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# Heat Island and Oasis Effects of Vegetative Canopies: Micro-Meteorological Field-Measurements

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With 10 Figures

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## Summary

Dry-bulb temperature, dew-point, wind speed, and wind direction were measured in and around an isolated vegetative canopy in Davis CA from 12 to 25 October 1986. These meteorological variables were measured 1.5 m above ground along a transect of 7 weather stations set up across the canopy and the upwind/downwind open fields. These variables were averaged every 15 minutes for a period of two weeks so we could analyze their diurnal cycles as well as their spatial variability. The results indicate significant nocturnal heat islands and daytime oases within the vegetation stand, especially in clear weather. Inside the canopy within 5 m of its upwind edge, daytime temperature fell by as much as 4.5 °C, whereas the nighttime temperature rose by 1 °C. Deeper into the canopy and downwind, the daytime drop in temperature reached 6 °C, and the nighttime increase reached 2 °C. Wind speed was reduced by $\sim 2\,\mathrm{m\,s^{-1}}$ in mild conditions and by as much as $6.7\,\mathrm{m\,s^{-1}}$ during cyclonic weather when open-field wind speed was in the neighborhood of $8\,\mathrm{m\,s^{-1}}$. Data from this project were used to construct correlations between temperature and wind speed within the canopy and their corresponding ambient, open-field values.

## 1. Introduction

Our objective in this study was to perform field-measurements to increase our understanding of the micro-climate variation within tree stands and to evaluate the repesentativeness of vegetation energy and moisture balance models we have been using in conjunction with the DOE-2 building energy analysis program[1]. The ultimate goal of this work is to evaluate the potential of trees for reducing building cooling energy and peak demand in hot climates by creating cool oases. This paper describes limited micrometeorological measurements done in and around an isolated orchard in Davis, California (Taha et al., 1989).

Urban heat islands in hot climates can significantly increase summer cooling loads in buildings, particularly those buildings that are small, uninsulated, and have low internal loads. Akbari et al. (1986), Huang et al. (1987), and Taha et al. (1988) investigated several strategies to alleviate the negative impacts of heat islands. They found that one promising strategy, the implementation of vegetative canopies and shelter belts, could reduce urban air temperatures and save up to 50% of cooling energy use and 30% of peak demand. To further investigate the effects of vegetative canopies on urban climates, this field-project analyzed micro-meteorological conditions upwind, downwind, and within an isolated orchard in Davis CA.

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[1] DOE-2 is a public domain program developed under the leadership of the Lawrence Berkeley Laboratory. It can simulate the hourly performance of heating and cooling systems and the indoor environmental conditions for any building/system configuration.

In particular, the effects of trees on ambient dry-bulb temperature and wind speed were studied.

## 2. Background

The micro- and meso-climate effects of vegetation have been extensively studied for a variety of purposes. Most studies stress the difference between the microclimate of vegetated areas and those of bare surroundings, particularly in terms of air temperature. In isolated measurements, for example, Geiger (1957) observed that noontime temperatures in a forest could be 5 °C lower than in open surroundings, and that an irrigated millet field could be 3 °C cooler than nearby bare ground.

Budyko (1977) studied the effects of strip forests on the wind field upwind and over a canopy and the effects of irrigation and evapotranspiration on the microclimate near vegetative canopies. He classified vegetation oases as either large (over 3 km across) or small (less than 3 km across) and studied their temperature depressions through the seasons. He noted the larger cooling effects of evapotranspiration in summer as compared to those in winter. In summer, big oases could be 3 °C cooler than desert surroundings, whereas small oases were 2.5 °C cooler. In wintertime, the large oases were about 0.8 °C cooler than their surroundings. These numbers were for a latitude of 42° and a height of 100 m above sea-level. Budyko (1977) also noted that the vapor pressure over large oases in summer could be 5 mb higher than over bare surroundings, whereas the vapor pressure over small oases was about 3.6 mb higher than that over bare surroundings.

Sebba et al. (1984) measured micrometeorological parameters in and around trees and canopies in arid zones. They analyzed the effects of vegetation on solar radiation, wind speed, temperature, and soil erosion in a hot-arid climate. They presented data for dry- and wet-bulb temperatures for various canopy/open space configurations. Their data from residential neighborhoods showed how a cluster of trees was significantly cooler than areas between buildings. For example, in late August, the air temperature near the trees (not in shade) was 0.5–1 °C lower than near the houses. Time-dependent temperature was also given for different tree covers and vegetation canopy patterns. The residential areas could be up to 3 °C cooler than their surroundings, and the difference in temperature was largest during the hours of peak heat[2]. The study concluded that "vegetation offers a comprehensive solution to most climatic problems in the desert".

On a larger scale, researchers have studied the effects of vegetation and irrigation on micro- and meso-climates. For example, Barnston and Schickedanz (1984) studied the effects of irrigation on precipitation and near-surface climates in the southern Great Plains. They reported that irrigation lowered the daily maximum near-surface temperature by 2.2 °C during hot and dry conditions, and by about 1 °C in cooler damper conditions. The data came from a low-resolution network of weather stations; the observations were made at intervals of 9.7 km along a 48.3 km transect from the center of an irrigated area to a nearby desert in Kimberly, Idaho.

In another project, Davenport and Hudson (1967 a, b) studied the rates of evapotranspiration along a 17 km transect in the Sudan Gezira. They installed many dish evaporimeters across several cotton fields at an average spacing of 1.6 km between adjacent evaporimeters. The smallest spacing was 300 m. They found that evaporation was maximal at the leading edge of the canopy and decreasing by about 30% over the first 60 m within the canopy. The rate of decrease was about 2% per km over the 17 km transect. They also found that the mean daily temperatures in December were 1.5 °C lower at the site leeward of a cotton field than at a windward site. Davenport and Hudson (1967 a, b) found that advective effects from vegetation canopies were more noticeable in hot-arid climates than in more temperate ones.

DeVries (1959) addressed the question of advection versus characteristic distances downwind of vegetation canopies. He stated that advective effects decreased rapidly with distance downwind, and although the decrease was an unknown function of distance, advective effects could still be detected sometimes 15 km downwind from the canopy (Lemon et al., 1957). Working on the Australian Riverina, DeVries (1959) found that advective effects of canopies were considerable up to 1 km downwind in summer.

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[2] This comparison is between temperatures of two open spaces, one within the residential settlement and the other outside of it.

## 3. Objectives and Project Design

In this project, we carried out limited micrometeorological field-measurements within and around a vegetation canopy in Davis, California. Our first task was to identify a well-defined and isolated orchard. The next step was to procure the weather stations and distribute them across the canopy and the bare surrounding fields. In comparison with the studies mentioned in the foregoing section, our measurements had the following characteristics:

1. They were taken from 7 stationary weather stations along a transect parallel to the prevailing wind direction.
2. They were high-resolution data with weather stations only 75 m apart.
3. Advection effects were generally analyzed by recording data from upwind and downwind stations located in open, bare fields and comparing them with data from stations within the canopy.
4. Data were collected at 5-second intervals but averaged and recorded every 15 minutes. The analysis in this paper addresses hourly averaged data.
5. The data accounted for the effects of both shading and evapotranspiration as well as wind speed on air temperature.

We carried out this project to evaluate the effects of potential evapotranspiration and wind speed modification in a soil-vegetation system on the microclimate within a vegetative canopy and downwind from it. Our emphasis was placed on dry-bulb temperature and wind speed. We studied the effects of evapotranspiration and wind under a variety of hot/warm conditions: clear, overcast, calm, and windy.

Specifically, we were interested in estimating the effects of trees during summer in the warm climate of California's Central Valley. Because the field we chose was well watered, we did not measure soil moisture and temperature as the soil was saturated and we assumed that evapotranspiration under these conditions was maximal (potential).

We were interested in studying the rates of change in temperature and wind speed along the wind path to estimate the effects of the canopy on the air entering at the upwind edge. We also wanted to estimate the necessary depth of a vegetation belt required to achieve significant effects on air temperature and wind speed.

## 4. Site and Canopy Description

We selected a well-defined vegetative canopy in Davis CA to investigate the effects of trees on micro-meteorological conditions within and around the stand. As seen in Fig. 1, eleven automatic weather stations, labeled A through K, were set parallel to the clear-weather prevailing wind direction (north to south during daytime and south to north at night)[3]. At the time of our experiment, in October 1986, the 150 × 307 m-canopy had a uniform tree cover with a slight discontinuity near the middle, where the soil and a weather station (G) were relatively more exposed to the sky. The canopy was 5 m high with a stem height of 2 m. At the southern edge of the orchard, there were taller, closely-spaced evergreen trees with an average height of 20 m, forming a belt at the edge of the canopy. This belt was on the average 10 m wide and followed the orchard's south-

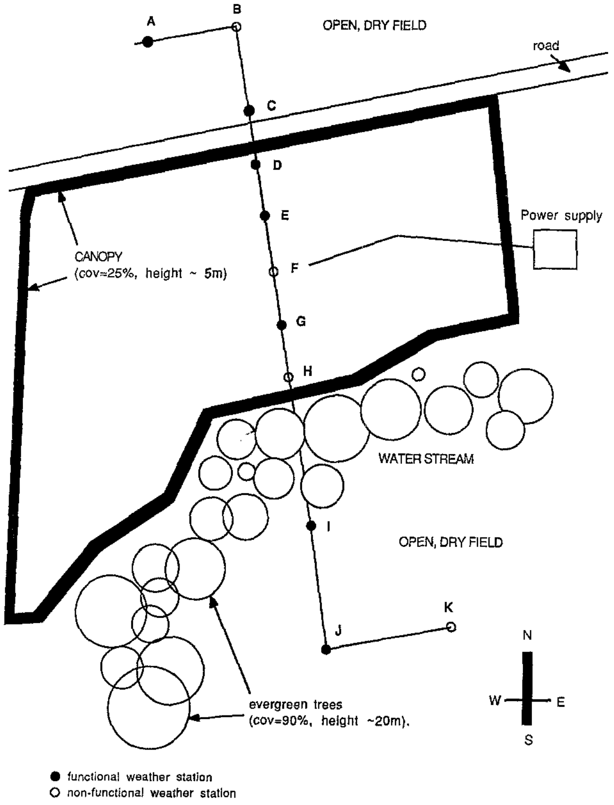

Fig. 1. Site plan representing the vegetation canopy and the location of the weather stations in Davis, California

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[3] Four of these stations (B, F, H, K) were not discussed in this paper because some or all of their data were not reliable. In Fig. 1, they are labeled as "non-functional weather stations".

ern edge. In the canopy, the cumulative leaf-area index (LAI), integrated over the foliage depth, was about 3. This LAI was uniform across the entire canopy except near the middle of the tree stand where a slight discontinuity in cover brought the LAI down to about 2. The tall trees at the south end of the stand, on the other hand, had a cumulative LAI between 4.5 and 5.

At the south edge of the canopy, a stream ran in east-west direction. There were dry, fallow, and open fields to the north and south of the orchard that streched out over a kilometer away from the canopy. The southern field was of particular interest to us because it was downwind during daytime, and therefore, the destination of the evaporatively-cooled air advected from the canopy. The orchard was watered five days prior to the start of the experiment and the soil was saturated when our weather stations were set up. These conditions were ideal for studying the effects of potential evapotranspiration from the soil-vegetation system. Station A, at the northern open field, was used as a control weather station for data normalization.

## 5. Equipment

The meteorological variables of interest were measured 1.5 m above ground surface (just below the stem height of the canopy) at 7 stations. Each weather station consisted of a weather head (anemometer and vane), a dry-bulb sensor, a dew-point sensor, a conditioning box, and a data-logger. The anemometer was of type Weather Measure W 200-SD and the vane of model W 200-WS. The dry-bulb sensor was an AD 590 semiconductor whereas the dew point sensor was a General Eastern DEW-10 chilled-mirror hygrometer. The conditioning box converted output signals into voltage (within 0–5 volts range) and also supplied power to the hygrometer (DEW-10) and its aspirating fan. The data-logger was a microprocessor-controlled Energy Signature Monitor (ESM) with up to 16 channels for data input.

Our field observations and wind tunnel tests indicated that the anemometers had an average starting wind speed threshold of 1.5 $\mathrm{m\,s^{-1}}$ and an average stopping threshold of 1 $\mathrm{m\,s^{-1}}$. The vanes, on the other hand, responded at $\sim 2\,\mathrm{m\,s^{-1}}$. The semiconductor dry-bulb sensors were either separately mounted inside PVC radiation shields or within the same compartments as the dew-point sensors. EPROM (Erasable Programmable Read Only Memory) modules of 24 K each were used with the data-loggers (ESMs) to record 15-minute averaged micrometeorological data.

Static and dynamic calibrations were performed at the Lawrence Berkeley Laboratory and the Richmond Field Station (RFS) of the University of California. The first involved:

1. Anemometer calibration by adjusting the output to 4 volts while an input of 9.4 VAC was

Table 1. *Overall Dry-Bulb* (T), *Wind Velocity* (V), *and Dew-Point Data* (D) *for the Labeled Stations* ($n = 288$), *and Reference* (TMY) *Total Horizontal Solar Radiation* (Rs) *for Two Days.* Temperature and dew-point are in °C, wind velocity is in $\mathrm{m\,s^{-1}}$, and solar radiation in $\mathrm{W\,m^{-2}}$

| Station → | A | C | D | E | G | I | J |
|---|---|---|---|---|---|---|---|
| $T_{\min}$ (°C) | 2.6 | 1.8 | 2.0 | 2.9 | 3.3 | 1.8 | 1.8 |
| $T_{\max}$ (°C) | 28.3 | 28.0 | 24.8 | 25.5 | 25.5 | 25.5 | 29.0 |
| $T_{\mathrm{mean}}$ (°C) | 13.04 | 12.39 | 11.96 | 12.38 | 13.09 | 11.91 | 12.33 |

| Station → | A | C | D | E | G | I | J |
|---|---|---|---|---|---|---|---|
| $V_{\min}$ ($\mathrm{m.s^{-1}}$) | 0 | 0 | 0 | N/A | 0 | 0 | 0 |
| $V_{\max}$ ($\mathrm{m.s^{-1}}$) | 8.5 | 7.4 | 5.7 | N/A | 1.8 | 2.8 | 4.6 |
| $V_{\mathrm{mean}}$ ($\mathrm{m.s^{-1}}$) | 1.63 | 1.5 | 0.718 | N/A | 0.299 | 0.365 | 1.403 |

| Station → | I | J |
|---|---|---|
| $D_{\min}$ (°C) | 3.3 | 0.5 |
| $D_{\max}$ (°C) | 15.8 | 15.7 |
| $D_{\mathrm{mean}}$ (°C) | 8.77 | 7.29 |

| Hour → | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Clear day Rs ($\mathrm{W\,m^{-2}}$) | 28 | 170 | 362 | 529 | 646 | 700 | 684 | 608 | 479 | 302 | 117 |
| Overcast day Rs ($\mathrm{W\,m^{-2}}$) | 13 | 113 | 268 | 394 | 444 | 362 | 243 | 129 | 101 | 60 | 22 |

applied (representing a wind speed of 40 m s$^{-1}$). The corresponding calibration line's slope was 0.01 volts m$^{-1}$ s.

2. Vane calibration by pointing it due south and adjusting the output to 2.048 volts.
3. Dry-bulb sensor calibration by adjusting the corresponding resistance to 10 000 Ω with an output of 10 mv K$^{-1}$. The sensor thus produced an output of 1 μa K$^{-1}$.
4. DEW-10 calibration by adjusting the corresponding resistance to 200 Ω, for an output range of 0.8–4 volts. The sensor's output range of 4–20 milliamperes then corresponded to a dew point range of 0–50 °C.

Dynamic calibration, on the other hand, was performed by running the weather stations for two full days in an open area in the RFS, during which data were logged every 15 minutes. The stations were set up on a straight line with 1 m spacing between adjacent units. Longer dynamic calibration would have been more desirable was it not for time constraints.

## 6. Data Presentation and Discussion

In Table 1, a brief description of the observational period's micrometeorological conditions is given. This includes day/night times and clear/overcast conditions.

Heat islands and oases resulted from spatially-differentiated atmospheric cooling and heating rates[4]. At the time of data collection, we estimated that the heat capacity of the canopy was negligible in comparison to that of the wet soil. The differential in cooling and heating between the orchard and the open fields was caused by different sky view factors and degrees of wind-shielding. The smaller exposures to the sky and the wind resulted in the orchard warming up and cooling down slower than the open fields, i.e., the orchard's daily range of temperature fluctuation was damped. In clear weather conditions, the ratios of the canopy's mean cooling and heating rates to those of the open fields were about 86%. In overcast conditions (less microclimate contrast between canopy and open fields), the ratios were about 94%.

### *6.1 Heat Island and Oasis Effects*

Figures 2 and 3 show time-series of temperature differences with respect to control station A. We can see that within the canopy (stations E and G), a heat island developed during evening and night hours, and that an oasis appeared during daytime. This was particularly true in clear weather (Fig. 2), but still observable to a lesser extent during overcast conditions (Fig. 3). The heat island and oasis effects were most pronounced in clear and calm conditions. The average heat island (and oasis) in the canopy stations G and E was 1.5 °C (− 1.5 °C) during clear weather and 0.7 °C (− 0.7 °C) under cloudy conditions. Instantaneous temperatures could be lower (− 6 °C at station I) or higher (+ 2 °C at station E) than these average values. Heat islands were caused by wind speed reduction and smaller sky view factors in the canopy, whereas oases were caused by shading and evapotranspiration. Since stations C and A were in the same open field, their temperature profiles were almost similar. In clear conditions (Fig. 2), stations D and I had a daytime oasis because of the canopy's cooling effect, but they had no nighttime heat island because their sky view factors were large. In overcast conditions (Fig. 3), the oasis effect was reduced at both locations.

We can see that station I, situated not within the canopy but just south of the bushy stream (Figs. 1 and 2), had considerably lower temperatures than other open-field stations. During the day this station was affected by cool air advection from the north. The air was cooled by evapotranspiration from the canopy and the stream and by contact with the orchard's cooler soil. During clear weather the temperature at station I was as much as 6 °C lower than at control station A and also lower than at the stations within the canopy. The temperature at station I reached that at station A only very briefly at noontime. At night, this location was cooled by long wave radiation to the unobstructed clear sky.

Figure 4 shows the mean deviation in temperature (with respect to the temperature at station A) across the site during hours when the wind direction was parallel to the line of weather stations. There were only eight such hours during the observational period[5]. The dry-bulb temperature

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[4] The warming and cooling rates are hereby defined as the average trend in temperature ($\partial T/\partial t$) over the period of time when there was warming or cooling.

[5] Oct. 13 at 1400, Oct. 15 at 1300, Oct. 19 at 1100 and 1600, Oct. 21 at 1300, Oct. 22 at 1500, 1600, and 1700.

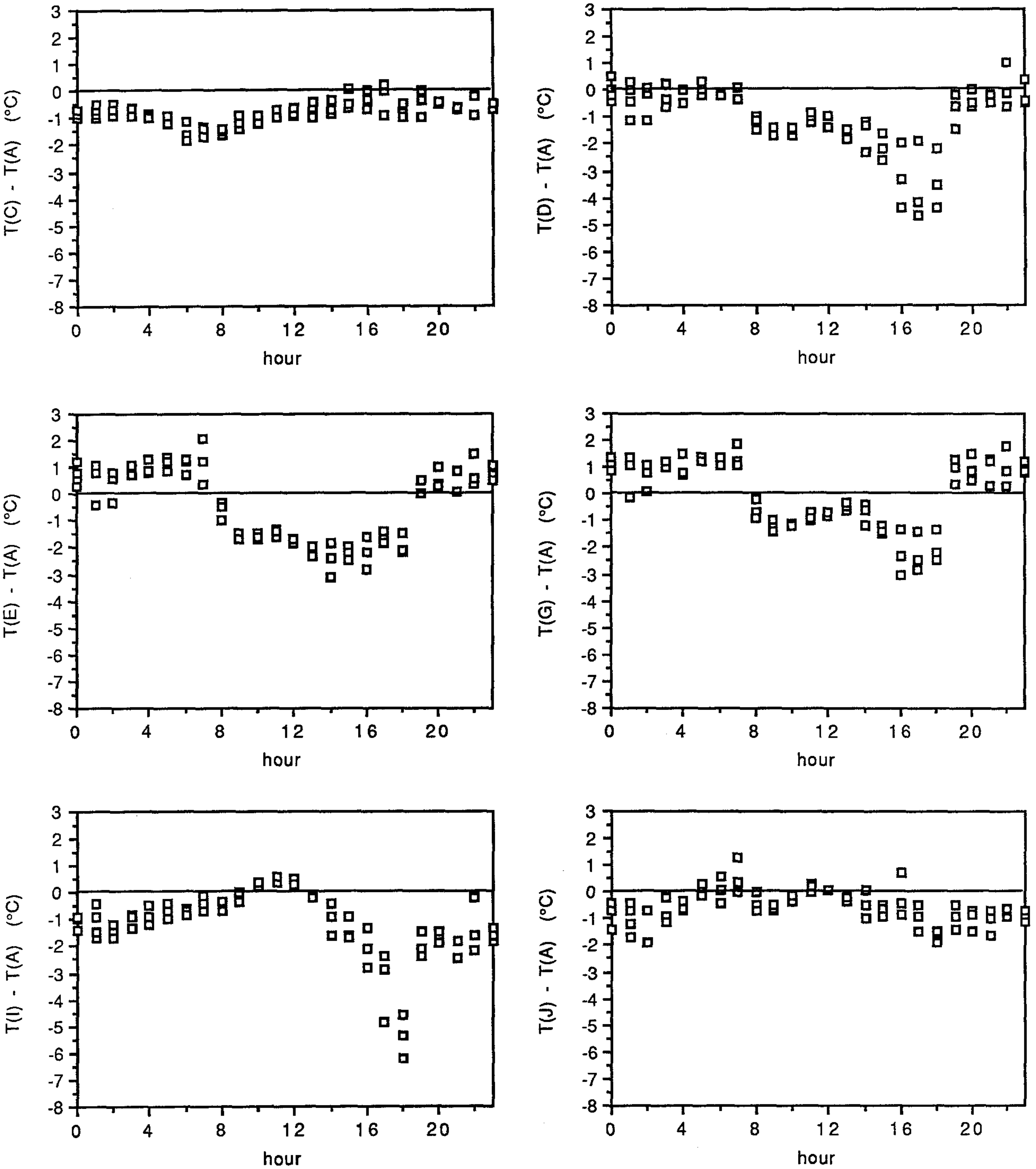

Fig. 2. Clear day and night temperature differences from station A (°C). October 12 through 15

dropped sharply within the first few meters inside the canopy (through station E), but increased again at station G which was in a clearing. The drop in temperature at station I is also clear. Table 2 depicts the same information for the first two stations within the canopy, and shows that the greatest effect was achieved within the first 5 m of the orchard. Additional downwind distance inside the canopy was not as effective as the first few meters from the upwind edge.

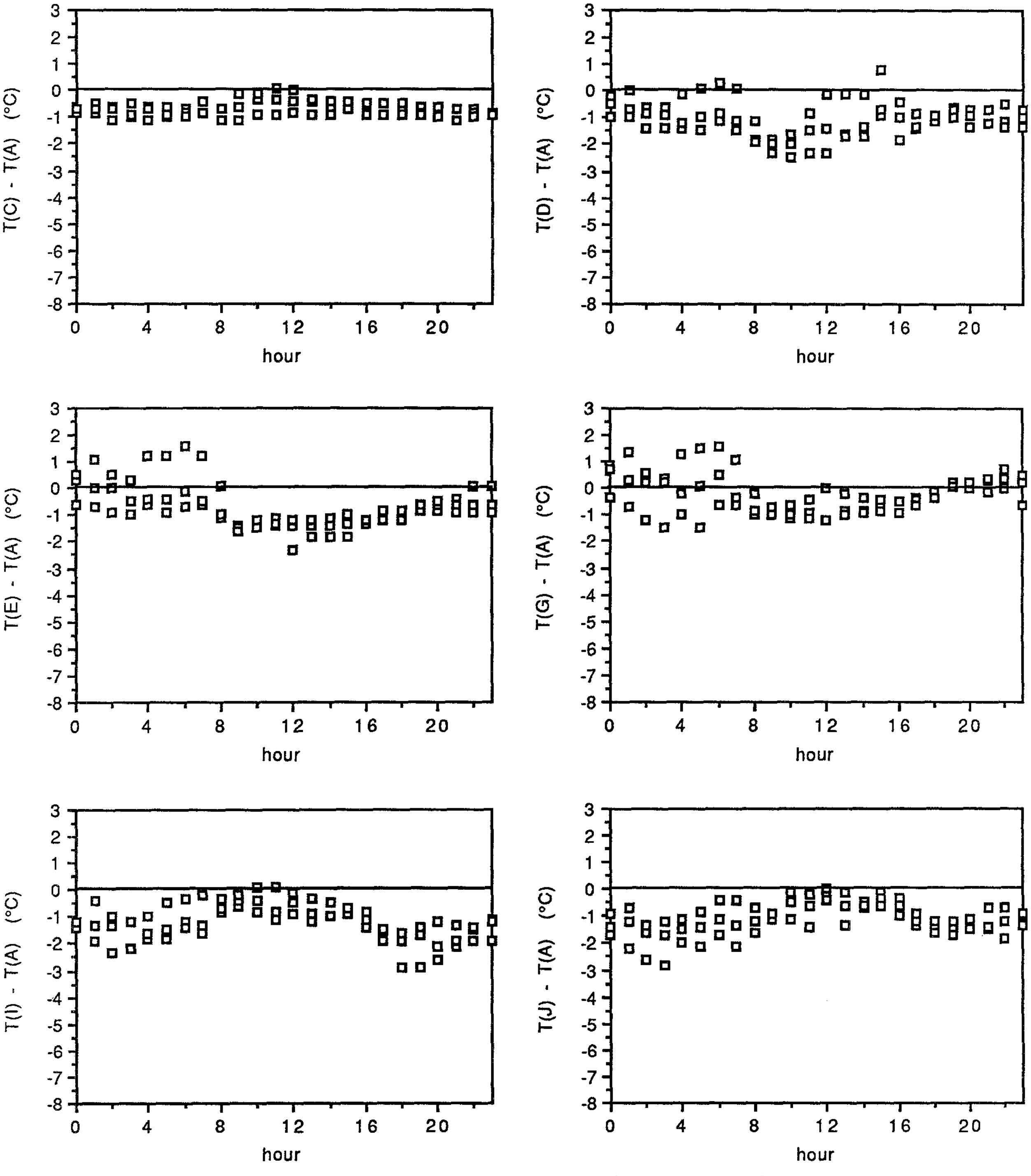

Fig. 3. Overcast day and night temperature differences from station A (°C). October 16 through 18

### 6.2 Wind Speed

Although stations C and A were in the same open field, it was observed that the former had slightly lower wind speeds than the latter. This was particularly true during overcast conditions with higher wind speeds associated with a low pressure system. The reason why station C had slightly slower winds was the upward deflection of the flow upon approaching the leading edge of the vegetation canopy from the north. At station D, the wind speed depression was in phase with that of temperature. The depression increased at station

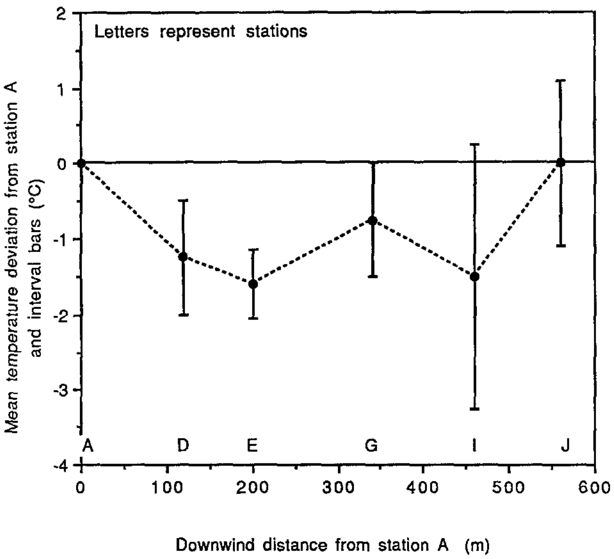

Fig. 4. Mean temperature deviation across the canopy

G, within the canopy, and was still well-defined at station I in an open field downwind of the canopy. Station J had high wind speeds at night because of the unobstructed flow from the south.

When a low-pressure system arrived, the same general pattern remained, but the contrast between the open and canopy stations' wind speeds increased. Both stations I and J were under the canopy's wind-shielding effect indicating that the wind characteristic distance increased with wind speed and reached a length of more than 5 times the height of the tall trees at the south edge of the canopy. This observation will be explained later in detail.

### *6.3 Clear Versus Overcast Conditions*

In overcast conditions, the diurnal dry-bulb temperature range was damped by as much as 17.3 °C in the open sites and 12.5 °C in the canopy. During cyclonic weather, the highest wind speed in the open field (control station A) was 8.5 m $s^{-1}$ while in anticyclonic and neutral conditions, the highest was about 2.6 m $s^{-1}$. Within the canopy (station G), the typical highest wind speed in cyclonic weather was 1.8 m $s^{-1}$, and in anticyclonic weather it was 0.7 m $s^{-1}$. The cyclonic system overrode the prevailing wind directions, so that the winds became west and south-west instead of north and south winds.

Heat islands and oases were strongly affected by increasing cloudiness and faster winds brought on by the cyclonic system. There was an average ± 2 °C deviation (heat islands or oases) from the open sites during clear weather but in overcast conditions, the difference was reduced to an average of − 1 °C, i.e., there was no longer a heat island, but only a constant, mild oasis. This can be seen in Fig. 3; aside from a short time interval at stations E and G, the temperature scatter was below the zero line of station A. The mild oasis in cloudy conditions can still be attributed to evapotranspiration from the soil-vegetation system. It is interesting to note that station (I) was no longer the coldest during overcast conditions and that its temperature profile became more similar to those of stations in the canopy and in the open fields (Fig. 3). This was another result of the overriding winds associated with the approaching frontal system.

### *6.4 Characteristic Distances*

One of the objectives in this paper was to estimate the downwind characteristic distances over which the temperature and wind-shielding effects of the canopy could still be detected. Because we were ultimately interested in daytime cooling effects of vegetation and because of prevailing daytime north-to-south winds, the southern site was the one on which these distances could be measured. Accordingly, data from stations I and J were examined and compared to data from other stations.

Table 2. *Dry-Bulb Temperature Drop °C* (deviation from temperature at control station A) *at Two Interval Distances Downwind Within the Canopy*

| Day/Hour → | 13/14 | 15/13 | 19/11 | 19/16 | 21/13 | 22/15 | 22/16 | 22/17 |
|---|---|---|---|---|---|---|---|---|
| 5 m downwind (D) | −1.2 | −1.8 | −0.5 | −1.3 | −1.9 | −0.7 | −2.1 | −2.0 |
| 75 m downwind (E) | −1.8 | −2.0 | −1.1 | −1.4 | −1.9 | −1.2 | −1.5 | −1.8 |

### 6.4.1 Temperature

To analyze the characteristic distances for temperature, we used the data to construct two typical days. These days, one cloudy and one clear, were made up of 24 average hours each. Two-hour intervals from these days are shown in Table 3 (differences in temperature among stations I, J, and A). Station I was 12 m south of the canopy's southern edge, whereas station J was 100 m south of I. To determine whether these stations were within the characteristic distance (i.e., influenced by the canopy), their data was compared to that of control station A in the northern field.

In clear weather, the differences from station A were larger at station I than station J, indicating a stronger canopy effect at station I (Table 3). Station J was cooler than A especially after 1600 hours, indicating that it was also within the characteristic distance of the canopy. In overcast conditions, the temperature contrast between stations I and J was damped.

With these conditions in mind, we can see that the canopy, during that observational period, had a temperature characteristic distance between 10 and 110 m (up to five times the height of the tall trees at the southern edge) most of the time. There were also times when station J was clearly influenced by the canopy, meaning that the temperature characteristic distance exceeded 110 m. Determining the exact hourly fluctuations in characteristic distance will require an even higher resolution network of weather stations on the 100 m downwind stretch over the southern open field between stations I and J.

### 6.4.2 Wind

To establish the characteristic distance for wind, we analyzed data from the 18th of October, which was the windest day during that observation period. The consistency in wind direction on that day was remarkable. With the exception of station I, all stations had a consistent north-west wind (~ 30° off the stations' line). Station I had a stronger westerly component, probably resulting from local turbulence effects caused by the tall trees to the north and west of the station. Table 4 represents 2-hour interval wind speed data for the 18th of October. This table can be thought of as a north-south section across the field, with north at the top of the table[6]. Station E was dropped because its wind speed sensor was not reliable.

Table 3. *Upwind/Downwind Comparison of Temperature (°C) Shown at 2-Hour Intervals for Clear and Overcast Typical Days*

| Hour → | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ΔT (a–i) clear | 1.1 | 1.4 | 0.8 | 0.7 | 0.5 | −0.3 | −0.3 | 1.0 | 2.1 | 5.4 | 1.6 | 1.3 |
| ΔT (a–j) clear | 0.6 | 0.4 | 0.5 | −0.1 | 0.4 | 0.2 | −0.1 | 0.5 | 0.2 | 1.7 | 1.0 | 0.7 |
| ΔT (a–i) over. | 1.3 | 1.6 | 1.5 | 1.0 | 0.6 | 0.4 | 0.5 | 0.8 | 1.1 | 2.1 | 2.0 | 1.6 |
| ΔT (a–j) over. | 1.3 | 1.9 | 1.5 | 1.1 | 1.2 | 0.6 | 0.2 | 0.6 | 0.6 | 1.4 | 1.3 | 1.3 |

Table 4. *Wind Speed m s$^{-1}$, on October 18, 1986*

| Hour → | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station A | 1.0 | 1.8 | 3.5 | 1.2 | 3.0 | 7.0 | 8.3 | 8.0 | 7.4 | 4.2 | 2.7 | 3.8 |
| Station C | 1.0 | 1.8 | 3.1 | 1.2 | 2.7 | 6.3 | 7.3 | 7.0 | 6.6 | 3.6 | 2.4 | 3.3 |
| Station D | 0.2 | 1.0 | 1.8 | 0.3 | 1.6 | 4.3 | 5.4 | 5.4 | 5.1 | 3.2 | 1.3 | 1.8 |
| Station G | 0.1 | 0.1 | 0.5 | 0.1 | 0.4 | 1.5 | 1.8 | 1.7 | 1.6 | 0.8 | 0.4 | 0.9 |
| Station I | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | 0.8 | 1.1 | 1.1 | 0.9 | 0.3 | 0.1 | 0.2 |
| Station J | 0.8 | 0.9 | 1.7 | 0.6 | 1.7 | 3.6 | 4.6 | 4.4 | 4.1 | 2.4 | 1.3 | 2.1 |

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[6] One should recall that the anemometers' average wind speed threshold was 1.5 m s$^{-1}$. In this paper, when a value under that threshold is reported, it is an average value for wind speeds integrated over the time interval of interest. Although hourly-interval wind speed values are reasonably representative of the wind speed regime during that interval (because of the large number of records) one still has to be cautious in interpreting indicated wind speeds below that threshold.

Comparison of wind speeds at stations A and C with those at stations I and J shows that the latter two were within the wind characteristic distance of the canopy, with the wind-shielding effect particularly stronger at station I. Wind speed at J, although higher than at I, was still lower than that at stations A and C. Therefore, we can state that the wind characteristic distance for this canopy under these conditions was larger than 110 m (over five times the height of the trees) at high wind speeds (hours 600 through 1800). During slower winds, the characteristic distance fluctuated between 10 and 110 m. Wind speed gradients across the canopy were considerable. For example, at the highest wind, at 1100 hr, station A had 8.5 m $s^{-1}$ whereas station I had only 1.0 m $s^{-1}$. During the lowest winds, at 00 hr, station A had 1.0 m $s^{-1}$, while station I had 0.1 m $s^{-1}$.

In addition to October 18, data from other days are presented in Fig. 5. This figure shows the deviation in wind speed (with respect to the wind speed at station A) across the canopy and open field at hours when the wind blew parallel to the stations' line (these are the same hours mentioned in footnote 5). The wind speed dropped sharply within the canopy (stations D and G), but returned to the undisturbed speed in the open field (station J).

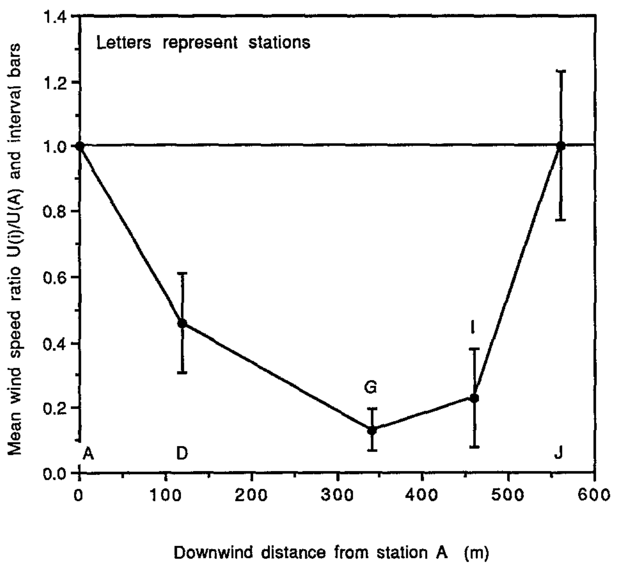

Fig. 5. Mean wind speed ratio across the canopy

Table 5 summarizes the decrease in wind speed as compared to station A at two stations within the canopy and can be compared to Table 2 for the temperature drop at these same hours. In Table 5 the 75 m interval, corresponding to station E, was omitted because of anemometer malfunction at that location. As in the case with temperature (Table 2), the canopy effect on wind was much more noticeable within the first 5 m than the next 220 m.

### 6.5 Temperature and Wind Speed Impacts on Heat Islands and Oases

The dry-bulb temperature within the canopy was first separately correlated to the open-field's air temperature and wind speed (at control station A). Then, a bivariate analysis of the temperature within the canopy versus both open-field air temperature and wind speed was performed. Initially, the regressions were carried out for all hours, including clear and overcast conditions as well as day and night times. Correlations indicate that the canopy's heat island intensity varied inversely with the open-field temperature and that the oasis intensity varied directly with it. Keep in mind that these heat islands and oases are relative to a "balance point temperature" which is location-dependent within the canopy[7].

To refine this analysis, the same regressions were repeated for clear weather only, including day and night hours. The canopy stations (D, E, and G) showed better correlations indicating, as

Table 5. *Wind Speed Reduction at Two Stations Within the Canopy, i.e., Reduction* = $(V - V_a)/V_a$

| Day/hr → | 13/14 | 15/13 | 19/11 | 19/16 | 21/13 | 22/15 | 22/16 | 22/17 |
|---|---|---|---|---|---|---|---|---|
| 5 m downwind (D) | 0.45 | 0.5 | 0.53 | 0.6 | 0.38 | 0.63 | 0.35 | 0.46 |
| 225 m downwind (G) | 0.2 | 0.21 | 0.2 | 0.16 | 0.15 | 0.13 | 0.07 | 0.07 |

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[7] The term "balance point temperature" is used to indicate the open-field temperature (at station A) below which a heat island exists within the canopy, and above which an oasis is in effect. For this canopy and observational period, the balance point at the edge of the orchard was 6.5 °C and at the middle of the canopy it was 12.5 °C.

expected, that the effects of evapotranspiration, shading, and the sky view factor were larger during clear weather. It is known that evapotranspiration increases with both temperature and solar radiation, both of which are larger during clear days. In addition, the effect of shading is significant in clear days with higher insolation and more direct (as opposed to diffuse) radiation. Finally, on clear nights, the effect of the sky view factor is larger than on overcast nights because of larger sky temperature depressions associated with clear skies.

From this analysis, two correlations were derived. Equation (1) can be used to predict the heat island or oasis within the denser part of the canopy, closer to its edge, while Eq. (2) can be used to predict their magnitudes at locations within the canopy that are more open to the sky[8].

$$\Delta T = 0.85\text{–}0.13\,T \qquad r^2 = 0.62,\ T_b = 6.5\,°\mathrm{C}\,(dense) \tag{1}$$

$$\Delta T = 2.00\text{–}0.16\,T \qquad r^2 = 0.76,\ T_b = 12.5\,°\mathrm{C}\,(open) \tag{2}$$

In this equations $\Delta T$ is the heat island or oasis (°C), $T$ is the open-field air temperature (°C), and $T_b$ is the corresponding balance temperature. Keep in mind that these are correlations with temperature only, assuming that wind speed is known and that it is similar to the one measured here.

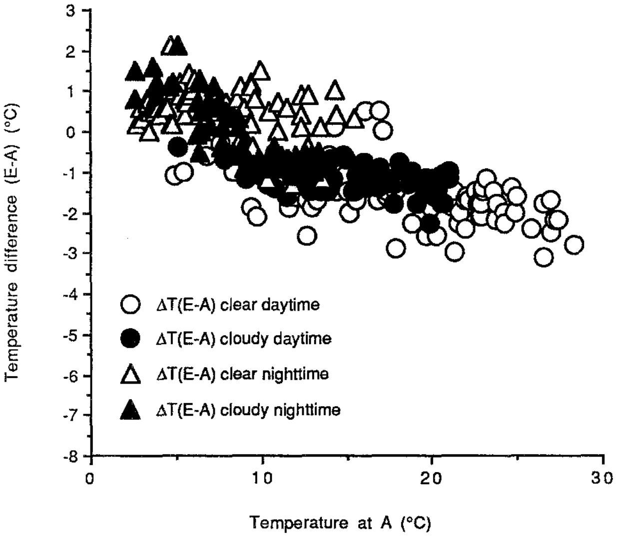

Fig. 6. All-times temperature differences between canopy station E and open-field station A (°C)

Figures 6 and 7 depict another way to look at the temperature data. They represent $\Delta T$ at stations E and I, respectively, plotted against the open-field temperature, segregated by day and night times, and clear and overcast conditions. We can see that station E (Fig. 6) could be up to 2.2 °C warmer than the open sites at night, because it was well sheltered (small sky view factor), whereas station I (Fig. 7) was cool during daytime because of the cold air advected from the canopy. Also, there was no significant nighttime heat island, since station I was open to the sky. The high temperature depression seen in the lower right part of Fig. 7 occurred at times of highest open-field

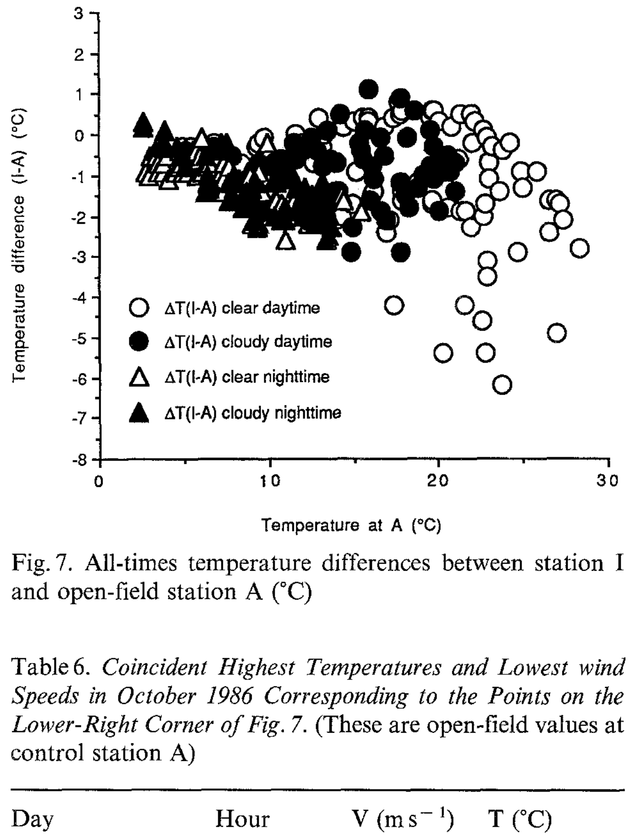

Fig. 7. All-times temperature differences between station I and open-field station A (°C)

Table 6. *Coincident Highest Temperatures and Lowest wind Speeds in October 1986 Corresponding to the Points on the Lower-Right Corner of Fig. 7.* (These are open-field values at control station A)

| Day | Hour | V ($\mathrm{m\,s^{-1}}$) | T (°C) |
|---|---|---|---|
| October 13 | 18 | 1.0 | 22.6 |
| October 14 | 15 | 0.9 | 27.0 |
| October 14 | 16 | 0.5 | 27.4 |
| October 14 | 17 | 0.3 | 27.0 |
| October 14 | 18 | 0.1 | 23.7 |
| October 15 | 14 | 0.8 | 26.5 |
| October 15 | 16 | 0.5 | 28.3 |
| October 15 | 17 | 0.8 | 26.6 |
| October 15 | 18 | 0.1 | 22.8 |

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[8] These equations were generated for this canopy, observational period, and balance point temperatures of 6.5 and 12.5 °C, respectively. Also, these equations are for clear days and nights with wind speeds under $2\,\mathrm{m\,s^{-1}}$.

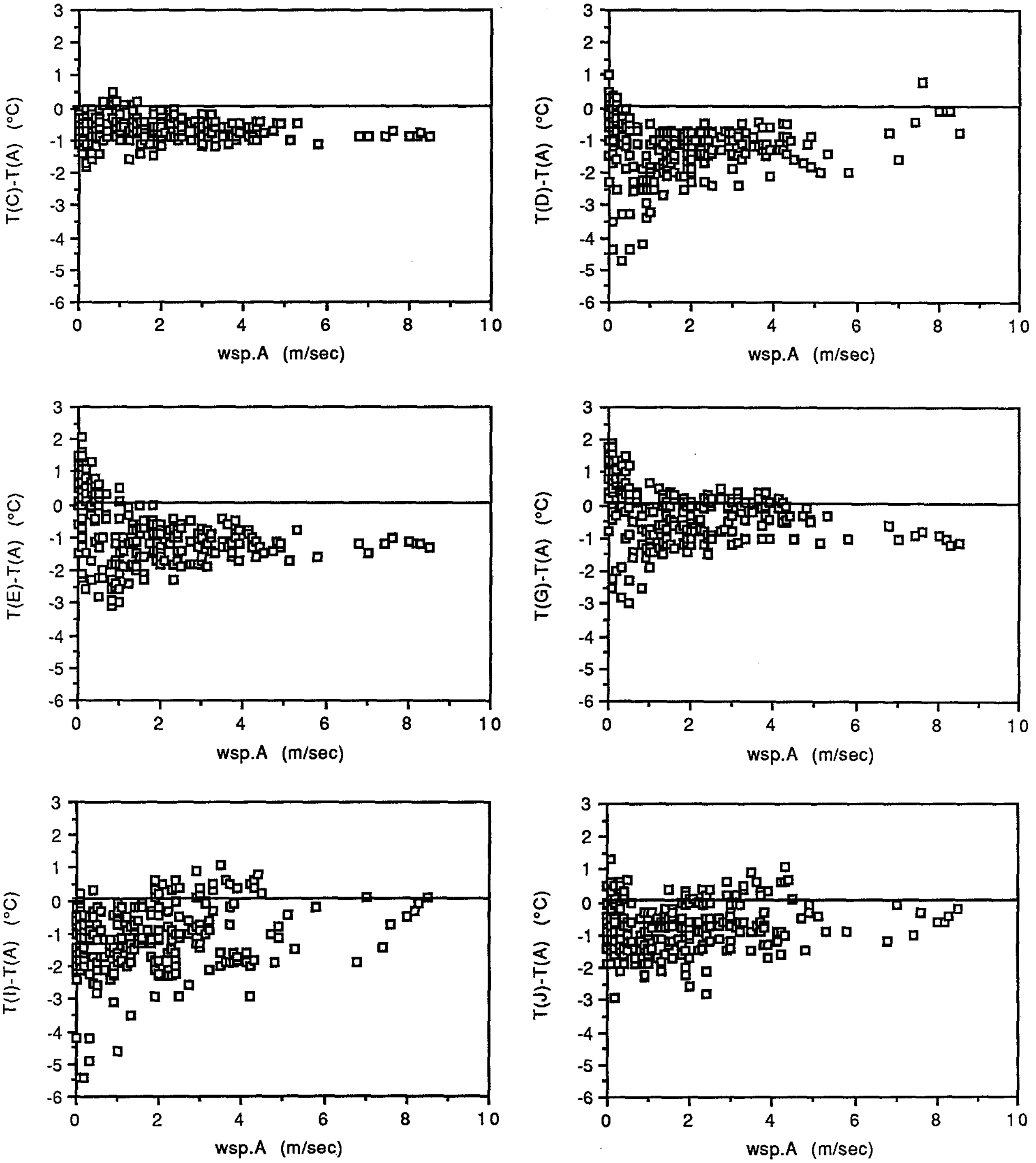

Fig. 8. ΔT (°C) versus wind speed ($m\,s^{-1}$) at all times. Control station is A

temperatures coinciding with the lowest ambient wind speeds, during clear daylight hours in that observational period. Table 6 shows the times of coincidence.

In order to test the correlation between heat islands, oases, and open-field wind speeds, these variables were plotted against each other in Fig. 8. The heat island (positive scatter) and oasis (negative scatter) were largest at lowest wind speeds, especially in canopy stations (E and G). The temperature at control station A is shown by the horizontal line at y = 0. The minimal temperature

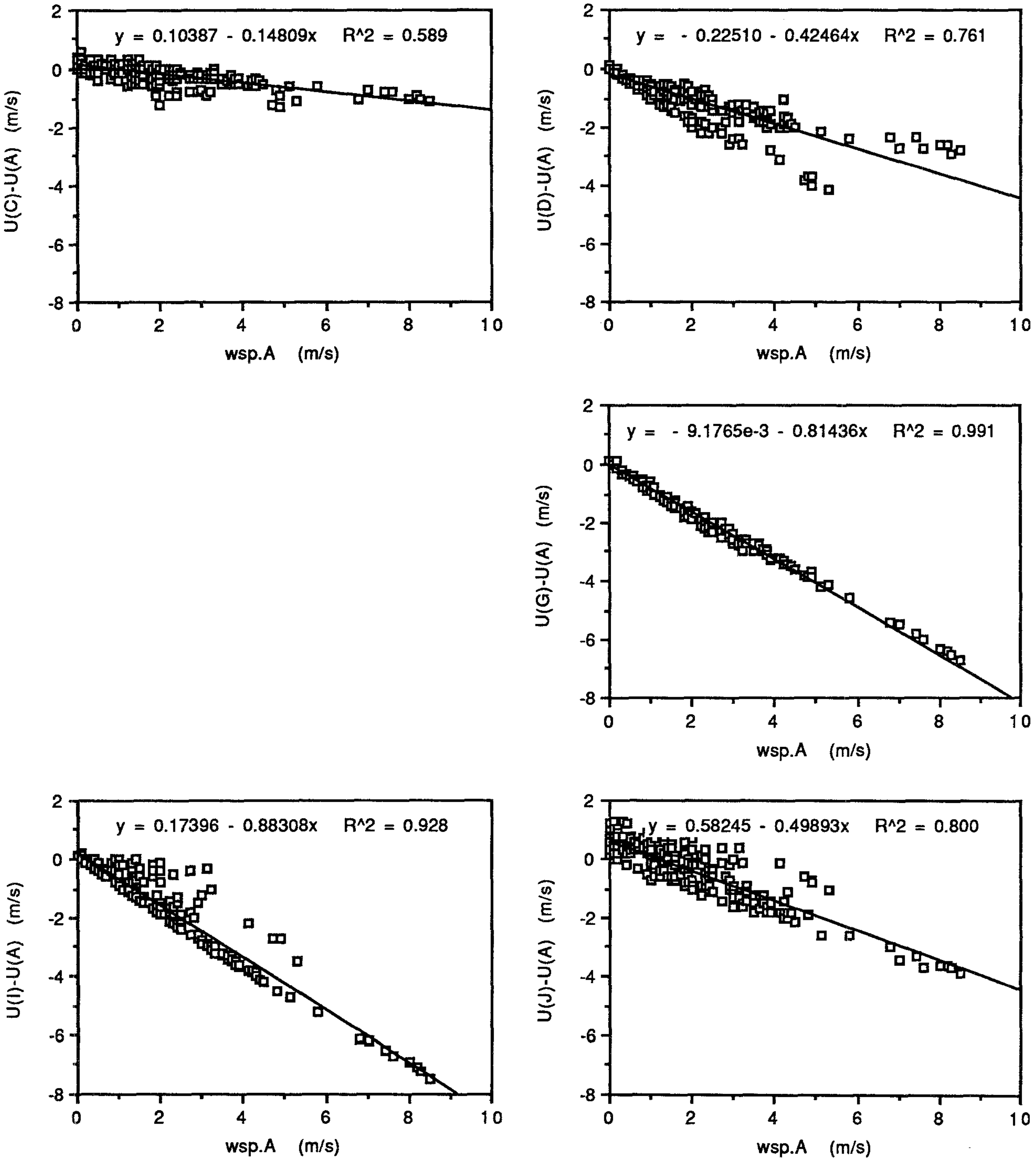

Fig. 9. ΔV (m s$^{-1}$) versus absolute wind speed (m s$^{-1}$) at all times. Control station is A

depression occured at wind speeds greater than 6 m s$^{-1}$, seen as a tapering scatter. Another remarkable characteristic is that the ranges of $\Delta T$ decreased in the open field station (C) and increased in the canopy stations. Station I shows large depressions at low wind speeds, and station J still shows some temperature depression despite being in the open field. As explained earlier, this was a result of the canopy's temperature characteristic distance effect.

### 6.6 *Wind Reduction Versus Wind Speed*

To investigate the effects of canopy on wind speed, two tests were performed: (1) wind speed reduction versus absolute, open-field wind speed, and (2) normalized wind speed versus horizontal distance within the canopy and over the open fields. Figure 9 shows the first test. The y-axis represents the depression in wind speed at a given station (at all times) and the x-axis represents the absolute wind speed at control station A. The correlation is quite good, especially in the middle of the canopy (station G). At the edges (stations D and I), the correlation is still strong but some "forked" scatter is obvious. This was probably caused by the shifting wind direction, which means that each station was upwind (at the leading edge) at some times, and downwind (at the trailing edge) at others. Station C shows a shallow slope because it lies in the same open field as station A, but is slightly lower than A because of the upward deflection of the wind flow at about that location. Although station J is in the open, it still shows some strong correlation, indicating that it is within the wind characteristic distance of the canopy, as discussed earlier.

The second test was performed to describe the deceleration and acceleration of wind towards and away from the canopy, respectively. The test was performed on hours when the wind blew within 30° on either side of the stations' line. A strong correlation was found between wind speed and distance to, within, and away from the canopy. In a decelerating case (Fig. 10 a), the horizontal distance was measured downwind from the leading edge of the canopy whereas in the accelerating case (Fig. 10 b), it was measured downwind from the downwind (trailing) edge. The best fits were:

$$\frac{U_x}{U_a} = 0.76\,e^{-0.0053x}, \quad r^2 = 0.983\,(\textit{deceleration}) \tag{3}$$

$$\frac{U_x}{U_j} = 1 - 0.5\,e^{-0.14x}, \quad r^2 = 0.902\,(\textit{acceleration}) \tag{4}$$

where the wind speed $U_x$ (m s$^{-1}$) at a downwind distance ($x$) is normalized with respect to that at station A or J, depending on wind direction, $x$ is the horizontal downwind distance (m) from the starting point, which is the upwind edge of the canopy in a decelerating case, and the downwind edge, in an accelerating case.

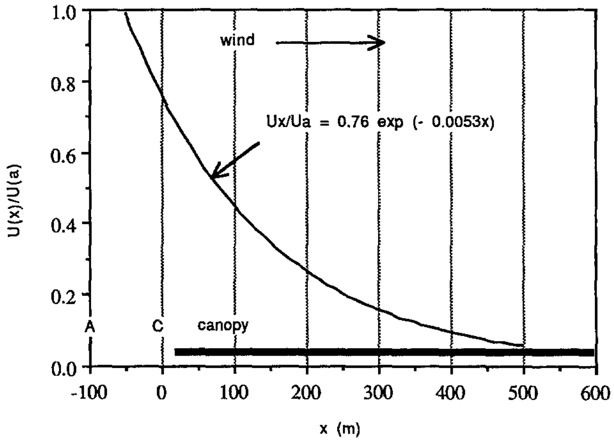

Fig. 10 a. Normalized wind speed (with respect to station A) versus distance from the leading edge of the canopy (decelerating wind)

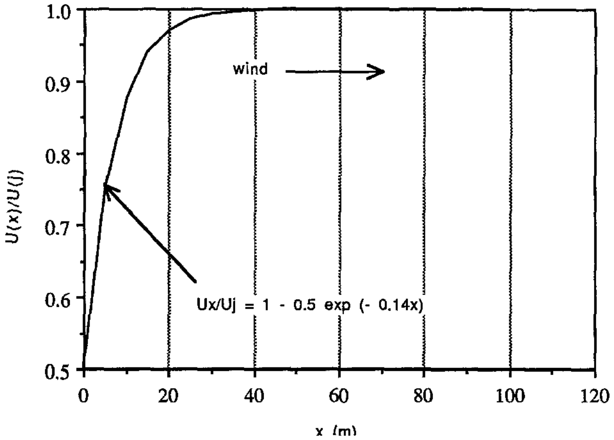

Fig. 10 b. Normalized wind speed (with respect to station J) versus distance from canopy (accelerating wind)

Equation (3) indicates that wind speed starts to drop to below the open-field value well before reaching the canopy: at about 52 m upwind of the upwind edge. Physically, this means that the upward-deflected flow of air begins at about that point and is the reason why the horizontal wind speed at station C is lower than at station A (also see Fig. 9). On the other hand, Eq. (4) predicts that wind speed downwind of the canopy gets back to the upwind, open-field value at a distance of 50 m from the downwind edge. The high $r^2$ values suggest that these correlations can be used to describe wind speed patterns in and around this canopy. Equations (3) and (4) may not be exactly applicable to other canopies but they certainly can give a rough estimate of similar canopies' effects on wind speed.

### *6.7 Correlations With Heat Islands and Oases*

A bivariate analysis was performed to correlate the magnitudes of heat islands and oases with absolute open-field temperatures and wind speeds. The analysis indicates that the nighttime heat island correlates better to temperature and wind speed than does the daytime oasis. In the canopy stations, a significant correlation was found between nighttime temperature depression and $T$, $V$, and $V^2$, as well as with $V$, $V^2$, and $V^3$ where $T$ and $V$ stand for open-field temperature and wind speed respectively. Daytime data, however, showed that the correlation was best with $T$, $V$, and $V^2$, though generally weaker than the night correlations. It was also clear that wind speed assumed a more important role in temperature depressions than absolute temperature.

Equations (5) through (7) summarize these correlations and can be used in predicting the temperature within a uniform canopy when upwind, open-field temperatures and/or wind speeds are known. These equations are based on data from stations E and G, which were within the canopy.

*Nighttime, T and V known*

$$\Delta T = 1.33 - 0.063\,T - 1.16\,V + 0.20\,V^2 \qquad (5)$$

$(r^2 = 0.80)$

*Nighttime, V known*

$$\Delta T = 1.02 - 2.14\,V + 0.82\,V^2 - 0.10\,V^3 \qquad (6)$$

$(r^2 = 0.77)$

*Daytime, T and V known*

$$\Delta T = -0.79 - 0.037\,T + 0.406\,V - 0.043\,V^2 \qquad (7)$$

$(r^2 = 0.33)$

where $\Delta T$ is the temperature depression (heat island or oasis, °C) within the canopy, and $V$ and $T$ are the upwind wind speed ($\mathrm{m\,s^{-1}}$) and temperature (°C), respectively. All these correlations are at statistical significance of better than 99%. Equation (5) predicts the nighttime heat island and yields realistic results in the domain $0.5 \leqslant V \leqslant 1.5\,\mathrm{m\,s^{-1}}$ and a balance point temperature of $\sim 6\,^{\circ}\mathrm{C}$. Similarly, Eq. (6) has a domain of $0 \leqslant V \leqslant 1.0\,\mathrm{m\,s^{-1}}$, with a balance wind speed of $0.6\,\mathrm{m\,s^{-1}}$. Equation (7) predicts the daytime oasis, and should be used with wind speeds higher than $2.5\,\mathrm{m\,s^{-1}}$.

## 7. Conclusions

In this report, we analyzed and quantified micro-meteorological conditions upwind, within, and downwind of a tree stand in Davis, California, for two weeks during a warm period in October 1986. The objective was to estimate the microclimate effects of potential evapotranspiration and wind speed reduction of a soil-vegetation system in the warm climate of California's Central Valley. Our emphasis was placed on dry-bulb temperature and wind speed.

Heat islands and oases within the canopy were quantified and related to open-field microclimate conditions. There were large spatial and temporal fluctuations in temperature but it was possible to make some general observations. On the average, the canopy was 2 °C cooler during the day than the bare and open surrounding fields. Depressions of up to 6 °C were also noted at times. Such reductions in air temperature can be very beneficial in lowering the need for cooling demand in buildings. Our data also indicate that the temperature effects in the tree stand were immediate. The first 5 m in the canopy depressed the temperature by over 65% of the total temperature depression across the entire canopy. In practical terms, this says that we do not need to plant extensive vegetation belts to achieve significant cooling: one or two rows of trees upwind of a building cluster can result in significant savings in cooling energy.

Trees also reduced wind speed by an average 50% over the first 5 m within the tree stand, and by as much as 90% over the next 200 m inside the canopy. As is the case with temperature, one or two rows of trees is all it takes to significantly reduce wind speed at the buildings' site. Summertime wind speed reductions of this magnitude can be beneficial particularly in dry climates. As trees reduce the amount of warm air infiltrating to the inside of buildings, large savings in cooling energy and peak demand can be achieved.

The contrast between the wind speed inside the canopy and that of the open fields increased as the open-air wind speed went up. An example was seen during the passage of a low-pressure system, when wind speeds in the open rose to $8.5\,\mathrm{m\,s^{-1}}$ and were only $\sim 2\,\mathrm{m\,s^{-1}}$ inside the canopy.

Canopy effects on temperature and wind speed were traced downwind of the tree stand and into the open fields. In general, the canopy effects on downwind microclimates was seen in lowered temperatures and lowered wind speeds. The characteristic distance for temperature fluctuated between 1 and 5 times the height of the trees at the southern edge of the canopy depending on weather conditions. The characteristic distance for wind, on the other hand, was almost always greater than 5 times the height of the trees. This says that it is not necessary to place the trees very close to buildings in order to benefit from their microclimates. Our data indicate that trees 1 to 5 times their height upwind of a building would still influence the microclimate at the building's site.

Several correlations between conditions inside the canopy and those in the open fields were proposed. They can be used to predict the temperature and wind speed within and downwind of the canopy when their upwind values are known.

Our findings in this study are site-specific and their transferability to other geographical locations and microclimates is unknown. But we believe that the findings can give a rough estimate of the microclimate effects of similar canopies. Denser canopies with wet soils will probably have greater effects on wind speed and temperature than the canopy we have studied.

In conclusion, this field-project indicates that in warm climates, trees can be a real asset in reducing the cooling loads in envelope-dominated buildings.

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## References

Akbari, H., Taha, H., Huang, J., Rosenfeld, A., 1986: Undoing uncomfortable summer heat islands can save gigawatts of peak power. *Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, August 1986, Santa Cruz, California*, **2**, 7–22.

Barnston, A. G., Schickedanz, P. T., 1984: The effect of irrigation on warm season precipitation in the southern great plains. *J. Climate Appl. Meteor.*, **23**, 865–888.

Bernatzky, A., 1982: The contribution of trees and green spaces to a town climate. *Energy and Buildings*, **5**, 1–10.

Budyko, M. I., 1977: *Climatic Changes*. American Geophysical Union, Washington, DC.

Davenport, D. C., Hudson, J. P., 1967 a: Changes in evaporation rates along a 17-km transect in the Sudan gezira. *Agric. Meteor.*, **4**, 339–352.

Davenport, D. C., Hudson, J. P., 1967 b: Meteorological observations and Penman estimates along a 17-km transect in the Sudan gezira. *Agric. Meteor.*, **4**, 405–414.

DeVries, D. A., 1959: The influence of irrigation on the energy balance and the climate near the ground. *J. Meteor.*, **16**, 256–270.

Geiger, R., 1957: *The Climate Near the Ground*. Boston: Harvard University Press, 611 pp.

Huang, J., Akbari, H., Taha, H., Rosenfeld, A., 1987: The potential of vegetation in reducing summer cooling loads in residential buildings. *J. Climate Appl. Meteor.*, **26**, 1103–1116.

Lemon, E. R., Glaser, A. H., Satterwhite, L. E., 1957: Some aspects of the relationship of soil, plant, and meteorological factors to evapotranspiration. *Soil Sci. Soc. Am. Proc.*, **21**, 464–468.

Sebba, R., Enis, R., Hoffman, M. E., 1984: The Kibbutz landscape in arid zones. *Energy and Buildings*, **7**, 205–211.

Taha, H., Akbari, H., Rosenfeld, A., Huang, J., 1988: Residential cooling loads and the urban heat island: the effects of albedo. *Building and Environment*, **23**, 271–283.

Taha, H., Akbari, H., Rosenfeld, A., 1989: Vegetation canopy micro-climate: a field-project in Davis, California. Lawrence Berkeley Laboratory Report LBL 24593, Berkeley, California.

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