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ENVIRONMENTAL EFFECTS OF SOLAR-THERMAL POWER SYSTEMS

ECOLOGICAL OBSERVATIONS DURING EARLY TESTING OF THE BARSTOW 10-MWe PILOT STPS

NOVEMBER 1982

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Editor
Frederick B. Turner

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Abstract

Environmental measurements were continued at Solar One during 1982, while final steps in construction and early testing were carried out. Measurements of sand depths downwind (east) of the heliostat field indicated that some of the sand blown of the field (most of it between September 1979 and March 1980) has been carried farther east, reducing sand depths somewhat in areas just east of the field. Observations of birds between March and June 1982 revealed that 1) the natural avifauna of the field has been altered, although the area is still used for feeding by some icterids (larks, blackbirds) and aerial insectivores (swallows, swifts), 2) of 15 bird casualties ascribable to the presence and/or operation of Solar One, 12 followed collisions with heliostats, 3 resulted from incineration in heliostat beams, 3) the central receiver tower does not appear to be a source of mortality. Numbers of rodents (particularly kangaroo rats) trapped in areas downwind of the site declined steadily between 1978 and 1982 in areas both close to the field and as far east as 600 m from the fence. The most likely interpretation of these changes is a reduction in reproductivity and/or early survival caused by four consecutive years (1978, 1979, 1980, 1981) of suboptimal autumn rainfall. Micrometeorological measurements in areas downwind of Solar One showed small effects on air temperatures ($<0.5^{o}$ C), wind speeds (<0.4 m/sec), and evaporation rates (<1.5 ml/hr). Effects were detected only in areas 100-190 m from the east perimeter fence. Because these differences are so small, relative to natural heterogeneities, the effects of Solar One on rates of evaporation, air temperatures and wind speed will not affect the downwind biological community. The relevance of these findings to construction of a larger solar thermal power plant (e.g., Solar 100) are considered.

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1. Introduction

The goal of the Solar Thermal Energy Systems Division of the U.S. Department of Energy (DOE) is to support and accelerate development of a self-sustaining solar thermal industry. Construction and operation of demonstration facilities to validate technical and economic feasibility, as well as to confirm environmental acceptability of the technology, is an important element of DOE strategy. The DOE, together with the Southern California Edison Company (SCE), the California State Energy Commission, and the Los Angeles Department of Water and Power, has constructed a 10 MWe solar thermal power system (STPS) near Barstow, in San Bernardino County, California (Fig. 1). This project, Solar One, represents the first large central receiver-type solar facility for generating electricity constructed in this country. The Laboratory of Biomedical and Environmental Sciences (LBES), acting for DOE, was assigned responsibility for assessing environmental consequences of constructing Solar One.

Solar energy is generally perceived as ecologically benign, but it is important to confirm this perception by observations made during the construction, testing and operation of a solar thermal power plant. Possible environmental impacts of solar thermal power systems have been discussed in a number of earlier reports and papers (Pritchett, 1975; Energy Research and Development Administration, 1977; Environmental Improvement Agency, 1977; Black and Veatch and Electric Power Research Institute, 1977; Davidson and Grether, 1977; Patten, 1978; Energy and Environmental Analysis, 1979; Turner, 1980; Strojan, 1980; Bhumralkar et al., 1981; and Lindberg and Perrine, 1981). Almost all these writings have been based on guesses and whatever general theory can be adapted to operation of a solar thermal power system.

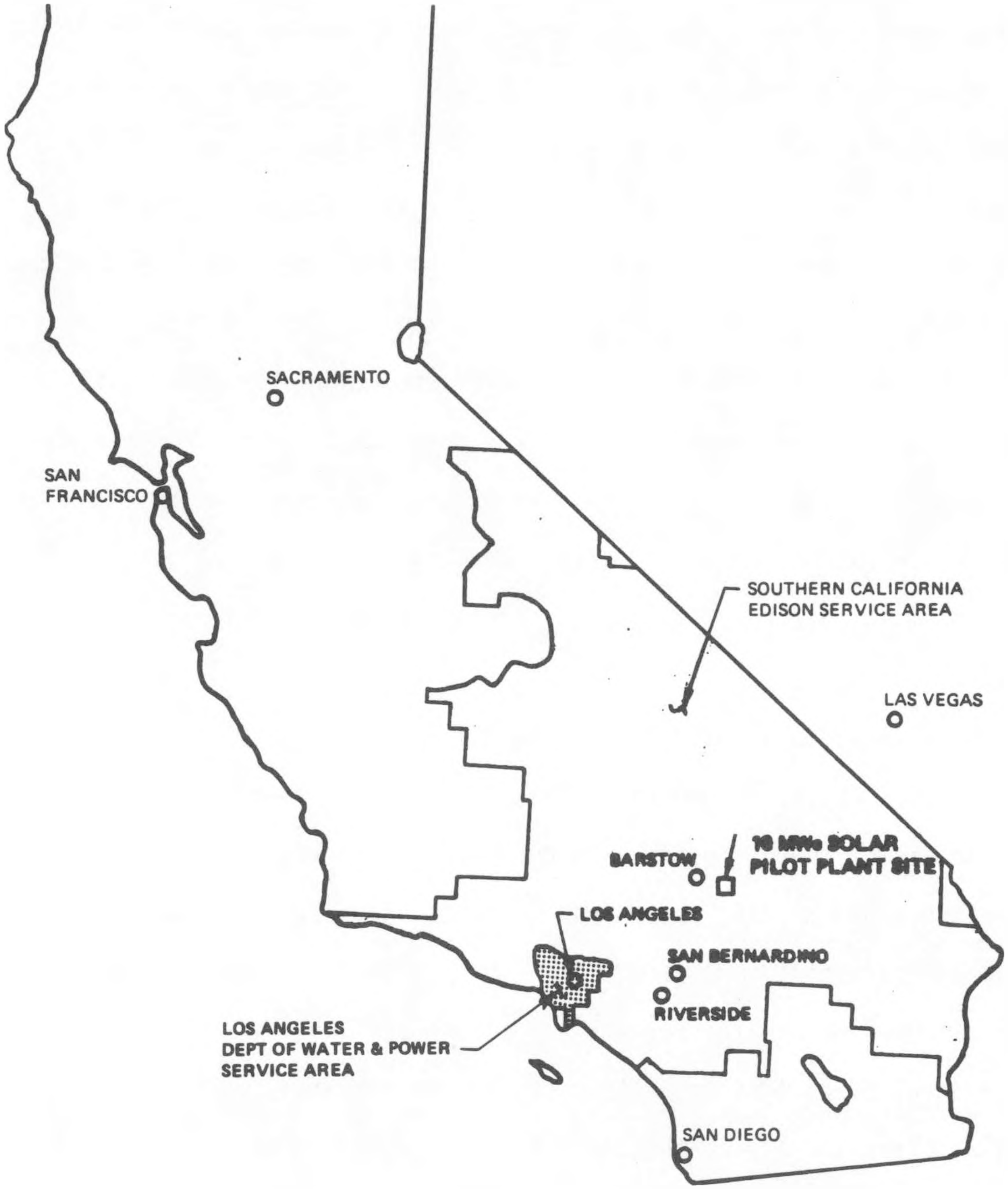

Figure 1. General area map showing Barstow, California, and site of 10 MWe solar thermal power plant (EIA, 1977).

The early testing of Solar One afforded an invaluable opportunity to examine off-field environmental effects in a real-life setting--research which can serve to promote commercial development of an emerging technology.

Solar One was built about 19 km east of Barstow, California, on land owned by SCE. The site is at an elevation of 590 m and in the western portion of the Mojave Desert on the ancient flood plain of the Mojave River. A detailed discussion of site geology and hydrology was developed in the environmental impact analysis. The plant site receives about 3500 hours of sunshine annually. The perennial vegetation of the site and environs is composed mainly of three shrubs: bursage (*Ambrosia dumosa*), saltbush (*Atriplex polycarpa*) and creosotebush (*Larrea tridentata*). The heliostat field was originally cleared of natural vegetation in 1953 and crops grown until 1956. After the field was abandoned natural processes of recovery began, and in 1979 the predominant shrub on the mirror field was saltbush. Farther east the most common shrubs are creosotebush and bursage. Annual plants and animals occupying the area are typical of the Mojave Desert. Lists of species may be found in the original impact analysis and in a pre-construction site description conducted in 1978 and 1979 (Environmental Improvement Agency, 1977; Turner, 1979).

The purpose of the pre-construction observations was to i) establish normal attributes of the ecosystem, ii) evaluate seasonal variations in these attributes, and iii) identify selected species or groups of species whose status could be conveniently monitored during construction. This work was summarized in an earlier report (Turner, 1979). Further observations were carried out during the construction of the facility (Turner, 1981). The present report describes work done during 1982, most of it after various tests of the facility had begun.

2. Review of final phases of construction and early testing

Steps in construction of Solar One through the summer of 1981 were reviewed in an earlier report (Turner, 1981). Basic construction of the facility was completed by the end of September 1981. Then followed a 6-month "start up" period extending to the end of February 1982. Tests of functioning of heliostats were begun in March. Steam was introduced into the receiver panels at about this time, and steam was passed into the turbine in early April. Formal plant operation began on April 12, but the power plant only produced about 3.5 MW_e at that time. Further testing of the thermal storage system began in May. Steam was conducted from the receiver to the storage tank in June.

By October 1982 the plant had supplied--intermittently--a total of 785 MW/hr to the power grid. The plant produced a net of 10.4 MW in early October, but so far has not achieved overall positive power production.

3. Observations during 1982

3.1. Measurements of sand depths downwind of Solar One

In February 1982 we laid out four lines, 40, 80, 130 and 200 m east (downwind) of the east perimeter fence around the heliostat field. Lines were 240 m long and ran in a north-south direction, with south ends along a line running due east from the receiver tower. Calibrated aluminum stakes were placed 10 m apart along each of these lines (100 in all), and the initial level of soil surface recorded at each stake on February 23. Measurements were made again on April 23, June 16 and October 7, 1982.

Measurements of sand mounds deposited downwind of shrubs east of the heliostat field were made between October 1978 and January 1980 and again in May 1980 (Turner, 1981: 22). These same mounds were measured again in October 1982. From these measurements we were able to draw inferences as to rates of sand deposition at varying distances downwind of the field.

Table 1 gives mean changes in soil surface levels based on inspections of calibrated stakes in 1982. Along the two lines closest to the heliostat field there was a net reduction of surface levels owing to movements of sand to areas farther downwind. Between 130 and 200 m of the field we measured small increases in surface levels. Note, however, that this pattern was not consistently expressed over shorter intervals between February and October. Between June 17 and October 7 we measured inputs of new sand at all distances.

Table 1. Mean changes in soil surface levels (mm) ± one standard error at four distances downwind of the Solar One heliostat field in 1982.

Distance from field (m)	Feb 23 - Apr 23	Apr 24 - June 16	June 17 - October 7	Net change, Feb - Oct[1]
40	-4.1 ± 1.4	-1.2 ± 1.7	2.0 ± 0.6	-2.9 ± 1.4
80	-3.4 ± 1.3	1.3 ± 0.7	1.6 ± 0.5	-0.3 ± 0.5
130	0.0 ± 0.5	-1.6 ± 0.4	2.7 ± 0.6	1.9 ± 0.7
200	-0.2 ± 0.6	-0.8 ± 0.4	1.3 ± 0.5	0.3 ± 0.7

[1] Net values may differ slightly from sums because of rounding and loss of stakes owing to traffic and accidents.

Past measurements of downwind sand mounds and observations during 1982 are summarized in Table 2. Figures for 1978 to 1981 are corrections of values given in an earlier report (Turner, 1981: 22) where actual mound heights were represented as "mean increases in height." The 1982 measurements are similar to those reported above, i.e., implying recent ablation close in (26-37 m east of the field), with deposition in areas more than 50 m from the fence.

Table 2. Changes in peak heights of sand mounds deposited downwind of shrubs east of the Solar One heliostat field in 1982. Sample sizes are given in parentheses.

Distance from field (m)	Mean changes (cm) in mound heights ± one standard error Oct 1978-Jan 1980	 Jan 1980-May 1981	 May 1981-Oct 1982
26-37	18 ± 7 (3)	10 ± 2 (4)	-7 ± 2 (7)
40-49	14 ± 2 (5)	1 ± 1 (4)	0 ± 2 (9)
51-58	7 ± 2 (3)	6 ± 2 (3)	2 ± 2 (7)
60-79	-	-	3 ± 1 (12)
87-98	0.4 ± 0.2 (10)	1.1 ± 0.4 (11)	0.2 ± 0.2 (12)

Comparisons of particle size distributions of sand and soil from bare areas east of the heliostat field showed that 90% of sand was composed of coarse particles (53μ - 2 mm in diameter) and 6-8% of particles 20-53μ in diameter. Soil from bare areas exhibited somewhat larger fractions of silt and clay particles (<20μ).

3.2 Birds

Previous studies of birds in the vicinity of Solar One included preconstruction counts of birds in the prospective heliostat field and areas east of the field between September 1978 and May 1979 (Turner, 1979), and further work in these areas during construction during 1980 and 1981 (Turner, 1981).

Observations within the future heliostat field during 1978 and 1979 revealed the presence of a few raptorial species (vulture, marsh hawk, prairie falcon, burrowing owl), some smaller insectivorous predators (e.g., western kingbird, shrike, Say's phoebe) and various passerines--most notably icterids and fringillids (Turner, 1979: 46). Horned larks were by far the commonest bird in the area, with estimated densities exceeding 500/km^2. The most common winter migrants were white-crowned sparrows and song sparrows, with densities of around 9-10/km^2.

Observations during construction in 1981 were summarized by Turner (1981: 62). During this period the only larger raptorial species observed was the kestrel. Horned larks were still the most commonly recorded species. No sparrows were seen during censuses of January 1981.

Herbert Hill carried out seven 3-day censuses within the heliostat field between March 4-6, March 22-25, April 14-16, April 27-30, May 12-14, May 26-28 and June 8-10, 1982. This work was carried out along 9 transects: one 450-m transect completely encircling the innermost ring of heliostats, four 150-m transects (one in each quadrant of the field) following the outermost ring of heliostats, and four 100-m transects (one in each quadrant) midway between the innermost and outermost rings of heliostats. Observations were made twice each day--in the early morning and again in late afternoon. Table 3 summarizes counts of living birds within the field.

Table 3. Counts of birds within the heliostat field at Solar One in 1982.

Species	Mar 4-6	Mar 22-25	Apr 14-16	Apr 27-30	May 12-14	May 26-28	June 8-10
White-faced ibis		1					
Ring-billed gull		1	2				7
Killdeer							1
Avocet				2	2		
Red-tailed hawk	1						
Mourning dove				2	5		
Say's phoebe						1	
Horned lark	1				3	17	4
Barn swallow	1		1		3		
Raven	1				2		
Starling		30	4	1	12	40	36
Brewer's blackbird			2		5	8	4
Yellow-headed blackbird			6				
Red-winged blackbird			3				
Brown-headed cowbird						1	
House finch							1
Totals	4	32	18	4	32	67	53

Other observations in and around the heliostat field were made in 1982 by Patricia Flanagan, working for the Los Angeles County Museum of Natural History. Flanagan reported most of the species recorded by Hill, and also observed six additional species: prairie falcon, Vaux's swift, white-throated swift, western kingbird, cliff swallow and western meadowlark.

The roster of species recorded by these two investigators includes most of the birds tallied in 1978 and 1979. The notable omissions are three raptors: vulture, marsh hawk and shrike. Hill's 1982 list includes four species normally associated with the evaporating ponds west of the solar facility: killdeer, ring-billed gull, avocet and white-faced ibis. A gull was seen on the ground in mid-April, but in all other instances these birds were simply flying over the field. Neither observer conducted censuses at a time when migrant sparrows might have been observed.

Almost all of the birds observed by Hill were flying over the field at heights ranging from just above the heliostats to above the top of the receiver tower. Of the 210 sightings listed in Table 3, only one was of a bird perched on a heliostat--a housefinch during June 1982. Birds seen feeding on insects in the air were various swallows and swifts and a few tyrannids (e.g., Say's phoebe, kingbird). The other birds feeding in the field were horned larks and starlings, often seen in substantial numbers feeding on seeds. In one instance (May 13), Hill reported a horned lark feeding on ants among the heliostats.

The greatest interest in birds at Solar One has to do with mortality following collisions with structures or inflicted by heliostat beams. During the early phases of testing, heliostats were brought to standby positions--creating luminous orbs about 100 m from the receiver panels (Fig. 2). Many insects were vaporized at these points, creating visible puffs of white smoke.

In the course of all of his censuses, Hill found 12 dead birds in the heliostat field (Table 4). Three of these (the coot, ruddy duck and grebe) were old remains of birds which had apparently died in the area, or were carried into it by predators, before any structures were erected. Eight birds were evidently killed as a result of collisions with heliostats. The hummingbird was killed in a heliostat beam. Flanagan reported other instances of bird mortality in or near the heliostat field. Four mourning doves were found during May--dead as a result of collisions with heliostats. A horned lark was found dead on the entrance road to Solar One in May, but showed no visible signs of death. A Vaux's swift and a barn swallow were mortally burned during May, although the swallow survived for a time after the accident. Records of the two investigators revealed, then, 15 deaths of birds attributable to the presence and operation of the solar facility between March and June 1982. Eighty percent of these casualties followed collisions with heliostats or other structures.

It appears unlikely that birds mortally burned in heliostat beams are entirely incinerated. According to Flanagan, the death of the Vaux's swift was witnessed by several people. Although there was a large puff of smoke, the body of the bird was subsequently recovered. Even the hummingbird was not entirely burned. Hence, we judge that the reported incidence of birds killed by collisions and burning is a reasonable measure of the relative frequency of such events. Birds apparently often survived entry into heliostat beams. Flanagan reported several instances when

Figure 2. Receiver tower at Solar One showing luminous areas at standby focal points.

Table 4. Bird casualties within the heliostat field at Solar One in 1982.

Species	Date	Apparent cause of death
Eared grebe	April 15	not known, old remains
Coot	March 5	not known, old remains
Ruddy duck	March 6	not known, old remains
Kestrel	April 13	collision with heliostat
Mourning dove	April 28	collision with heliostat
4 Mourning[1] doves	May 12	collision with heliostat
Vaux's swift[1]	May 18	burned in heliostat beam
Anna hummingbird	April 1	burned in heliostat beam
Horned lark	March 6	collision with heliostat
Barn swallow[1]	May 12	burned in heliostat beam
Yellow warbler	May 27	collision with heliostat
Starling	March 22	collision with heliostat
Starling	April 14	collision with heliostat
Brown-headed cowbird	April 14	collision with heliostat
House finch	June 10	collision with heliostat

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[1] reported by Flanagan

workers observed the passage of a bird into a beam. In both cases smoke was observed, followed by erratic flight, but both birds recovered and survived their exposure. Some birds apparently perceive and evade the beams. Hill reported that avocets "...flew near the receiving tower and... suddenly swerved to avoid the beam." Flanagan described a group of Canadian geese which flew east from the evaporating ponds towards Solar One and then turned in a manner suggesting deliberate avoidance of heliostat beams.

The conclusions to be drawn from observations made at Solar One during 1982 are that 1) the natural avifauna of the field has been altered, although the area is still used for feeding by some icterids and aerial insectivores, 2) birds are killed because of collisions with heliostats and, less commonly, by incineration in heliostat beams, 3) the absolute incidence of facility-imposed mortality cannot be estimated, but does not appear to be great, 4) the central receiver tower has not emerged as an important source of mortality.

3.3 Rodents

Rodents were trapped within the prospective heliostat field and at various distances east of the field between September 1978 and July 1979 (Turner, 1979) and east of the field between October 1979 and July 1981 (Turner, 1981). The most abundant species in the area was the kangaroo rat, *Dipodomys merriami*, which occurred at densities of around 75 to 82 per hectare in the fall of 1978. Between 1978 and the summer of 1981 apparent densities of *D. merriami* declined fairly steadily in areas 150 m east of the solar field and 600 m east of the field. By July 1981, estimated densities were only about 6% of those recorded in September 1978 (Turner, 1981: 65). Analyses of densities and dates showed that the negative slopes of regression lines for the two areas were the same, although the area closest to the solar field almost always sustained greater numbers of kangaroo rats (Turner, 1981: 66). These analyses were judged to provide "...no evidence that numbers of kangaroo rats... in the proximal plot were adversely affected by construction activities," and that the "...decline in numbers of kangaroo rats in both plots was apparently owing to a sequence of conditions unfavorable for reproduction and/or survival of young" (Turner, 1981: 67).

Trapping was continued, on a reduced scale, during 1982, while both construction and testing were in progress. Two areas were used--one between 55 and 95 m east of the heliostat field perimeter fence, and another between 155 and 195 m east of the fence. The former was in an area where substantial amounts of windblown sand were deposited during 1980 and 1981. The latter was beyond the areas of obvious sand deposition. Live-trapping was conducted along two 300-m north-south lines in each area between

19-21 April and 19-21 July 1982. Each line had 20 stations and two traps at each station. Earlier trapping efforts were designed to afford estimates of density (Turner, 1981), but in 1982 we trapped only to provide comparisons between sandy and non-sandy areas.

Very few animals were taken during either trapping period (Table 5).

Table 5. Numbers of rodents trapped along two lines in each of two areas east of Solar 1 during the spring and summer of 1982.

Dates	Lines 55-95 m from east edge of field	Lines 155-195 m from east edge of field
April 1982	4 Dipodomys merriami	4 Dipodomys merriami 3 Perognathus longimembris
July 1982	2 Dipodomys merriami	2 Dipodomys merriami 1 Citellus tereticaudus

The data are so limited we can only point out the similarity of the two areas in terms of numbers of kangaroo rats trapped. Three of the four kangaroo rats trapped in July were in reproductive condition (two males, 1 adult pregnant female).

The 1982 sampling sustained a trend in apparent reduction of numbers of kangaroo rats which has now continued for almost four years. We can contrast the trapping effort in 1982 with that in earlier years by calculating the number of different individuals captured per trap-night of effort. Between September 1978 and July 1979 each trapping period in each of three areas sampled involved 976 trap-nights. Between October 1979 and July 1981 trapping periods in each of two areas sampled involved 1832 trap-nights. Trapping along all four lines in 1982 involved 480 trap-nights both during April and again in July.

Dipodomys merriami is a seed-eater, and its well-being is directly tied to production by plants affording these foods. Germination, growth and reproduction by plants are, in turn, influenced by rainfall. Relationships between germination and growth of Mojave Desert plants and amounts and seasonal distribution of rainfall have been analyzed in southern Nevada by Beatley (1967, 1969a, 1974), and these observations extended to the dependence of desert rodents on winter annuals and rain (Beatley, 1969b). According to Beatley (1974), "Phenological events in Mojave desert systems are triggered by heavy rains (>25 mm). The most predictable and consequential of these is a regional rain between late September and early December. This rainfall event is usually the precursor of successful vegetative and reproductive growth of plants the next spring..." Rainfall during the latter part of 1977 at Daggett was around 37 mm, in excess of that amount needed to promote good plant growth and a source of food for rodents. However, in the subsequent years of 1978, 1979, 1980 and 1981, autumn and early winter rainfall was less than 25 mm, and none at all fell in 1981.

In Table 6 we set forth trapping experience related to *D. merriami* between the fall of 1978 and the summer of 1982, and autumn rainfall totals for 1977, 1978, 1979, 1980 and 1981. The point of this table is that it complicates the interpretation of trapping data from areas within 150 m of the east fence and from areas at greater distances from the

Table 6. Numbers of kangaroo rats (Dipodomys merriami) trapped at Solar One site between September 1978 and July 1982 and autumn rainfall, 1977-1981.

Dates	Different individuals captured	Number of trap-nights	Number taken per trap-night	September-December rainfall (mm) in preceding year
Sept. 1978	406	2,928	0.139	37
July 1979	304	2,928	0.103	18
July 1980	62	3,664	0.017	13
April 1981	49	3,664	0.013	0
April 1982	8	480	0.017	12
July 1982	4	480	0.008	-

facility. It is certainly clear that the abundance of D. merriami declined markedly between 1978 and 1982 (see also Turner, 1981: 65). But there are two possible explanations. First, we can argue that the declines in proximal and more distant areas follow from four years of distinctly suboptimal autumn rainfall, and that the construction of Solar One is in no way implicated. This is the view expressed by Turner (1981). The alternative explanation is that the activities attending construction and testing of Solar One were sufficiently pervasive that all the areas examined, including those 600 m east of the fence, were affected. There is no unequivocal basis for choosing between these two possibilities, but we favor the first interpretation.

Another factor worth noting is that large numbers of tenebrionid beetles (e.g., Eleodes armata, Cryptoglossa verrucosa) were observed in both trapping areas in 1982. During July nearly every trapping station had several beetles in the immediate vicinity of the trapping bait. It was not unusual to open a closed trap and find 5-12 beetles within. Some traps were rendered inoperable because beetles secreted themselves beneath the treadle. More important, however, was a possible interference with trapping success because of offensive secretions of Eleodes armata. The emitted substance is a quinone compound (Eisner, 1966) which is known to cause distress among rodents exposed to it (French et al., 1974). Traps entered by these beetles or traps inadvertently closed with beetles inside were tainted by the beetles' secretions. This may have had something to do with the reduced trapping efficiency illustrated in Table 6.

3.4. Micrometeorology

3.4.1. General background

Possible influences of solar thermal power plants on microclimatic variables have been considered by several authors (Davidson and Grether, 1977; Patten, 1978; Bhrumralkar et al., 1979, 1981; Lindberg et al., 1982). Simulation studies have generally suggested that effects of altered energy exchange properties or heat ejection by solar plants would be minor or nonexistent (Davidson and Grether, 1977; Bhumralkar et al., 1981) unless the facility were of enormous size (Bhrumralkar, 1979). Analyses of this nature involve simulations of extremely complex processes, and the following comments by Bhumralkar et al. (1979a) are well worth bearing in mind: "The most important finding of the study to date is that there are...questions and uncertainties about the capability of the two-dimensional mesoscale model to simulate real atmospheric conditions realistically. In view of these, it is not possible at this stage to make a definitive and quantitative assessment of the effect of a solar power plant on...local and regional weather conditions."

Patten (1978), Patten and Smith (1980) and Lindberg et al. (1982) have discussed micrometeorological parameters which could be influenced by solar thermal power plants. Some of these variables have been investigated to explore the possible influence of such facilities within and downwind of heliostat fields (Patten and Smith, 1980; Turner, 1981). The following section extends earlier work by our laboratory on downwind influences of Solar One on air temperature, wind speeds, and evaporation rates.

3.4.2 Methods

Micrometeorological observations were made over 2½-day periods six times between March and September 1982. All work was carried out in areas downwind (east) of the solar facility or, during August, within the heliostat array near the eastern margin of the field. Measurements made related to evaporation rates, air temperature profiles, and wind speed profiles. Evaporation measurements were not related to large water body evaporation or evapotranspiration as is commonly done. Rather, we used this variable as an integrating measure of possible downwind effects of Solar One.

The general observational strategy was to select two areas for investigation and to make paired measurements at the same moment--or over the same time intervals. The idea was to select the areas to be compared so that some inferences as to possible influences of the solar thermal power plant might be drawn. Statistical comparisons were based on paired t-tests. We expected any possible off-field effects to be most clearly expressed in areas downwind of the heliostat field. Hence, some measurements were made directly east of the field during west wind conditions and contrasted with measurements made in areas outside the field's influence. Another technique was to compare measurements in downwind areas, but at increasing distances from the eastern edge of the field. During August we compared measurements made within the heliostat array with corresponding observations just outside the mirror field.

When measurements of air temperatures and wind speeds were to be made, we set up two 2-m masts at points selected for comparison. Each mast supported four microbead type-T thermocouples at 2, 10, 50 and 200 cm heights. Surface temperatures were also measured with a thermocouple at each mast location. Lightweight three-cup anemometers were placed at 100 and 200 cm and a wind direction transducer at 200 cm on each mast. Wind speed, direction and temperature data were recorded on a Campbell Scientific CR-5 Data Logger which produced a paper and cassette tape log. Data were transferred to an IBM-3033 computer for conversion into engineering units and statistical testing. The data logger scanned sensor outputs about every 0.6 sec and divided the accumulated total by a 5-min integrating interval. A typical field experiment consisted of placing the masts 25 to 200 m apart for a recording period of at least 20 5-min integrating intervals.

Measurements of evaporation rates

Evaporation was measured with 12 screen-protected 16.75 cm diameter evaporation cans. We used small cans rather than standard Class A pans (122 cm diameter) because our cans were easy to make, maintain and handle. The construction and use of small cans to measure evaporation is well established (Marston, 1961; Davis, 1963; Iruthayaraj and Morachan, 1978). Cans were placed 25, 50, 75, 100, 150 and 200 m downwind (east) of the solar site fence where prevailing easterly winds moving across the solar field would influence evaporation. The fence line was 50 m from the outermost row of heliostats so the pans were 75 to 250 m downwind of the field. The control site was about 850 m north and 400 m northeast of the solar site fence line and evaporation cans were placed in the same sequence. Micrometeorological conditions at the control site were assumed to be uninfluenced by Solar One. Evaporation was recorded and cans refilled every 2 days from April to September.

Measurements of air temperature and wind speed profiles

The general procedure followed was to compare measurements made about 25 m downwind of the eastern fence around the heliostat field with simultaneous measurements made between 100 and 200 m downwind of the heliostat field. These techniques were used in every month except August.

During August of 1982 we set up two sampling points inside the facility. The first of these was 125 m west of the easternmost edge of the heliostat array--i.e., among the heliostats. The other was outside the heliostat array, but positioned in the 50-m gap between the heliostats and the perimeter fence. We also made another type of comparison during August. In these instances we selected two random points 200 m apart, but so far east (ca. 700 m) of the heliostat field that we considered them beyond any important influence of the facility. These measurements were taken as representative of differences one would observe owing to natural heterogeneities in topography and vegetation.

3.4.3. Results

Maximum daily air temperatures near Solar One increased from about 20° C in March (day 90) to about 40° C in late July and August (days 200-240). During the same period minimum daily air temperatures increased from about 10° C to roughly 27° C and dew point temperatures rose from -15° C in late April (day 112) to 18° C after summer rains (Fig. 3). These observations are similar to 30-year patterns established at nearby Barstow-Daggett Airport (Turner, 1979).

Table 7 contrasts differences in air temperatures at 50 cm and 2 m measured at points about 25 m east of the perimeter fence and at points 100 and 150 m east of the fence. Samples include measurements

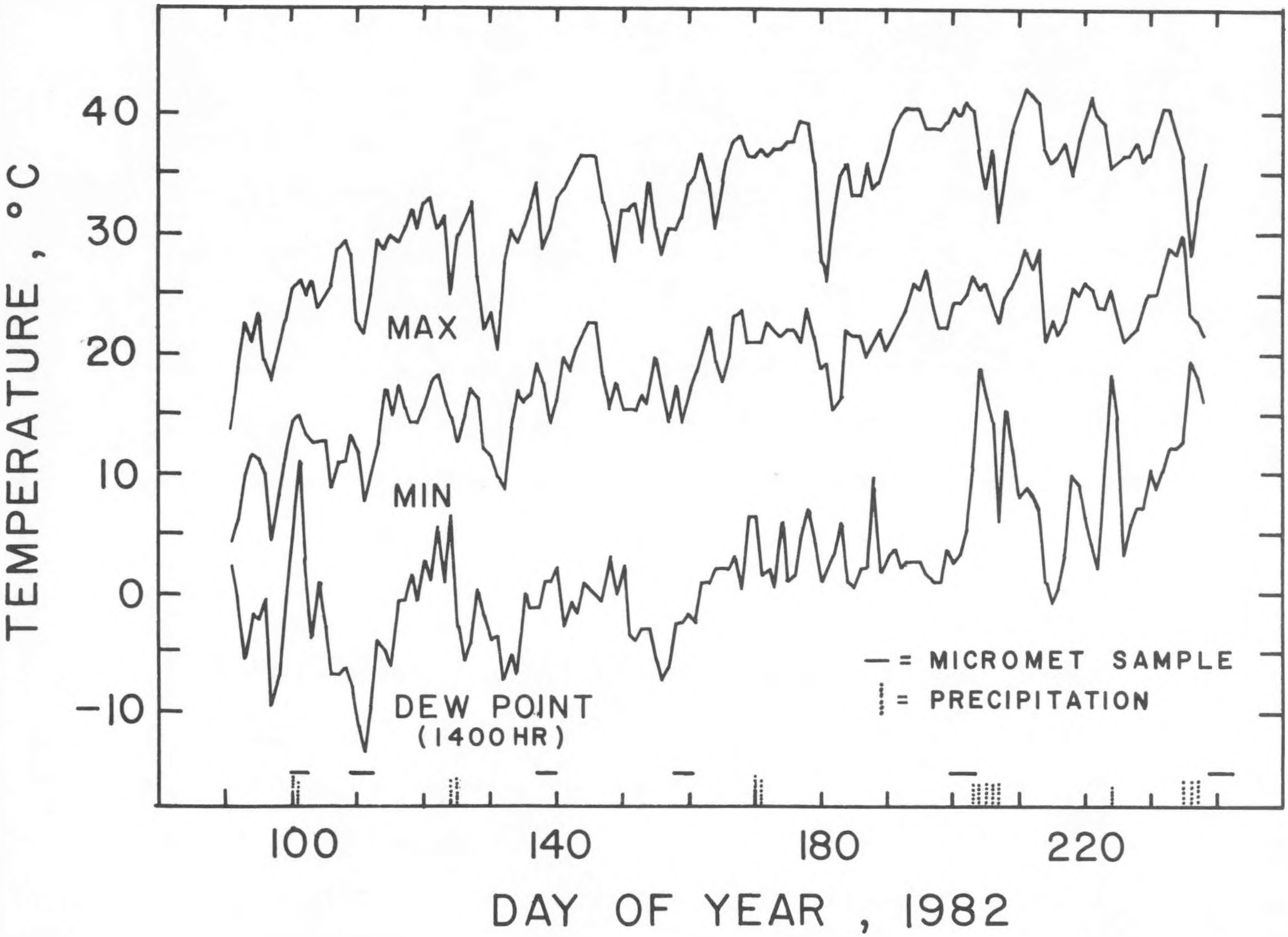

Figure 3. Maximum and minimum air temperatures and dew point temperatures recorded at Barstow-Daggett airport in 1982.

Table 7. Mean air temperature (°C) differences ± standard errors of means measured at points 25 m (P) and 100-150 m (D) downwind of the east perimeter fence at Solar One. Paired differences were computed as D-P.

Hours	*n*	Distance of more remote sampling point (m)	Height of sampling points	
			50 cm	2 m
0001-0600	60	100	0.01 ± 0.004	0.05 ± 0.003**
0601-1200	75	100	0.31 ± 0.017*	0.24 ± 0.013*
1201-1800	60	100	0.01 ± 0.014	-0.15 ± 0.009*
1801-2400	80	100	0.09 ± 0.002	0.11 ± 0.002*
1201-1800	120	150	0.21 ± 0.009*	0.59 ± 0.009*

*Difference significant at 5% level.

made at all times between March and September 1982 (except those during August). These measurements were made during west wind conditions. The table shows that air temperature differences at 2 m were greater during the day (0601-1800) than at night. Temperature differences 150 m downwind were generally greater than at 100 m downwind. Measurements in Table 7 show that locations near the field were cooler than sites up to 100 m downwind, except between 1201-1800 h when sites closest to the field were warmer than ones 100 m downwind. Between 1201-1800 h temperatures 150 m downwind were also cooler than those closer to the field.

Table 8 gives mean differences in wind speed measured at points close (ca. 25 m downwind) to the perimeter fence and 100 and 150 m downwind) to the perimeter fence and 100 and 150 m downwind. Differences

Table 8. Mean wind speed (m/s) differences ± standard errors of means measured at points 25 m (P) and 100-150 m (D) downwind of the east perimeter fence at Solar One. Paired differences were computed as D-P.

Hours	n	Distance of more remote sampling point (m)	Height of sampling points 1 m	2m
0001-0600	60	100	0.07 ± 0.003*	0.24 ± 0.004*
0601-1200	75	100	0.19 ± 0.005*	0.22 ± 0.004*
1201-1800	40	100	0.12 ± 0.010	0.37 ± 0.010*
1801-2400	100	100	0.04 ± 0.005	0.01 ± 0.005
1201-1800	78	150	0.13 ± 0.008	0.28 ± 0.008*

*Difference significant at 5% level.

between stations are greater at 2 m, and wind speeds near the field are less than those farther downwind. At 1 m above the ground only differences between 0001 and 1200 h were significantly different.

How do the differences reported in Tables 7 and 8 compare with measurements made at randomly selected points in undisturbed desert? Tables 9 and 10 give mean differences in air temperatures and wind speeds at 1 and 2 m measured at points 200 m apart.

The absolute values of the differences shown in Tables 9 and 10 are clearly greater than most of those obtained by making measurements 25 m and 100-150 m downwind of the Solar One perimeter fence (Tables 7 and 8). Only the wind speed differences at 2 m reported in Table 8 are of a magnitude comparable to differences measured at randomly selected sites (Table 10).

Table 9. Mean air temperature (^{0} C) differences ± standard errors of means measured at random points 200 m apart and beyond the influence of the Solar One heliostat field.

Hours	n	Height of sampling points	
		50 cm	2 m
0001-0600	60	0.24 ± 0.004*	0.13 ± 0.003*
0601-1200	124	0.55 ± 0.010*	0.24 ± 0.009*
1201-1800	138	0.44 ± 0.009*	1.22 ± 0.010*
1801-2400	60	0.95 ± 0.021*	0.55 ± 0.018*

*Difference significant at 5% level.

Table 10. Mean wind speed (m/sec) differences ± standard errors of means measured at random points 200 m apart and beyond the influence of the Solar One heliostat field.

Hours	n	Height of sampling points	
		50 cm	2 m
0001-0600	60	0.67 ± 0.018*	0.32 ± 0.007*
0601-1200	124	0.36 ± 0.006*	0.32 ± 0.004*
1201-1800	138	0.55 ± 0.005*	0.21 ± 0.003*
1801-2400	60	1.02 ± 0.010*	0.39 ± 0.010*

*Difference significant at 5% level

Between August 27 and 29, we made air temperature profile measurements (0 to 2 m) at a point 125 m into the eastern part of the heliostat field. At the same time we made corresponding measurements at a point about 25 m east of the last row of heliostats, but still within the perimeter fence. Differences between temperatures recorded at these two points simultaneously were computed by subtracting temperatures measured outside of the heliostat array from those within (Fig. 4).

Surface temperatures within the heliostat field were much lower than those outside during the morning (0800-1200 h), but warmer between 1500 and 1900 h. Similar patterns, though of less amplitude, were exhibited at 2, 10 and 50 cm. At 2 m the pattern was reversed on August 28, but was similar to the other profiles on August 29.

Figures 5 and 6 illustrate air temperature profiles within (Fig. 5) and outside of (Fig. 6) the heliostat array for a 41-h period between 1900 h on August 27 and 1200 hr on August 29, 1982. These figures illustrate two points of note. First, between 0800 and 1000 h on both mornings lapse conditions outside the heliostat array were strongly developed. At the same time this condition was more weakly expressed within the heliostat field. (The lapse condition occurs when temperatures decrease with height above ground). Shapes of lapse curves within and outside of the heliostat array were also different throughout the day. Second, almost no inversion occurred--either inside or outside of the heliostat area.

Figure 7 illustrates differences in wind speeds (m/sec) measured inside of and outside of the heliostat array, as well as actual wind speeds measured outside the heliostat array. Wind speeds inside were clearly less than those measured outside the heliostats.

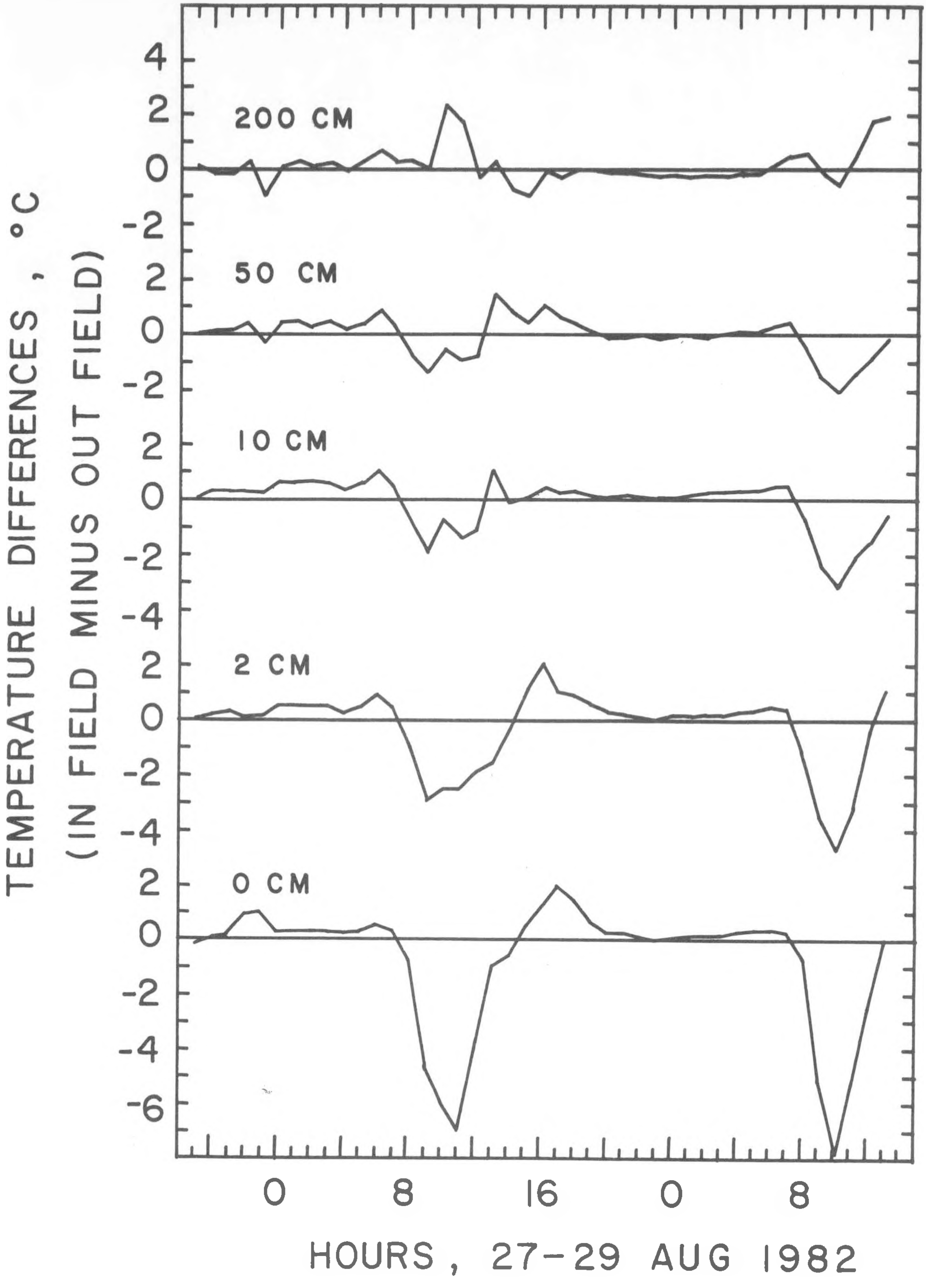

Figure 4. Differences in air temperatures measured within the Solar One heliostat field and 25 m outside of the heliostat array in August 1982.

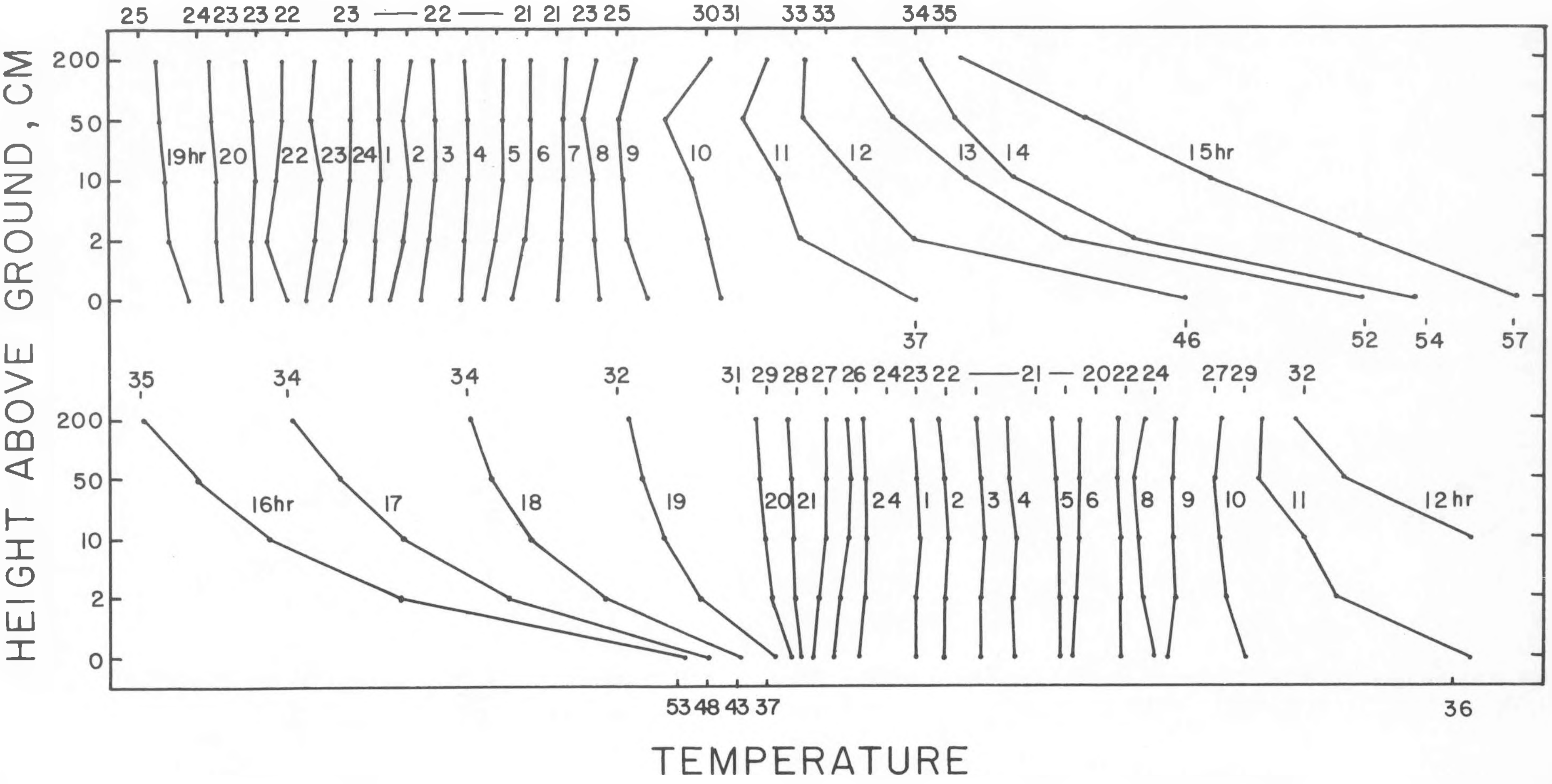

Figure 5. Air temperature profiles measured within the Solar One heliostat field over a 41-h period between 1900 h August 27 and 1200 h August 29, 1982.

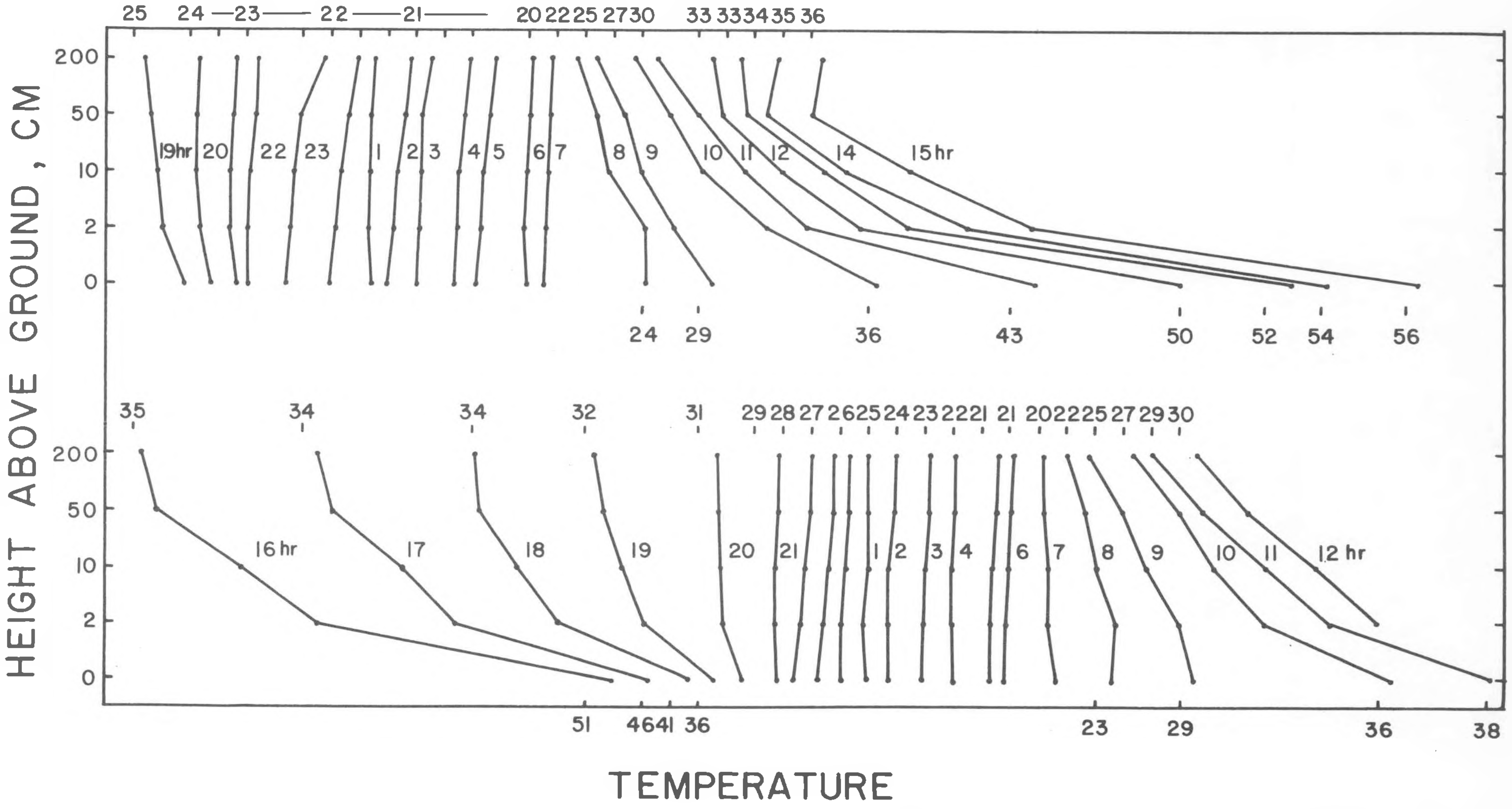

Figure 6. Air temperature profiles measured outside of the Solar One heliostat field over a 41-h period between 1900 h August 27 and 1200 h August 29, 1982.

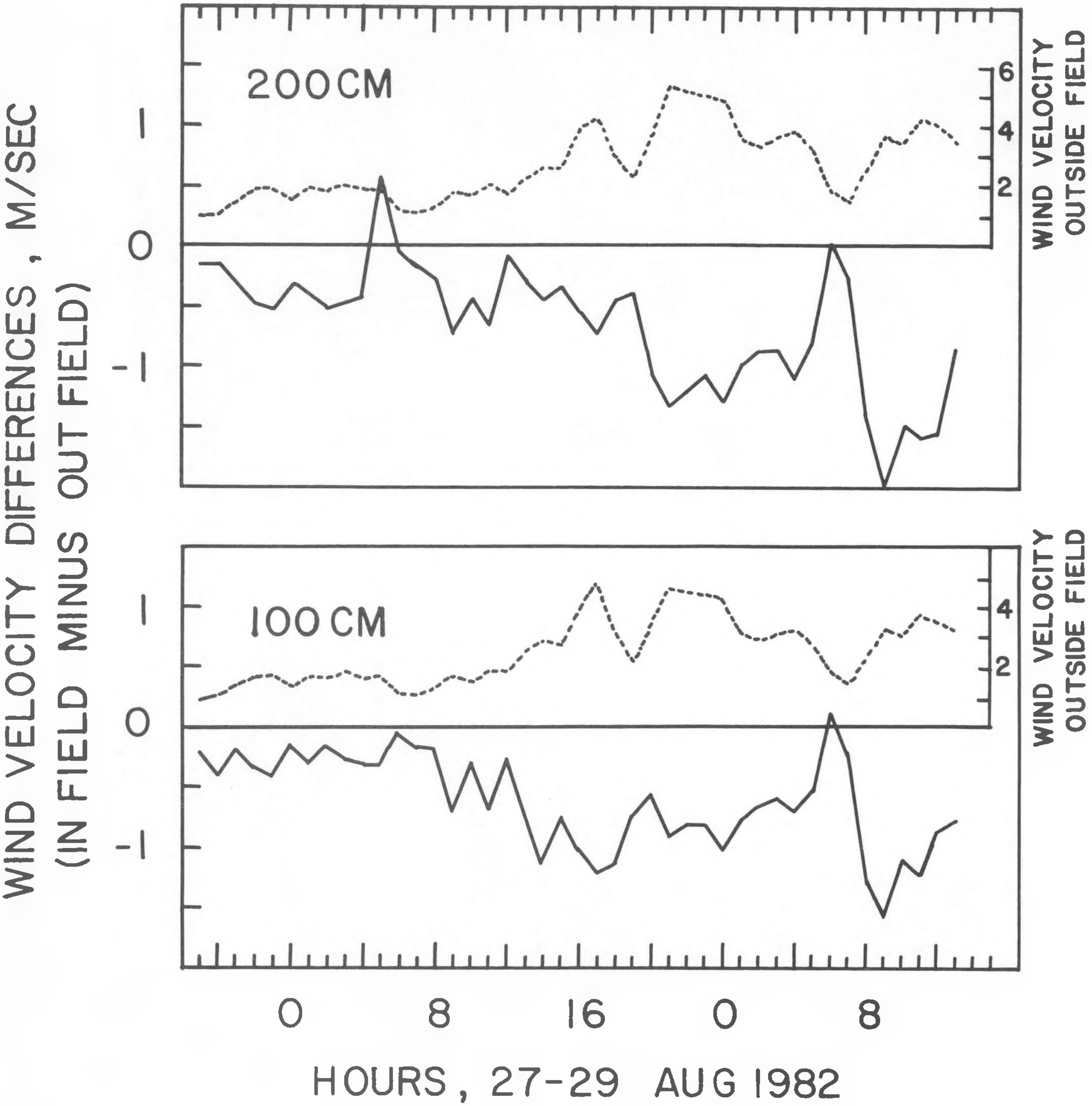

Figure 7. Wind speeds measured outside the Solar One heliostat field (above) and differences between wind speeds measured within and outside the heliostat array (below).

Measurements of evaporation rates

Pan evaporation rates at the control site increased, on average, from about 8 ml/h in April (day 110) to about 22 ml/h in early July (day 195)--with subsequent decreases in late July and August (Fig. 8).

The evaporation rates we measured are typical of arid and semi-arid environments (Rosenberg, 1974). The pattern of increasing evaporation rate through day 195 was driven by increasing air temperatures over this interval, while the decrease in evaporation after that point was probably due more to high dew point temperatures (high atmospheric water content). An evaporation rate peak on day 112 in a cool part of the year was due to a cool, very dry air mass which moved through the area. Sharp evaporation rate decreases later in the year (days 182, 210, 225 and 237) were typically related to precipitation events with their high dew point and relatively low air temperature (Figs. 3 , 8).

In order to compare evaporation rates at experimental and control sites we examined differences in observed rates (control minus experimental) between days 110 and 240 (Fig. 9). Evaporation averaged about 1.2 ml/hr greater at the control site over this interval of time. These differences were compared by paired _t_-tests and results indicated that statistically significant differences occurred more often later in the period of observation.

We commented previously that we expected the heliostat field to affect the downwind environment only during periods of west winds (i.e., winds blowing across the field from the west). We compared relationships between evaporation rates at control and experimental sites under west wind conditions and at times when west winds were not blowing by

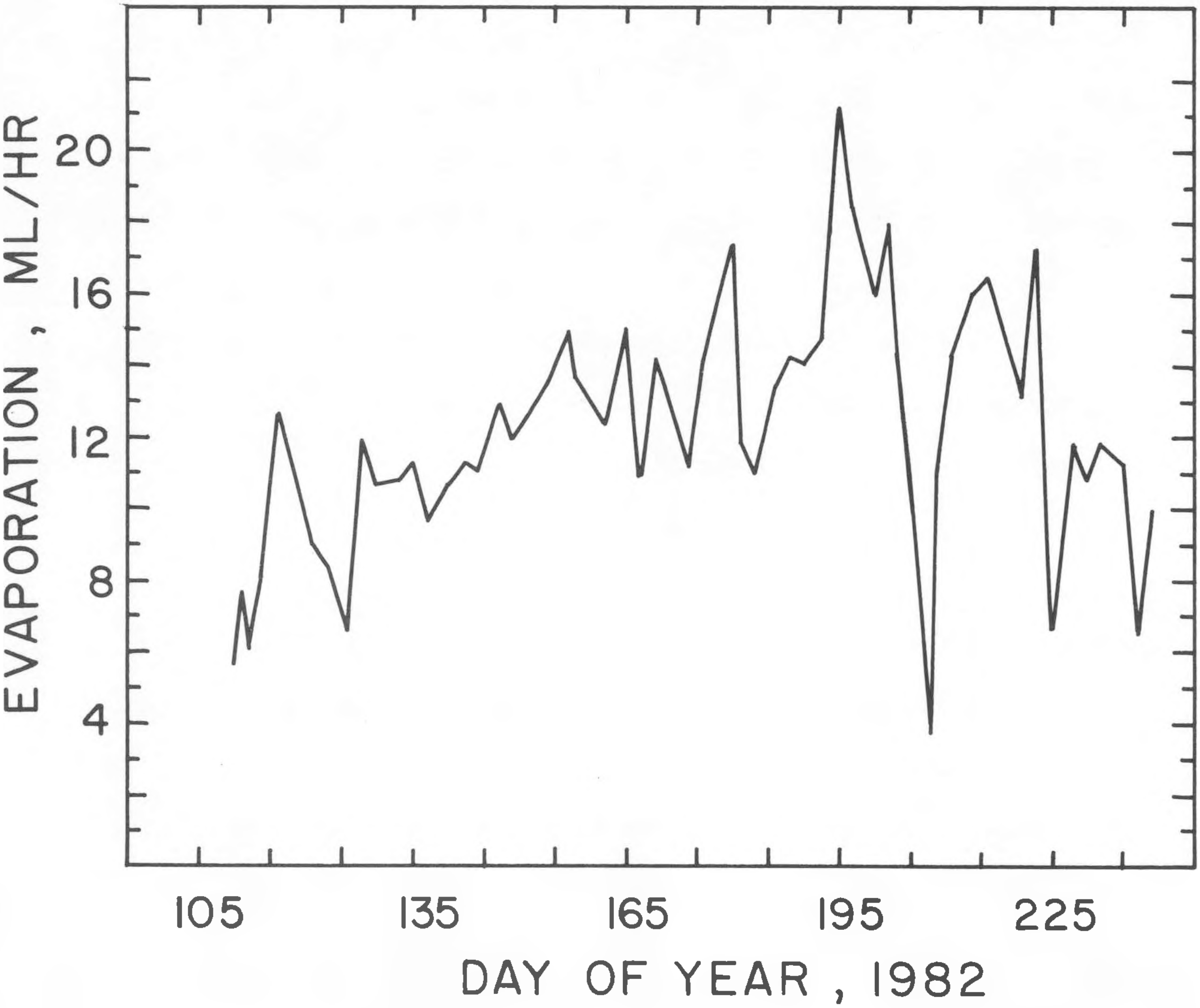

Figure 8. Evaporation rates measured at a control station north and east of the Solar One heliostat field in 1982.

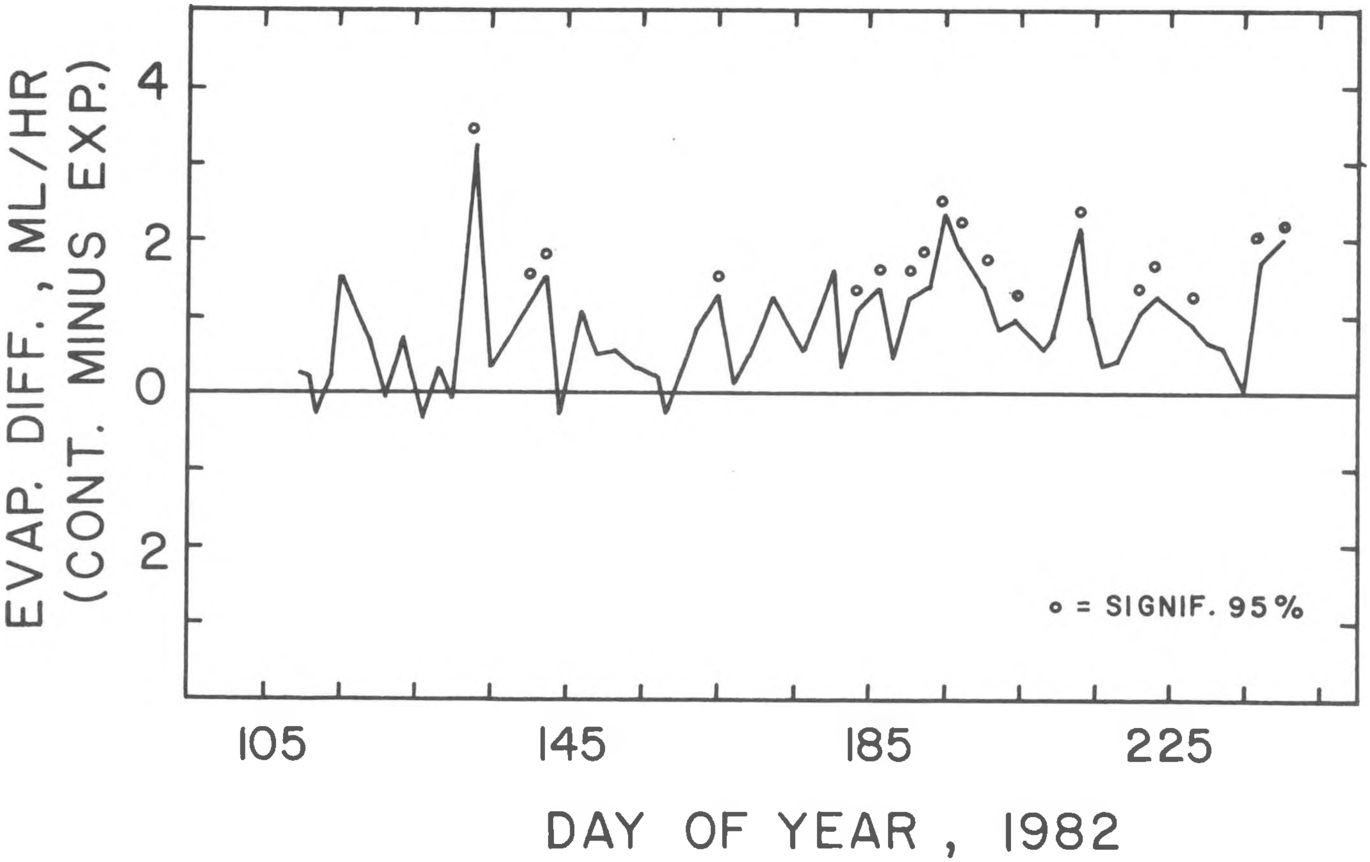

Figure 9. Differences in evaporation rates measured at a control site and at a point 25 m downwind of the Solar One heliostat field in 1982.

regressing control site rates on experimental site rates (Fig. 10). The two regression lines in Fig. 10 have the same slopes, but differ significantly in their intercepts. That is, evaporation rates under west wind conditions at the experimental site were slightly (but significantly) lower than those measured at the control site.

The decrease in evaporation rate from cans downwind of the site during westerly wind flow conditions was almost certainly owing to a shelter effect caused by the heliostat field. Shelter belts commonly influence downwind regions for distances 10 to 25 times the height of the barrier, depending on barrier physical parameters (Oke, 1978; Rosenberg, 1974). The influence of belts depends on height, length and porosity. Increasing porosity permits wind penetration of a barrier and prevents the turbulent return of air which has overtopped the barrier. Longer barriers exert more constant influence, but gaps may cause jetting--thus increasing rather than decreasing air movement behind the barrier. Shelter belts generally are thought of as altering wind conditions (speed, turbulence) behind it, but conditions in the lee of a barrier are complex and not well understood (Rosenberg, 1974). Evaporation is reduced in the lee of shelter belts (Hanson and Ranzi, 1977; Rosenberg, 1974). A mid-northern states study indicated that a 50% reduction in wind resulted in a 14% reduction in evaporation (Hanson and Ranzi, 1977). It is reasonable to view the heliostat field as a variable highly porous shelter belt with a height of up to 7 m. The influenced region (10-25 times height for a porous barrier) would then be up to from 140-175 m downwind with a maximum influence about 42 m downwind of the field perimeter (Rosenberg, 1974).

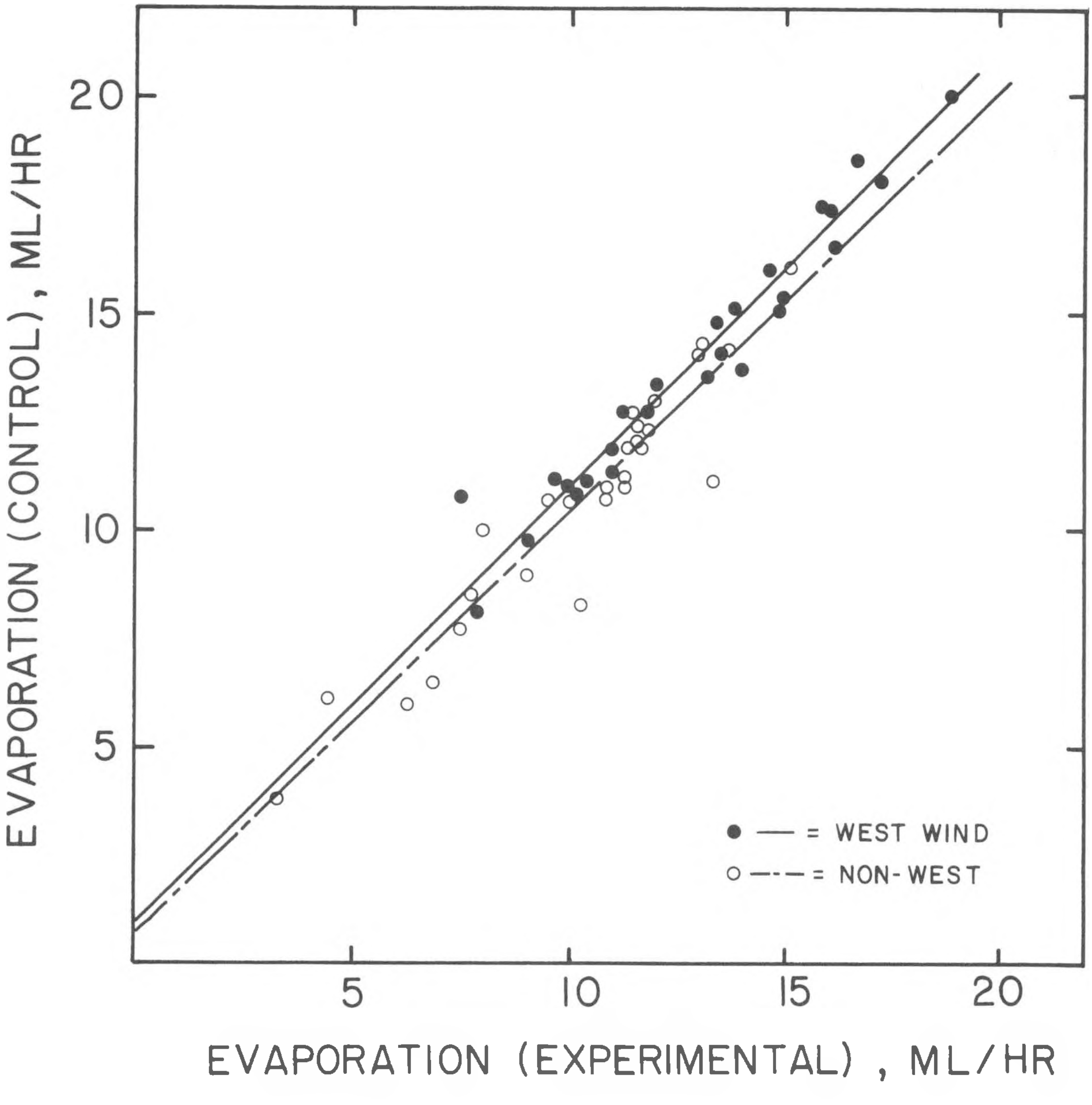

Figure 10. Evaporation rates measured at a control site plotted against those measured simultaneously downwind of the Solar One heliostat field.

4. Discussion

Following several years of work during the construction of Solar One we wrote: "Our observations...are reassuring in that off-field environmental effects were apparently highly localized. Wind removal of loose sand from the cleared heliostat field and ensuing indirect effects on some species of plants and animals occupying close-in areas were the only impacts identified" (Turner, 1981: 77). Observations during 1982 were consistent with earlier results.

Measurements of sand depths at various distances downfield suggested that sand is moving gradually east, and that present rates of removal from the heliostat field are too low to replace losses of sand from those areas heavily impacted in 1980. Unless the surface of the field is further disturbed, we predict that the sand blown off the field in late 1979 and early 1980 will eventually be redistributed progressively farther east.

Of the 15 bird fatalities ascribable to the presence and/or operation of Solar One, 12 apparently resulted from collisions with heliostats. Clearly, more intensive searching would have revealed more casualties, though we have no reason to believe that proportions killed by collisions and incineration would have changed. Any further studies of bird mortality could be sharpened by attempting to relate numbers of fatalities to total exposure, i.e., by attempting to estimate deaths per bird-hour within the solar facility. Such a program would require a substantial observational effort.

One of the ideas underlying our monitoring plan was that if "...construction and operation of the facility affected organisms beyond the heliostat field, the effects would be more conspicuously expressed in areas adjoining the field than at greater distances." We recognized that our approach "...could not discriminate between non-divergence owing to lack of effects and non-divergence because of equivalent impacts in areas immediately next to, and at a distance from, the field" (Turner, 1981: 79). This problem actually arose in the interpretation of rodent trapping data between 1978 and 1982. Our data showed a persistent decline in numbers of kangaroo rats live-trapped near the field as well as in areas as far east as 600 m. Do these data indicate a climatically induced general response or do they suggest that our "control" and "experimental" trapping areas were unsuitably chosen? We believe the former, but the problem may guide future planning.

Our measurements in 1982 showed that the presence of the Solar One heliostat field affects certain micrometeorological states in downwind areas: rates of evaporation are slightly but significantly lower, and wind speeds are slightly reduced. Air temperatures just east of the perimeter fence were usually less than those 100-150 m downwind (at heights of 50 cm and 2 m). We also showed that air temperature profiles among an array of heliostats differ from those measured concurrently outside. Morning surface temperatures are much lower inside the field (although this difference disappears by late afternoon).

A major causal basis for these observations is that the heliostat field apparently acts as a shelter barrier, reducing wind speed but increasing turbulence intensity in the wake of the facility (Radkey and Zambrano, 1982). Measurements by Aerovironment, Inc., on June 1, 1982, showed that air flow retardation in the far wake of the field was about

15% with the heliostats up but negligible when heliostats were stowed (Radkey and Zambrano, 1982). We measured wind speed reductions within the heliostat field of as high as 50%, but the average retardation at 1 and 2 m was about 20% (Fig. 7). This is similar to wind speed reductions measured in a simulated heliostat array (Patten and Smith, 1980). Our downwind measurements of wind retardation (10-12%) are consistent with a shelter belt interpretation (Rosenberg, 1974) and with measurements made by Aerovironment, Inc. The differences we measured in evaporation rates are also consistent with wind observations and other studies relating to shelter effects (Hanson and Ranzi, 1977).

Temperature conditions within the heliostat field may also bear on observed downwind observations. The temperature difference profiles in Fig. 4 clearly show a reduction of surface temperature within the field in the morning because of shading by heliostats. The influence is apparent up to 50 cm. At 2 m a morning period of warmer air in the field may be due to a more complex wind structure within the field than outside. These periods (0800-1200 h) are associated with distinctly non-typical temperature profiles. Temperatures at the 50 cm level within the field are similar to those found by Patten and Smith (1980) i.e., less than 2% difference between field and control sites. Advected energy may influence downwind conditions during these time periods (as suggested by values in Table 7). An increase of 0.24 ^{0}C at 2 m 200 m downwind between 0601-1200 h could represent the influence of the higher level heating in the field (Table 7). Similarly, the small decrease between 1200-1800 h could be related to an afternoon reduction in temperatures at 2 m within the field. This reduction is also a common effect of wind structure in the lee of shelter barriers (Rosenberg, 1974). The 0.59 °C increase 150 m downwind is not consistent with reported shelter effects but such effects are quite variable and may reflect edge effects from the relatively small expanse of the field.

So far we have discussed differences measured within the heliostat array as opposed to outside of the field, or differences between points immediately downwind of the field and 1) points north of the field (evaporation rates), or 2) 100-150 m downwind of the field (air temperatures and wind speed profiles). We have attempted to explain these differences in terms of the heliostat field and its influence on wind structure and air temperature profiles. With the exception of some of the wind speed differences, all of the differences discussed are small.

In fact, as shown by measurements reported in Tables 9 and 10, one could expect to observe larger differences in air temperature and wind speeds by simply comparing simultaneous measurements at random points in open desert. This point does not negate the reality of the site-related measurements, but raises the question of whether the kinds of differences analyzed really are reduced in the situations we examined. Does, for example, a reduction in air flow reduce local heterogeneities in wind speed and air temperature profiles? Our data are not sufficient to draw any conclusions of this nature.

Although the measurement procedure we used led to useful results, we can suggest a better protocol for the future. A sequence of at least four two-meter masts should be established: at least one within the heliostat array, one at the edge of the field, and two or more deployed within 50 to 100 m downwind of the field periphery. Each mast should be equipped with a series of wet and dry bulb thermometers and cup anemometers at 4-6 levels. Data collection should be carried out in line for periods of 24 hours or longer. This procedure would provide a basis for more accurate inferences as to influences of the solar field on micrometeorological variables.

In summary, we have presented evidence for small effects on temperature (less than 0.5 ^{o}C) wind speed (less than 0.4 m/sec) and evaporation (less than 1.5 ml/hr) in a limited region downwind of the Solar One heliostat field (up to 190 m from the outer fence). Because these differences are so small, relative to apparently natural heterogeneity, the effects of Solar One on rates of evaporation, air temperatures and wind speed will not affect the downwind biological community. The picture could be different for a facility the size of the projected Solar 100 plant.

A good case may be made that the extension of irrigated agriculture into California desert areas will have a much greater effect on climatic and micrometeorological variables than 10 MW solar thermal power plants. Irrigated fields in arid regions can influence downwind reaches up to the width of the field--more than 1 km under some conditions (de Vries, 1959). Air temperatures can be $\geq 5^{o}$C greater at the transition from an irrigated region to a non-irrigated area (Rider et al., 1963).

Our observations at Solar One have relevance not only to the pilot facility, but also to future construction of larger solar thermal power plants. For example, Southern California Edison is already looking ahead to the possible design of the plant in Johnson Valley which calls for two solar collector systems, each with a central receiver atop a 200-m tower. Each heliostat field will require about one square mile and will contain from 7,500 to 8,000 heliostats (SCE, 1982). The plant will require construction of two 3-million-gallon storage tanks for molten salts, a wet cooling tower, a turbogenerating system, a control building and a 35-acre evaporating pond. The plant will use about 2,600 acre-feet of water annually.

In our view, the two most important features of Solar 100 are 1) the area to be graded and cleared for heliostats, and 2) the width of the heliostat fields along the azimuth of prevailing winds (west to west-northwest in Johnson Valley). The size of the heliostat fields is important because cleared surfaces are a source of windblown sand unless specific steps are taken to stabilize surfaces <u>while work is in progress</u>. Richard Hunter estimated that about 160 metric tons of sand were blown off the area cleared for Solar One (ca. 47.5 ha). Each heliostat field of Solar 100 would be about 259 ha in area. The width of a heliostat field affects the extent of downwind influences on air flow. At Solar One the far field wake was estimated to be "...detectable 1000 to 2000 m... downstream with the amount of retardation a maximum within 300 m...of the array" (Radkey and Zambrano, 1982). With a heliostat field one mile (1610 m) across, one would expect the extent of the far field wake to be roughly twice that measured at Solar One--where field width is roughly 780 m (Radkey, pers. comm.). The height of the internal boundary layer would also be increased, but not doubled (Radkey, pers. comm.).

Increases in bird mortality at Solar 100 are more difficult to foresee because birds are--at present--much less abundant than at Solar One. The long-term influences of a 35-acre evaporating pond are difficult to forecast, although one would expect an influx of some species of birds not presently occurring in Johnson Valley. The presence of two towers, each about twice the height of the one at Solar One, could be an added source of casualties.

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