Street Design and Urban Canyon Solar Access

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ABSTRACT

In his recent papers, Oke has challenged urban climatologists to establish quantitative and readily understood guidelines which might assist planners in the design of climatically rational cities, and has shown by example how such an approach might be taken for street canyon geometry. This study pursues Oke's arguments relating canyon structure to solar access within the canyon space using a numerical simulation methodology to explore the dependence of irradiance on the canyon facets, on a pedestrian within the canyon and the net irradiance at the canyon top on aspect ratio, street orientation, city latitude, season and sky condition. In addition, wall, floor and pedestrian 'access indices' are defined as the relevant irradiances divided by the equivalent horizontal surface, open-site solar irradiance, and it is suggested that such quantities, if presented in a form convenient to the planning practitioner, might constitute one type of parameter of use in an urban planning context.

INTRODUCTION

An encouraging trend in recent years has been the recognition on the part of urban planners and architects of the role played by climatic interactions with land use and urban form on human health, environmental quality and energy use in cities [1-5]. Concomitantly, there are signs that urban climatologists are beginning to appreciate the needs of such practitioners for data and models [6, 7]. Oke [8] has challenged climatologists working in the built environment to establish quantitative and easily understood relationships which might help in the formulation of urban design guidelines. This convergence of interest at the climatology-planning interface is a welcome one given the increasing urbanization of world population, especially in those regions outside the temperate mid-latitudes within which most urban development has hitherto been concentrated, in the tropics [9] and, to a lesser extent, in the high latitudes. While climatic criteria must take their place alongside architectural, aesthetic, social, economic and other guidelines in the planning process, the compromise and weighing of alternatives which is the essence of planning practice is only possible if urban climatic research is able to provide the types of quantitative predictions of the effects of urban design prescribed by Oke [8]. It is to this end and, more specifically, as a response to the question "Does urban climate research have quantitative guidelines to offer regarding street geometry?" [8], that this work is offered.

The urban street canyon has been adopted as the basic structural unit of analysis in much urban climate research, both measurement- and modelling-based [10-16]. At its simplest, the urban canyon may be conceived as a rectangular trough (height $H$, width $W$), with specified surface materials, oriented at some angle $\theta$ (in this study measured clockwise from north). In many applications, the absolute dimensions of the canyon are not relevant and its geometry may be characterized by its 'aspect ratio', $H/W$. Oke [8] sought to find a 'zone of compatibility' among aspect ratios for a hypothetical mid-latitude city in terms of shelter and warmth of street-level air (favoured by large $H/W$) and pollution diffusion and solar access (requiring small $H/W$). His review of the urban climate literature suggests that the range $0.4 < H/W < 0.6$ represents an acceptable compromise in meeting these criteria.
This study focuses on one of the goals discussed by Oke — that of maintaining solar access to the intra-canyon environment. Solar radiation availability on surfaces within street canyons is of major significance to the efficiency of solar collectors in city environments [17], to the heat budgets of the buildings bordering the canyons (and, hence, to the energetic costs of heating and/or cooling them), to the daylighting of building interiors [18], to illumination levels on the street and to the radiation budgets of organisms, including plant life and humans, occupying the canyon floor.

Oke suggests that a maximum $H/W$ ratio near 0.6 would be satisfactory for a canyon with $\theta = \pi/2$ at 45° latitude to ensure winter noontime direct beam irradiation of the equator-facing wall over two-thirds of its area and to provide adequate diffuse irradiance on walls under cloudy skies [8]. However, his conclusions were not based on irradiances for the canyon facets. This study seeks to re-evaluate this aspect ratio criterion using such data and to extend the analysis for a wider range of canyon types, site latitudes and dates.

**METHODS**

The approach taken here is to simulate numerically some irradiances of significance to the planning process (see below) for a variety of canyon geometries, sky conditions, dates and latitudes. The computational scheme employed is that of Arnfield [19, 20]. However, a number of modifications have been introduced into the algorithm which improve its generality and computational speed. Initialization of the canyon multiple reflection model for the diffuse solar irradiances follows Arnfield [21] with skyline zenith angles computed from receptor and canyon geometry. The radiance distribution employed may be isotropic or may be described by empirical formulae for clear skies [22] or for an overcast sky [23]. In addition, integration of multiply reflected contributions along the x-axis (i.e., up- and down-canyon) is performed analytically rather than numerically, as was done in ref. 19.

The numerical experiments reported are for the following model inputs. Canyon $H/W$ ratios are 0.25, 0.5, 1.0, 2.0, 3.0 and 4.0 to represent a variety of surface geometries found in urban areas. Uniform albedos of 0.3 and 0.15 are employed for the walls and floor, respectively. These magnitudes represent approximate means for typical construction materials on these facets (see, for example, ref. 24, Table 8.2) and are also those adopted by Terjung and Louie [25] for their 'city structure systems'. Data are presented for north–south and east–west canyons, and for the average of these two orientations to represent approximately a city with a 'gridiron' street pattern.

Initialization of the canyon radiation model requires irradiances of direct and diffuse solar radiation on an unobstructed, horizontal plane; these are provided for clear skies by the MAC model [26]. Gaseous attenuation by Rayleigh scatter and absorption due to water vapour and ozone are parameterized using 'bulk' radiative properties [26 - 28]. Aerosol attenuation makes use of a zenithal sun transmission of 0.91, a single scattering albedo of 0.98 and a forward-to-total-scatter ratio of 0.85 [26]. The 'backscatterance' contribution to the diffuse irradiance uses a surface albedo of 0.15 to represent an urban area [24]. Under clear conditions the diffuse radiation is treated as isotropic. Estimates of within-canyon irradiances are made also for overcast conditions. Cloud attenuation of the clear sky global radiation follows [29] using the transmission for stratocumulus cloud from ref. 30 and the radiance distribution of ref. 23. The global solar irradiance is treated as totally diffuse under overcast skies. Calculations are performed at half-hourly intervals for the fifteenth day of each month for latitudes from 0° to 70° N, at 10° increments. (Results are applicable to southern hemisphere locations for dates approximately half a year away from the months used here.) Precipitable water inputs to the MAC model are zonal means.

Instantaneous irradiances at points within the canyon are used to compute the following:

(a) wall irradiance ($K_{w}$), the mean irradiance over all elements on both walls;

(b) floor irradiance ($K_{f}$), the mean irradiance over all elements across the canyon floor;

(c) the irradiance on a model human ($K_{p}$), situated in that part of the canyon
floor which is typically used by pedestrian traffic, and

(d) the absorbed irradiance at the canyon top \(K_{T}\), averaged over all elements across the canyon at roof height.

Quantity (c) is represented by the mean irradiance on the vertical surfaces and top ends of vertical right-cylinders with height/ radius ratios of 14.1 \([31]\) located at distances from each wall equal to 15% of the canyon width. Direct irradiance is determined from solar position \([32]\) and the shadow pattern on the canyon floor. Diffuse irradiances are contributed from the sky, by multiple reflections between the facets of the canyon and by reflection of the global irradiance from the canyon floor.

The half-hourly irradiances for the fifteenth day of each month are averaged to yield the monthly mean. Monthly means are averaged to approximate the annual mean.

In addition, all of the quantities defined above are expressed in dimensionless form, as proportions of the unobstructed global solar irradiance on a horizontal surface \(K_{W}\). For \(K_{W}, K_{F}\) and \(K_{p}\) this number represents the proportion of the potentially available solar energy intercepted by the facet or solid; these ratios are referred to below as 'solar access indices' and are symbolized by \(\sigma_{W}, \sigma_{F}\) and \(\sigma_{P}\). For \(K_{T}\), the ratio with \(K_{W}\) is the canyon system absorptivity, \(a_{T}\).

RESULTS

The experiments described in the previous Section yielded 6912 monthly means and 576 annual means (and many more half-hourly values) for cloudless conditions alone. Only a small sample of these data is reported here*.

Clear-sky canyon-floor irradiance

The irradiance \(K_{F}\) is a major component in the energy budget of the canyon floor and, as such, will play an important role in the thermal and moisture status of low vegetation at street level (e.g. lawns, ground covers), in determining the thermal stress placed on paving materials and, possibly, in modifying ice incidence on urban streets and sidewalks. It may also be taken as a useful surrogate for the general illumination level for pedestrians and road traffic within the canyon.

Figure 1 shows mean \(K_{F}\) data for December, June and the year, by latitude, for all canyon configurations investigated. In all cases, floor irradiance decreases with increasing \(H/W\), with the dependence being strongest for shallower canyon types. In winter, irradiances are qualitatively similar for N-S, E-W and grid configurations; with increasing latitude, solar elevation decreases, leading to complete shading in canyons of decreasing aspect ratio. The floors of shallow canyons still receive higher \(K_{F}\), however, because of their larger view factors for the sky and, hence, larger diffuse radiation receipts.

In summer, mean irradiances for N-S canyons vary relatively little with latitude (<100 W/m² in the most extreme case). However, E-W canyons show large changes with latitude at higher \(H/W\) ratios. Peak irradiances are at latitudes close to the solar declination where high solar elevations permit maximal penetration into the canyon cavity. At such latitudes, the effect of canyon depth is least apparent; for example, at 30° N, the floor of an E-W canyon with \(H/W = 4\) receives about half of the solar irradiance incident on an unobstructed horizontal surface. Irradiances generally fall off away from the subtropics, more rapidly towards the equator than towards the pole. For example, all E-W canyons except that with a square cross section have higher \(K_{F}\) values at 70° N than at the equator. Because of the relative independence of latitude in \(K_{F}\) with N-S canyons, the latitudinal pattern of grid \(K_{F}\) resembles that for E-W canyons, with reduced magnitudes. About one third of the unobstructed June \(K_{F}\) reaches street level at 30° latitude for the deepest canyons arranged in a grid pattern, and high latitude canyon floors can still show an excess of radiation over those in equatorial regions.

Annual means of \(K_{F}\) for shallow E-W canyons decrease towards the pole while deeper ones show peak irradiance in the subtropics with decreases towards both higher

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*A comprehensive tabulation of all mean irradiances generated in the numerical experiments described is available on request.
Fig. 1. Canyon floor irradiances (W/m²) by latitude (° N), canyon orientation, season and aspect ratio. Line symbols denote aspect ratios, as follows: ++ H/W = 0.25; x-x H/W = 0.5; - - - H/W = 1.0; △-△ H/W = 2.0; □-□ H/W = 3.0; ○-○ H/W = 4.0. Broken line shows irradiance on an unobstructed, horizontal surface. ‘GRID’ denotes mean of irradiances for north-south (‘N-S’) and east-west (‘E-W’) canyon orientations.

and lower latitudes. Intermediate canyon aspect ratios result in relatively constant $K_F$ in low latitudes with decreases polewards in mid-latitudes. Canyons oriented N-S show decreased $K_F$ as latitude increases but gradients are much smaller than in the December case. Grid annual mean $K_F$ decreases little between the equator and 20° N (for deeper canyons, it increases slightly); beyond that latitude it declines poleward.

The irradiance on an urban canyon floor obviously depends both upon the characteristics of the surface geometry and on the irradiance at the canyon top. Since the latter factor varies with latitude through its effect on solar elevation and day length, Fig. 1 does not isolate the dependence of solar access on canyon form. This objective is best satisfied by computing the canyon floor solar access index, $\sigma_F$. This ratio, for the grid street pattern only, is depicted in Fig. 2, for the year, for December and June, and for the average of data for March and September (to represent spring/autumn). The $K_F$ and $K_\downarrow$ data vary slightly between the two transition season months due to varying solar declination on the fifteenth day of the month and differences in precipitable water data at higher latitudes. However, differences in $\sigma_F$ are small enough that averaged data are quite representative of the individual seasons.
In both the June and March/September graphs, zones of higher solar access to the street are found at latitudes close to the solar declination, where high solar elevations permit direct irradiation of the floors of E–W canyons for large portions of the day, even for deep canyons. These latitudes are those in which roof-level irradiances are also high due to solar position; hence the high canyon-floor irradiances depicted in Fig. 1 are due to the combined effect of solar path on $K_\downarrow$ and $\sigma_F$. For both summer and spring/autumn, deep canyons vary markedly in the amount of solar access which they permit at different latitudes while, for shallower structures, $\sigma_F$ is only weakly dependent on location. The largest gradients of solar access lie on the periphery of high $\sigma_F$ values and at small $H/W$ ratios, with only modest changes at latitude–aspect ratio combinations in which much of the street is shaded for large portions of the daylight period. In the December case, maximum $\sigma_F$ will be in the southern hemisphere, around the Tropic of Capricorn. Solar radiation penetration to street level is only weakly dependent on latitude but changes rapidly as $H/W$ increases to 1.5, with less-marked changes beyond that.

Annual data show some aspects of all three patterns. Latitudinal gradients of canyon-floor solar access are small in low latitudes (even reversed for deeper canyons) but $\sigma_F$ decreases rapidly poleward of the subtropics, especially for deep canyons. For a street canyon with a square cross section, for example, about 60% of the annual roof-level irradiance will be available at street level at 0° latitude but this percentage will decline to 50% at 30° and to about 30% at 70° latitude.
Clear-sky canyon-wall irradiance

The irradiance $K_{\downarrow W}$ is a significant component in the energy budget of buildings bordering the street and, as such, will play an important role in the energetic costs of heating and cooling them to maintain a comfortable environment for human activities within. In addition, $K_{\downarrow W}$ may be taken as an appropriate surrogate for the daylighting of interior building spaces through fenestration.

Figure 3 shows mean $K_{\downarrow W}$ data for the solstice months and for the whole year, for all canyon configurations, by latitude. Overall, irradiances are smaller than those on the canyon floor, with the difference being most marked at low latitudes. In addition, $K_{\downarrow W}$ shows a much smaller dependence on latitude than does $K_{\downarrow F}$, a reflection of the tendency for lower horizontal surface irradiances at high latitudes to be offset by smaller angles of incidence on vertical surfaces, such as canyon walls. In common with Fig. 1, however, canyon-wall mean irradiances decline with increasing $H/W$ in all cases.

In June, $K_{\downarrow W}$ for N–S canyons is virtually independent of latitude for high aspect ratios while shallower structures actually exhibit increased wall irradiances at high latitudes. Canyons with an E–W orientation show smaller differences between the canyon forms, with minimum irradiance at latitudes
Fig. 4. Canyon wall access indices for a grid street pattern by aspect ratio, latitude (° N) and season. Isoline interval is 0.1.

close to the solar declination where solar paths will result in large angles of incidence for vertical receptors. The highest $K_{\downarrow w}$ values are at 70° N with small $H/W$ ratios. For a grid canyon pattern, $K_{\downarrow w}$ is virtually independent of latitude for deep canyons while shallow ones exhibit an increase in $K_{\downarrow w}$ with increasing latitude.

In December, wall irradiances decrease monotonically with latitude for N–S canyons, gradients being greater for the shallow forms. For E–W streets, results are more complicated. Aspect ratios of 2, 3 and 4 give an inverse relationship between $K_{\downarrow w}$ and latitude. Smaller $H/W$ ratios, however, show peak $K_{\downarrow w}$ in the subtropics, with the latitude of the maximum moving poleward, especially for the shallowest canyons, a result of the interaction between decreasing $K_{\downarrow}$ and more favourable angles of incidence with increasing latitude, and the increasing importance of shading effects on south-facing walls with a high solar zenith angle. It is noteworthy that at 50° and 60° N, the walls of an E–W canyon with $H/W = 0.25$ receive a higher global solar irradiance in December than does an unobstructed horizontal surface. Grid results for December show small gradients in the equatorial and tropical regions with relatively weak decreases towards the poles in the mid-latitudes.

Annual $K_{\downarrow w}$ data show remarkably little dependence on latitude for N–S, E–W or grid canyon forms, especially for larger aspect ratios. For a gridiron street pattern, for example, the largest difference between $K_{\downarrow w}$ at the equator and 70° N is about 50 W/m² (for a square cross-section canyon).

Figure 4 shows data for grid street pattern $\sigma_w$ for the same time periods as were used for
Fig. 2. Largely, these figures isolate the effect of solar elevation on angle of incidence and on mutual shading by canyon walls. In both June and in the equinox months, lowest solar access is found at latitudes near the solar declination for the date, where high solar elevations minimize the irradiance on canyon walls. The data for December reflect this in the decreasing values of \( \sigma_W \) apparent at latitudes below 20° N. Higher solar access is found at high latitudes with small \( H/W \); this tendency is most marked in December (when \( \sigma_W \) for the grid street pattern is near 1) and least apparent in June, again a manifestation of the advantage of a low sun for vertical surface irradiance. At larger \( H/W \), mutual shading of canyon walls under low sun conditions partially offsets this advantage, leading to smaller access indices and a weaker dependence on latitude. While gradients of \( \sigma_W \) are smaller in the annual data, the advantage of high latitude to the walls of open canyons is still apparent. Naturally, this tendency, when combined with the latitudinal dependence of \( K_{\downarrow} \), is the explanation for the weak dependence of \( K_{\downarrow} \) on latitude in Fig. 3.

**Clear-sky irradiance on model pedestrian**

The calculations for the model pedestrian are intended to provide preliminary data on an important component of the energy budget (and hence comfort) of a human being, exposed within canyons of varying geometries at different latitudes. Any application of these results should recognize that the method of computation implies outdoor human activity within the urban environment to be random with respect to time of the day and with respect to the sunlit and shaded portions of the canyon floor.

Figure 5 shows mean irradiances on the model pedestrian for June and December and for annual conditions, for N–S, E–W and grid configurations. As in the previous results, irradiance decreases as \( H/W \) increases, with the largest changes occurring at small aspect ratios. Latitudinal patterns depicted in Fig. 5 are very similar to those for canyon walls (cf. Fig. 3). This is perhaps unsurprising given the location of the pedestrian modelled, at the margin of the canyon floor, and the fact that 97% of the surface area of the solid used to simulate a person is vertical. Magnitudes of irradiances are generally lower than those for walls, however, since direct solar radiation can be received on only half of the vertical surface of the model. In June, \( K_{\downarrow} \) varies little with latitude for deep N–S canyons and increases slightly with latitude for shallow ones. For E–W streets, however, deep canyons show a maximum at latitudes close to the solar declination, brought about primarily by reflection of \( K_{\downarrow} \) onto the vertical surfaces of the model pedestrian (cf. Fig. 1). In winter, \( K_{\downarrow} \) is very small for deep canyons and decreases poleward for shallow ones. On an annual basis, mean irradiances on the model pedestrian show remarkably little spatial variation; location within the city, manifested in varying canyon geometry, is likely to play a far more potent role in determining this component of the human energy budget than is the city's location by latitude.

Figure 6 shows values of the solar access index \( \sigma_F \) for a grid street pattern. Despite the similar latitudinal dependence of \( K_{\downarrow} \) and \( K_{\downarrow} \) their differing magnitudes result in lower values of \( \sigma_F \) than \( \sigma_W \) and a rather different distribution by latitude and \( H/W \). In June, the previously mentioned effect of enhanced floor reflection in deep canyons beneath a high sun is apparent for canyons with \( H/W > 1.5 \). For small aspect ratios, \( \sigma_F \) shows little latitudinal dependence. A similar distribution occurs in the transitional seasons, with highest solar access now occurring at near-equatorial latitudes for deep canyons and with only small changes in \( \sigma_F \) with location for small \( H/W \). In December, all canyon forms give \( \sigma_F \) magnitudes which vary little with latitude, except for those with \( H/W \) greater than \( \sim 1 \) at high latitudes. However, the significance of these high latitude differences is less than might be implied by the solar access indices because of the small horizontal surface global solar irradiances at this time of the year. On an annual basis, solar access to pedestrians shows independence of latitude at \( H/W \sim 1.0 \), increases slightly with latitude for shallower canyons and is extremely small with a tendency to decrease with latitude for \( H/W > 1.0 \).

Table 1 shows \( K_{\downarrow} \) data for the grid canyon configuration at selected dates and latitudes, expressed as a ratio of the same irradiance
for an open site, unobstructed by buildings, for a model human standing on a surface with the same albedo as the canyon floor. These data isolate the effects of canyon geometry (as distinct from receptor geometry) on the solar access to a pedestrian. In winter, when open site $K_{\downarrow P}$ decreases poleward, canyon shading effects reduce the irradiance on a person within the canyon further with increasing latitude, as canyon bottoms and walls are thrown increasingly into shade (cf. Fig. 5), except for the deepest canyons which are significantly shaded at any latitude. In summer, $K_{\downarrow P}$ actually increases slightly with latitude at an open site and, although canyon wall shading reduces the mean irradiance significantly, even for cases with $H/W = 0.25$ or $H/W = 0.5$, it does not offset the general latitudinal trend; indeed, for latitudes less than 40° N in Table 1, the positive association between $K_{\downarrow P}$ and latitude is enhanced.

**Clear-sky net solar irradiance at canyon top**

Figure 7 shows mean net solar irradiance at the canyon top for June, December and the whole year, for all canyon forms and latitudes investigated. In all cases, maximum absorbed radiation decreases as $H/W$ decreases. However, irradiance differences for different canyon depths are extremely small (about 35 W/m² maximum), far smaller than
Fig. 6. Access indices for model pedestrian for a grid street pattern by aspect ratio, latitude (° N) and season. Isoline interval is 0.1.

Table 1
Mean irradiance on model pedestrian within street canyons in grid configuration expressed as a proportion of that on the same solid figure located in an open site with the same surface albedo as the canyon floor.

<table>
<thead>
<tr>
<th>Latitude (degree)</th>
<th>Month</th>
<th>H/W</th>
<th>0.25</th>
<th>0.50</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° N</td>
<td>June</td>
<td>0.77</td>
<td>0.58</td>
<td>0.43</td>
<td>0.19</td>
<td>0.12</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>0.78</td>
<td>0.58</td>
<td>0.43</td>
<td>0.19</td>
<td>0.12</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>20° N</td>
<td>June</td>
<td>0.77</td>
<td>0.64</td>
<td>0.49</td>
<td>0.32</td>
<td>0.23</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>0.65</td>
<td>0.52</td>
<td>0.27</td>
<td>0.16</td>
<td>0.10</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>40° N</td>
<td>June</td>
<td>0.77</td>
<td>0.67</td>
<td>0.48</td>
<td>0.32</td>
<td>0.24</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>0.60</td>
<td>0.55</td>
<td>0.22</td>
<td>0.12</td>
<td>0.10</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>60° N</td>
<td>June</td>
<td>0.72</td>
<td>0.55</td>
<td>0.42</td>
<td>0.20</td>
<td>0.14</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December</td>
<td>0.34</td>
<td>0.24</td>
<td>0.15</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>

The differences generally found by aspect ratio for the irradiances on the canyon floor and walls and on the model pedestrian. Differences due to canyon orientation are even smaller. For all canyons in June, $K^*_T$ increases between the equator and the Tropic...
Fig. 7. Net irradiances at canyon top (W/m²) by latitude (° N), canyon orientation, season and aspect ratio. Line symbols denote aspect ratios as follows: +---+ H/W = 0.25; x-x H/W = 0.5; *---* H/W = 1.0; □-□ H/W = 2.0; Δ-Δ H/W = 3.0; ○-○ H/W = 4.0. Broken line shows irradiance on an unobstructed, horizontal surface. 'GRID' denotes mean of irradiances for north-south ('N-S') and east-west ('E-W') canyon orientations.

Of Cancer, after which it varies little to 70° N. In December, $K^*_T$ decreases poleward for all canyons.

In all months, $\sigma_T$ is only weakly dependent on latitude, varying in the range 0.85 - 0.94, implying a canyon 'top albedo' of 0.06 - 0.15 (Table 2). The lowest albedos are associated with the deepest canyons but Table 2 suggests that, at least in the transitional seasons and winter, albedo tends to increase poleward.

Since no divergence of solar radiation occurs in the canyon air volume in the model employed, it follows that

$$K^*_T = (H/W)K_{\downarrow W}(1 - \alpha_w) + K_{\downarrow F}(1 - \alpha_f)$$

where $\alpha_w$ and $\alpha_f$ are the wall and floor albedos, respectively. The rather smooth dependence of $K^*_T$ on latitude and the small differences among canyon types contrasts markedly with the latitudinal behavior of $K_{\downarrow W}$ and $K_{\downarrow F}$ in many of the graphs in Figs. 1 and 3, suggesting a low degree of association between the individual irradiances on the right-hand side of the above equation and that on the left. This is revealed in Table 3, which shows the linear correlation coefficient between $K_{\downarrow W}$, $K_{\downarrow F}$ and $K^*_T$, by month. For much of the year, the net canyon top irradiance is a poor predictor of the irradiances on the canyon facets or on a model pedestrian for canyons of different orientation, aspect ratio and location. In general, the highest correlations are found in that part of the year when the solar de-
TABLE 2
Top albedo of street canyons in grid configuration by aspect ratio, season and latitude

<table>
<thead>
<tr>
<th>Latitude (degree)</th>
<th>H/W (December)</th>
<th>H/W (March/September)</th>
<th>H/W (June)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H/W (December)</td>
<td>H/W (March/September)</td>
<td>H/W (June)</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>0° N</td>
<td>0.13</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>20° N</td>
<td>0.13</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>40° N</td>
<td>0.13</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>60° N</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

TABLE 3
Linear correlation coefficient between net solar irradiance at canyon top and irradiances on canyon facets and model pedestrian

<table>
<thead>
<tr>
<th>Month</th>
<th>Correlation between canyon top ( K^* ) and irradiance on:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wall</td>
</tr>
<tr>
<td>January</td>
<td>0.74</td>
</tr>
<tr>
<td>February</td>
<td>0.64</td>
</tr>
<tr>
<td>March</td>
<td>0.30</td>
</tr>
<tr>
<td>April</td>
<td>-0.15</td>
</tr>
<tr>
<td>May</td>
<td>-0.42</td>
</tr>
<tr>
<td>June</td>
<td>-0.16</td>
</tr>
<tr>
<td>July</td>
<td>-0.31</td>
</tr>
<tr>
<td>August</td>
<td>-0.30</td>
</tr>
<tr>
<td>September</td>
<td>0.07</td>
</tr>
<tr>
<td>October</td>
<td>0.53</td>
</tr>
<tr>
<td>November</td>
<td>0.72</td>
</tr>
<tr>
<td>December</td>
<td>0.76</td>
</tr>
</tbody>
</table>

TABLE 4
Canyon absorptivity and solar access indices for overcast skies, by aspect ratio

<table>
<thead>
<tr>
<th>Aspect ratio H/W</th>
<th>Canyon absorptivity</th>
<th>Solar access index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wall</td>
<td>Floor</td>
</tr>
<tr>
<td>0.25</td>
<td>0.87</td>
<td>0.45</td>
</tr>
<tr>
<td>0.50</td>
<td>0.89</td>
<td>0.41</td>
</tr>
<tr>
<td>1.00</td>
<td>0.90</td>
<td>0.34</td>
</tr>
<tr>
<td>2.00</td>
<td>0.92</td>
<td>0.24</td>
</tr>
<tr>
<td>3.00</td>
<td>0.92</td>
<td>0.18</td>
</tr>
<tr>
<td>4.00</td>
<td>0.92</td>
<td>0.14</td>
</tr>
</tbody>
</table>

clination is in the southern hemisphere and simple gradients of all irradiances tend to exist between the equator and 70° N.

The poor correlations shown in Table 3 suggest that an empirical approach to street canyon design, using remotely sensed urban terrain albedos [33 - 35] as surrogates for irradiances on canyon facets or pedestrians at street level, can be expected to have only limited applicability.

Overcast-sky irradiance

The simulation procedure employed in this study for overcast conditions gives \( K_{w}, K_{F}, K_{p} \) and \( K_{T} \) data which are independent of canyon orientation. Expressed relative to the unobstructed local global irradiance, as \( \sigma_w, \sigma_F, \sigma_p \) and \( \sigma_T \), the data become additionally independent of latitude and month. Table 4 shows these results as functions of canyon aspect ratio. As with the clear sky results, solar access indices decrease and canyon absorptivity increases as \( H/W \) increases. In general, however, the differences are smaller than in Figs. 2, 4 and 6 because deep canyons are not so markedly deprived of irradiation on their floors and lower walls since shading effects are not significant and a heavy overcast gives high radiance in the zenithal region of the sky [18, 23], maximizing penetration to street level.

THE ZONE OF COMPATIBILITY: SOME OBSERVATIONS

Mid-latitude cities under clear skies

Oke's [8] suggested maximum aspect ratio of 0.6 for an E–W canyon at 45° latitude is a form sufficient to maintain direct-beam irradiation over two-thirds of the equator-facing wall at noon on the winter solstice. The results presented above show that an urban surface with a gridiron street pattern of N–S and E–W canyons having this aspect ratio will experience wall irradiances equal to 64%, 36% and 51% of \( K_{T} \) under cloudfree skies in winter, summer and spring/autumn, respectively. On an annual basis, the walls will receive somewhat less than one-half
(46%) of the horizontal surface irradiance. The access index $\sigma_w$ is smaller in the high sun season, so that $K_{\downarrow w}$ will not increase as much from winter to summer as will $K_{\downarrow}$, a desirable attribute in the temperate latitudes where buildings may require heating in winter and cooling in summer.

This maximum desirable aspect ratio will result in floor irradiances of 42%, 70%, 56% and 60% of the available horizontal surface flux density in winter, summer, the transitional seasons and the year as a whole, respectively. Pedestrians will intercept about 30% of the potential solar radiation on an annual basis.

Canyons at the lower end of Oke's zone of compatibility (with $H/W = 0.4$) in all cases exhibit access indices greater than those for the maximum recommended aspect ratio; $K_{\downarrow w}$ is increased by 15% in winter but remains nearly unchanged in the summer. Street-level solar irradiances are increased (by 11% on an annual basis and up to 17% in winter), as are radiation loads on pedestrians (7% annual, 11% in winter).

More generally, for the mid-latitude belt between 35° and 55° latitude, aspect ratios in the range 0.4 - 0.6 will result in irradiances on the floor, walls and model pedestrians which are 58 - 75%, 42 - 55% and 27 - 36% of the yearly total of $K_{\downarrow}$, respectively.

Tropical cities under clear skies

Under low latitude conditions, minimization of solar irradiances within the urban environment may often be a desirable criterion in urban design. For gridiron canyons with $H/W$ ratios in the zone of compatibility, annual access indices decrease equatorward of 35° latitude to magnitudes around one-third at the equator. The dominance of the direct component of the global solar irradiance under clear high-sun conditions ensures the favourable circumstance that $\sigma_w$ will be small when $K_{\downarrow}$ is large. Solar access to walls can always be decreased by increasing $H/W$ to larger values than those appropriate for the temperate latitudes. However, significant reductions in $\sigma_w$ require extreme changes; for example, at 0° latitude, a fivefold increase in $H/W$ from 0.6 would be necessary to reduce annual totals of wall irradiance by one-half. Floor irradiances are more readily manipulated by changing ratios of wall height to street width, the practical benefit of which is reflected in the vernacular architecture of parts of the dry tropical world (e.g., Arab housing in North Africa [18]). For example, at 25° latitude, $\sigma_F$ varies from 0.78 at $H/W = 0.4$, to 0.68 at the high end of the mid-latitude zone of compatibility, and has been reduced to 0.34 for buildings which are twice as high as the street is wide. Controlling canyon floor solar irradiation may be more critical than doing so for building walls given that solar geometry requires that the floor access index at low latitudes will increase as $K_{\downarrow}$ increases.

Under sunny tropical conditions, human irradiances may be excessive and their reduction may be a realistic objective of urban planning. At 25° latitude, for example, an aspect ratio of 0.6 will give $\sigma_F = 0.26$. This can be halved by increasing $H/W$ to about 2.0. In tropical latitudes, $\sigma_P$ varies little with season so that $K_{\downarrow P}$ will be approximately proportional to $K_{\downarrow}$ throughout the year (although this irradiance varies relatively little under clear conditions in such regions).

High latitude cities under clear skies

Poleward of 55° latitude, city buildings will require heating and street-level environments will exhibit adverse characteristics, by virtue of low temperatures, for a significant portion of the year. While solar access indices are in some cases markedly dependent on street geometry at high latitudes, the small magnitudes of $K_{\downarrow}$ may militate against manipulation of canyon geometry for solar access at the expense of the competing requirements of shelter and nocturnal heat-island intensity. Indeed, poleward of the Arctic (and Antarctic) Circles, solar access arguments will be irrelevant for much of the year during polar night. Nevertheless, the energetic costs of ‘high rise’ construction are profound in a relative sense. For example, at 70° latitude, the annual total of $K_{\downarrow w}$ is halved as $H/W$ increases beyond the mid-latitude zone of compatibility to 1.7 and is reduced to one-third by $H/W = 2.8$. Street-level irradiance is halved with a square canyon cross section and is reduced to one-quarter by $H/W = 2.75$.

Cities under overcast skies

In climates characterized by a high frequency of heavy cloud cover, control of
solar access by the manipulation of street geometry is less readily achieved. For all latitudes under such conditions, a canyon with $H/W = 0.6$ will receive 39% of annual $K\uparrow$ on its walls, 66% on its floor and 32% on a human located within its pedestrian zone. Widening the canyon to an aspect ratio of 0.4 will increase floor irradiance to 75% of annual $K\uparrow$ but the other irradiances will show only minor increases.

CONCLUDING REMARKS

The major purpose of this study has been to present and explore the potential utility of a methodology intended to assist in the formulation of urban design guidelines from the point of view of solar access to street canyon facets and to the human occupants of those canyons. Numerical simulations of ‘solar access indices’ are proposed as a simple means of exploring the interactions of a far larger number of combinations of potentially plannable characteristics of street canyons than would be convenient with even a large measurement program. In this study, only the simplest combinations of these variables have been treated. In a particular planning application, the effects of a greater diversity of canyon geometries, construction materials and seasonally dependent source geometries (especially seasonally varying diffuse proportions brought about by cloud cover) could be investigated. Moreover, in some cases, access indices applicable for different time periods from those used here might be more appropriate; for example, access indices for pedestrians might be more usefully based on the human activity period in the outdoor city environment. Access index data could be conveniently tabulated, presented in nomogram form or approximated by interpolating formulae for use by the planning practitioners. Such instruments would constitute the types of quantitative and easily understood relationships sought by Oke, at least within the limited context of manipulating the solar radiation environment within the urban canopy layer.

ACKNOWLEDGEMENTS

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REFERENCES

2 A. Bitan (ed.), The Impact of Climate on Planning and Building, Elsevier Sequoia, Lausanne, 1982.
5 See, for example, Energy Build., 11 (1) (1988).
18 M. Evans, Housing, Climate and Comfort, Halsted, New York, 1980.