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Effects of Turfgrass Evaporation on External Temperatures of Buildings

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With 12 Figures

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Summary

Evaporative cooling of air by urban vegetation has been considered to be primarily a mesoscale process. Recent studies, however, indicate that localized evaporation may be equally as effective at lowering air temperatures and may substantially reduce summer cooling loads in buildings. An experimental study was conducted in a moderately humid environment to explore how changes in evaporation and the surface energy balance of turfgrass may affect external temperatures of buildings. Surface temperatures of a building shell and the energy balance of adjacent bermudagrass were measured as evaporation from the grass decreased during two drying cycles. In spite of large decreases in latent heat flux and increases in sensible heat flux from the turfgrass, no systematic changes in wall temperature were observed. If evaporative cooling occurred, it was obscured by other environmental factors. Wall temperatures did vary in response to changes in irradiance and wind speed. Changes in wind speed had a considerable effect on wall temperatures during periods of predominantly free convection. When forced convection was dominant, changes in wind speed had a relatively small effect on wall temperatures. Results support the view that evaporative cooling of air is mainly a mesoscale process, and that changes in evaporation within an individual landscapes are unlikely to have a major effect on building energy balance in many climatic regimes.

1. Introduction

Studies of urban climate have shown that vegetation modifies both mesoscale and microscale climates by changing the surface energy balance (Myrup, 1969; Outcalt, 1972). These modifications can affect human comfort in both indoor and outdoor spaces (Mayer and Hoppe, 1987; Heisler, 1974; Heisler, 1977) and potentially reduce requirements for air conditioning in hot climates. A number of publications, summarized by Hutchison and Taylor (1983), describe how to use vegetation to design landscapes for energy conservation.

Mechanisms by which vegetation affects building energy balance include shading, alteration of wind speed and direction, and evaporative cooling of vegetation and air (Hutchison and Taylor, 1983). Shade and wind alteration operate at the microscale, and their effects on building temperatures and cooling costs have been well-documented (Deering, 1956; Buffington, 1978; Thayer and Maeda, 1985; Huang et al., 1987; McPherson et al., 1988). Evaporative cooling of air was thought to be a mesoscale process and to have little impact at the microscale level (Hutchison and Taylor, 1983). Huang et al. (1987) used computer simulation to evaluate the potential of vegetation for reducing building cooling loads in Los Angeles, Sacramento, Phoenix and Lake Charles. They found that evapotranspiration (ET) from vegetation was more effective than shading in reducing energy consumption. They also found that wind speed reductions by landscapes had little effect on cooling loads.

McPherson et al. (1989) evaluated effects of three landscapes (irrigated turfgrass, rock mulch with foundation planting of shrubs, rock mulch with no plants) on energy and water consumption for cooling 1/4-scale model buildings in Tucson. The shrubs, characterized by the authors as low to moderate water use species, were planted to produce dense shade. Irrigated turfgrass and shrubs produced comparable energy savings. Water costs exceeded energy savings for the turfgrass, while energy savings exceeded water costs for the shrub landscape. Cooling of the building by the grass was attributed to lower air temperatures and reduced radiation loads. Results of McPherson et al. (1989) indicate that, in arid regions, microscale effects of evaporative cooling may be as important as mesoscale effects.

Not only can vegetation affect building energy balances, but the external energy balance of the building can affect the energy balance of landscape plants. Heilman et al. (1989) showed that emitted and reflected radiation and convective heat transport from walls can significantly affect water use of adjacent shrubs. They found that maximum transpiration occurred when wall temperatures were at their maxima.

When water shortages occur, the first action usually taken is to restrict or eliminate landscape irrigation. If water is withheld from landscapes and ET reduced, a greater proportion of the net irradiance will be used for generating soil and sensible heat. If evaporative cooling is effective at microscales, such changes in landscape energy balances may affect the energy balance of buildings. We conducted an experimental study to explore how external building temperatures may be affected by reducing irrigation of adjacent turfgrass and changing the surface energy balance of the grass.

2. Materials and Methods

The study was conducted on a 1-ha plot of bermudagrass (*Cynodon dactylon* L.) at the Texas A&M University Turfgrass Field Laboratory in College Station, Texas (30.4° N, 96.2° W). The bermudagrass was maintained at a cutting height of 0.03 m and was irrigated by sprinklers. The orientation of the bermudagrass plot was southeast to northwest, parallel to the prevailing summertime wind direction. A cotton field used as breeding nursery was upwind of the grass, and a slightly elevated 10 m wide dirt road was between the cotton and the grass.

A 4.9 m × 4.9 m building shell with 2.5 m high rough-cut pine walls was constructed in the bermudagrass plot at a distance of 35 m from the dirt road (Fig. 1). The thickness of the walls was 19 mm, and interior surfaces were insulated with R 5 foam board insulation. Walls were painted

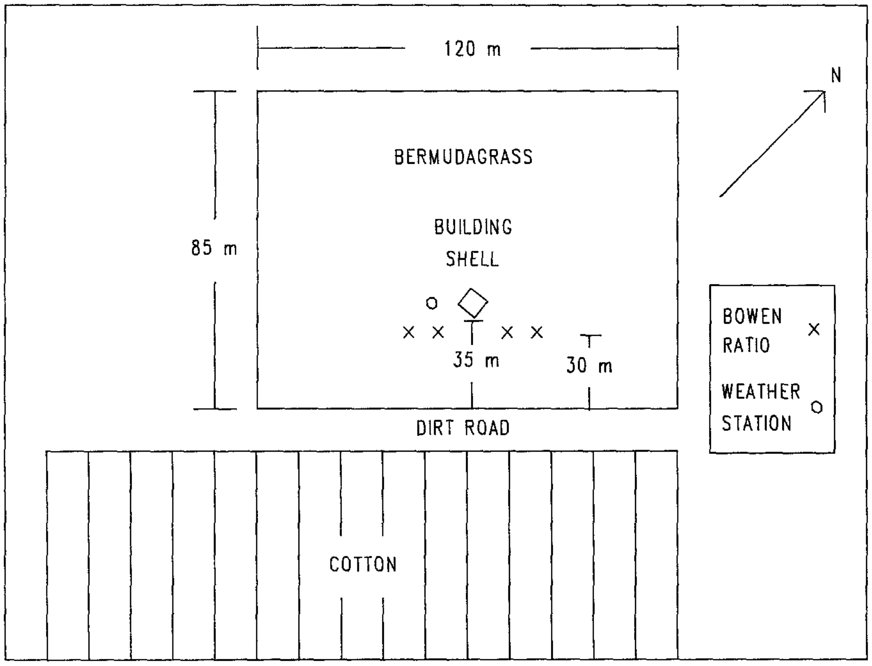

Fig. 1. Diagram of the plot layout showing the location of the building shell, Bowen ratio systems and the weather station

(color no. 1D44C, Devoe and Raynolds, Inc., Louisville, KY) which produced an albedo of 0.17. Azimuths of the four walls were 10°, 100°, 190°, and 280° measured east of north. No roof was constructed. The minimum thickness of the internal boundary layer of the grass at the building was 5.7 m as estimated by the equation of Munro and Oke (1975).

Apparent surface temperatures of the walls were measured with 4° FOV infrared transducers (model 4000, Everest Interscience, Tustin, CA) mounted on tripods at a distance of 2 m from the walls. Air temperatures adjacent to each wall were measured with shaded, fine-wire (30 AWG) thermocouples at a distance of 0.5 m from the walls and an elevation of 1.5 m above the grass, while wind speeds at the same locations were measured with Gill anemometers (model 12102, R. M. Young Co., Traverse City, MI). Temperature of the bermudagrass was not measured. Heat transfer coefficients for wind-induced convection were calculated for each wall as a function of wind speed and direction using the model of Gandrille et al. (1988).

Air temperature, humidity, wind speed and direction were measured at an elevation of 1.5 m above the grass at a portable weather station 10 m west of the building. Temperature and humidity were measured with a shielded, aspirated probe (model CSI207), Campbell Scientific), while wind speed and direction were measured with a Gill anemometer and wind vane. Air temperatures at screen height were also obtained from Easterwood Airport, 3 km south of the experimental site, for comparison. Global irradiance was measured at the weather station with a LI-COR model LI-200SCZ pyranometer, while diffuse irradiance was measured with a similar pyranometer shaded with an occulting ring. Direct beam irradiance was calculated as the difference between global and diffuse irradiance. Direct beam irradiance on the walls was calculated using the equation

$$E = (E_h/\sin a)\,[\cos a \cos \alpha_d \sin i + \sin a \cos i]$$

where E (W m^{-2}) is direct beam irradiance on the wall, E_h (W m^{-2}) is direct beam irradiance on a horizontal surface, a is solar elevation angle, α_d is the difference between solar and wall azimuth angles, and i is wall inclination angle.

Weather station sensors and anemometers adjacent to the building were interrogated every 10 s and outputs averaged over 30-min periods with a model CR21X data logger (Campbell Scientific). Infrared transducers and thermocouples adjacent to the building were sampled every 10 s and 30-min averages recorded with a Campbell Scientific model CR7 data logger.

The Bowen ratio method (Tanner, 1960) was used to determine flux densities of latent and sensible heat from the grass upwind of the building. Four battery-powered Bowen ratio systems designed by Gay and Greenberg (1985) were placed upwind of the building at a distance of 30 m from the dirt road (Fig. 1). Wet and dry bulb temperatures were measured at elevations of 0.3 and 1.3 m above the surface by aspirated psychrometers containing resistance thermometers and ceramic wicks mounted on an exchange mechanism. The minimum fetch : height ratio produced by this configuration was 23 : 1 (southeast winds) which Heilman et al. (1989) found to be adequate for Bowen ratio measurements.

Psychrometers were exchanged every six minutes to eliminate sensor bias. Net irradiance was measured with net radiometers (model Q3, Micromet Systems, Inc., Seattle, WA) mounted at an elevation of 1.5 m above the grass. Net radiometers were calibrated against a precision pyranometer (model 50, Eppley Laboratory, Inc., Newport, RI) using the shading technique. Soil heat flux was determined using heat flux plates (model HFT-1, Micromet Systems) at 5 cm below the soil surface and calculations of the change in heat content in the 0 to 5 cm layer using soil temperature measurements. Three heat flux plates wired in series were used for each system, while three thermocouples wired in parallel were used for soil temperature measurements for each system.

All Bowen ratio sensors were interrogated several times per minute and data transmitted to microcomputers for processing. Energy balance components for each system were calculated as 12-min averages, assuming equality of eddy diffusivities for heat and vapor transport. Fluxes from all four Bowen ratio systems were then averaged.

Irrigation water was withheld from the bermudagrass for two 7-day periods, 12 to 18 July (days 193 to 199) and 28 August to 3 September 1989 (days 242 to 248), to gradually reduce evapotranspiration (ET). Energy balance, wall temperature and microclimate measurements previ-

Table 1. *Daylight Totals of Global Irradiance (Rs), and Average Values of Air Temperature (T_{air}), Relative Humidity (RH), Wind Speed (U) and Wind Direction (Dir.) During the Two Drying Cycles*

Day	Rs ($MJ\,m^{-2}$)	T_{air} (°C)	RH (%)	U ($m\,s^{-1}$)	Dir. (° from north)
First Drying Cycle					
193	24.8	32.0	70.9	3.2	180
196	21.1	32.1	70.8	3.3	182
197	26.2	33.5	66.9	3.0	172
198	25.3	33.3	68.3	3.8	169
199	26.1	33.5	64.0	4.1	170
Second Drying Cycle					
242	18.2	32.4	66.5	2.3	153
243	21.2	33.5	63.6	3.0	165
244	21.2	33.6	62.9	2.6	172
245	21.6	34.0	61.7	1.9	168
246	23.4	34.3	56.9	2.0	172
247	19.8	33.9	61.4	2.1	101
248	22.7	33.1	52.8	2.7	83

Averages were determined from sunrise to sunset. Data for days 194 and 195 were not included because skies were overcast

Table 2. *Daylight Totals (Sunrise to Sunset) of the Surface Energy Balance of Bermudagrass, and Average Daylight Temperatures of North (N), East (E), South (S) and West (W) Walls*

Day	Energy Balance ($MJ\,m^{-2}$)				Wall Temps. (°C)			
	Rn	G	LE	H	N	E	S	W
First Drying Cycling								
193	18.4	−1.3	−14.2	−2.9	40.2	43.1	37.3	41.0
196			missing		37.1	36.7	38.6	42.6
197	18.3	−1.3	−13.1	−3.9	41.7	45.9	39.9	43.2
198	17.4	−1.1	−10.9	−5.4	38.7	40.2	38.8	43.6
199	17.2	−1.1	−8.8	−7.3	39.3	40.9	38.9	42.2
Second Drying Cycle								
242	12.8	−1.1	−10.7	−1.0		43.3	41.4	41.2
243	15.3	−1.1	−12.5	−1.7		42.6	41.9	42.5
244	15.4	−1.1	−12.5	−1.8		44.2	42.8	43.2
245	15.6	−1.2	−12.3	−2.1		48.6	44.8	44.0
246	16.7	−1.2	−11.9	−3.6		50.8	46.6	44.9
247	14.0	−0.9	−8.8	−4.3		47.1	45.6	44.3
248	16.7	−0.7	−7.4	−7.6		47.1	45.9	43.5

Energy balance data for day 196 and north wall temperatures during the second drying cycle were not obtained because of instrument malfunctions. Minus signs indicate fluxes which are away from the surface.

ously discussed were made during the drying cycles. Irrigation was resumed following the July measurement period to allow the bermudagrass to recover.

3. Results

Environmental conditions during the study are summarized in Table 1. Skies were partly cloudy on most days which led to differences in global irradiance within each drying cycle. Air temperatures were high and wind speeds were low to moderate. Winds were southerly except on days 246 through 248.

Daylight totals of the surface energy balance of the bermudagrass are listed in Table 2. Unstable conditions prevailed during daylight hours so the bermudagrass was generating rather than consuming sensible heat. During the first drying cycle, latent heat flux (LE) decreased from 14.2 to 8.8 MJ m^{-2}, while sensible heat flux (H) increased from 2.9 to 7.3 MJ m^{-2}. Soil heat flux decreased slightly as the soil dried. At the beginning of the cycle, H was 16% of net irradiance (Rn), while at the end, H accounted for 42% of Rn. During the second drying cycle, LE decreased from a maximum of 12.5 MJ m^{-2} to 7.4 MJ m^{-2} (82% to 44%, respectively, of Rn). Sensible heat flux increased from 1.0 to 7.6 MJ m^{-2} (8 to 46% of Rn). Soil heat flux decreased from 1.1 to 0.7 MJ m^{-2}. Net irradiance varied within each drying cycle, due primarily to partly cloudy skies.

In spite of substantial decreases in latent heat flux as the grass dried, no systematic increases in average daily wall temperatures were observed during the first drying cycle (Table 2). Either changes in the energy balance of the grass had little influence, or variations in other environmental factors obscured any effects of the reduced evaporation. During the second drying cycle, average daily wall temperatures did increase as the grass dried, but so did global irradiance (Table 1). To clarify how the walls interacted with the environment, measurements from two days during each drying cycle (days 197 and 199, 16 and 18 July; and 246 and 248, 3 and 5 September) were compared. These days, the fifth and seventh of their respective drying cycles, had relatively clear skies and substantial differences in latent and sensible heat fluxes (Tables 1 and 2).

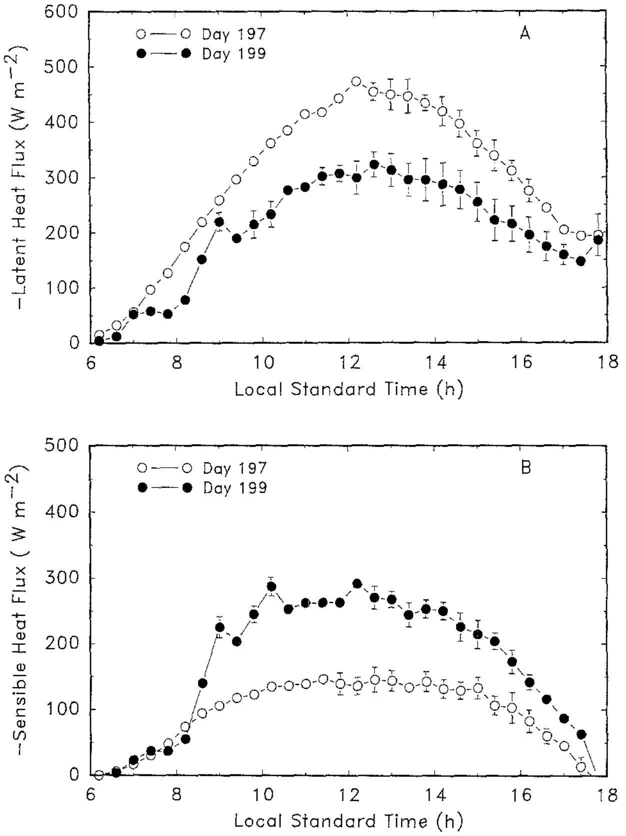

Fig. 2. Latent (A) and sensible heat fluxes (B) from bermudagrass on calendar days 197 and 199. Minus signs indicate fluxes away from the surface. Fluxes are averages of the four Bowen ratio systems, with error bars representing ± 1 standard deviation

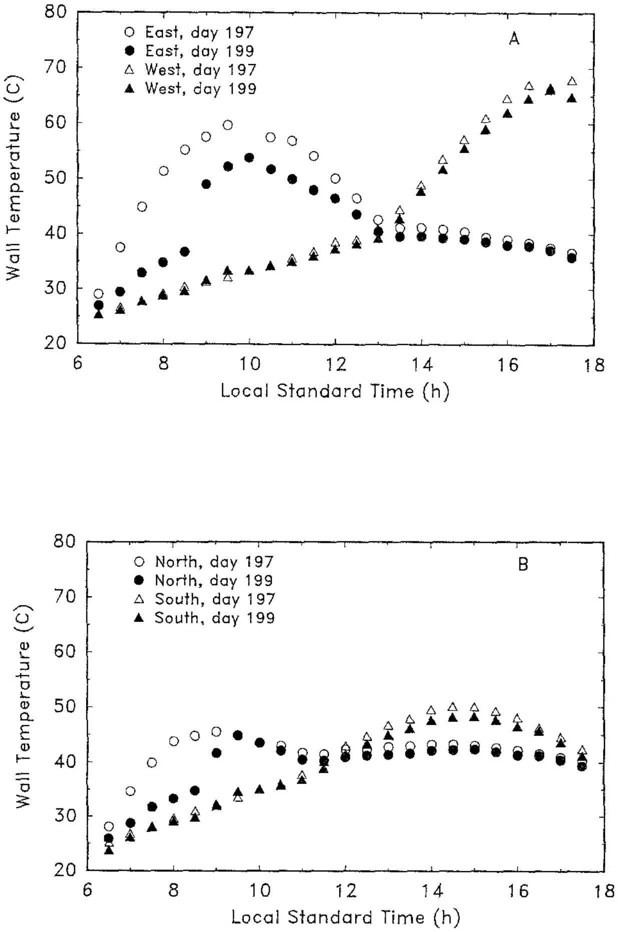

Fig. 3. Surface temperatures of east and west walls (A), and north and south walls (B) on calendar days 197 and 199

Diurnal patterns of global irradiance on days 197 and 199 were similar, except for an overcast period prior to 1000 h on day 197, while air temperature and relative humidity on those days were nearly identical during the diurnal cycle. Air temperatures at Easterwood Airport on days 197 and 199 were similar to those measured above the turfgrass. Diurnal variations in LE and H from the turfgrass are shown in Fig. 2. Maximum LE, which occurred near solar noon, decreased from 473 $\mathrm{W\,m^{-2}}$ on day 197 to 324 $\mathrm{W\,m^{-2}}$ on day 199. Sensible heat flux increased from a maximum of 146 $\mathrm{W\,m^{-2}}$ on day 197 to 291 $\mathrm{W\,m^{-2}}$ on day 199.

During much of the day, external wall temperatures on day 199 were slightly lower than on day 197, in spite of greater sensible heat generation from the surrounding grass (Fig. 3). Maximum temperatures of the east wall occurred at mid-morning and exceeded 60 °C on day 197. Maximum temperatures of the west wall, which occurred in late afternoon, approached 70 °C on both days. North and east walls were much cooler during the morning of day 199 because of overcast conditions. Maximum north and south wall temperatures were lower than those of east and west walls.

Diurnal variations in wall temperature coincided with changes in direct beam irradiance on the walls (Fig. 4). Maximum irradiance on the east wall occurred 3 h before solar noon and was lower than the maximum irradiance on the west wall which occurred 4.5 h after solar noon. Lack of symmetry about solar noon was due to the 10° offset of wall azimuths from true north, south, east and west. Direct beam irradiance on the south wall was low due to the high solar elevation angle (77° at solar noon) during the middle of the day. Irradiances on south and west walls on day 197 were nearly identical to those occurring on day 199 (Fig. 4).

On day 199, wind speeds adjacent to all four walls were higher than on day 197 (Fig. 5) which contributed to the lower wall temperatures by increasing convective heat transport coefficients

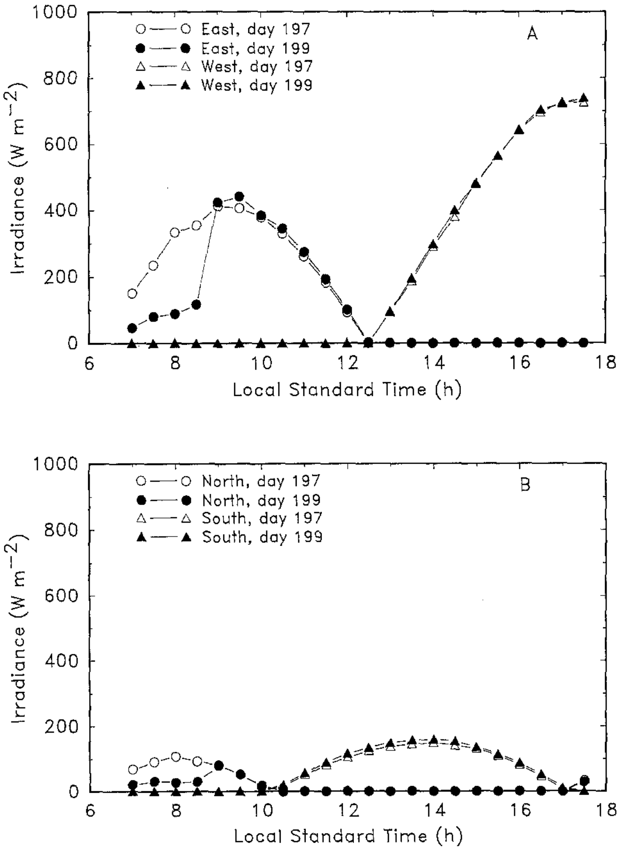

Fig. 4. Direct beam irradiance on east and west walls (A), and north and south walls (B) on calendar days 197 and 199

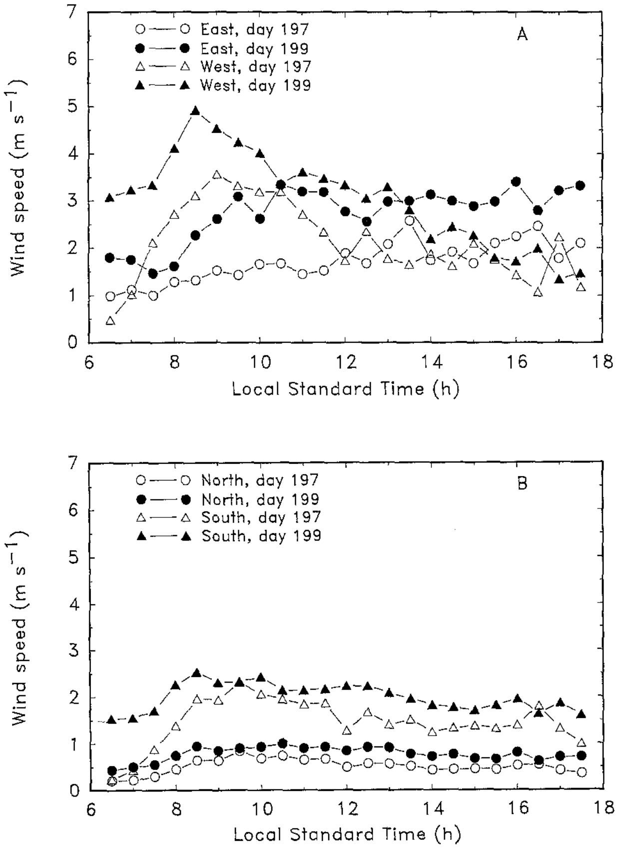

Fig. 5. Wind speeds adjacent to east and west walls (A), and north and south walls (B) on calendar days 197 and 199

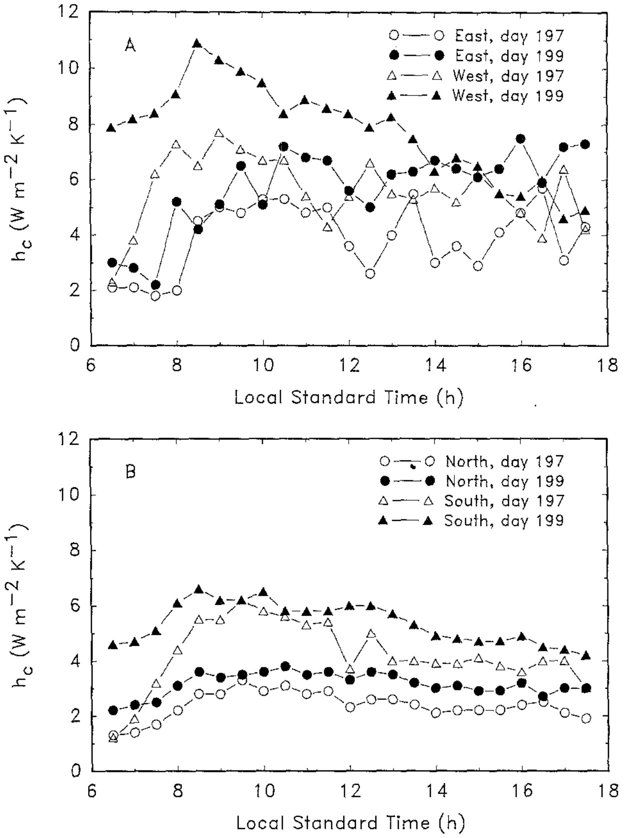

Fig. 6. Wind-induced heat transfer coefficients (h_c) for east and west walls (A), and north and south walls (B) on days 197 and 199, calculated using the model of Gandrille et al. (1988)

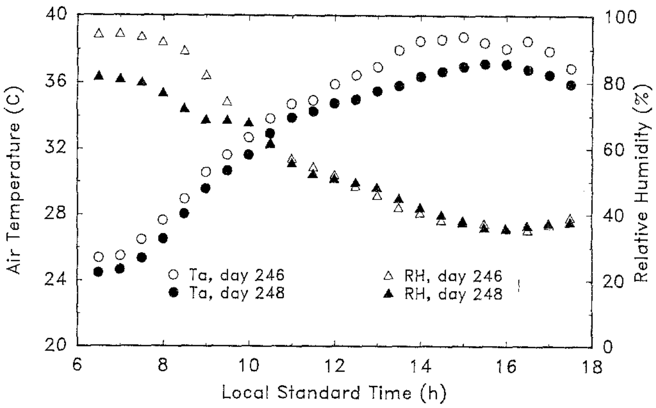

Fig. 7. Air temperature (Ta) and relative humidity (RH) on calendar days 246 and 248

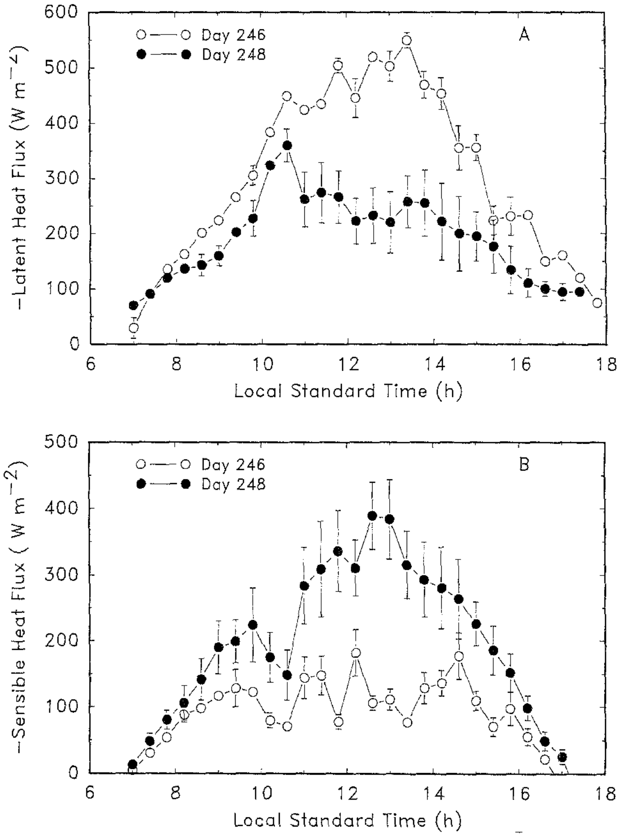

Fig. 8. Latent (A) and sensible heat fluxes (B) from bermudagrass on calendar days 246 and 248. Minus signs indicate fluxes away from the surface. Fluxes are averages of the four Bowen ratio systems, with error bars representing ± 1 standard deviation

(Fig. 6). Wind speeds adjacent to east, south and west walls were generally between 1 and 3 m s^{-1} which Gandrille et al. (1988) reported to be a region of mixed convection. Ratios of Grashof number (Gr) to the square of the Reynolds number (Re), an index of the ratio of buoyancy to inertial forces, were generally between 0.1 and 0.8, indicating that forced convection was the dominant component. Free convection had a greater influence on the north wall where wind speeds were less than 1 m s^{-1}. Winds were southerly on both days.

The second drying cycle was hotter and drier than the first. Global irradiances on days 246 and 248 were nearly identical prior to solar noon, but differed by as much as 10% after noon due to scattered clouds on both days. Afternoon global irradiance was generally higher on day 246. Air temperatures were higher on day 246, as was relative humidity prior to 1000 h (Fig. 7). Air temperatures at the airport were again similar to those measured above the turfgrass. Latent heat flux from the turfgrass was substantially higher on day 246, reaching a maximum of 549 W m^{-2} at 1 324 h (Fig. 8). On day 248, the LE reached a maximum of 359 W m^{-2} at 1 048 h, and then declined steadily throughout the day. Maximum H on day 246 was

181 W m^{-2}, while on day 248, H reached 389 W m^{-2}. Variability in heat fluxes among the four Bowen ratio systems increased considerably as the grass dried (Fig. 8).

Walls were considerably warmer on day 246 than on day 248 even though H was much lower (Fig. 9). The east wall warmed more rapidly on day 246 and its temperature in the morning was as much as 9 °C higher than on day 248. The east wall reached a maximum temperature of 75.1 °C on day 246 but just 69.1 °C on day 248. The west wall reached 72.8 °C on day 246 and 67.0 °C on day 248 while maximum temperatures of the south wall on those days were 66.1 and 62.1 °C, respectively. Temperatures of the north wall were not measured because of an instrument malfunction. Direct beam irradiances on the walls on both days were comparable except in the late afternoon (Fig. 10).

Wall temperature differences between days were due primarily to differences in wind speed. Wind speeds adjacent to walls were lower on day 246 than on day 248, though wind speeds were generally less than 1.5 m s^{-1} on both days (Fig. 11). Winds were from the west during the morning of day 246 and shifted to the east in the afternoon, while on day 248, winds were easterly the entire day. On day 246, winds at the east wall were calm and wind-induced heat transfer coefficient was zero (Fig. 12) for nearly 2 h after sunrise. During this period, when direct beam irradiance on the east wall went from 0 to greater than 400 W m^{-2}, heat transport was driven only by buoyancy forces. As a result, wall temperature increased rapidly. Average morning wind speed for the east wall was 0.3 m s^{-1} and the average Gr/Re^2 was near 6. On day 248, the average morning wind speed at the east wall was 0.8 m s^{-1}, and the average Gr/Re^2 was near 1, indicating mixed convection. Differences in wind speed between the two days were generally lower for south and west walls than for the east wall, and convection was mixed.

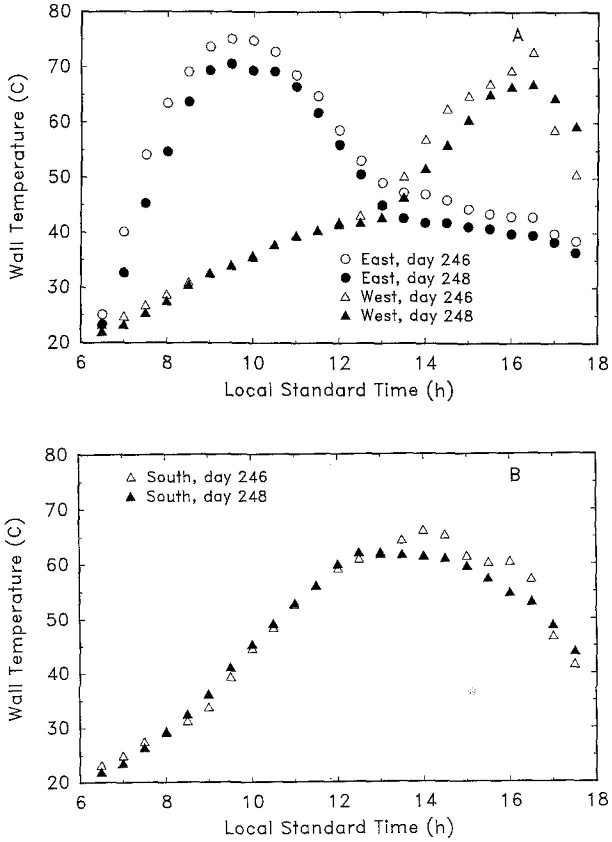

Fig. 9. Surface temperatures of east and west walls (A), and north and south walls (B) on calendar days 246 and 248. Temperatures of the north wall were not measured because of an instrument malfunction

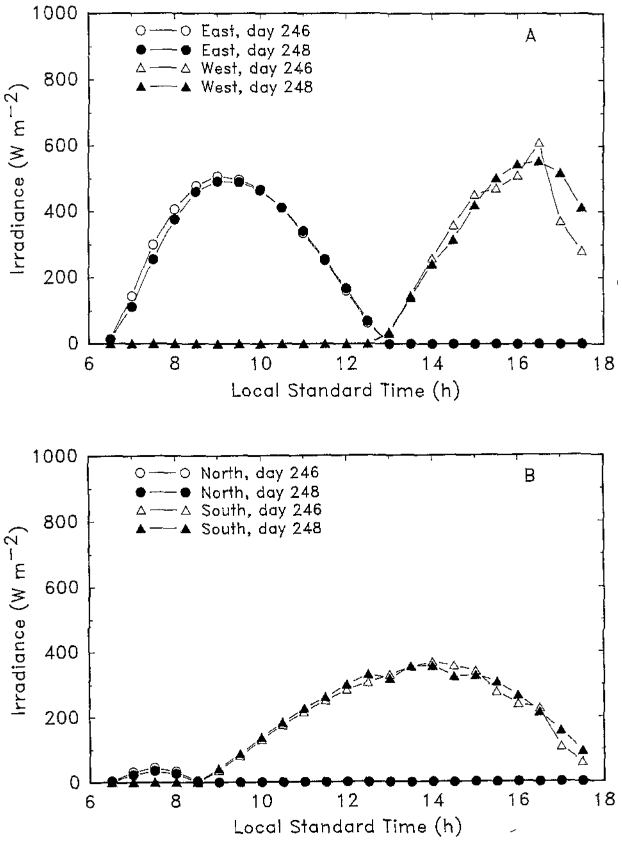

Fig. 10. Direct beam irradiance on east and west walls (A), and north and south walls (B) on calendar days 246 and 248

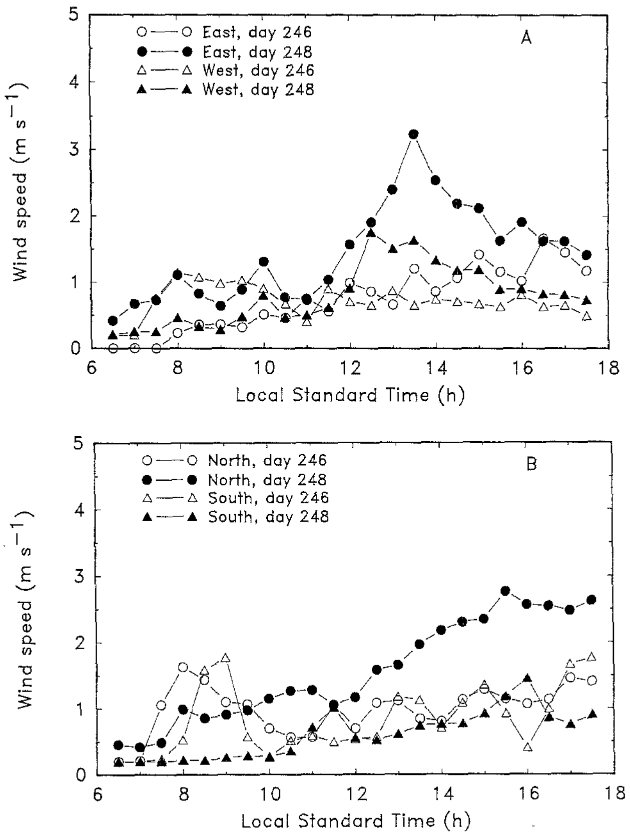

Fig. 11. Wind speeds adjacent to east and west walls (A), and north and south walls (B) on calendar days 246 and 248

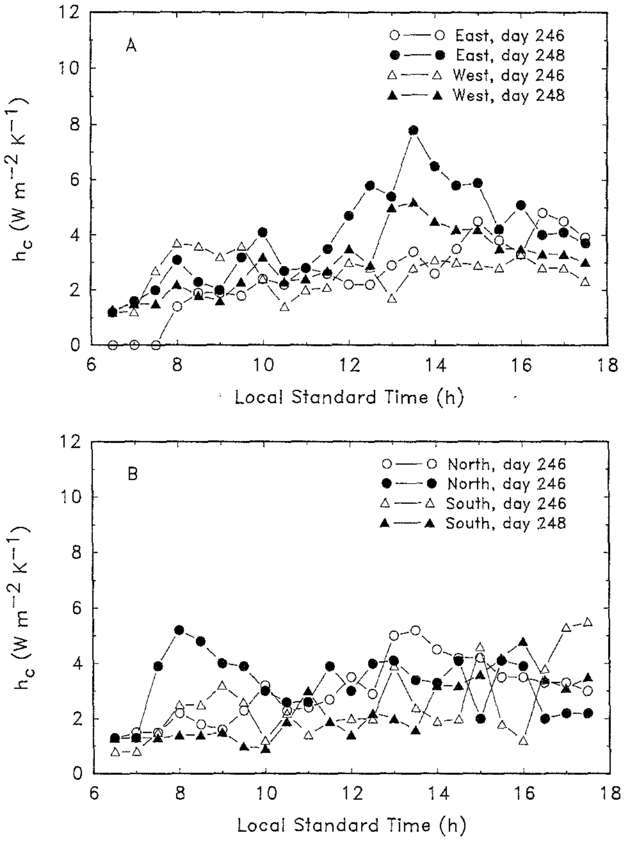

Fig. 12. Wind-induced heat transfer coefficients (h_c) for east and west walls (A), and north and south walls (B) on days 246 and 248, calculated using the model of Gandrille et al. (1988)

4. Discussion and Conclusions

The drying cycles imposed in our study severely stressed the bermudagrass and greatly reduced latent heat flux and increased sensible heat flux. Yet, these large changes in the energy balance of the grass had little apparent effect on the external temperatures of the building shell. No systematic differences were found between air temperatures above the turfgrass and those at the nearby airport which supports the conclusions of Hutchison and Taylor (1983) that evaporative cooling of air is mainly a mesoscale rather than a microscale process. Our results do not preclude a small effect of evaporative cooling on wall temperatures, but other environmental factors were clearly more important. A paired comparison with one building shell surrounded by irrigated grass and a second surrounded by drying grass might have been more revealing, but such a study was not possible at our research site.

The major factors affecting wall temperatures were irradiance and wind. Irradiance affected diurnal variations in temperature. Changes in wind speed had the greatest effect on wall temperatures during periods when free convection was dominant. During periods of predominantly forced convection, changes in wind speed had relatively small effects on wall temperature. Also, changes in albedo and longwave exitance as the grass dried presumably increased the radiation load on the building.

These results suggest that localized reductions in irrigation and evaporation are unlikely to affect building energy balances in many climatic regions. They do not negate the findings of McPherson et al. (1989) who showed microscale evaporative cooling by irrigated turfgrass in hot arid regions. Our results also suggest that water-conserving landscapes can be developed and installed without increasing building energy loads.

Acknowledgements

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