Human Thermal Comfort in Urban Outdoor Spaces

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ABSTRACT.—Measurements of the physical environment of urban open spaces in Syracuse, New York, were used to compute the physiological responses of human users of the spaces. These calculations were then used to determine what environmental variables were both important to human comfort and susceptible to control by site design. Although air temperature and humidity are important to human thermal comfort, these variables were found not to be related in any way to site features; temperature and humidity in the central business district were uniform over space. The other variables found to be important to human thermal comfort are, in order of importance: solar radiation, infrared radiation, and wind speed. We found that all of these can be controlled to some extent by site design. Thus site design can be used to control human thermal comfort in outdoor urban spaces.

THE SUCCESS of an urban open space is influenced by many factors. The myriad components of the physical and social environment and the location of the space within the structure of the city all play primary roles. In this paper we focus on just one aspect of the physical environment: the thermal environment. We define the thermal environment as those physical-environment elements which determine human thermal comfort. This comfort is controlled by the energy exchange between the body and its surroundings and, in general, can be said to exist when the body can effortlessly maintain a constant deep body temperature of about 98.6°F. Thus the thermal environment consists of elements which determine heat exchange between the body and its surroundings: solar and infrared radiation, temperature and humidity of the air, and wind velocity. Of course, the activity of the person also plays a role, since as activity increases so does metabolic heat production.

The purpose of this study was to determine how various physical features of urban open spaces were related to human thermal comfort through their influence on the environmental elements. The basic question was "What features of the thermal environment, and hence human thermal comfort, are susceptable to control by site design?" Our study was a prelude to the development of design guidelines, some of which appear elsewhere in these proceedings *(Plumley)*.

METHODS

The experimental design of our study centered around the determination of human thermal comfort in various urban open spaces with different features. The role of various site features was determined from the study of their influence on the variables which determine thermal comfort. Comfort was determined by means of a model of the physiological response of humans to the environmental conditions as measured at each site. Psychological comfort could then be inferred from the predicted physiological state.

Human Thermal Comfort

Thermal comfort is a psychological interpretation of the physiological state of the body and should not be confused with temperature sensation. Gagge *(1969)* summarized comfort and temperature sensation as follows:

1. For sitting, resting persons:
   a. A sense of neutrality, of comfort or pleasantness, always coincides with a state of thermal neutrality (maintenance of deep-body temperature at 98.6°F without regulatory effort via vascular constriction or dilation or sweating).
   b. Discomfort correlates best with skin temperature in cold conditions and with increased skin sweating in hot conditions.
   c. Temperature and comfort sensations do not behave the same way with changing environment. Temperature sensation changes more rapidly than comfort sensation and, cold discomfort changes more rapidly than does warm discomfort.
2. Under conditions where the subject is active the following changes in sensation occur:
   a. Temperature sensation in warm and cold conditions is best correlated with skin temperature and air temperature and is *not affected by the level of activity.*
   b. Warm discomfort is best correlated with increased skin sweating.

It is evident that skin temperature and sweating are the important sensible physiological reactions of the body to a thermal stress. Thermal stress is created when the net loss of thermal energy from the subject's body does not equal the production of heat by metabolism within the body. In order for deep body temperature to remain constant, this balance of heat losses and gains must be obtained. Under cold conditions the losses usually exceed the gains, and several physiological systems act to reduce heat loss from the body. Vascular constriction reduces blood flow to the skin, and, as a result, skin temperatures drop. Heat production can be increased by voluntary activity or by involuntary shivering. Under warm conditions the body is gaining more heat than it can dispose of without effort, and vascular dilation occurs, with the result that the skin warms. If this action is insufficient to balance the heat budget, then sweating will occur. If the sweat rate exceeds the ability of the environment to evaporate the moisture, the skin will become wet.

The exchange of heat between the body and the environment can take place in several ways (table 1). For each heat-flow route, we have listed the controlling environmental factors and the conditions which determine whether the flow of heat in the route is toward (source) or away (sink) from the body. To actually predict the thermal state of the body in any given situation, equations must be written for each of these routes, and the set of simultaneous equations which results must be solved for the condition of interest: skin temperature and/or skin wettedness.

We have used a relatively old model of physiological response developed by Belding and Hatch *(1955)* and improved by Lee and Henschel *(1963)*. This model computes a Relative Strain (RS) for any given environmental condition and level of activity. Lee and Henschel *(1963)* related the various levels of RS to psychological conditions of "comfort," "discomfort," "failure," etc. However, since all of these correlations have been developed for subjects *indoors,* caution must be taken in applying these comfort ranges to people outside.

The Relative Strain model is:

$$RS = \frac{\text{Evap. cooling required to maintain heat balance}}{\text{Maximum evap. cooling possible under existing conditions.}}$$

$$= \frac{M\ (I_2 + I_c) + 5.55\ (T_a—35) + RI_a}{7.55\ (44 — P_a)}$$

where

M =	metabolic rate	Kcal $M^{-2}hr^{-1}$
I_a =	insulation of air	clo
I_c =	insulation of clothing	clo
T_a =	air temperature	C
R =	radiant load	Kcal $M^{-2}hr^{-1}$
P_a =	vapor pressure of air	mm Hg

and

$$\ln I_a = 0.5662 + 0.4026 \ln U + 0.0072 \ln U^2$$

U = wind speed mph

Radiant Loads (infrared and solar) are included by adding the energy absorbed to metabolism. This model was incorporated into an interactive computer program which computed RS from the environmental data gathered in each site. Table 2 shows the psychological response in terms of RS.

Site Selection

Figure 1 shows the Syracuse downtown area and the general location of the eight sites used by Vittum *(1974)*. For this report we will be discussing

Table 1.—Summary of heat flow between a body and its environment

Heat-flow route	Controlling environmental elements	Conditions for route being — Source	Sink
Metabolism	Activity of subject	Always	——
Radiation			
Solar	Shade-producing elements	Daytime	——
Infrared	T_r, T_s	$T_r > T_s$	$T_r < T_s$
Convection	T_a, T_s, w	$T_a > T_s$ (increasing with increasing w)	$T_a < T_s$
Evaporation	P_s, P_a, w	——	$P_a < P_s$ (increasing with w)

T_s = Skin (clothing) temperature.
T_r = Radiant temperature of surroundings.
T_a = Temperature of the air.
w = Wind speed.
P_s = Vapor pressure of skin (f(T_s).
P_a = Vapor pressure of air (f(T_a, RH).
RH = Relative humidity.

Table 2.—Interpretations of physiological responses to relative strain for the standard man (Lee and Henschel 1963, p. 24).

Relative strain	Physiological effects for the standard man
0—0.2	100 percent of individuals comfortable.
0.25	50 percent of individuals comfortable.
0.30	100 percent of individuals uncomfortable.
0.30—0.40	75 percent of individuals show stress.
0.40+	100 percent of individuals show distress.
0.40—0.50	50 percent of individuals show signs of physiological failure.
0.50—0.60	100 percent of individuals show signs of physiological failure.
0.60+	Responses approach or exceed range within which system experiences breakdown.

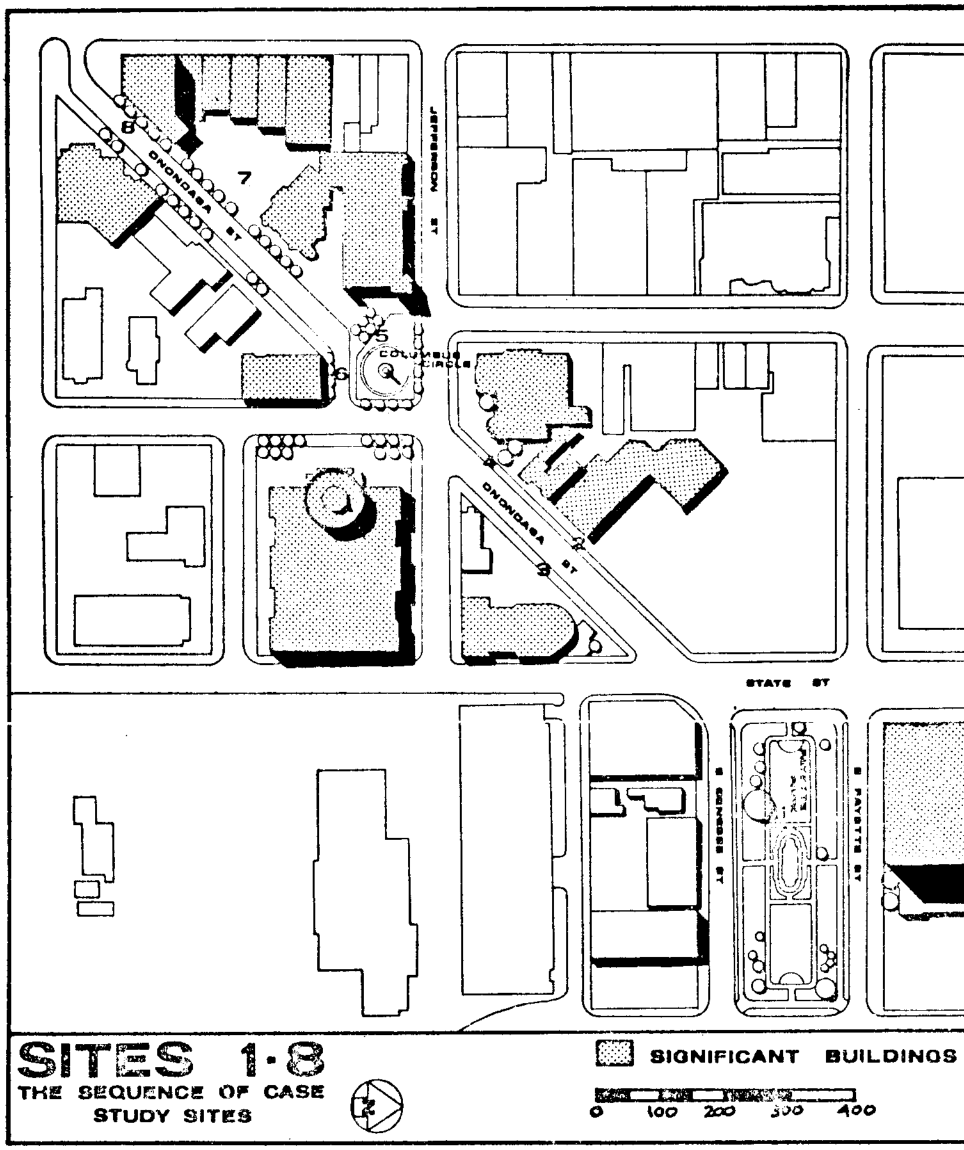

Figure 1.—Plan of the study site, showing the location of sites 1 to 8 as well as the significant buildings.

only four sites (1, 2, 6, and 7), which are shown in figures 2, 3, 4, and 5.

Site 1 is located in a park with very little enclosure, since most of the surrounding buildings are only two to three stories high. The ground surface at the site is grass. Table 3, which lists the view factors for the predominant surfaces at each site, shows that the surfaces as seen by a person at this site are nearly evenly split between sky and grass. Site 2, located on the sidewalk in a fairly open space on Onondaga Street, has nearly the same view of the sky and ground, but the ground surface is primarily concrete. Site 6, located on the north side of a building within Columbus Circle has a relatively low view of the sky since the site is more enclosed, as indicated by the high view factors for the surrounding buildings and trees. The ground surfaces are brick and asphalt. Site 7 has a high view of the sky, and the ground surface is

Figure 2.—Site 1. 'X' marks point where measurements were taken and for which view factors were calculated.

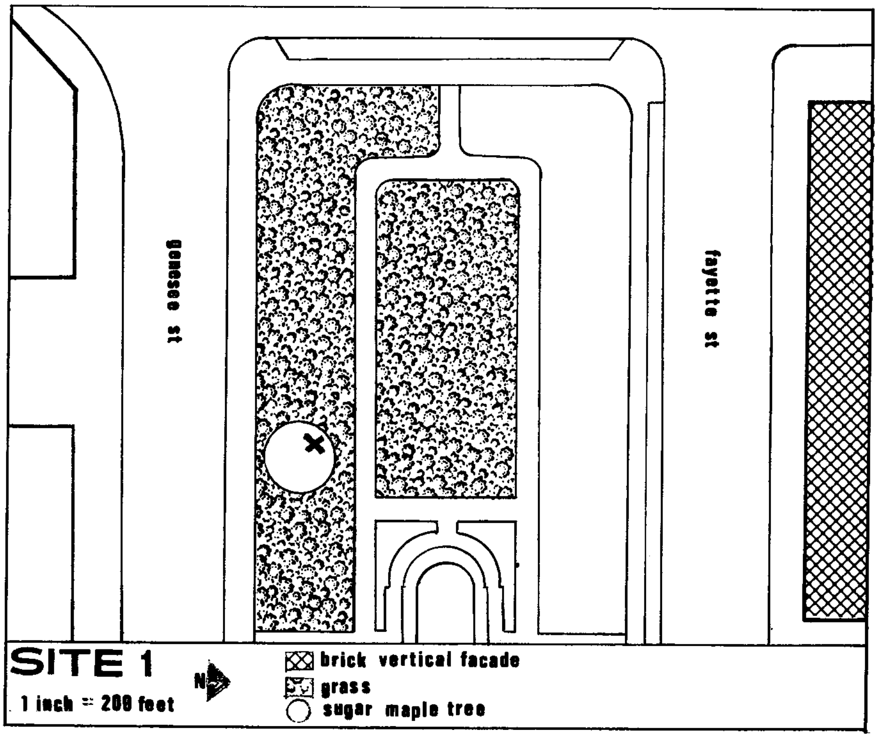

Figure 3.—Site 2.

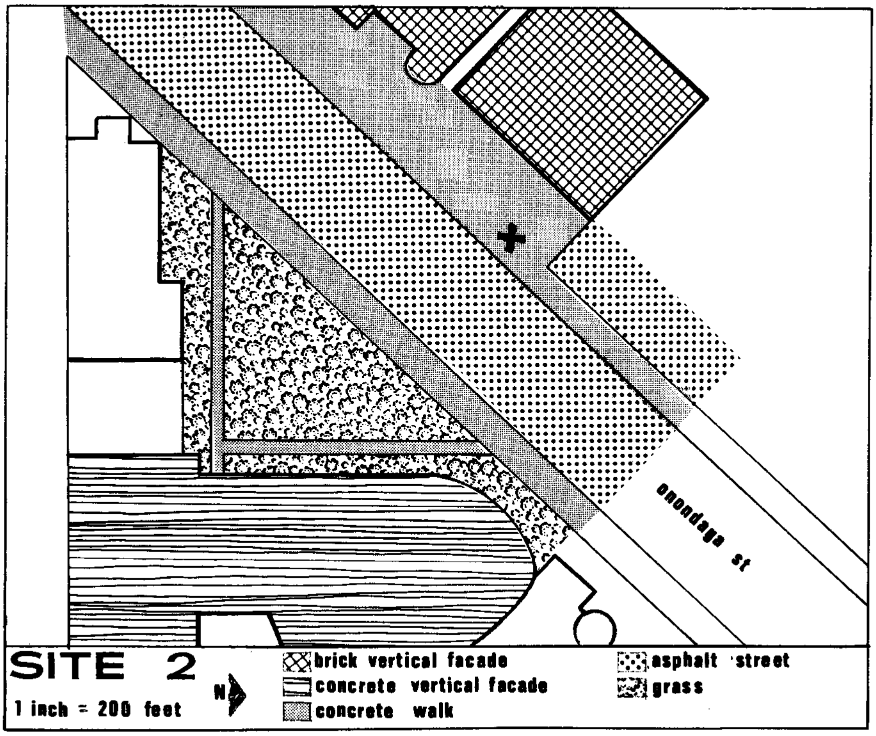

Figure 4.—Site 6.

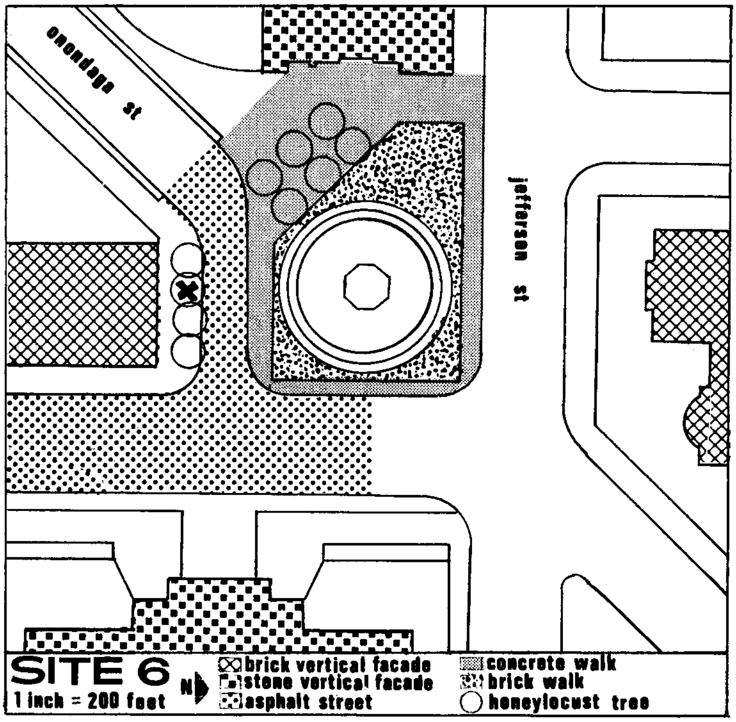

Figure 5.—Site 7.

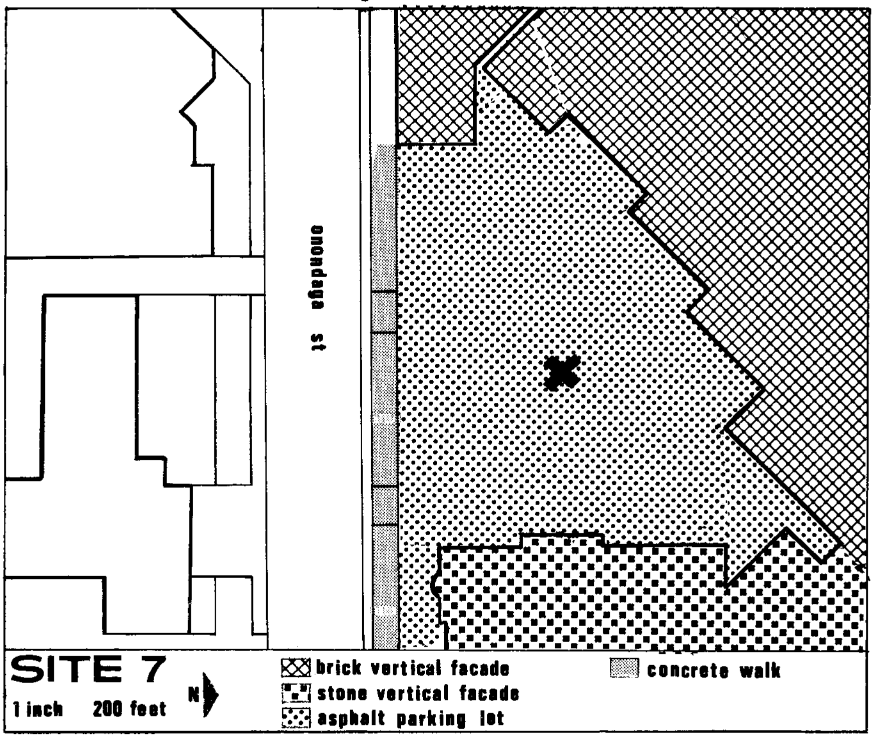

Table 3.—View factors between subject standing at site location and surrounding surfaces.

Site No.	Surfaces									
	Sky	Street	Walks		Tree(s)	Grass	Building Facing			
			Brick	Concrete			N	E	S	W
1	39	—	—	—	7	50	4	—	—	—
2	38	4	—	42	—	—	—	10	—	5
6	14	8	34	—	10	—	21	7	1	4
7	36	50	—	—	—	—	—	2	5	6

primarily macadam. Vegetation is a feature only in site 6, which is located beneath a row of street trees.

Environmental Measurements

A portable instrument system was used to measure air temperature and humidity, solar radiation, and wind speed at each site. The radiant load was computed from the measured solar radiation and from knowledge of the sun's position in the sky at the time of measurement. The infrared load was computed from view factors, and surface temperatures were measured with a radiation thermometer. The view factor is the proportion of the total spherical field of view from a subject taken up by the surface or object of interest. The infrared exchange between the subject and the surface is proportional to the view factor and the difference in temperature between the subject and the surface (table 3).

RESULTS AND DISCUSSION

Table 4 lists environmental and comfort data typical of the four sites at three times of day: morning, noon, and evening.

The air temperature and humidity data for each measurement period show a surprising uniformity once the trend in temperature caused by the time it took to move from site to site is removed. Note that temperatures are increasing with site sequence in the morning and decreasing with site sequence in the evening. This uniformity of temperature prompted us to investigate further the uniformity of temperature within the Syracuse CBD. This was done simply by moving around very quickly with a single psychrometer (Bendix Psychron). This procedure indicated that the temperature at any given spot could vary by as much as 6°F in a short time due to changes in solar radiation caused by clouds. However, these changes took place over a large area; and moving from tree shade, to sun lit areas, to building shade showed that the temperature is not an element of open-space environment that can be controlled or moderated by site design. The same pattern was true for relative humidity.

Solar radiation showed considerable variation from site to site. Comparison of the radiation figures in table 4 with the maps of the sites shows that the variation in solar radiation is due primarily to shading by buildings or vegetation.

The IR radiation load, as listed in table 4 or as expressed as the mean radiant temperature (MRT) of the space obviously varies with the time of day. During the day site 7, which was located in an open macadam parking lot, showed the highest IR load (MRT) because of the high view factor between the person and the blacktop surface (table 3). No shade is provided by buildings or vegetation. Site 1, in the open grassy park, shows the lowest IR radiant load, again due primarily to the nature of the surface; grass in this case. Sites 2 and 6, both street sites, tend to behave in a similar way in relation to infrared radi-

Table 4.—Summary of environmental conditions and relative strains

Variable	0800—23 Aug 1973				1300—10 Sept 1973				2130—22 Aug 1973			
	1	2	6	7	1	2	6	7	1	2	6	7
Dry bulb temp. (°C)	15	16	17	18	22	24	24	24	15	15	15	13
Relative humidity (%)	65	63	60	59	41	35	36	37	73	67	75	77
Solar radiation $\left(\frac{Kcal}{M^2hr}\right)$	444	168	84	360	84	648	96	600	—	—	—	—
IR radiation $\left(\frac{Kcal}{M^2hr}\right)$	-51	-58	-55	-32	-69	-32	-35	-10	-98	-82	-71	-87
Wind speed (mph)	1.8	2.1	3.4	2.1	2.7	1.4	1.8	1.7	1.9	2.1	2.3	1.5
Relative strain	- 0.26	- 0.30	- 0.28	- 0.22	- 0.18	- 0.01	- 0.11	- 0.02	- 0.36	- 0.33	- 0.35	- 0.38
w/wind=zero	- 0.23	- 0.26	- 0.25	- 0.18	- 0.16	- 0.01	- 0.10	- 0.01	- 0.36	- 0.32	- 0.34	- 0.38
w/solar=zero	- 0.30	- 0.30	- 0.28	- 0.25	- 0.18	- 0.11	- 0.12	- 0.10	- 0.36	- 0.33	- 0.35	- 0.38
w/IR=zero	- 0.20	- 0.20	- 0.25	- 0.20	- 0.14	- 0.02	- 0.08	- 0.02	- 0.30	- 0.27	- 0.31	- 0.31
Mean radiant temperature (°C)	20	19	19	24	16	24	23	30	10	13	16	15
Weather condition	Partly cloudy, cool, breezy				Clear, cool, breezy				Clear, cool, breezy			
Sky temperature	18				5				5			

ation. According to table 3, site **6** "sees" considerably less sky, which on these days had an apparent radiant temperature of about 5 to 8°C, than site 7. Therefore it is not surprising that the infrared load in site 7 is more negative (MRT is lower) than in site **6**.

Wind speed was variable over both site and time. The urban surface wind tends to be gusty but with a low average velocity. Wind speeds greater than 8 mph were rare. Wind direction was also variable and did not seem to be strongly related to the wind direction above the buildings as indicated by flags.

The lower part of table 4 lists relative strain as calculated for each site by using the environmental variables listed and also the relative strain which would occur if (1) the wind speed were reduced to zero, (2) the solar radiation were reduced to zero, and (3) the infrared radiation load were reduced to zero. These manipulations allowed us to determine the relative importance of the variables. Air temperature and humidity were not modified since they had already been shown to be inalterable by design.

Since the relative strains are all negative, we are dealing with a cool situation; the body requires more heat to achieve balance between inputs and outputs of thermal energy. Unfortunately we do not have any data relating the negative physiological strain to the psychological measure of comfort. However, we do know that to conserve heat the body will constrict the vascular system of the skin with the result that skin temperature is lowered. As mentioned above, cool discomfort is directly related to skin temperature, and the sensation of cool discomfort changes more rapidly below the neutral skin temperature (comfort condition) than above that point. Since we know that on the warm side, relative strain values of between 0 and 0.2 are "comfortable," and that discomfort increases with increasing relative strain (table 2), we can safely assume that the same will occur below thermal neutrality. In other words, we can use table 3 with absolute values of relative strain for a rough indication of comfort.

Wind speed had relatively little effect on relative strain (RS). The average change in relative strain when wind was reduced to zero was only 0.02 or about 10 percent of the RS value. The effect of wind does increase in magnitude with increasing strain, however: compare site 7, 0800 and site 2, 1300.

The effects of solar radiation are quite large as can be seen by comparing sites 1 and 2 at 0800 (RS of —.26 and —.30 respectively) and by studying the difference in relative strain when solar radiation is eliminated (see site 1, 0800; site 2, 1300; site 7, 1300 for example). The presence or absence of solar radiation has a strong influence on human thermal comfort.

At all sites the infrared radiation balance was negative; that is, heat is flowing away from the body, because all surfaces have temperatures below 30°C (skin/clothing temperature). Sites which have large view factors with sky will tend to have larger negative infrared radiation balances since the sky is usually cold, particularly on clear days. Thus sites 1 and 7 show a strong improvement in relative strain when the infrared radiation balance is reduced to zero. On the other hand, site 6, which has only 16 percent of its view occupied by sky (table 3) shows little change when the infrared balance is reduced to zero. Note that as the apparent sky temperature decreases, the effect of eliminating the infrared heat balance increases.

CONCLUSIONS

These data indicate that solar radiation, infrared radiation, and wind are important to human thermal comfort in urban outdoor spaces and, further, that they can be controlled through site design. Trees and other vegetation can be used to provide shade during hot periods to reduce the input of solar energy to the user's body. If spaces are used during cooler periods, then shading should be kept to a minimum. Structures, of course, can be used for the same purpose. Vegetation can be used to screen the user from sources of infrared radiation such as sun-heated walls and streets during the warm season and to limit infrared radiation loss to cold surface such as the sky during cold periods. Although it is not very important in the city under warm conditions, wind speed can play an important role during the cold season as is indicated by the popularity of wind-chill factors in winter weather reports. Various arrangements of vegetation and structure which could be used to reduce the heat losses due to high winds in winter would have little effect on RS in summer.

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