Outdoor Comfort of Pedestrians in Cities

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ABSTRACT.—The outdoor comfort of pedestrians has been neglected by architects and planners because of difficulties in determining comfortable and uncomfortable climatic conditions and predicting the climatic characteristics of a planned urban site. Available information on comfort in a cold environment is summarized. The mechanical effects of wind on comfort are better understood than the thermal effects of climate and have proved to be practical criteria for assessing pedestrian comfort in designs. Climatic-prediction techniques and a procedure for determining the probability of discomfort on a proposed site are described.

HUMAN COMFORT is determined by many factors, both psychological and physiological. Some of these factors, such as acoustics and indoor climate, have an extensive history of quantification and control. The existence of standards for these variables requires that they be considered in design.

Other factors, such as outdoor visual effects (light, surface, forms) and spatial relations (enclosure, security), though not quantified or standardized, are of concern to the architect and are intuitively incorporated in design.

The effect of outdoor climate on comfort, however, is often ignored by the architect or planner. It has been neglected to date because of difficulties in (1) determining what climatic conditions are comfortable or uncomfortable, and (2) predicting the climatic characteristics of a planned site.

In this paper, available information about discomfort due to wind effects is summarized and tentative design criteria are presented. A model describing pedestrian cooling in a cold climate is also given, and its shortcomings in defining design criteria are described. Design criteria from these two methods are applied to an urban site, using climatic data and data from wind- tunnel and sun-shadow tests on a scale model. A procedure for designing for outdoor comfort by controlling wind and sun (the most important and most easily varied factors) is presented.

INFLUENCES OF CLIMATE ON COMFORT

Mechanical Influences of Wind

Wind influences comfort through pressure effects and particle transport. Wind pressure affects comfort through disturbance of clothing and hair, resistance to walking, and buffeting of the body and carried objects like umbrellas. Comfort is also affected when the wind lifts dust and grit particles to eye level, or drives rain horizontally into the eyes or beneath clothing. At higher speeds, wind can also interfere with walking and cause safety problems.

These different effects begin at different wind speeds. Their threshold velocities suggest the onset of various types of discomfort and perhaps the basis for some wind-comfort criteria.

A summary of wind effects in terms of the well-known Beaufort scale (table 1) is taken from a land-effects version prepared by the British Meteorological Office, with additions by Penwarden *(1973)*. Most of the included effects have been observed by ourselves and others in the natural wind and in wind-tunnel experiments *(Arens 1972)*.

Although the Beaufort scale is commonly used to describe velocities averaged over perhaps an hour, our observations show that the wind effects listed for each Beaufort category correspond more closely to the wind velocities observed as they happened. The averaging time might be on the order of, say, a minute and includes the effects of small-scale gusts and lulls but not large ones. Therefore an hourly averaged wind in one Beaufort category will probably include gusts that cause effects ascribed to higher Beaufort categories.

Wind pressures in steady winds

The wind pressure on the human body and the angle of lean needed to counteract it are summarized in the equation *(after Penwarden 1973)*:

$$\frac{1}{2} \rho u^2 A_P C_D / W = \tan \theta / \cos \theta$$

in which θ is the angle of lean from the vertical to counteract wind.

$$\tan \theta = \frac{\text{wind force}}{\text{body weight}} .$$

W is body weight.
$\frac{1}{2} \rho u^2 A_P C_D$ equals wind force.
ρ is the density of air.
u is wind speed.
A_P is projected surface area normal to wind, found to be 0.3 total body surface area for frontal winds *(Pugh 1971)*.
C_D is a dimensionless drag coefficient, experimentally determined to be between 1.0 and 1.3 *(Pugh 1971)*.
$\cos \theta$ is a term reflecting reduction of A_P with lean.

Total body surface area (A_{Du}) is obtained from body height and weight by DuBois formula:

$$A_{Du} = 0.203\ W^{0.425} \cdot h^{0.725}$$

in which W is in kilogram force (kgf) and h is in meters.

Assuming a man of 75 kgf, 1.8 meters height, total DuBois surface area of 1.93 m^2, and drag area of 0.84 m^2, the relation between wind speed, drag force, and angle of lean can be calculated (fig. 1).

Energy required to walk against a steady wind

The rate of performing external work is the product of the wind force and walking speed:

$$\text{Work rate} = \frac{1}{2} \rho\ (u+V)^2 A_P C_D V$$

in which V is the velocity of walking into the wind.

The total increase in metabolic rate of the body M resulting from the work of walking into the wind is

$$\Delta M = \frac{1}{2} \rho\ (u+V)^2 A_P C_D V / \eta$$

in which η = mechanical efficiency, or (work rate) / (metabolic rate), which Pugh *(1971)* found to be 0.44 for walk-

Figure 1.—Wind forces and equilibrium angles.

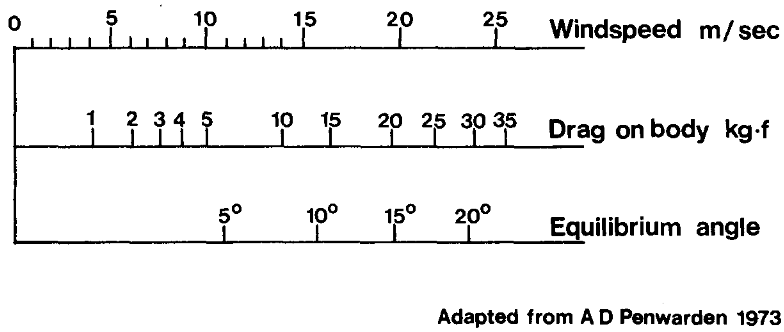
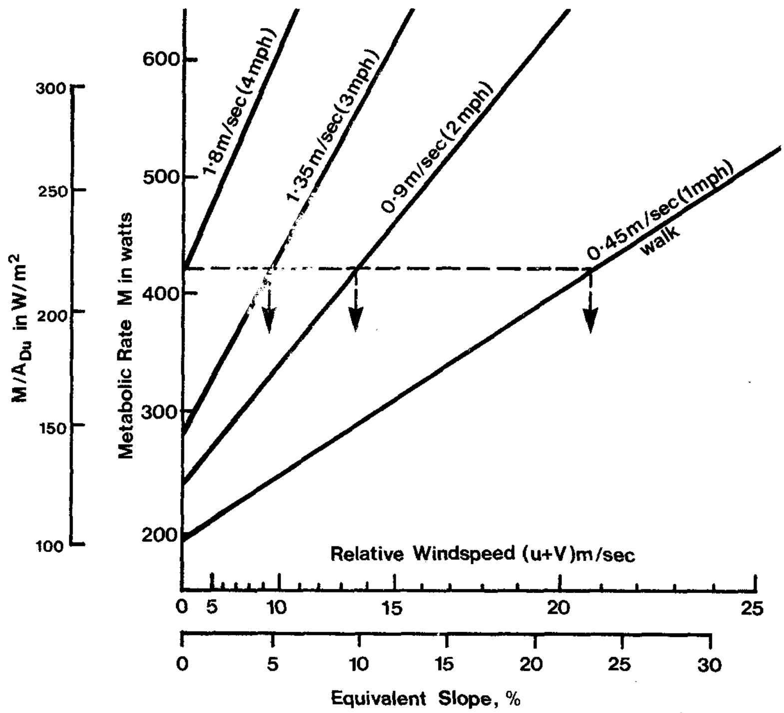


Figure 2.—Work rates of walking against the wind *(Penwarden 1973)*.



ing against the wind and 0.33 for climbing hills. Penwarden *(1973)* presented these data in a diagram (fig. 2) in which the metabolic rates required for walking into the wind are compared to those for walking uphill. The metabolic rates are expressed in watts and in watts/m^2 for the man mentioned above. Penwarden *(1973)* suggests that, if the upper metabolic rate limit for average unathletic people is taken as 220 watts/m^2 (equivalent to walking 4 mph in still air), walking speed into the wind is reduced as follows:

Wind speed	*Walking speed*	
(m/sec)	*(m/sec)*	*(mph)*
0	1.8	4
9	1.35	3
14	.9	2
21	.45	1

These values may be compared to the subjective estimates in the Beaufort scale (table 1).

Effects of turbulent winds

Wind at the pedestrian level is accompanied by turbulence, which is perceived as a varying velocity, as gusts, or as eddies. The intensity of turbulence for any given windspeed varies from place to place but tends to be greater in urban or built-up surroundings than in open countryside.

To learn the effect of most natural winds on comfort, it is necessary to quantify the influence of the turbulent component of that wind. This information has not been available until very recently.

In an exemplary study, Hunt and others tested subjects in both steady and turbulent winds in a wind tunnel *(Hunt et al. 1976, Poulton et al. 1975)*. They also tested the effects of wind variation over a short distance, such as when one walks out of a doorway into the wind. They assessed wind influence on comfort, disarrangement of clothing and

Table 1.—Summary of wind effects

Beaufort number	Description	Wind[1] (m/sec)	Effects
0	Calm	0	Calm
1	Light air	0-1	No noticeable wind; direction shown by smoke.
2	Light breeze	2-3	Wind felt on face; newspaper reading becomes difficult.[2]
3	Gentle breeze	4-5	Wind extends light flag; hair is disturbed; clothing flaps.
4	Moderate breeze	6-7	Dust, dry soil, and paper raised; *rain and sleet* driven;[2] hair disarranged.
5	Fresh breeze	8-10	Force of wind felt on body; drifting snow becomes airborne; limit of agreeable wind on land.
6	Strong breeze	11-13	Umbrellas hard to use; difficulty walking and standing; wind noise in ears unpleasant; windborne snow above head height (blizzard).
7	Near gale	14-16	Strong inconvenience felt when walking.
8	Gale	17-20	Generally impedes progress; great difficulty with balance in gusts.
9	Strong gale	21-24	People blown over by gusts; slight structural damage occurs; slate blown from roofs.
10	Storm	25-28	Seldom experienced on land: trees broken or uprooted; considerable structural damage occurs.

[1] Rounded from knots in the original scale. (1 m/sec = 1 meter per second = 1.94 knots = 2.2 miles per hour).
[2] Our observation.

Table 2.—Summary of wind-pressure effects on people
[Symbol $<$ denotes 'should be less than']

Wind and effect	Criterion
Steady uniform wind:	
For comfort and little effect on performance	$u <$ 6 m/sec
For ease of walking	$u <$ 13-15 m/sec
For safety of walking	$u <$ 20-30 m/sec
Non-uniform winds (if u varies by 70% over a distance less than 2 m):	
To avoid momentary loss of balance and to be able to walk straight	$u <$ 9 m/sec
For safety (for elderly people this criterion may be too high)	$u <$ 13-20 m/sec
Gusty winds:	
For comfort and little effect on performance	$u_s <$ 6 m/sec*
Most performance unaffected	$u_s <$ 9 m/sec
Control of walking	$u_s <$ 15 m/sec
Safety of walking	$u_s <$ 20 m/sec

*Note: u_s is not the "peak gust" as used in engineering.
Source: Hunt and others (1976).

hair, eye watering, performance of tasks, and balance while standing and walking. Quantification was based on subjective verbal assesments by the subjects and on physical measurement of task performance and of wind forces while walking as transferred to an instrumented floor.

These findings show people to be very sensitive to turbulence in the wind. To compare turbulence effects to other wind effects, an equivalent steady wind is defined:

$$u_s = u\ (1 + 3 \cdot \text{turbulence intensity})$$

in which

u_s = Equivalent steady-wind velocity.
u = Mean velocity.
turbulence intensity = (root mean square of the instantaneous

deviations from
the mean
velocity)/u

The limiting velocities have been summarized (table 2).

Wind-driven rain and particles

A pedestrian may also be inconvenienced by rain or grit blown into his face. Blowing grit may well be the most unpleasant single effect of the climate on a pedestrian.

The suspension of a solid or liquid particle requires an upward air velocity equal to the terminal velocity of the particle (table 3). A horizontal wind equal to or exceeding the terminal velocity will cause a particle to descend at an angle of 45° or less to the horizontal.

It can be seen that a horizontal wind speed of 7 m/sec will cause large raindrops to descend at 45°. This value is used by building climatologists for driven-rain data; however, fine drizzle will be driven at 45° by velocities as low as 1 m/sec.

The size of droplet and angle of fall that individually and in combination are considered unpleasant are unknown. It is probable that flatter angles of descent are acceptable for smaller droplet sizes, since wetting by rain takes time. This might allow us to define a single limiting velocity for rain. We do not have information at present, but it will be between 1 and 7 m/sec.

Wind-lifted dust has a major impact on human comfort. In the Beaufort scale, dust and loose papers are described as being lifted at velocities between 5.5 and 8 m/sec.

A physical formulation of this process depends on a number of unresolved factors such as the minimum particle size needed to cause irritation in the eye and on the skin, the mechanisms of particle lifting from urban paved surfaces, and the extent to which moisture cements particles together.

The lifting mechanism is described by Bagnold *(1941)* and Chepil *(1965)* in relation to desert sand and soil particles, respectively. Bagnold shows that particles begin rolling at around one-seventh the velocity needed to lift them. This suggests that grit traps (lawns, gratings, and water) might be useful in reducing the supply at the surface.

Lifting requires vertical velocities that are inherent in a boundary layer over a surface or that are caused by obstructions protruding from the surface. When the eddies are caused by surface friction, Bagnold shows that a horizontal velocity at 1.5 meters of 8 to 14 m/sec will lift 0.1-mm grit from flat surfaces.

Near wind-deflecting vertical obstructions, the vertical velocities close to the ground for a given mean wind speed are much higher. These vertical velocities may be in the form of vortices in fixed locations relative to the obstruction. Examples are eddies behind lamp posts, near building corners, or in streets near moving vehicles. Although these local eddies may lift dust and paper when the winds are light, they are often not perceived because the dust supply in their immediate area is exhausted.

Wind between 5 and 8 m/sec will probably cause pedestrian discomfort by blowing dust, paper, or rain.

Table 3.—Terminal velocities of airborne particles

Velocity	Diameter of particles	Character of particles
m/sec	*mm*	
10^{-2}	0.01	Dust
10^{-1}	.03	Extremely fine sand, dry snow
0.6	.1	Fine sand
1	.2	Medium sand, snow, sleet, fine rain
2.5	.3	Average sand in the desert
7	1.0	Large raindrops*
10	1.0+	Sand to pebbles, great rain, hail

Sources: Bagnold *(1941)*, Reidat *(1970)*.*

Design criteria: mechanical wind effects

The British Building Research Establishment recommended 5 m/sec as the design wind velocity under urban outdoor conditions *(Wise 1970)*. As described above, recent results by Hunt et al. define this design value more closely in terms of the steady and turbulent components.

With a design value in hand, the designer must judge what percentage of the time (or how often in a year or season) it may be exceeded. For comfort, 10 to 20 percent may seem reasonable. For safety, lower exceedance percentages (say 1 percent) should be applied to the higher design values. Davenport *(1972)* has suggested acceptable exceedance frequencies for a variety of activities based on a 5 m/sec design windspeed; the reasons for the suggested frequencies are not given.

Penwarden *(1974)* analyzed cases of shopping centers that had caused wind complaints. He found that in centers where 5 m/sec was exceeded 20 percent of the time or more, the owners invariably spent the money to add protective screens or roofs. Centers with frequencies of 10 to 20 percent caused complaints but no remedial action, and few complaints were heard in centers with frequencies below 10 percent. Penwarden's study gives the most concrete evidence in support of specific design criteria to date.

THERMAL INFLUENCES OF CLIMATE ON COMFORT

A person's thermal comfort is influenced by the surrounding air temperature, wind, radiation, and humidity, as well as his clothing insulation and activity level. Thermal comfort has been studied extensively for indoor conditions (see *Fanger 1970*).

Because of the increased range of climatic variables outdoors, investigators have not been able to quantify the perception of thermal comfort versus climate in outdoor environments. See Penwarden *(1973)* for a summary of such work.

Most attempts to define the effects of climate on people have used thermal budget models in which it is assumed that comfort results from the thermal balance between the body's heat production and heat losses to the environment. These models assume equilibrium heat flow, which in reality occurs only after 1 to 2 hours' exposure to constant surroundings. The physical and psychological response of people to changing thermal environments has been studied only for nude subjects in indoor laboratory conditions *(Gagge et al. 1967)*.

Model for heat loss to a cold outdoor environment

The following describes a model of thermal comfort used to assess the environmental quality of buildings in the cool San Francisco environment. Total heat loss from the body is the sum of dry heat loss (convective, radiative, and conductive) and insensible evaporation from skin and lungs. Evaporation is roughly independent of atmospheric humidity and represents a roughly constant 25 percent of the body's heat loss. It has not been possible to demonstrate any difference between the popular "wet cold" and "dry cold." Conductive losses are low in pedestrians and are ignored. The dry heat loss is thus defined as:

$$kQ = \frac{A_c}{A_{Du}} \left(\frac{T_b - T_a}{R_b + R_c + R_a} \right) + \frac{A_n}{A_{Du}} \left(\frac{T_b - T_a}{R_b + R_a} \right)$$

in which:

Q is total heat loss from body.

k is the fraction of non-evaporative heat loss (0.75).

A_c and A_n are the surface areas of clothing and exposed nude skin, respectively.

A_{Du} is the DuBois total nude surface area (see previous definition in section on "Wind pressures in steady winds.")

T_b is body core temperature, normally 37° C.

T_a is mean radiant temperature, the average temperature of air and radiant surroundings.

R_b is the insulation of body tissues commonly assessed as 0.09 m² deg C/watt.

R_c is insulation of clothing itself.

$$R_a = \frac{1}{h_r + h_c} = \frac{1}{4.3 + 12u^{0.5}}$$

where h_r and h_c are the radiative and convective heat transfer coefficients; h_c has a minimum value of 4 watts/m² °C in still air.

Insulation of clothing is commonly given in "clo" units, equal to 0.155 m²-°C/watt. Clothing insulation is usually quantified by measuring the power consumption of a dressed heated mannikin in still air and describing the resulting insulation as uniformly distributed over the entire body surface. Because this method does not allow for the disproportionate influence of wind on nude as opposed to clothed surfaces, the above formula treats the two surfaces as parallel heat losses. The value of R_c must be selected to represent the garments themselves. For example, 1 clo traditionally represents the insulation of a business suit distributed over the entire body, whereas the insulation over the clothed area itself is 1.2 clo.

Solar energy absorbed by the body counteracts heat loss. The incoming radiation's effectiveness in heating the body is proportional to the amounts of insulation within and without the point of absorption; i.e., solar heat gain Q_I is greater for nude than clothed surfaces:

$$\text{For nude, } Q_I = \frac{R_a}{R_b + R_a} I\,(1 - a)$$

$$\text{For clothed, } Q_I = \frac{R_a}{R_b + R_c + R_a} I\,(1 - a)$$

where $I\,(1 - a)$ = Absorbed solar radiation at the surface.

- I = Total solar influx on the body surface, watts/m².
- a = Reflectivity of clothing or skin, ranging from 0.8 for white clothing, 0.43 for white skin, to 0.16 for black clothes or skin.

If we let $I(1-a) = S$, then the net dry heat loss equals

$$kQ - Q_I = \frac{A_c}{A_{Du}} \left(\frac{T_b - T_a - SR_a}{R_b + R_c + R_a} \right) + \frac{A_n}{A_{Du}} \left(\frac{T_b - T_a - SR_a}{R_b + R_a} \right)$$

Solar radiation influx includes direct beam, diffuse sky, and reflected components. The proportions of the total body surface A_{Du} exposed to these streams have been calculated and measured *(Blum 1945)*. Body surface area exposed normally to the direct beam varies from 7 percent A_{Du} to 30 percent A_{Du} as the sun moves from the zenith to the horizon. In practice, the increased area exposed to low-altitude sun nearly compensates for the decreased intensity of the direct beam. One-half of A_{Du} is assumed to be exposed to the diffuse radiation from the sky vault and the other half to the radiation reflected from the ground. These exposure proportions of the total body surface are assumed to apply to the clothing and exposed skin surfaces as well. The sky and ground may be assumed to radiate at uniform intensities for the purposes of this model.

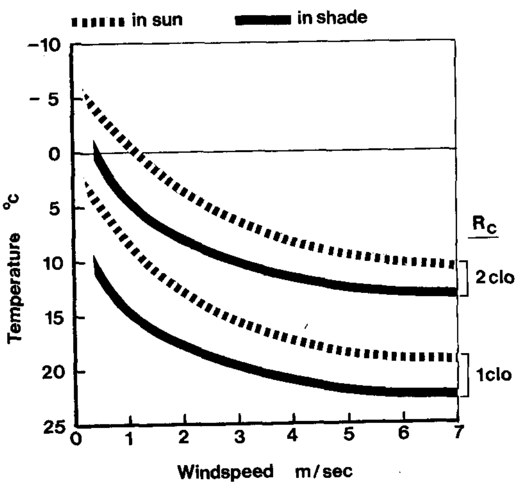
An equivalent treatment can be applied to longwave radiation gain or loss when the temperatures of surrounding surfaces are substantially different from air temperature. In these cases air temperatures would represent the surroundings and a is 0.05. The differences between the air and outdoor surface temperatures are usually too small to warrant this refinement.

Thermal balance exists when the net heat loss (Q-Q_I) is equal to the metabolic heat production M (table 4). "Comfort curves" (fig. 3) can be drawn for heat loss versus wind and temperature for various sun and clothing levels.

Table 4.—Metabolic rates

Activity	Metabolic rate M/A_{Du}
	Watts/m²
Sleeping and digesting	47
Sitting quietly	59
Standing	71
Strolling—0.7 m/sec (1.5 mph)	107
Level walking—0.9 m/sec (2 mph)	116
Level walking—1.35 m/sec (3 mph)	150
Level walking—1.8 m/sec (4 mph)	220
Level walking—4.5 m/sec (10 mph)	590
Sprinting—10 m/sec (22 mph)	2,400

Figure 3.—Sample comfort curves for a range of temperature and windspeed. $M/A_{Du}=150$ watts/m², equivalent to walking 3 mph. Direct sun on horizontal surface=285 watts/m².



These have the following shortcomings:

1. They assume thermal equilibrium, which requires 1 to 2 hours' continuous exposure to the outside environment. This is rare for pedestrians.
2. They show no effect of wind penetration or infiltration of clothing. There is a serious lack of experimental data on clothing performance in wind.
3. Clothing resistance is not easily defined for any civilian population, due to the extreme variability of clothing worn at any time. The curves are sensitive to the chosen value of R_c.
4. There is virtually no experimental evidence describing how physiological heat loss influences the psychological perception of comfort outdoors.

DESIGN PROCESS

The designer should consider outdoor comfort early in his design. Because the relationship between the physical form of the design and the climate and comfort around it is often complex, he may have to follow a climatic design process in order to find a satisfactory solution. The process is basically to: (A) determine the climatic characteristics of the site and the preliminary project, partly by model tests; (B) assess its effects on outdoor comfort; and (C) modify the project design and test the climate and comfort again until a solution is reached.

PREDICTING THE LOCAL CLIMATE OF A SITE

Solar radiation and wind are the most important climate information for comfort prediction. Of the various climatic elements, these have the greatest variation across a site of architectural or planning scale. They are also the climatic elements over which the designer has most control. Elements with less site variations and importance to comfort analysis are longwave radiation, air temperature, and air humidity.

Solar Radiation

The important facts about sunlight are its duration and its intensity. These are influenced by both the geometrical and meteorological nature of the site and its location.

Regional scale. — Daily possible solar duration is readily available in standard meteorological tables and is a geometric function of latitude. Solar duration is further influenced by the meteorological probability of sunlight or cloud. These data are readily available from the Weather Service as seasonal or hourly values of percent cloudiness, percent of possible sunshine, or number of hours of cloud.

Solar intensity is influenced by latitude (atmospheric path length) and atmospheric turbidity. Solar intensity is not widely measured and, if available, is usually in the form of daily total energy per unit area.

A most useful method of obtaining average hourly solar intensities is given by Liu and Jordan *(1960)*, based on observed constancy between daily and hourly values in regions of equal atmospheric clarity.

Local Scale. — On the site itself, solar radiation is described by its extent and by the amount of time it is either on or off. The surrounding buildings either obstruct or admit light to the pedestrian areas. There is little variation in the intensity of direct sunlight in most outdoor spaces. Local exceptions might occur in places screened by thin vegetative canopies or near highly reflective surfaces.

Sunlit and shaded areas may be predicted from a model with a light source representing the sun. The daily sunlight characteristics of an existing site are conveniently determined by use of a globoscope or of fisheye photographs of the sky hemisphere overlain with appropriate sunpath diagrams. An excellent description of solar geometry prediction techniques for designers is given by Burberry *(1966)*.

A computer program has been developed at the Department of Architectural Science, University of Edinburgh, to integrate shadow areas over any period of day and present these shadow durations in contour form. We have not used this technique, although it could be useful in the eventual preparation of daily "comfort contours."

Wind

Regional scale. — Wind records are available for most locations; recording stations are commonly found at airports in open terrain. For most sites wind information must be extrapolated geographically from the recording station to the vicinity of the site. The effects of topography, vegetation, and structures must be carefully considered in this extrapolation. If possible, wind-recording equipment installed on site should be run synchronously with nearby weather stations for a suitable period of time to establish the relation between winds at the two locations. This is expensive and time-consuming, however.

The meteorological data base should provide information necessary to determine the amount of time that pedestrians will be uncomfortable on the site. This requires hourly wind data, preferably in conjunction with data on temperature and sun. The most useful wind summary is a cumulative frequency distribution providing the percentage of time that each wind velocity is exceeded for each wind direction. This data format is rarely available and must usually be calculated from the station's raw data.

Local scale. — Winds at pedestrian level will often be strongly affected by the building, planting, and grading configuration of the project. The wind patterns over the pedestrian areas of a site are far more difficult to predict than the presence or absence of sunlight. If a yet-unbuilt project seems likely to be windy, it should be tested in model form in a wind tunnel. This technique is also useful for defining winds on existing sites, since the flow strength, stability, and direction can be controlled during the tests. Physical modeling with limited field verification is most desirable.

Physical modeling requires the use of a specialized wind tunnel that reproduces the boundary-layer conditions above the actual site. Both the velocity and the turbulence intensity profiles should be modeled to scale. The most satisfactory means of achieving this at present is to generate the boundary layer with turbulence generators and long lengths of roughness similar to that of the terrain upstream of the project site.

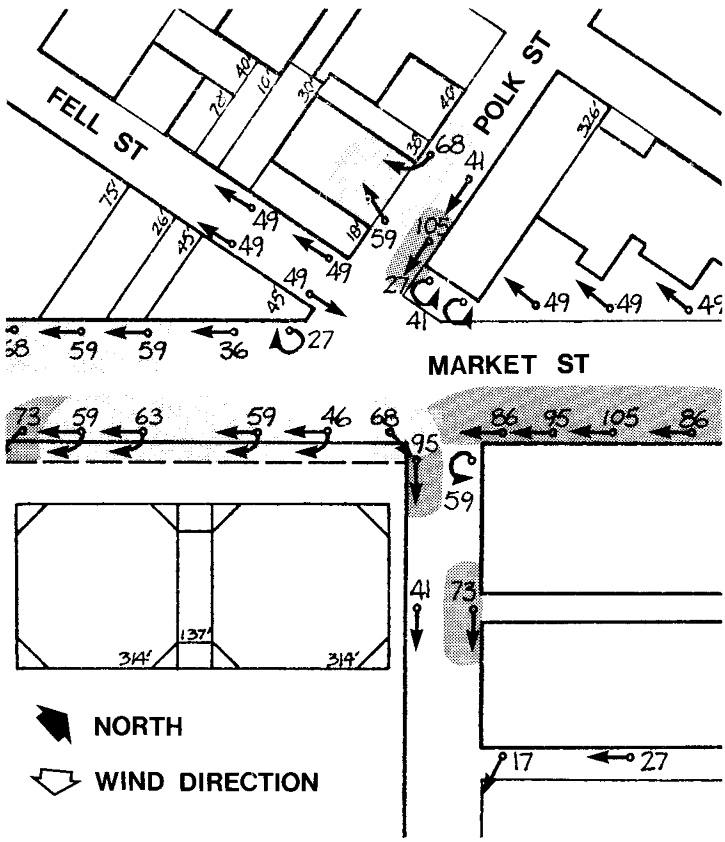


Figure 4.—Nondimensional wind speeds obtained from wind-tunnel tests of a scale model. Shading indicates areas of high wind speeds.

Wind speeds measured in the wind tunnel are nondimensionalized and are expressed as a percentage of a reference wind speed. The reference wind speed is that measured at the reference height, often chosen as the height of the wind instrumentation of the weather station providing climatological wind data. By relating wind-tunnel measurements to climatological data, wind-speed frequency distributions on the site are defined.

Measurements of wind speed are normally made at a network of grid points within and around the project model. A hot-wire anemometer is used to measure wind speed and turbulence at each grid point. Its small size allows it to measure within millimeters of the surface, representing pedestrian height at model scale. Separate tests are made for each wind direction, the number of directions normally corresponding to the number of points of the compass considered in the meteorological wind data base. An example of wind-tunnel data for a downtown San Francisco site is given (fig. 4).

Temperature, Longwave Radiation, Humidity

Air temperature, longwave radiation from the ground and atmosphere, and humidity are important heat-transfer mechanisms; however, they vary little across normal architectural sites.

Temperature. — At a regional scale, one should consider microclimatic effects when extrapolating a regional air temperature value to the site. Temperature may be substantially modified by frost pockets and urban heat islands, for example. On the site itself the variation is usually much less.

Longwave radiation. — In comfort models, air temperature and the temperature of the surroundings are either assumed equal or averaged into a "mean radiant temperature" that is used as the ambient temperature. Since surface temperatures usually do not differ from air temperatures by more than a few degrees, the difference between longwave radiation contributed by the surfaces on site and that of surroundings at air temperature is very small. In light of the accuracy of the thermal model, calculation of surface temperatures and longwave radiation flux is not justified. In hot environments, where the thermal requirements for comfort are more closely quantified, local surface temperatures and radiation exchange are important design characteristics.

Humidity. — Humidity has no quantified role in cold environment heat loss. In hot environments, humidity plays a critical part in determining comfort.

ASSESSING COMFORT ON A SITE

The complicated interaction of climatic variables that determine comfort can be handled best statistically. A logical and simple measure of comfort is the percentage of time that comfort or discomfort will occur on a given day at a specific time. Care should be taken in selecting the proper season and time for the analysis of comfort so that the period of greatest use or sensitivity to discomfort is considered.

We have used two different criteria defining uncomfortable conditions in our analyses, based first on the thermal and then on the mechanical effects of climate. The computation process for determining discomfort probability is different under these two methods (fig. 5).

Thermal comfort prediction method

For each measurement point, the time of day, day of year, expected type of human activity, and expected level of clothing are specified. The average temperature for this period is then found.

The first step in the calculation involves defining the "discomfort threshold wind speed" from the comfort curves. Separate threshold values are defined for sunny and shady conditions. If the point of interest is shaded by structures or topography, the calculations need only consider the sunless case. If it is in the sunshine, separate calculations must be made for the sunny and shady cases.

The nondimensional wind speeds obtained in the wind tunnel are then used to specify the reference wind speed corresponding to the threshold wind speed on the site for each wind direction; i.e., the threshold wind speed is divided by the nondimensional wind speed.

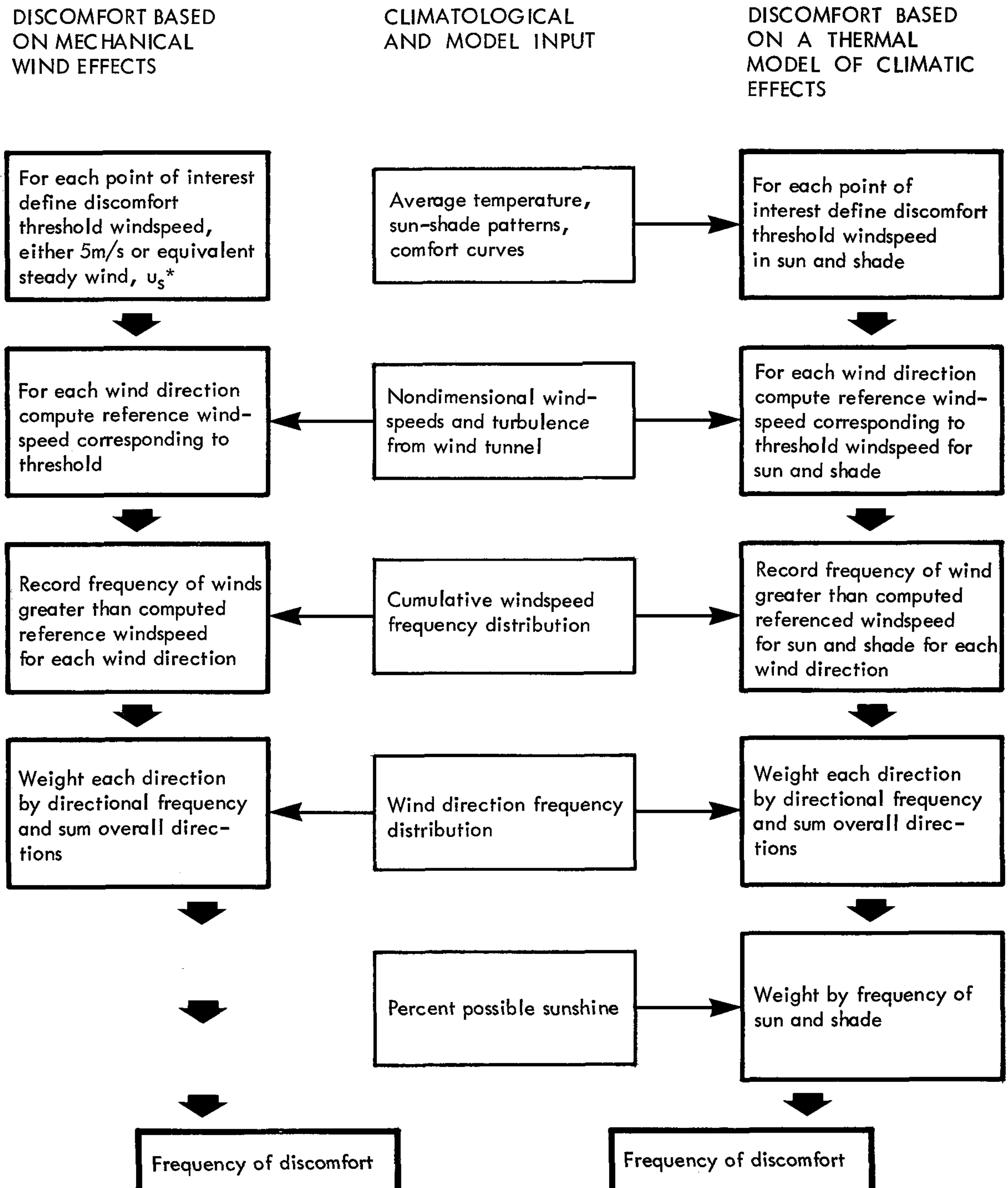
The frequency of reference winds exceeding the specified level is then obtained from cumulative wind-speed frequency curves, again separately for each wind direction and for the sun and shade cases.

The result is the probability of discomfort occurring during wind from each direction. These probabilities are then weighted by the probability of each wind direction's occurrence. For a point in the sun, two separate discomfort probabilities are calculated. They are then weighted by the climatological probabilities of sunshine and clouds and combined into a single probability.

Calculated discomfort frequencies for a downtown San Francisco site are shown as an example (fig. 6). The clothing level chosen is light but corresponds to our estimate of average men's and women's clothing at this time of year.

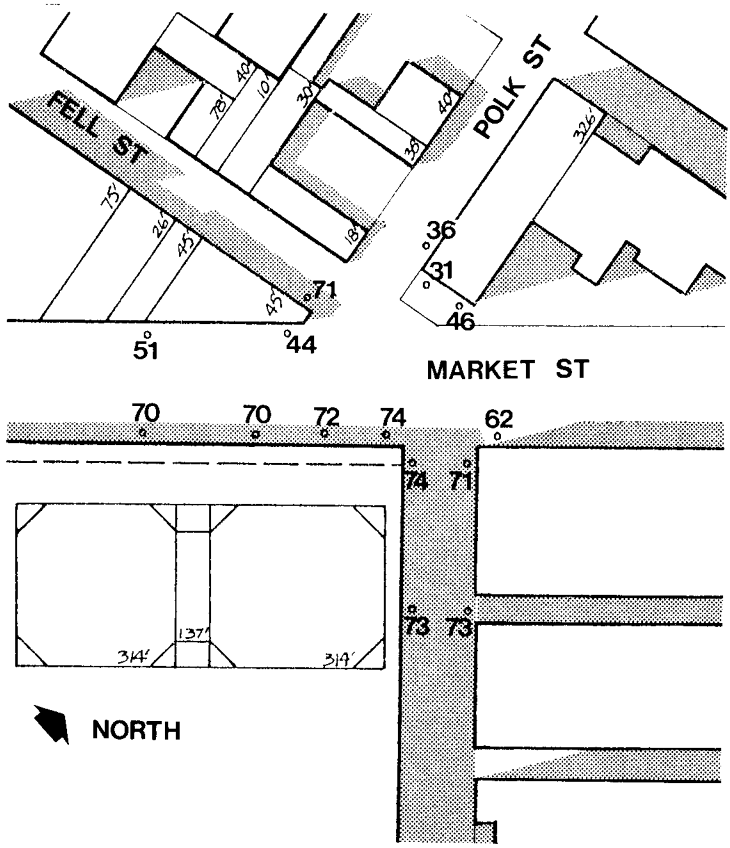
The pattern of discomfort frequency seems reasonable in that shaded areas exhibit a much higher discomfort frequency than areas in the sun. The absolute values, however, are extremely high, especially in the shaded areas. The

Figure 5.—Calculation process in determining discomfort frequency.



*See Table 2

Figure 6.—Frequency of discomfort based on thermal influence of climate. The analysis is for the first day of spring at 1 p.m. with a temperature of 15°C (61°F). The discomfort frequencies are for a person walking 3 miles per hour, wearing clothing with $R_C = 1$ clo, averaged as 0.8 clo over the entire body.



uniformity of the frequencies within the shaded areas is unexpected considering the variation of windspeeds over these areas.

The explanation of these discrepancies lies in the assumptions of the thermal comfort model. As a steady-state model, a period on the order of 1 hour is required for a person to come to thermal equilibrium with the environment. The average duration of a pedestrian trip is more on the order of 5 to 10 minutes, however, so that the steady-state conditions would never be reached.

Applying the steady-state model to a transient situation underestimates the discomfort threshold wind speed. In shady areas the model is so oversensitive to wind that almost any wind will cause discomfort, resulting in discomfort frequencies uniformly approaching the climatological probability of non-calm winds.

While providing poor estimates of comfort in pedestrian areas, the thermal model may be useful in other applications. The assumptions of the model apply to outdoor sports arenas and theaters, picnic areas, and beaches; and the model could provide usable discomfort estimates for such areas.

Comfort prediction method based on mechanical wind effects

The inaccuracies of the steady-state thermal model are avoided by basing comfort prediction on mechanical effects of the wind alone. The computational requirements of this method are also far less. The mechanical method will, of course, underestimate the discomfort frequency by neglecting discomfort caused by thermal cooling.

In the computation (fig. 5) the discomfort threshold speed is now set at 5 meters/second (11 miles per hour), regardless of temperature or sunshine. If turbulence is considered, the equivalent steady windspeed u_s is calculated for each point of interest and used as the discomfort criterion (table 2). The remaining steps are similar to those in the thermal prediction method, except that sun-shade effects are ignored.

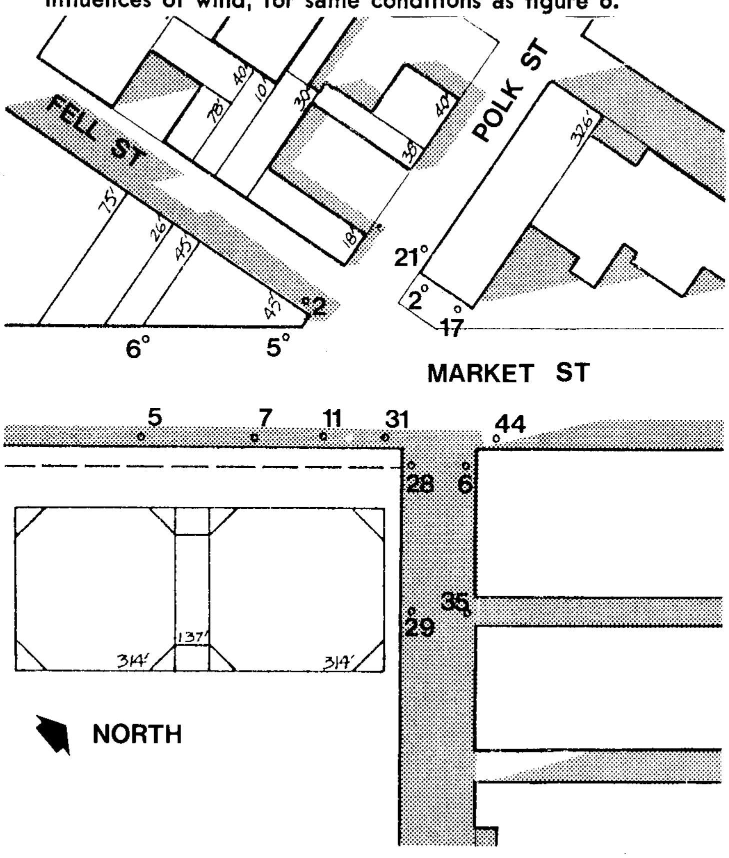
Discomfort frequencies calculated by using mechanical wind effects criteria are lower than those calculated by thermal prediction (fig. 7). There is also considerably more variation over the site, reflecting the varying strengths of the wind.

While ignoring temperature and sun-shade effects, the mechanical method provides a reasonable estimate of discomfort due to wind. Although the absolute values are known to be low, the pattern and relative values are both reasonable and useful. Sun-shade plots are included in the analysis to provide an intuitive judgment of thermal comfort as well.

IMPROVING SITE COMFORT

The comfort-prediction process described above estimates the levels of comfort to be expected at a site and

Figure 7.—Frequency of discomfort based on mechanical influences of wind, for same conditions as figure 6.



points out problem areas. This information can be used to design and locate building entrances, walkways, plazas, and balconies, as well as parks and recreational facilities. If the expected comfort levels are unacceptable, design modifications to improve conditions may be investigated.

Based on trials with wind tunnel models, design modifications within the site and budgetary limitations of the project are suggested. These modifications can range from changes in building height, bulk, or orientation to the provision of vegetation or landscaping to reduce winds.

For any given problem there is a range of possible solutions varying in effectiveness and cost. The procedures described in this paper may help optimize these factors. For example, roofing over a shopping mall would surely reduce winds, but construction of wind deflectors or latticework or use of vegetation may yield the same results at far less cost. The influence of such devices on sunlight should also be considered.

A model of the modified design is tested in the wind tunnel and the analysis of comfort repeated. Further modifications are again suggested and the process is repeated until a satisfactory design is obtained.

CONCLUSIONS

Prediction of discomfort frequency at a planned urban site is possible by using wind-tunnel tests of scale models to predict winds. There is insufficient knowledge at present to base discomfort frequencies on the thermal effects of climate. A simple prediction method, based on the better-understood mechanical effects of wind, yields results that are useful in the layout, orientation, and design of a project. This method provides a rationale and criteria for design modifications to improve outdoor comfort.

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Acknowledgment. The authors thank Nancy Tellefsen for many useful suggestions in the preparation of this paper.