory winter cyclonic storms as one moves northward. Within Arizona itself, this trend shows up as a 9-unit advantage of Tucson over Prescott with respect to per cent possible sunshine. It should be again stressed that, in drawing the isolines to such charts as these, I have not done more than interpolated mechanically between actual station data. Fine details associated with topography must not be looked for in the isoline analysis of these figures.

In the July-August period, represented in Figure 5, it is the Central Valley of California and the desert areas of Nevada and the lower Colorado Valley that have the highest percentages of possible sunshine. The San Joaquin and Sacramento Valleys average very close to 100 per cent of possible sunshine. These valley stations are uninfluenced by coastal stratus that cut down the values farther west and are seldom influenced by the monsoonal flow of moisture from the Gulf of Mexico that brings the summer rains to Arizona and New Mexico, with the result that clouds are seldom present to obscure the sun.

In view of nighttime duration differences from winter to summer, it seems clear that the sunshine data only tend to support the conclusion that the best opportunities for astronomical observing in the Southwest are to be found somewhere near Yuma. To be sure, these are strictly daytime data, but in winter this stricture is less severe. On the other hand, both the old Marvin and the new photoelectric duration records are designed to register obscuration only after enough cloud interposes itself between sun and instrument to "cast a faintly perceptible shadow." This amount of, say, cirrus is already above the threshold of serious disturbance to photoelectric photometry work, so the astronomer must keep this weakness in mind in assessing site possibilities on the basis of such sunshine data.

B. Mean numbers of clear and cloudy days. The Weather Bureau publication Local Climatological Data provides cumulative mean data on visually estimated sky-cover at a much larger number of stations than it provides averages of sunshine-duration. I have extracted 1956 cumulative cloudiness means of several types for 39 southwestern stations, and will discuss the analyses of these data in this and the next section.

In Table 8 are presented the 1956 cumulative mean monthly and annual numbers of "clear" days at the 39 stations, with record lengths N appended for reference. In this instance, a "clear day" is one for which the average cloud-cover from sunrise to sunset was three-tenths or less. (The profusion of definitions of "clear skies" is regrettable, but unavoidable here, since the basic data must be taken as published.) To give the reader a graphic view of the annual patterns over the Southwest, Figure 6 has been plotted. As in nearly every other mode of analysis, Yuma proves to be the best site here too, with a long ridge of high number of "clear" days extending up the middle of California. Again, southern Arizona appears less cloudy than northern Arizona and Utah. A strong gradient from coastal southern California towards more inland areas results from the stratus, and a similar band of strong gradient shows up near very cloudy Eureka.

The annual summaries of the Local Climatological Data give statistics not only on "clear days" as defined above but also on "partly cloudy days" and on "cloudy days." The 1956 cumulative means for just the latter category are given in Table 9. By the Weather Bureau definition, a "cloudy day" is one whose sunrise-to-sunset sky-cover averages eight-tenths or greater. A high frequency of such "cloudy days" is this an indication of prevalence of storms and other active cloud-generating processes at a station. No maps of this statistic are plotted here, since these data are of less astronomical interest than those for low cloud-cover amounts. Nevertheleess, it is to be noted that Yuma once again comes out in the preferred position, with only 37 cloudy days per year for its period of record (short because of a station-change about a half-dozen years ago).

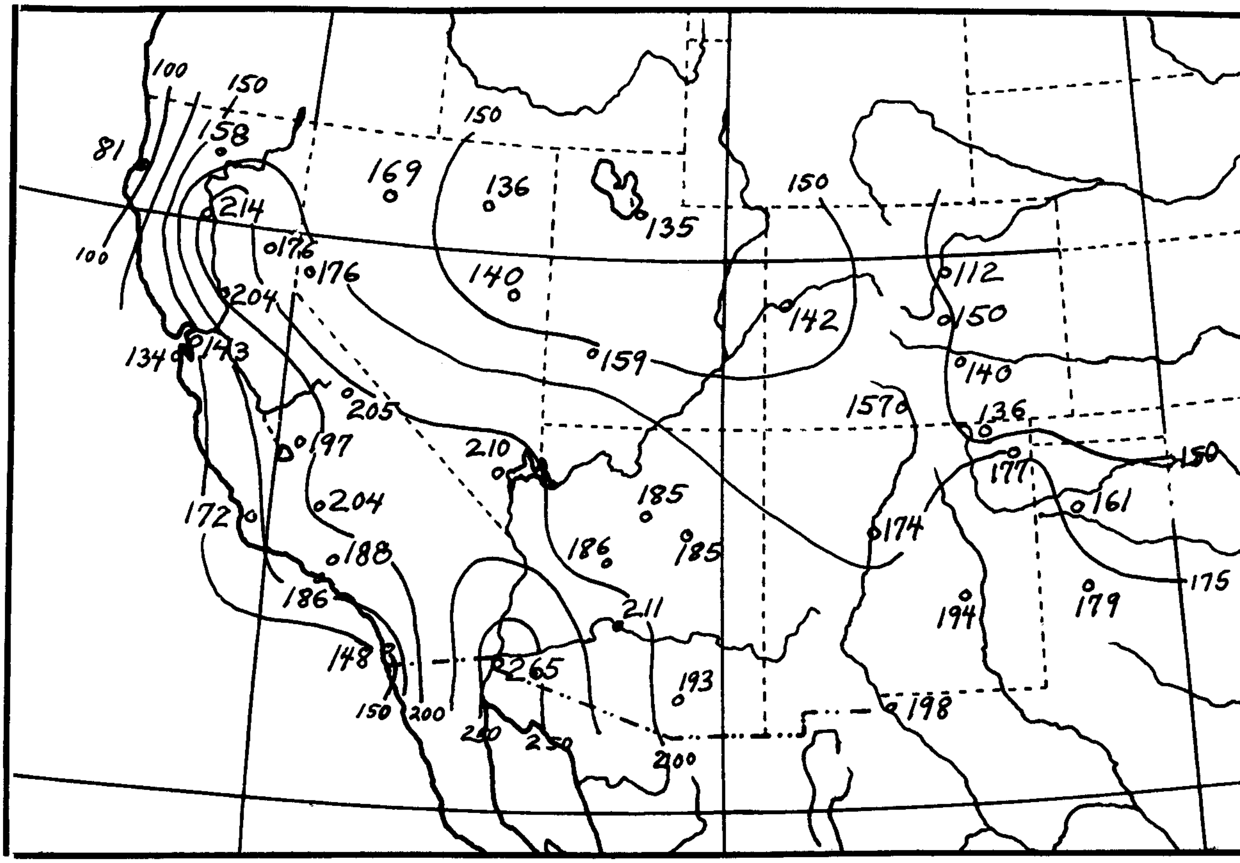


Figure 6. Mean annual number of clear days for thirty-nine southwestern Weather Bureau stations. A "clear" day is here one with 0-3 tenths mean sky-cover. For lengths of record (variable) see Table8.

Table 8

1956 cumulative mean monthly and annual number of clear days at thirty-nine southwestern Weather Bureau Stations. A "clear" day is here one whose sunrise-to-sunset average sky-cover was three-tenths or less. N is the record-length in years.

Station	N	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Arizona														
Flagstaff	7	10	14	15	13	17	22	9	10	20	22	19	14	185
Phoenix	19	13	13	15	16	21	23	17	17	22	20	19	15	211
Prescott	14	13	12	13	14	18	22	11	12	21	19	17	14	186
Tucson	16	13	13	14	16	20	22	9	12	20	20	19	15	193
Winslow	15	12	13	14	14	17	22	12	12	20	19	17	13	185
Yuma	6	16	20	19	21	25	27	22	24	27	25	22	17	265
California														
Bakersfield	16	8	9	11	13	18	24	27	27	25	21	14	7	204
Bishop	9	11	13	13	13	15	20	21	25	23	21	17	13	205
Blue Canyon	13	8	9	9	10	11	19	27	26	22	17	11	7	176
Burbank	25	14	12	14	12	13	15	20	21	19	18	17	13	188
Eureka	46	6	6	6	6	7	8	6	5	9	9	7	6	81
Fresno	17	6	8	11	12	17	24	28	28	25	20	12	6	197
Los Angeles	16	14	13	13	10	12	14	20	23	19	17	17	14	186
Mt. Shasta	14	8	8	8	9	12	15	24	24	21	13	9	7	158
Oakland	26	9	9	10	10	12	15	16	13	15	14	12	8	143
Red Bluff	79	11	11	13	15	18	22	28	27	23	20	15	11	214
Sacramento	8	7	11	12	13	17	23	29	27	24	22	11	8	204
San Diego	16	13	12	12	8	9	9	12	14	16	14	16	13	148
San Francisco	20	10	9	10	10	11	14	11	10	14	14	12	9	134
Santa Maria	14	13	13	12	11	13	16	16	15	17	17	16	13	172
Colorado														
Alamosa	11	13	13	12	10	8	15	10	11	17	18	15	15	157
Colorado Sprs.	8	12	12	10	8	8	12	12	12	17	19	14	14	150
Denver	22	10	8	8	6	6	8	9	9	13	13	11	11	112
Grand Junction	10	8	8	9	8	9	16	15	14	17	17	12	9	142
Pueblo	16	12	10	11	7	7	13	11	11	17	16	13	12	140
New Mexico														
Albuquerque	17	13	12	12	12	14	18	12	13	19	18	17	14	174
Clayton	10	13	12	12	12	11	15	15	17	20	20	16	14	177
Raton	11	12	10	13	8	7	11	7	8	15	16	14	14	136
Roswell	9	14	15	14	14	14	17	12	17	20	20	21	16	194
Nevada														
Elko	26	7	7	7	7	8	13	18	20	20	13	9	7	136
Ely	18	9	8	9	8	8	15	15	16	18	15	11	8	140
Las Vegas	20	13	12	14	14	18	23	20	21	23	22	17	13	210
Reno	15	9	9	10	11	12	18	25	25	23	16	11	7	176
Winnemucca	76	9	8	10	10	12	16	23	23	20	17	12	9	169
Texas														
Amarillo	16	13	10	13	11	10	12	12	15	18	16	17	14	161
El Paso	14	14	15	14	16	19	19	11	15	20	19	19	17	198
Lubbock	10	13	12	13	13	10	14	14	17	20	19	19	15	179
Utah														
Milford	8	6	8	11	11	10	19	14	18	20	19	13	10	159
Salt Lake City	28	6	6	7	8	10	14	17	16	18	15	11	7	135

Table 9

1956 cumulative number of monthly and annual number of cloudy days at thirty-nine southwestern Weather Bureau stations. A "cloudy" day is here one whose sunrise-to-sunset average sky-cover was eight-tenths or greater. N is the record-length in years.

Station	N	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Arizona														
Flagstaff	7	15	8	11	9	6	3	11	9	3	4	6	10	95
Phoenix	19	10	8	9	6	3	2	4	4	3	5	5	9	68
Prescott	14	11	9	10	7	5	2	9	7	3	4	6	10	83
Tucson	16	11	9	10	6	5	2	9	7	3	4	5	10	81
Winslow	15	12	9	9	7	5	3	9	7	3	5	6	10	85
Yuma	6	8	3	5	3	2	1	2	1	1	1	3	7	37
California														
Bakersfield	16	14	10	10	8	4	2	1	1	1	3	8	16	78
Bishop	9	11	7	9	9	7	3	3	1	3	4	7	10	74
Blue Canyon	13	17	14	16	13	12	6	1	2	3	8	14	18	124
Burbank	25	9	9	9	9	7	5	2	2	2	5	6	10	75
Eureka	46	19	16	17	15	14	12	13	15	12	14	16	18	181
Fresno	17	18	12	11	9	6	2	1	1	2	4	10	19	95
Los Angeles	16	9	8	9	10	7	5	1	1	2	5	6	9	72
Mt. Shasta	14	16	12	14	11	10	8	2	3	4	9	13	16	118
Oakland	26	15	12	12	10	7	4	3	4	4	7	9	15	102
Red Bluff	79	13	10	10	7	5	3	1	1	2	5	9	13	79
Sacramento	8	19	11	11	9	5	3	1	1	2	4	13	17	96
San Diego	16	11	9	8	12	10	7	5	4	4	7	6	10	93
San Francisco	20	14	12	12	11	9	7	7	8	6	8	10	14	118
Santa Maria	14	11	8	10	9	8	4	1	2	3	5	7	11	79
Colorado														
Alamosa	11	8	6	7	7	9	4	5	5	4	4	5	6	70
Colorado Sprs.	8	10	7	11	12	11	6	6	6	5	5	9	8	96
Denver	22	11	11	12	14	13	9	6	7	7	8	9	9	116
Grand Junct.	10	15	13	13	12	11	6	5	6	4	6	11	14	116
Pueblo	16	10	9	10	12	11	6	4	7	5	6	9	8	97
New Mexico														
Albuquerque	17	10	8	9	8	6	4	4	4	4	5	5	9	76
Clayton	10	11	8	9	9	10	6	5	4	5	4	8	9	88
Raton	11	8	7	7	10	10	5	8	7	6	5	7	7	87
Roswell	9	48	41	43	42	41	34	43	37	28	30	28	40	38
Nevada														
Elko	26	16	14	15	14	12	7	3	4	4	9	13	17	128
Ely	18	14	14	14	13	11	6	5	3	4	8	12	15	119
Las Vegas	20	11	9	8	7	4	2	3	3	3	4	5	11	70
Reno	15	14	11	12	9	9	5	1	2	2	8	11	16	100
Winnemucca	76	13	12	12	11	9	5	2	2	4	7	10	14	101
Texas														
Amarillo	16	11	10	9	10	9	6	6	5	6	7	6	10	95
El Paso	14	9	6	9	6	4	3	6	4	4	4	5	8	68
Lubbock	10	12	9	9	8	9	4	5	3	5	6	5	9	84
Utah														
Milford	8	16	10	12	10	9	4	6	4	3	6	8	14	102
Salt Lake City	28	17	14	14	12	10	6	4	4	4	8	12	17	122

C. Mean daytime sky-cover. The number of tenths of sky-cover as reported for each hourly observation time from sunrise to sunset is averaged by the Weather Bureau as the day's mean daytime sky-cover. 1956 cumulative means of this quantity for thirty-nine southwestern stations have been tabulated here in Table 10 and means for January-February and for July-August are plotted geographically in Figures 7 and 8, respectively. In the Table and in the Figures, mean tenths have been multiplied by ten to remove the decimal point, for convenience. Thus these numbers are mean sky-cover percentages.

Figure 7 tells essentially the same story that Figure 4 did, with Yuma again showing up best. The entire U.S.-Mexican border zone is distinctly less cloudy, according to Figure 7 than is a zonal belt running along, say the 40th parallel. The length of the winter night and the stronger carryover of daytime to nighttime cloud conditions in winter warrants placing a fair amount of weight on Figure 7 as an indication that the border zone is a preferred zone for astronomical observing. It should be noted that there is really quite good internal consistency within the data plotted in Figure 7. That is, no extremely sinuous isolines have to be drawn even in areas of fairly high station density. Even in Colorado, where several convolutions in the 50% isoline were necessary, the actual variation is seen to be only a few percentage units between stations.

The July-August pattern of Figure 8 shows Yuma having slightly higher mean percentage sky-cover than stations in the Central Valley of California, and by a factor of about two. While summer thunderstorms are virtually unheard of in the Central Valley, such storms do occasionally appear over the desert to the east of Yuma, within observing distance. Institute radar studies and camera-triangulation studies reveal that cirrus anvils are often found at altitudes from 50,000 to 60,000 ft msl. Considering effects of earth curvature, one finds that such anvil tops are geometrically visible at distances of

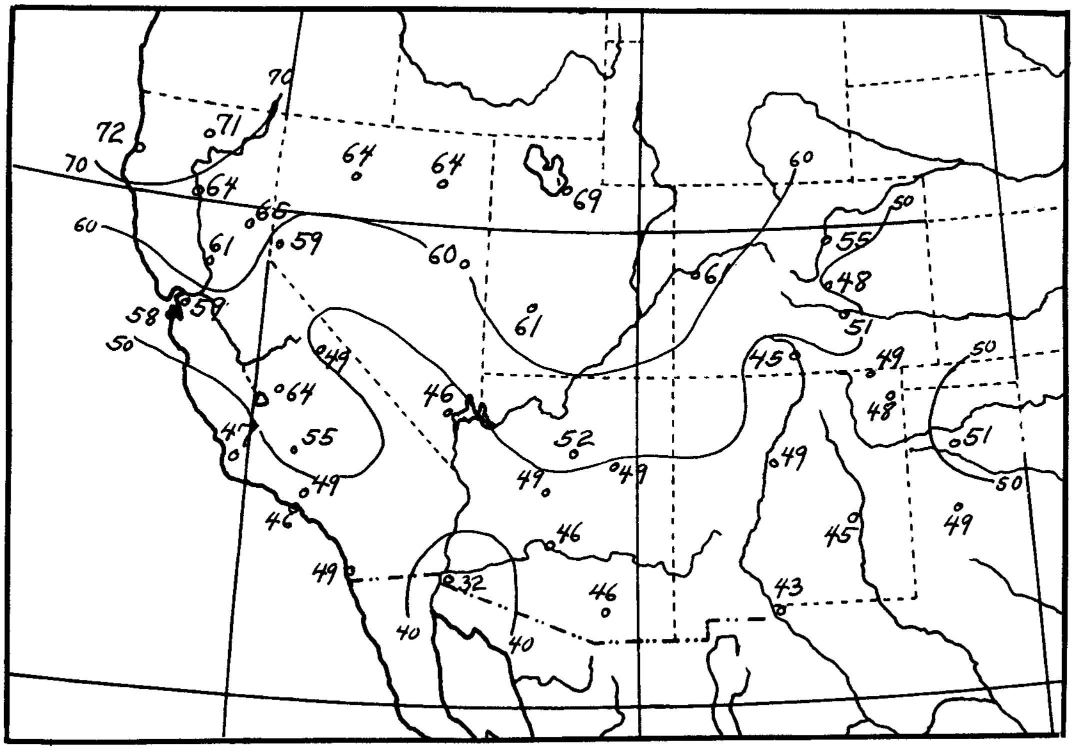


Figure 7. Mean daytime sky-cover (in per cent) for January plus February at thirty-nine southwestern Weather Bureau stations.

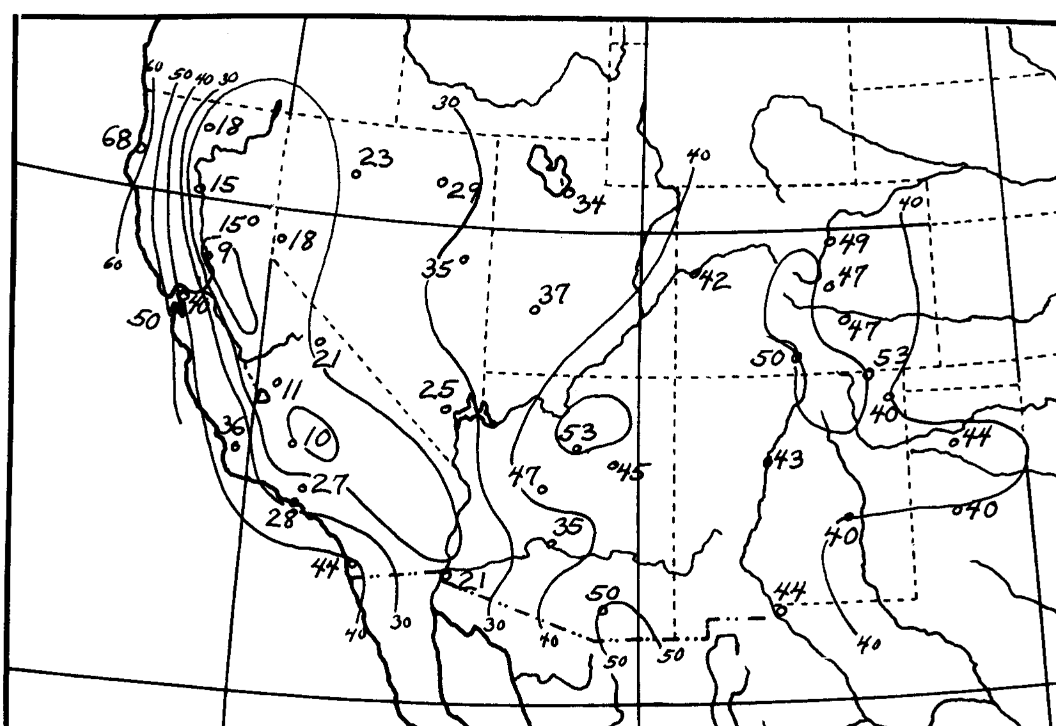


Figure 8. Mean daytime sky-cover (in per cent) for July plus August at thirty-nine southwestern Weather Bureau stations.

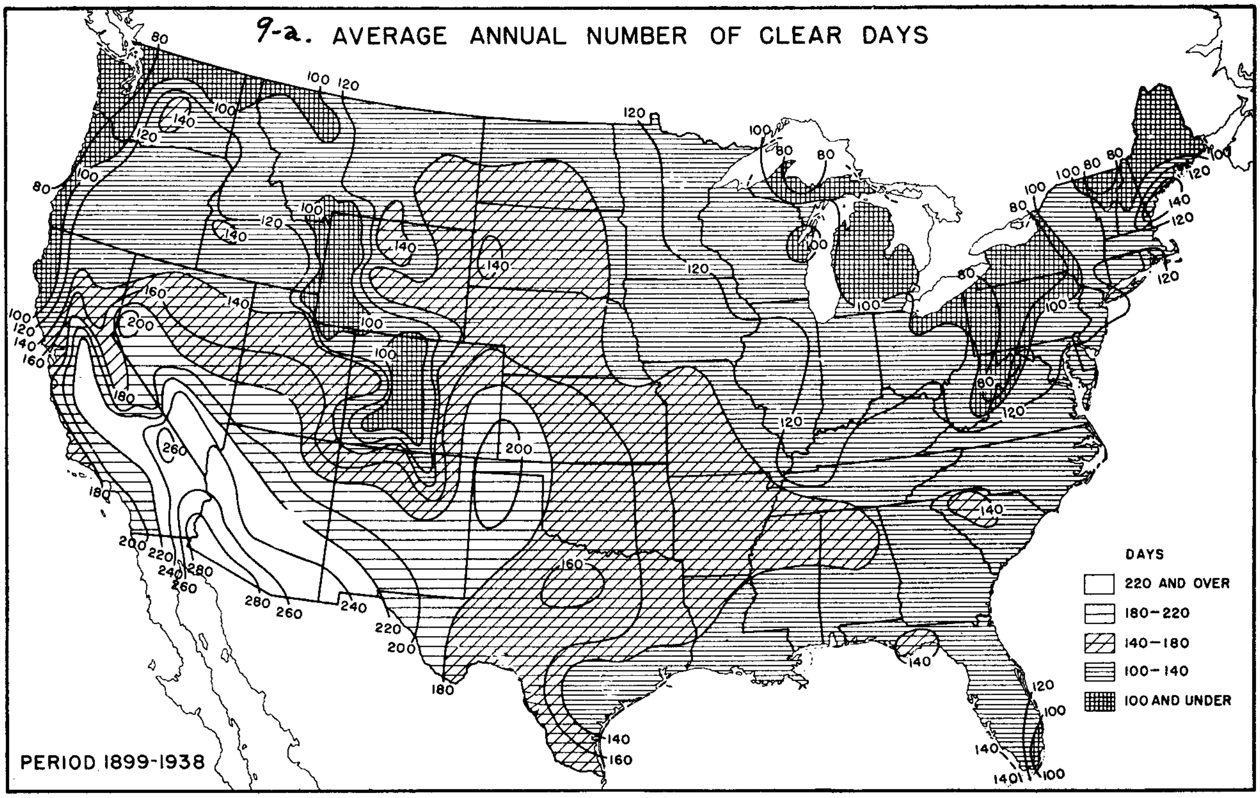
Table 10

1956 cumulative mean percentage daytime cloudiness for thirty-nine southwestern Weather Bureau stations. Record length N is given in years.

Station	N	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Arizona														
Flagstaff	7	52	51	41	50	39	23	55	51	34	35	36	48	43
Phoenix	11	50	41	42	38	27	20	39	31	19	25	29	35	33
Prescott	14	51	46	47	43	34	23	49	45	31	31	34	45	40
Tucson	15	48	43	45	37	29	22	54	46	27	29	30	44	38
Winslow	8	55	42	43	40	35	23	50	39	24	24	33	43	38
Yuma	6	41	23	29	21	15	10	24	18	9	15	21	34	22
California														
Bakersfield	11	59	51	52	44	30	13	11	8	12	25	42	64	34
Bishop	9	54	43	46	47	41	24	25	17	21	26	37	48	36
Blue Canyon	8	72	58	63	59	50	31	13	16	22	36	54	67	45
Burbank	8	56	42	48	55	46	39	27	26	25	35	38	44	40
Eureka	14	72	71	72	72	68	64	65	71	60	64	71	76	69
Fresno	17	70	58	53	47	36	18	11	11	14	29	51	71	39
Los Angeles	16	46	45	47	54	48	43	29	26	27	38	35	45	40
Mt. Shasta	8	77	64	64	60	52	40	14	22	27	45	62	72	50
Oakland	13	62	55	56	54	49	40	38	41	34	43	60	64	50
Red Bluff	12	66	61	61	54	47	32	13	17	21	40	58	71	45
Sacramento	8	70	52	50	48	35	19	7	11	16	27	53	69	38
San Diego	16	50	48	48	59	55	53	45	52	38	43	37	48	47
San Francisco	20	59	56	55	53	48	42	49	51	42	43	51	60	51
Santa Maria	14	49	45	48	51	46	36	35	36	33	35	38	50	42
Colorado														
Alamosa	11	46	43	48	53	57	37	52	48	35	33	40	41	44
Colorado Sprs.	8	50	46	53	58	59	44	48	46	34	34	45	44	47
Denver	8	55	54	57	63	63	49	49	48	39	40	51	48	51
Grand Junct.	10	63	59	59	58	56	38	40	43	32	36	51	59	50
Pueblo	16	50	51	51	59	58	45	46	48	37	39	46	48	48
New Mexico														
Albuquerque	17	50	47	49	48	42	33	44	42	31	34	36	46	42
Clayton	8	52	43	46	46	50	37	42	38	29	27	36	41	41
Raton	5	52	46	44	55	58	44	54	51	36	31	43	41	46
Roswell	9	48	41	43	42	41	34	43	37	28	30	28	40	38
Nevada														
Elko	8	72	60	64	61	57	37	30	27	26	40	54	68	50
Ely	13	61	58	60	59	59	41	38	32	29	40	56	61	50
Las Vegas	8	54	37	39	37	32	16	29	20	13	20	32	45	31
Reno	15	61	56	55	53	48	32	19	17	22	39	53	65	43
Winnemucca	26	64	63	60	58	52	40	24	22	24	40	52	65	47
Texas														
Amarillo	16	50	51	49	51	52	44	46	41	36	38	37	48	45
El Paso	14	46	40	45	37	33	31	48	40	30	31	30	41	38
Lubbock	8	53	45	47	45	51	38	45	36	34	30	32	45	42
Utah														
Milford	8	65	57	56	53	53	31	41	33	27	32	45	60	46
Salt Lake City	21	69	69	64	60	54	43	35	33	33	43	55	69	52

almost 300 miles. Summer dust and haze (see Appendix B) preclude visual ranges this great, under typical conditions, but it is easily possible for Yuma observers to report, at times, thunderstorms 150 miles to the east or southeast. This does not seem a complete explanation of a twofold excess of July-August mean Yuma daytime cloud cover over, say Fresno; but it probably contributes to this excess. An important additional factor seems to me to be the fact that occasionally, upper-level flow patterns do evolve in such a way that the monsoonal moist current invades as far west as Yuma and gives that area its scant summer rainfall; but seldom does the moisture work its way still farther into the Central Valley of California. Fresno's 98 per cent of possible sunshine in the July-August period *versus* Yuma's 92 (Figure 5) is not inconsistent with such an explanation, of course.

D. Comparisons with other published data. I have pointed out above in Section I that Irwin's chart of numbers of clear days seems to overestimate the clarity of the skies in the Southwest. His data, taken from a 1928 tabulation published in the U.S. Department's *Atlas of American Agriculture*, indicate more than 300 clear days in the Yuma corner of Arizona. By way of comparison, the corresponding chart in the 1941 *Yearbook of Agriculture* (p. 742), indicates only slightly over 280 clear days at Yuma. In Figure 9 this latter chart, as well as one displaying nation-wide distribution of cloudy days, is reproduced. The isolines of Figure 9-a are so drawn near Yuma as to suggest that Yuma lies on the *west* edge of a zone of maximum clarity of the skies, rather than near the middle of such a zone. Thus, Figure 9-a suggests that the number of clear days falls off to about 200 days as one goes only about 100 miles westward from Yuma, yet is still close to 280 days as one goes about the same distance east-southeastward. Aside from these numerical differences and differences of relative gradients near Tucson, Figure 9-a does not differ in broad outline from the map Irwin prepared from the *Atlas of Agriculture* chart.



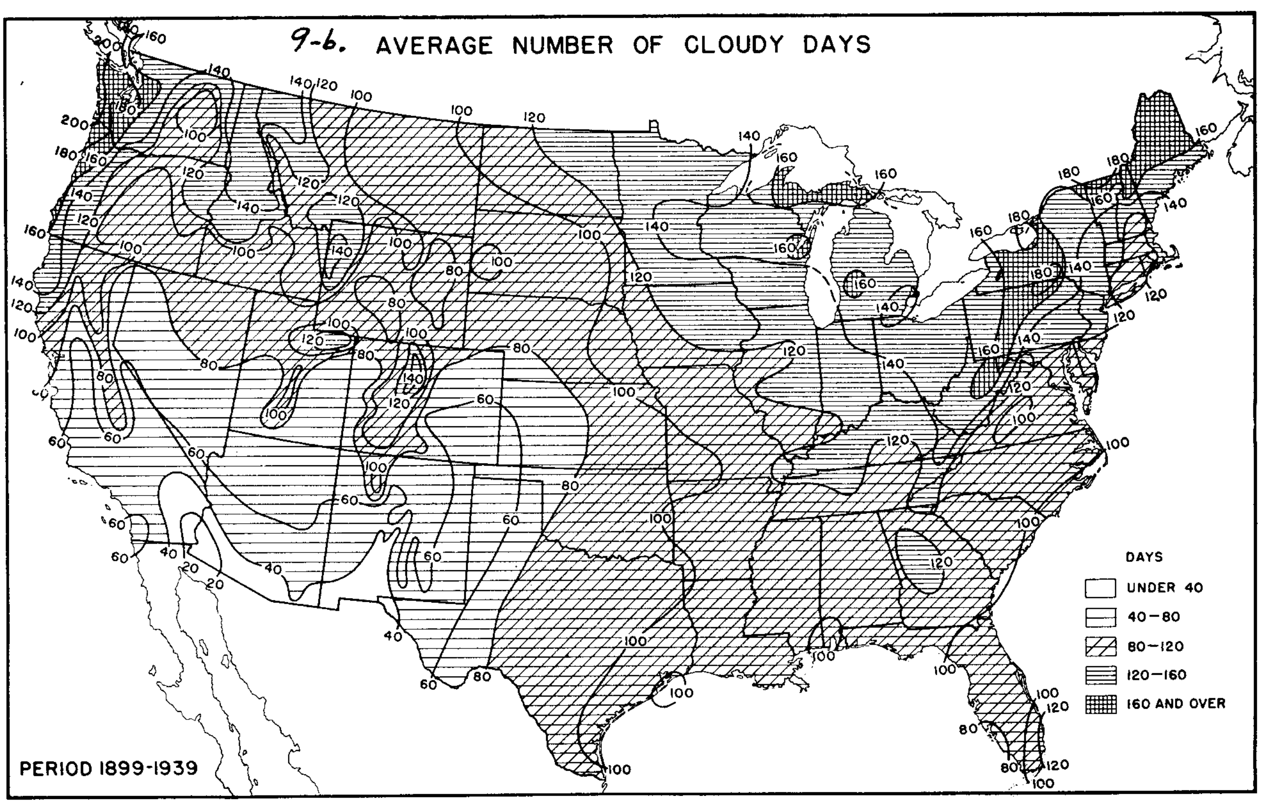


Figure 9. Nationwide pattern of average annual number of clear and cloudy days. From U. S. Dept. of Agriculture 1941 Yearbook of Agriculture, Climate and Man

Comparing Figure 9-a with Figure 6 of the present report shows rather significant numerical differences. My compilation from the 1956 Weather Bureau means gives values almost uniformly lower by a substantial amount than those suggested by Figure 9-a. Yuma in Figure 6 is plotted as 265 clear days versus Figure 9-a's 280. The Fresno area on Figure 6 has 197, but on 9-a about 240. The Flagstaff area on Figure 6 has about 185 clear days, while Figure 9-a gives 220 days, etc. Since no specific listing of stations actually used is available for the 1941 Yearbook of Agriculture chart, it is not possible to examine these differences in any detail. That no Flagstaff data were used is suggested by the fact that no Flagstaff data were employed in certain other charts in the same publication. A striking example of the effect of omission of Flagstaff data from the 1941 charts has been pointed out (Waterways Experiment Station, 1947) in connection with hail patterns. Failure to include hail data for Flagstaff led to a smooth pattern of hail distribution across the Southern Colorado Plateau. But when actual Flagstaff hail data were added and the analysis revised, a local center of high hail frequency, second in importance only to the hail center in eastern Colorado and western Nebraska showed up (see Figure 79 of Waterways Experiment Station, 1947, and discussion p. 153). Another factor leading to a seemingly consistently downward trend in published statistics on numbers of clear skies is probably the steady improvement in reporting and observing practices. Reporting instructions and administrative checking and control on observing practices has never been ideal in Weather Bureau practice for a variety of very practical reasons, but conditions today are greatly improved over what they were only a few decades ago. For these reasons, I believe that astronomers should find the data of Figure 6 more trustworthy than those previously published. The record-lengths underlying Figure 6 must, in almost all instances, be considerably greater than those underlying Irwin's chart; and total number of station-years of record entering into Figure 6 are probably twice as great, approximately, as those used in the 1941 chart of Figure 9-a. Figure 6 contains data for unequal periods of record, of course, and this is a weakness that could be removed by plotting only, say, means computed for the past ten years, but the time requirements of the present study have not permitted this refinement.

The fact that Irwin was apparently unaware of these 1941 charts suggested that there might be some point in reproducing 9-b as well as Figure 9-a for astronomical reference purposes. Figure 9-b, of course, will tend to suffer from about the same weaknesses that 9-a does. It may also be noted that there is no reason to believe that 9-a and 9-b were based on uniform record lengths, so this cited weakness of Figure 6 is <u>probably</u> also present in 9-a and 9-b. The legend "Period 1899-1938" is <u>not</u> to interpreted to mean that a uniform 40-year period of record was used. There is simply no information on this point in the 1941 <u>Yearbook</u>.

Smith and McCrosky (1953 and Section I of present report) carried out a very careful analysis of several years of synoptic weather reports for the Southwest and from it made inferences as to relative observing opportunities at about twenty stations in the region. They used only nighttime observations and cross-checked their findings with actual observing records to whatever extent was possible in each sub-area. By combining statistics on clarity of skies with nighttime-duration data throughout the year, they computed mean annual numbers of hours per night during which ordinary astronomical (not photometric) observing might be done. From their Figure 1, I have extracted just the section for Arizona and present it here as Figure 10. Because the data underlying Figure 10 are weighted for night-duration, Figure 10 is not <u>directly</u> commensurate with any of the charts I give in the present report. <u>Very</u> roughly, it may be compared with Figure 6, but the result of such rough comparison is only the not-too-surprising finding that the general isoline

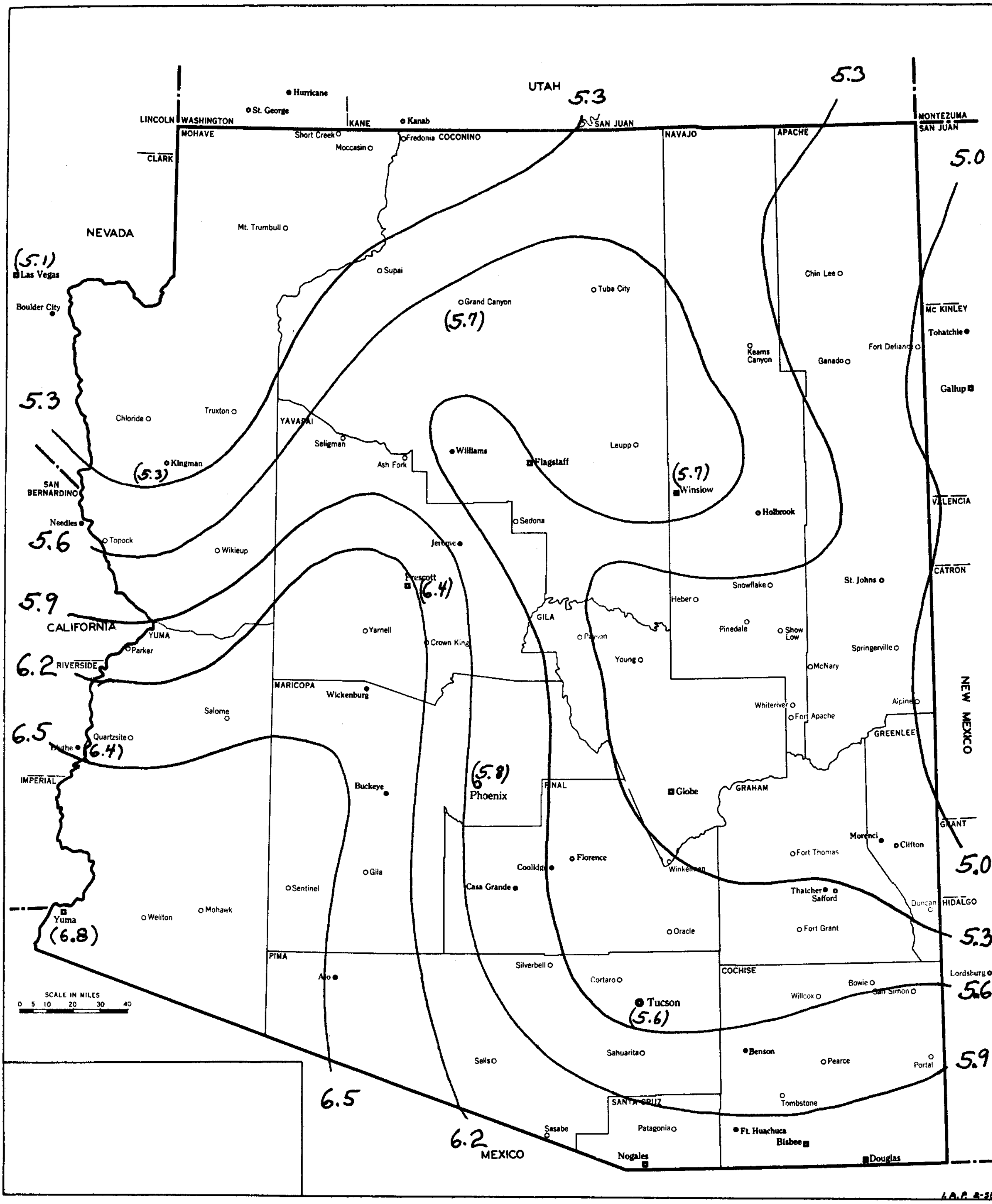


Figure 10. Year-round average number of observing hours per night for Arizona after Smith and McCrosky, 1953.

patterns of the two figures are broadly similar. Figure 6 is stronger in the sense of being based on much more data, but Figure 10 is stronger in the sense of being based on only nighttime cloud observations, on a uniform time period, and in the sense of being weighted for night-duration. It should also be noted that Smith and McCrosky did attempt to sketch in their isolines with topographic effects in mind. As a means of suggesting the extent of this merely inferential content of the isoline pattern of Figure 10, I have copied in the authors' computed amounts at the nine stations appearing in this section of their entire map. These are the figures enclosed in parentheses in Figure 10. Note that the value of 6.4 mean hours at Prescott seems to indicate that the 6.5-hour isoline should have been drawn farther northeast than Smith and McCrosky drew it. Since the mean annual observable hours are strongly influenced by winter conditions (for night-duration reasons), it is of interest to compare Figure 10 with Figures 4 and 7, which display winter daytime cloud-conditions for a much longer period of record. Note that Prescott has 49/46 as large a mean daytime sky-cover in the January-February period as does Tucson (Figure 7) and has 73/82 as large a per cent possible sunshine for the January-February period (Figure 4). These latter two implications suggest that perhaps the 6.5-hour isoline of Figure 10 may actually be drawn at about the correct position, despite Prescott's plotted value of 6.4 observable hours. Possibly Smith and McCrosky had some unstated reasons for not drawing to the Prescott figure based on examination of other data such as those contained in Figures 4 and 7 here.

In summary of these comparisons, it can only be said that there are broad similarities and also minor differences in the several published discussions of southwestern cloudiness. It would be desirable to be able to say conclusively which published data are the most reliable and meaningful. This, however, is not possible since there are so many factors complicating intercomparisons.

The conclusion reached by Irwin from quite old data, namely that the Yuma area has the clearest skies in the United States, is indisputable in its astronomical implications. Lack of high peaks near Yuma, however, forces the astronomer to look at cloudier sites in the Yuma region. All published charts then suggest a pattern of cloudiness isolines roughly concentric with Yuma. Hence peaks to the west of Yuma in California, to the north in California, to the northeast in Arizona, and to the east in Arizona are about equally attractive on grounds of cloudiness alone. If one looks too far east he encounters the disadvantage of increasing amounts of summer thunderstorm activity, but these are counterbalanced by generally decreasing amounts of winter cyclonic cloudiness (subject to local topographic variation). If one looks too far to the north, he encounters the disadvantage of increasing cloudiness from cyclonic storms, and this during the winter period of longest nights. If one looks too far to the west, a weaker maximum of winter cloudiness seems to appear, though nearly complete absence from strong summer convective activity is enjoyed in this area. The actual cloud conditions above mountaintop altitudes in the southern California region is very poorly documented at present, though I have pointed out above in Section IV that winter conditions may be better near Tucson and Yuma than they are near Los Angeles and San Diego. There is little theoretical reason to believe that cirrus conditions should be greatly different from one part of the Southwest to another, though one can only wish good observations were at hand. Again it should be stressed that routine cloudiness observations, as with a pole-star camera, are sorely needed and should be taken at all southwestern observatories for future use in studies such as the present site-survey study being made by AURA.

IX. ADDITIONAL STATISTICS FOR ARIZONA.

At time of preparation of this report, an extensive IBM punchcard tabulation of cloudiness statistics for a number of Arizona first-order

Weather Bureau stations is being carried out for AURA by Dr. W. D. Sellers of the Institute staff. This study will show in considerable detail what the seasonal and diurnal cloudiness patterns over Arizona have been during roughly the past decade for which punchcard data are available. There are, however, a few additional sources of data that can yield interesting supplemental data that will not be exploited in Sellers' study, and these will now be considered here rather briefly. In addition, it is of interest to extract from tables and figures included in the present report, some information specifically concerned with just the Arizona area.

Since the night-duration averaged over the winter half-year is significantly longer than the night-duration averaged over the summer half-year (about 13.2 winter hours versus 10.3 summer hours at latitude 35°N) it is astronomically relevant to combine into winter and summer averages some of the monthly data presented earlier in this report. This has been done in Tables 11 and 12. "Winter" is here taken as the six months most nearly centered on the winter solstice, and "summer" is the remainder of the year. Four types of data are so handled for winter (October through March) in Table 11, and five types of data are so treated for summer (April through September) in Table 12.

For both winter and summer, Yuma again proves least cloudy, so it will be chiefly the non-Yuma details that deserve attention here. For the winter half-year (Table 11) Tucson is second to Yuma in per cent of possible sunshine, though Phoenix is almost as high as Tucson. Prescott is about as far below Tucson as Tucson is below Yuma. With regard to total number of "clear" days (days with three-tenths or less cloud-cover averaged over the daylight period), Phoenix is next best after Yuma, with Flagstaff and Tucson only slightly lower. Prescott and Winslow are lowest with 88 days clear for the six-month period. With regard to winter total number of "cloudy days (days with eight-tenths or

Table 11

1956 cumulative mean sky-cover statistics for the winter half-year at Arizona's six first-order Weather Bureau stations. Here "winter" is the six-month period from October through March. The record-length N is given in years for each category of data.

	Per Cent Possible Sunshine		Number of Clear Days		Number of Cloudy Days		Daytime Sky-cover	
Station	N	Per Cent	N	Days	N	Days	N	Per Cent
Flagstaff	--	--	7	94	7	54	7	44
Phoenix	61	81	19	95	19	46	11	37
Prescott	10	78	14	88	14	50	14	42
Tucson	9	84	16	94	16	49	15	40
Winslow	--	--	15	88	15	51	8	40
Yuma	6	90	6	119	6	27	6	27

Table 12

1956 cumulative mean sky-cover statistics for the <u>summer</u> half-year at Arizona's six first-order Weather Bureau stations. Here "summer" is the six-month period from April through September. The record-length N is given in years for each category of data.

	Per Cent Possible Sunshine		Number of Clear Days		Number of Cloudy Days		Daytime Sky-cover		Thunderstorm Days	
Station	N	Per Cent	N	Days	N	Days	N	Per Cent	N	Days
Flagstaff	--	--	7	91	7	41	7	42	7	33
Phoenix	61	89	19	116	19	22	11	29	17	17
Prescott	10	82	14	98	14	33	14	38	14	43
Tucson	9	82	16	99	16	32	15	36	16	34
Winslow	--	--	15	97	15	34	8	35	8	36
Yuma	6	95	6	146	6	10	6	16	6	7

more cloud-cover averaged over the daylight period). Phoenix with 46 is a rather poor second to Yuma's 27, with Tucson next with 49 and Prescott and Winslow nearly the same. Flagstaff, with a high of 54 cloudy days, shows the influence of the more frequent passage of cyclonic storms across the northern part of Arizona. Note that these two categories of clear and cloudy are not exhaustive: a middle category, "partly cloudy" is not tabulated here. In terms of daytime mean sky-cover, Yuma's 27 per cent is followed by Phoenix's 37 with Tucson and Winslow next with 40 per cent each. Flagstaff again proves to be poorest, with 44 per cent mean winter sky-cover.

Turning to the summer half-year (Table 12) we find Phoenix running second after Yuma in sunshine statistics, with 89 per cent of possible sunshine versus Yuma's 95 per cent. Tucson and Prescott are noticeably lower with 82 per cent each. About the same pattern shows up in the number of clear days per summer: Phoenix with 116 is second to Yuma's 146, with Tucson and Prescott noticeably lower, and Flagstaff lowest of all with 91 clear days. The cloudy-day figures run in about the same order, ranging from 10 at Yuma to 41 at Flagstaff, and daytime sky-cover similarly, the range being from 16 per cent coverage at Yuma to 42 per cent daytime summer coverage at Flagstaff.

The statistics on thunderstorm days (days on which at least one such storm is reported at some time in the twenty-four hours) have been added because of their bearing on the nighttime cirrus problem. Yuma's low of 7 thunderstorms per summer emphatically documents the rarity of invasion of that corner of Arizona by the monsoonal current of moist air. Phoenix, though normally overlain by the July-August moist current, averages only 17 thunderstorm days because of absence of nearby topographic barriers to cause forced lifting of the moist air. Tucson, Flagstaff, and Winslow are all about twice as high as Phoenix with 33 to 36 days per summer and at least one storm per day is reported. Highest of all is Prescott, with 43 storms per summer, or about six times greater then Yuma's mere 7.

Summarizing the implications of Tables 11 and 12, it is again easy to see that the astronomer's ideal station in terms of mere sky-cover is, throughout the year, Yuma. Flagstaff and the surrounding area of the Mogollon Rim and the southern Colorado Plateau appear to be distinctly less favorable than the southwestern corner of Arizona, not only in winter when the effects of migratory cyclones make this trend meteorologically quite obvious, but, more surprisingly, also in summer due to a fairly large amount of convective activity in that region, comparable roughly to that of the extreme southeastern corner of Arizona. Reference to Smith and McCrosky's data (reproduced for Arizona only in Figure 10) yields essentially the same conclusion, of course.

Since only first-order Weather Bureau station data are published in Local Climatological Data, and since the record-lengths for some of the six first-order stations are rather short by climatological standards, it is of value to have even indirect indications of cloud climatology based on more extensive data. One such type of indirect data that seems pertinent is the long-term average number of days with more than 0.01 inch of precipitation at various stations. This quantity is available for scores of Cooperative Weather Bureau stations well-distributed over the state and having record lengths of up to fifty and sixty years. The observation of a "day with over 0.01 inch of precipitation" is much more reliable than almost all other types of weather phenomena for several reasons: First, cooperative observers in the arid Southwest are invariably keenly attentive to rainfall occurrences. Second, the observer does not have to be at his station at a definite time to make this kind of observation since his raingauge and other indirect indications are fairly trustworthy as to mere occurrences of more than traces of precipitation. Finally, it does not depend upon subjective estimates of amounts (once over the 0.01 inch threshold) as in cloudiness observations. On the other hand, number of rain-days is not, of course, highly correlated with overall cloudiness. All that one can say is that any day with over 0.01 inch of rain is almost certainly a day with fairly high sky-cover, especially in winter. So this quantity has both advantages and disadvantages. Since, however, it is entirely independent (in the observational sense) of all other types of data used here and since it is available for numerous stations, I have extracted data on rain-days for reference use here.

A tabulation of monthly average numbers of days with over 0.01 inch per day for a large number of Arizona's Cooperative Weather Bureau stations has recently been published by Smith (1956). As a measure of midwinter conditions, I have plotted in Figure 11 the average total number of days in January and February (combined) with over 0.01 inch; and as a measure of conditions in the rainy season of summer I have plotted the corresponding July-August average totals in Figure 12, using Smith's basic data. Each figure represents a single Weather Bureau cooperative station. Only records longer than ten years were used in these two figures. The isolines are drawn in purely mechanical fashion to delineate just the plotted data. No effort to infer topographic effects between actual reports has been made in Figures 11 and 12.

Figure 11 shows as its most salient feature the greater amount of winter storm activity over the Plateau than over the southern part of Arizona. By contrast, a large area extends from Yuma eastward past Sells and almost to Tucson wherein less than five rain-days are reported, on the average, in January and February combined. By contrast, two extensive areas of over ten days are found to the north. In several localities, as near Flagstaff, Irving, Sierra Ancha, and McNary, values three times higher than those of the Yuma corner are found. The southeastern corner of the state is infrequently enough influenced by lows and trailing cold fronts that, despite fairly high terrain, the total number of rain days does not rise above ten.

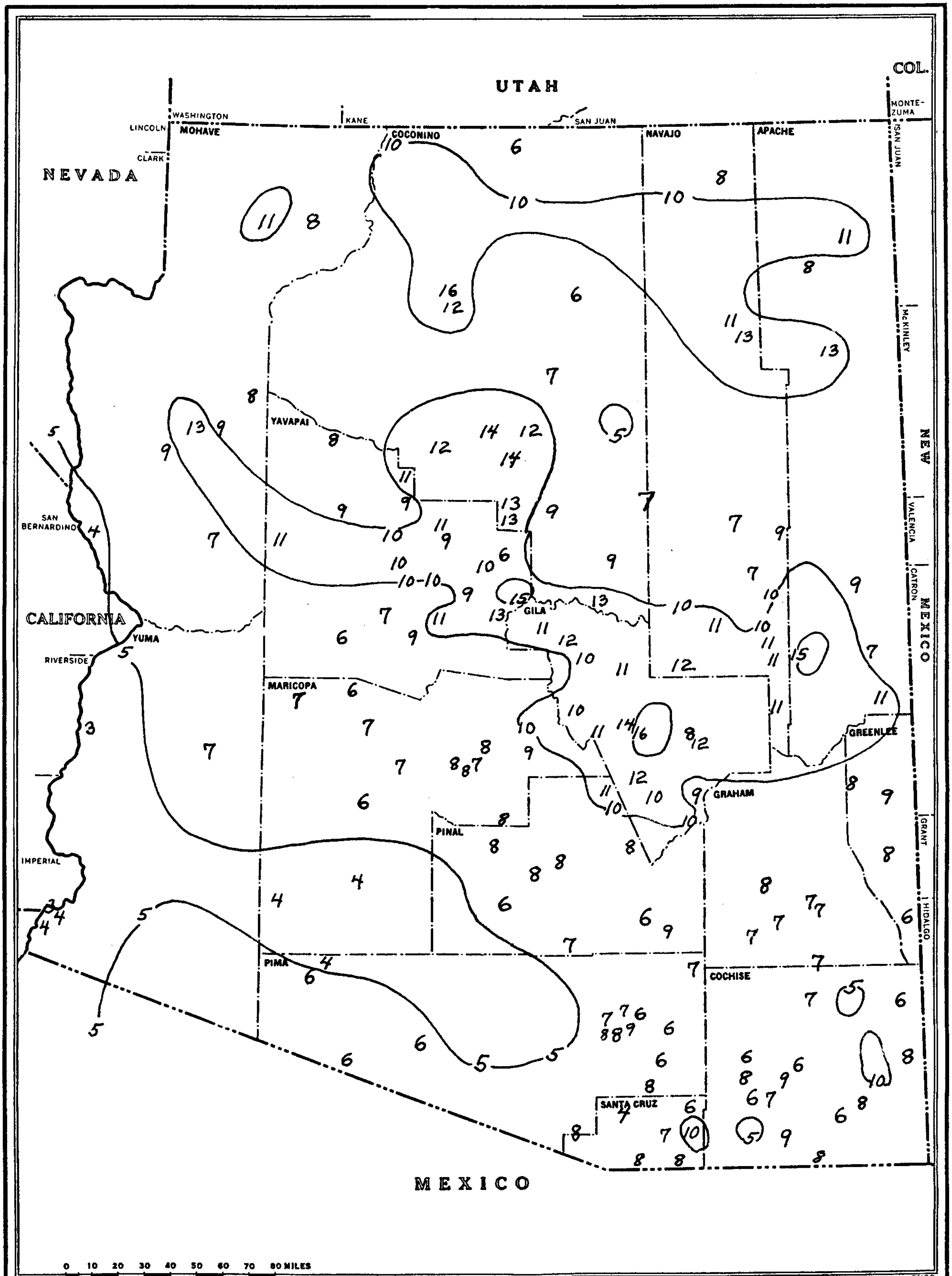


Figure 11. Average total number of days in January and February with more than 0.01 inch daily precipitation for Arizona cooperative Weather Bureau stations.

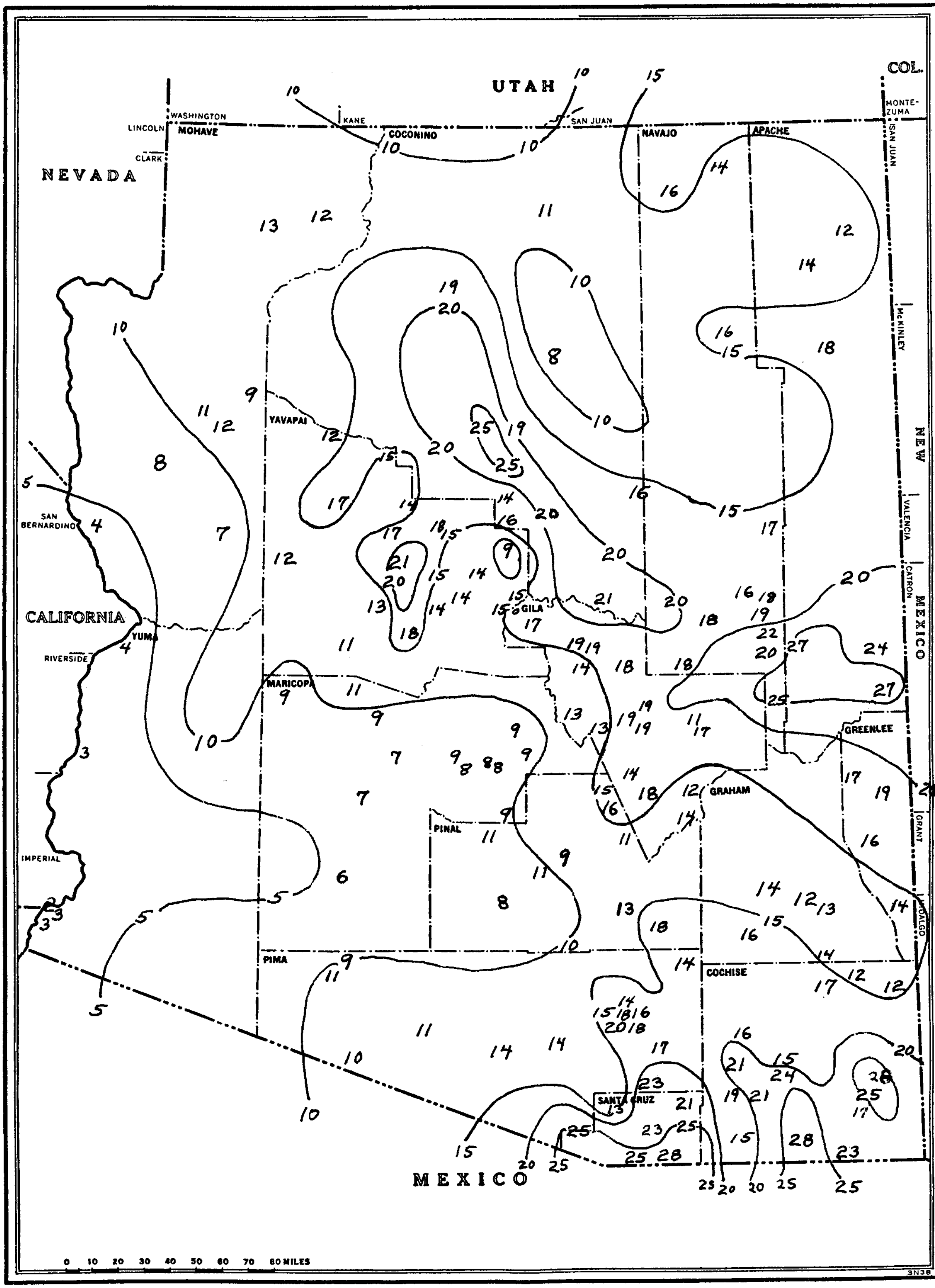


Figure 12. Average total number of days in July and August with more than 0.01 inch daily precipitation for Arizona cooperative Weather Bureau stations.

The pattern of Figure 12 for July and August combined is somewhat more complex. The southeastern corner of the state, especially very near the Mexican border, has a high number of rain-days, exceeding 25 near the Patagonia, Huachuca, Mule, and Chiricahua Mountains. A tight gradient bounds this area on its northwest edge, with values falling to less than 15 near Sells and then continuing to fall off westward to only about 3 near Yuma itself. The Mogollon Rim, exerting marked lifting action on the prevailing southerly flow of July and August, has almost as many rain-days as does the extreme southeast corner of Arizona. The White Mountains area from Alpine to McNary have counts in excess of 25 for the two-month period, and so does the Flagstaff area. Prescott has about 20, which seems, if anything, surprisingly low in view of Prescott's high number of thunderstorm days (Table 12), though perhaps this argues that it is the Prescott thunderstorm figures that are unduly high for some reason, since the rain-day statistics ought to be relatively more reliable. The low centered on Yuma extends predominantly northward, roughly perpendicular to the trend of the winter low reaching from Yuma towards Sells (Figure 11). This north-south trend in summer results, of course, from the general location of the monsoonal band of high moisture content extending northward into the United States from Sonora and seldom shifting over as far west as the lower Colorado River.

In Figure 13, a chart showing the nationwide pattern of annual total number of days with over 0.01 inch of precipitation is shown for comparison purposes. It will be seen that this 1941 chart indicates a maximum number of rain-days along the edge of the Mogollon Plateau, with a secondary center near Santa Cruz County due to summer thunderstorm activity. This chart, I would say, is relatively more trustworthy than the cloudiness charts from the same 1941 publication, since data on numbers of day with rain have been reliably taken for many decades. The 1941 tabulations underlying Figure 13 were probably

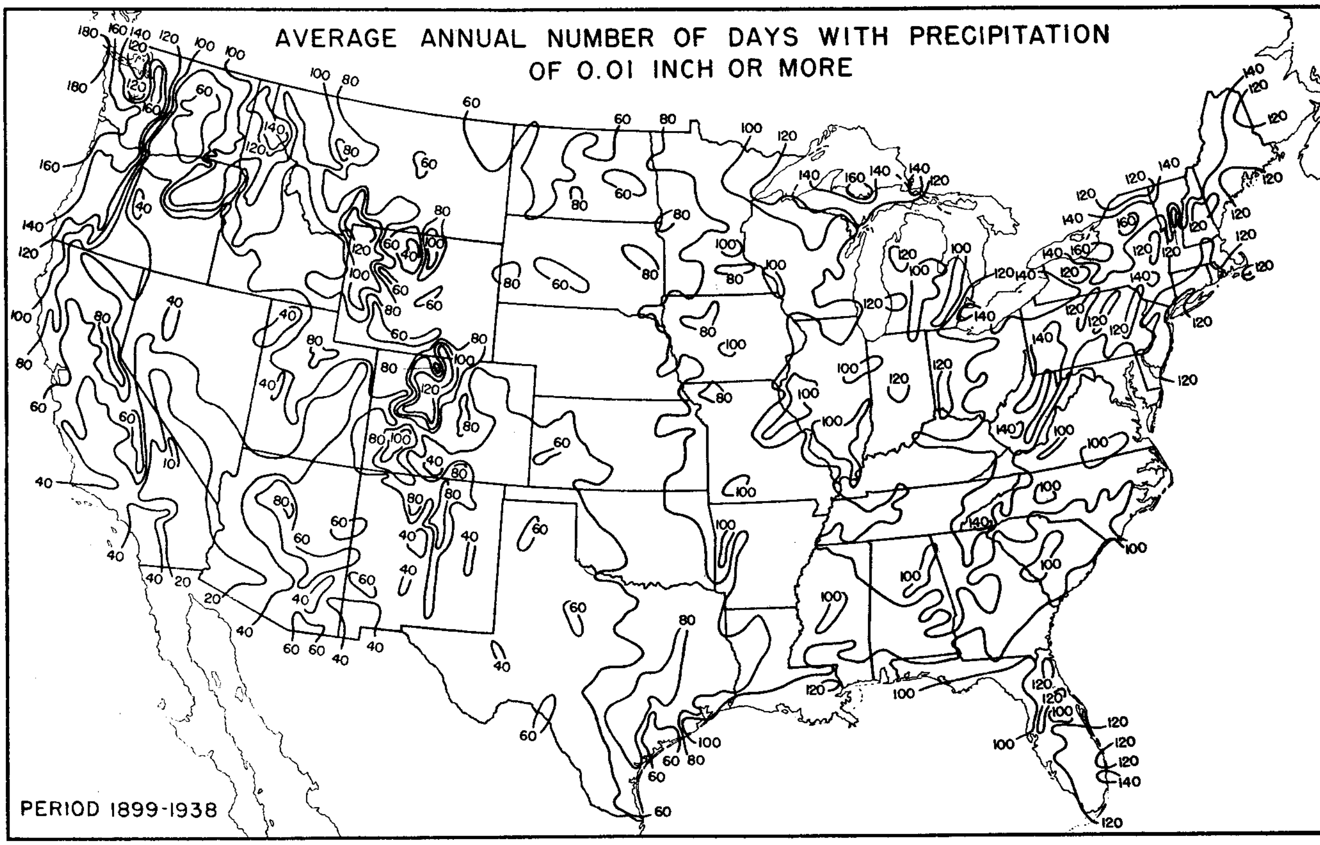


Figure 13. Nationwide pattern of average annual number of days with more than 0.01 inch of precipitation. From U. S. Dept. of Agriculture 1941 Yearbook of Agriculture, Climate and Man.

based on quite large numbers of cooperative station records, even in sparsely settled Arizona.

In summary of this examination of Arizona statistics, it seems entirely safe to say, once more, that the greatest total number of observing hours per year will be available at Yuma. But as has been stated before, this is already well-known and is not the answer to the astronomer's problem because Yuma has no high altitude sites in its immediate vicinity. If, then, one seeks a site as close to the Yuma center of clearest skies, the question is: In what general direction should one proceed in order to optimize the observing opportunities? I believe that these data strongly support the view that one should look to the northeast or east, because of the nature of winter cloud-cover and because of the night-duration argument. Within this sector one finds a peak at 4820 feet msl in the Kofa Mts, one at 5670 ft in the Harquahala Mts, one at about 5000 ft in the Harcuvar range, and several near 7000 ft in the Baboquivari-Quinlan range. Winter haze-level considerations (see Appendix B) and summer thermal instability considerations make peaks 5000 ft or under undesirable for seeing reasons, so it would seem that the Harquahala and the Baboquivari-Quinlan areas probably offer the best compromises, on purely physical grounds. One can only regret, in sympathy with the astronomers, that there is not a 7000 ft peak about thirty or forty miles in same direction from Yuma.

X. SUMMARY AND CONCLUSIONS.

In all of the annual and the winter analyses, Yuma proves to be the southwestern station whose cloud-climatology appears most favorable to astronomical observing. In summer it is second only to the Central Valley of California. But because of a number of climatological characteristics of the Yuma area (haze depths, dust depths, depths of adiabatic layers), transparency and seeing difficulties rule out any low-altitude sites near Yuma.

Lack of peaks near Yuma reaching to altitudes of over 5000 ft makes the basic astronomical problem one of optimizing site-selection in the region concentric with Yuma.

Use of standard Weather Bureau sunshine and cloudiness statistics in assessing sites is unfortunately not an entirely straightforward matter due to a number of inherent weaknesses in such statistics. However, when several independently observed parameters are jointly studied, as in the present report, a reasonably consistent and therefore probably reliable picture of the cloud climatology of the Southwest emerges.

Coastal southern California cloudiness data for summer are not astronomically relevant since locally high frequencies of stratus raise reported cloudiness yet do not directly interfere with mountaintop observing. In winter, on the other hand, intercomparisons are somewhat more meaningful due to less stratus and more cyclonically-produced cloudiness and are also rather more significant than those of summer because winter nights are appreciably longer than summer nights at 30-35° latitude. Both Yuma's and Tucson's winter nighttime cloudiness is lower than that reported at Los Angeles and San Diego, the 2330 MST averages over the half-year centered on the winter solstice being, respectively, 65,53,46, and 38 for these four stations. Tucson's summer cloud-cover is high during the two-month rainy season of July and August, whereas Yuma is almost uninfluenced by the monsoonal current of moist air invading the United States from Mexico in summer, e.s., only 3 days with over 0.01 inch precipitation in the entire July-August rainy period. A rapid decrease of cloudiness and thunderstorm activity from east to west across southern Arizona is shown in all maps and is consistent with impressions held by weather observers in the Tucson Weather Bureau office who report distinctly earlier cessation of convective activity to the west of Tucson than to the east on typical summer evenings.

Within the state of Arizona itself, joint considerations of cloud climatology and mountain geography indicate that the best observing opportunities may be expected in the Quinlan Range or in the Harquahala Mts. If one moves a hundred miles east of the Quinlans, the losses due to summer convective activity become a disadvantage, whereas to the west of the Quinlans, there are simply no peaks high enough to be astronomically useful. If one goes north or northeast from the Harquahala Mts, conditions also grow less favorable. To the northeast, both winter cyclinic cloudiness and summer orographic thunderstorm activity are disadvantageous. To the north, as in the Kingman area, the summer thunderstorm problem is less serious than to the northeast but the winter storms still raise the local cloudiness there in an unfavorable way.

Lack of data (i.e., lack of first-order Weather Bureau stations) to the immediate west and northwest of Yuma in California is a serious present difficulty in site assessment. There is little doubt on general climatological grounds, that a mountain site northwest of Yuma would be almost wholly free from summer convective activity of the type that leads to extensive cirrus anvils; but it is hazardous to speculate on the winter cloud climatology of such area. With respect to winter cirrus frequencies there is no reason to believe that such peaks would be superior to any in Arizona, since cirrus formation occurs at great heights under control of dynamical processes (notably jet-stream processes) not directly governed by low-level topography. With regard to lower overcasts of winter rain-releasing cloud decks, (e.g., altostratus) there is meteorological uncertainty as to whether peaks within a hundred or so miles northwest of Yuma would or would not be in the rain-shadow of the California coastal ranges. No peaks extending to above 6000 ft (estimated regional mean annual altitude of haze and dust tops) are to be found west or northwest of Yuma except in the area just west of Palomar (San Jacinto Mountains). Such far-west sites must begin to share that part of San Diego's winter cloudiness that is not simply low stratus. In all, I believe that it is not likely that the California peaks are superior to those of southwestern Arizona. Actual mountaintop cloud observations would be required to confirm or reject this climatological conjecture; but are unavailable, unfortunately. The coastal stratus problem, though a much less severe source of distortion of winter than of summer cloudiness statistics is still present to some extent even in winter and it has not been possible to make due allowance for these stratus effects in the present study.

The evident weaknesses of nighttime cloud observing and the general lack of good data on astronomically important traces of cirrus cloud make it highly desirable to institute automatic cloud-recording programs at all southwestern observatories. It is strongly urged that polestar cameras be adopted as recommended by Jones to routinely record passage of photometrically important wisps of cirrus. Even a half-dozen years of record of this type from a number of sites over the Southwest would be extremely helpful in any future site-survey work.

ACKNOWLEDGMENTS

The support of the Associated Universities for Research in Astronomy is gratefully acknowledged. Since Mr. Robert B. DesJardins' efforts were responsible for much of the basic data discussed in Section II-V, his work is an essential part of the present study. A number of other Institute staff members have assisted in the preparation of various tabulations used here and their assistance is also appreciated. Dr. A. R. Kassander, Jr., has aided both directly and indirectly in a number of ways in accomplishing this study. Dr. A. B. Meinel of the AURA survey team was responsible for the initiation of these analyses and has contributed in an important way by defining the problems of principal interest. Dr. E. F. Carpenter of the Steward Observatory has also aided through a number of helpful conversations on astronomical matters.

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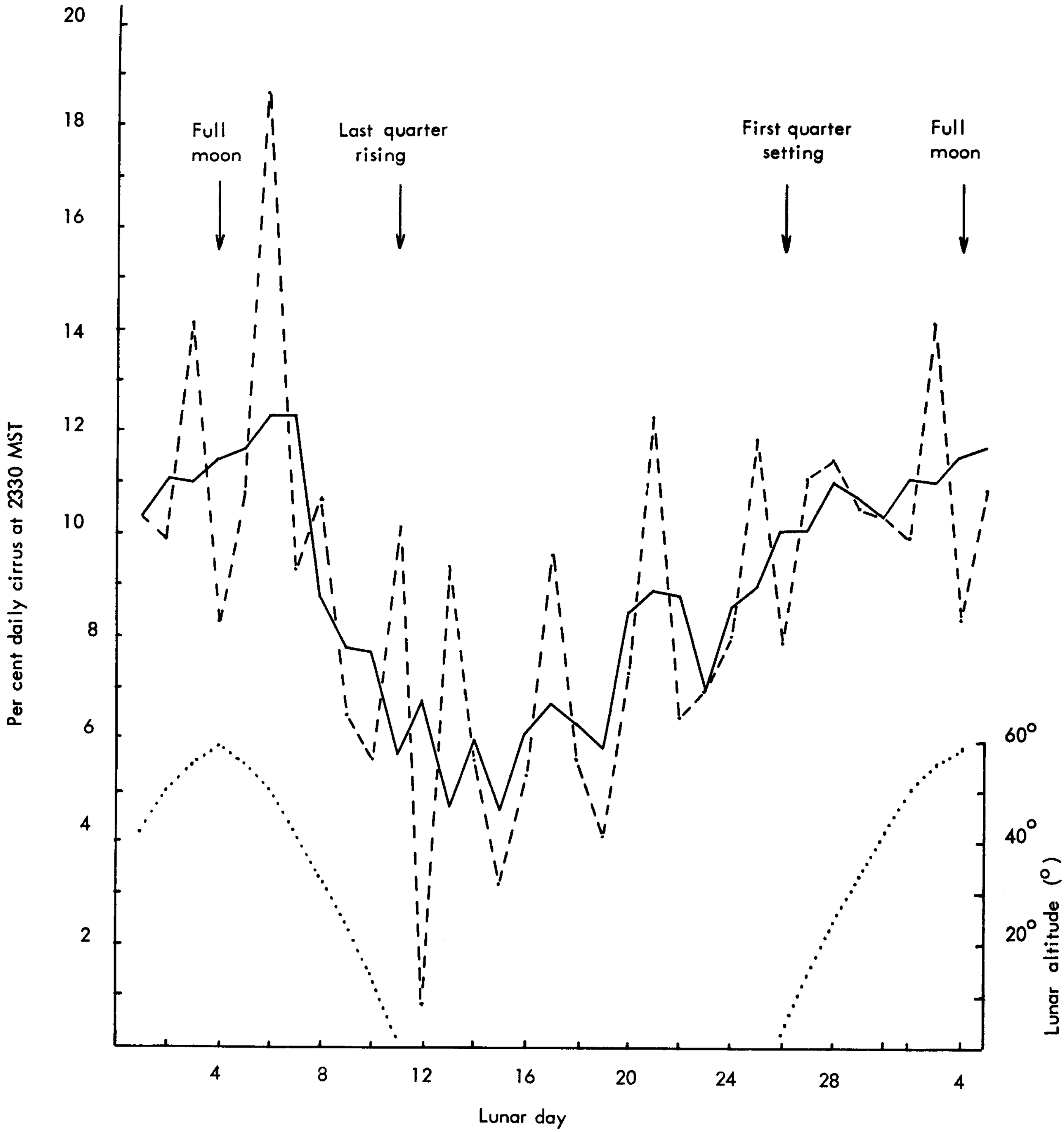

Fig. 14. Relation between frequency of nighttime observation of cirrus clouds and lunar altitude at Tucson. Data represent 41 lunar months in the calendar period January–June for years 1946–54. Dashed curve shows, for each lunar-month day the average amount of cirrus cloud observed at the 2330 MST observation at the Tucson Weather Bureau station expressed as a percentage of total cirrus observed per day. Solid curve represents 3-day running mean percentages derived from dashed curve. Dotted curve (ordinate scale at right) represents the average 2330 MST lunar altitude for a mean lunar declination of 0° at latitude 32°. The minimum in cirrus observations at those periods of the lunar month when the moon is not illuminating the sky and the maximum of cirrus observations near full moon are clear evidence that nighttime cloud frequencies must be corrected for lunar phase effects.

APPENDIX A. NIGHTTIME CIRRUS OBSERVATIONS.

Cirriform clouds are extremely difficult to see at night under ordinary conditions. Consequently, nighttime meteorological reports on cirrus tend to underestimate the true amounts of cirrus present. Because cirrus is such a source of difficulty in photometric work, it is of interest to have some rough measure of how much more cirrus may actually be present than are reported.

In a study carried out at the Institute several years ago, Baer (1956) tabulated Tucson Weather Bureau cirrus reports in a way that revealed rather clearly the extent to which illumination by the moon influences cirrus observation. He tabulated cirrus reports not according to calendar day, but rather according to days in the lunar month. In Figure 14 one of his figures is reproduced for reference use by astronomers. The caption gives adequate explanatory comment. It will be seen that roughly twice as much cirrus is reported near full moon as near new moon. Another informative graph will be found in Baer's 1956 paper cited above. The implication of prime interest is this: Nighttime cirrus reports are not really much better than daytime reports in assessing photometric observing opportunities. Larger cloud masses (e.g. cumuli, stratocumuli) are not nearly so easily missed as are wisps of cirrus, of course.

APPENDIX B. THE HAZE AND DUST PROBLEM.

One of the problems confronting anyone seeking optimum sites for astronomical observatories is the problem of haze layers and wind-raised dust. Both of these problems arise in the Southwest and bear on the general subject of this report even though they are not related directly to cloudiness. No routine Weather Bureau observations are made on these phenomena in a way that is astronomically relevant. Hence one must turn to other, less satisfactory types of information. I have made an effort to learn what several light-plane pilots who have flown in Arizona for many years have learned about haze and dust layers as a result of their flight experience. Their comments are summarized here as the only information readily available on this interesting matter.

Mr. A. A. Hudgins. Mr. Hudgins has flown in Arizona for about thirty years and operates a charter service out of Tucson and a tourist-flying service at Grand Canyon. He points out that pilots of small aircraft tend to be particularly conscious of haze layers because just above them one always finds very smooth air. Hudgins thought that as a year-round average figure, the top of the haze layer in southern Arizona would be at about 6000-7000 ft msl. In winter he estimated it at from 4000 to 6000 ft msl. He estimated the summer dust tops at about 10,000 to 12,000 ft msl. He had the impression that the haze and dust tops tended to be a matter of terrain clearance, and hence guessed that the corresponding heights over Yuma might run about 1500 ft lower. He was emphatic in saying that when one flies south from the Grand Canyon area and crosses the Mogollon Rim, he almost invariably hits, quite suddenly, a "wall" of haze, smoke, and dust at about the edge of the Rim. This, he felt sure, is Phoenix industrial smoke plus dust from field cultivation in the Salt River Valley. He said it is uncommon to see much haze or smoke north of the Rim.

Mr. John Thomas. Mr. Thomas has flown for fifteen years in this area and now flies with Tucson Aviation Co. His first reaction to my questions was that haze and smoke are relatively scarce around Tucson, Phoenix, by contrast, he described as frequently smoky and dusty to about 4000 ft msl in winter. He has the impression that the Phoenix situation has changed markedly in recent years. He feels that summer dust seldom gets above 7000-8000 ft msl except with local convection. He had the impression that Kitt Peak is often clear when the Santa Cruz Valley is slightly hazy or smoky. He observed that north of an east-west line through about Tucson, or possibly a bit north of that, cultivational activities often raise a noticeable amount of dust at least as far west as Gila Bend.

Mr. M. L. Clements. Mr. Clements operates Tucson Aviation Co. and has flown in this area for many years. He put the summer average top of the dust layer at 8000-10,000 ft msl, and the winter haze top at 4000 to 7000 ft msl. He feels that smelter smoke is a big factor and described a situation where he traced Ajo smelter smoke all of the way to Yuma.

Mr. G. A. Edwards. Mr. Edwards has been a flight instructor at the Marana Air Base and has been a charter pilot in the area for years. His opinion was that haze tops in southeastern Arizona are always under 8000 ft msl, with 6000 ft msl as an average. He also said that he felt that haze and smoke layers were really not very common. In summer, with strong convective activity, he said he has often seen dust rise to about 10,000 ft msl. He has not flown much in the northern part of Arizona but thinks it is typically clearer there at 8000 ft. msl He too noted that as one flies south towards Phoenix from the Plateau there is a rapid deterioration of horizontal visibility and he attributes this to cultivation. He does not often fly to Yuma and the coast, but it is his impression that during both winter and summer the haze layer is at about 8000 ft msl from Yuma towards the Salton Sea.

Each of these opinions were independently given, without hearing a preliminary summary of what other pilots had said. Hence, although the above is certainly rather scant evidence, the rough agreement between these independent estimates by pilots familiar with the area is of some value. The principal implication of astronomical interest is that peaks in southern Arizona much under 5000 ft msl will frequently have winter haze above them and peaks at even 7000 ft msl will occasionally have summer dust overhead if cultivation is carried on upwind. This problem will be acute in the Salt River Valley or other areas where a great deal of agricultural activity goes on.

From personal observations while driving between Tucson and Phoenix, I have concluded that there is prevailing much lower visibility in the area from about Picacho to Phoenix during winter. On passing southeast of Picacho Pass on U.S. 84, one encounters a rapid increase of visibility during cultivating periods, due to the very much smaller total area in cultivation to the south.

No Institute research up to the present time has been concerned with the winter haze layer. However, while engaged in the present study I made several automobile trips to an altitude of about 6500 ft msl in the Santa Catalina Mountains northeast of Tucson in order to make some personal observations of late-afternoon haze layers. From a fairly detailed knowledge of the distant peaks, I was able to deduce the altitude of the haze tops and then compare these with the concurrent lapse rate conditions as found from Tucson Weather Bureau 1700 MST radiosonde report. The results seem worth summarizing.

In each instance, the visual estimates of the height of the haze top were made without having previously seen the 1700 MST Tucson radiosonde report (which, in fact was being taken at exactly the time I was driving up to the 6100 ft level in the mountains each day).

On 15 February at 1800 MST I visually estimated the haze top at 5500 ft msl. Subsequently, from the Tucson radiosonde report I found a distinct break in the lapse rate on the 1700 MST sounding at 5300 ft msl, with adiabatic lapse rate below 5300 and about a 6°C/km lapse rate above that level.

On 16 February at 1745 MST, I estimated the haze top at about 5000 ft msl. The 1700 MST Tucson sounding showed an inversion with base at 5100 ft msl, again agreeing remarkably well with the mountain estimate.

On 17 February at 1750 MST, I estimated the top of the valley haze at 5000 ft msl. The 1700 MST sounding showed a 15-mb-thick isothermal layer centered at 5000 ft msl, again in excellent agreement with the observation made from the mountains.

In each of these instances a nearly adiabatic layer extended, near sunset, from the surface to almost exactly (plus-or-minus 200 ft) the altitude marked by the haze top. Although an exact explanation of this close agreement would require much more observation and analysis, my strong suspicion is that the underlying process is simply this: Depending upon the total amount of solar radiation converted into low-level air-mass heating each day, a surface layer of variable depth of the order of 5000 ft minus 2500 ft (Tucson terrain altitude) develops a neutral (adiabatic) lapse rate. Smoke or dust is then carried in turbulent currents to the upper limit of this neutrally stable (or, on some days, slightly unstable layer) and thereby forms that day's haze top. Since each of the three days cited above had nearly clear skies and was almost calm, and since other conditions (general lapse rate, surface dryness, etc.) were also typical, I would imagine that the greatest altitude to which surface particulates can be distributed must not be greatly in excess of 5000 ft msl in winter. Earlier in the fall or later in the spring, the daily heating is greater and a deeper adiabatic layer can form and then the haze layer will be higher. (This is in fairly good agreement with the preceding pilot estimates, from which a winter mean of about 6000 ft msl was inferred.)

If this latter conjecture is essentially correct, then about the same processes must be expected to operate throughout southern Arizona, with slight variations imposed by valley-mountain circulation systems. As a result, the lower mountains to the west of the Baboquivari-Quinlan ranges would be rather unsatisfactory, on account of haze, as would almost all of the low peaks near Yuma. On each of the three days cited above, Kitt Peak rose quite distinctly above the haze layer, which was easily visible all along the Quinlan and Baboquivari slopes as viewed from fifty miles away in the Catalinas.

The above evidence is far from adequate in either quantity or quality, but is appended here as the only information now available to me. In an effort to get better observations on haze tops, I have arranged for routine logging of haze layers by two aviation companies that do a large amount of flying in Arizona. None of their observations are, however, available yet, since this program was only begun within the past week, (as a direct result of the realization that the Institute needs to get better data on this interesting meteorological problem).