Title
Urban form and climate: case study, Toronto

Permalink
https://escholarship.org/uc/item/5c3460r1

Journal
Journal of the American Planning Association, 61(2)

Authors
Bosselmann, Peter
Arens, Edward
Dunker, Klaus
et al.

Publication Date
1995-04-01

Urban Form and Climate

Case Study, Toronto

Peter Bosselmann, Edward Arens, Klaus Dunker, and Robert Wright

This article describes a joint urban design study by the Berkeley Environmental Stimulation Laboratory and the Centre for Landscape Research at the University of Toronto. The study analyzed the effect of future development in Toronto's Central Area on street-level conditions of sun, wind, and thermal comfort. The study originated in response to public concern about the quality of the downtown environment and to implementation measures adopted by the Toronto city council in May 1993. The research presented in this article examines the shadowing produced by downtown buildings and recommends procedures and standards for preserving sunlight on Toronto's downtown sidewalks and open spaces. Second, this study considers the effects of buildings on wind conditions at street level. Third, the study evaluates the combined effects of sun and wind conditions on pedestrian comfort. Rather than focusing on just the effects of individual buildings, this research evaluates the cumulative effects of area-wide development.

Bosselmann and Arens are faculty members at the College of Environmental Design, University of California at Berkeley. Bosselmann is a professor of urban design and Director of the Environmental Simulation Laboratory, and Arens is Director of the Building Science Laboratories. Dunker and Wright are faculty members of the Department of Architecture and Landscape Architecture, University of Toronto.

Journal of the American Planning Association, Vol. 61, No. 2, Spring 1995.

This article makes use of knowledge as old as the experience of living in cities. The dimensions of streets and the placing of buildings affect city climate. The subject is especially attractive because writers who are known for their thoughts on what is pleasing to the eye have frequently covered issues related to climate.

During the Italian Renaissance, when the writings of antiquity were republished, Leon Battista Alberti and, later, Andrea Palladio reported on the observation by Cornelius Tacitus that parts of Rome became hotter during the summer—and also less healthy after the streets had been widened during the reign of Emperor Nero. Palladio recommended that streets be made "ample and broad" in cities with cool climates, because such cities would be "much wholesomer, more commodious, and more beautiful," but that for cities in a hot climate (like Rome), streets would be healthier if made narrow, with houses high for shade. Vitruvius's writings about city layout and climate apparently inspired Alberti and Palladio. Vitruvius, writing at the time of Emperor Augustus, gave detailed instructions to those laying out new colonial cities.[1] Vitruvius was especially concerned about winds and had detailed advice on how to avoid their violent force by directing streets away from those quarters of the compass from which the wind generally blows. Vitruvius's writings were studied in Spain's colonial office and incorporated into the "Law of the Indies," proclaimed by King Philip II of Spain in 1573,[2] and were sometimes applied in the layout of New World cities.

Thomas Jefferson, upon returning from England and France, complained about the constantly gray skies of England and commented on the collective psyche of the English as showing suicidal tendencies due to lack of sunlight in the North. In America, he noted, the skies are usually blue, but high humidity makes people suffer during the summer months.[3] He designed an ideal city plan in the form of a checkerboard where the black squares denote built-up city blocks, and the white squares denote garden squares with diagonally traversing roads. He expected the cooler air from the shaded garden squares to create natural air circulation between the gardens and the hotter built-up city blocks.

The health benefits of direct sunlight and air circulation became the focus of studies carried out by the medical profession before the turn of the century and into the first quarter of this century. The findings on the relation between sunlight and, for example, bone diseases or tuberculosis, and on ventilation as a factor in health had a major effect on the practice of architecture and urban planning worldwide.[4]

In the last half century, however, local climate conditions have had less influence on the form, spacing, and style of buildings. The architect Bruno Taut (1977, 69) was right when he observed that fellow members of the modern movement had disregarded differences in local climates: "The modern buildings built up high in the north [of Europe] have the same appearance as those built along the Mediterranean Sea."

Each decade has brought new building styles, and changes in functional and structural requirements have changed building dimensions; but modern cities have rarely been shaped by a concern for a comfortable outdoor climate. The buildings of downtown Toronto, located in a climate with cold winters and hot and humid summers, are similar to those of downtown Phoenix, located in the arid Arizona climate. Street dimensions and the spacing between tall buildings in Houston, Texas are similar to those in Shinjuku, Tokyo. Here, and in other downtowns, urban form has worsened the local climates; streets and squares have become windier, hotter, or colder.

Although the relationship between the form of a city and its climate has been intuitively understood, intuitive predictions of how specific future buildings will affect climate conditions are not generally feasible. Nor does a comprehensive mathematical model exist that can predict how proposed structures will affect the comfort of pedestrians on sidewalks or in public open spaces. A combination of experimental and computational techniques is necessary to make comfort predictions. By comfort, we mean here the thermal conditions that affect the physiological and psychological well-being of a person leisurely walking along a sidewalk or sitting on a bench outdoors.

Six variables affect thermal comfort outdoors. **Solar radiation** provides warmth for the human thermoregulatory system. A human body exposed to **wind** exchanges body heat through convection. Two other climate variables, **humidity** and **ambient air temperature,** also affect thermal comfort. Additional factors are people's **activity levels** and their **clothing.**

Depending on local climate and seasonable weather conditions, a person may prefer to sit or walk in warm sunlight or in the cool shadow of buildings, may enjoy a cool breeze on her face and body, or may take shelter in buildings or inside arcades. Cities have been and can be built to provide these choices.

In 1990, the opportunity arose to carry out extensive modeling experiments on the effects of urban form on microclimatic conditions in Toronto.[5] Planners in Toronto were searching for a rationale to use in setting new building height limits and density controls for areas near the city's financial district.

The research presented here examines, first, the effects of buildings on wind conditions at street level, and second, the combined effects of sun and wind conditions on pedestrian comfort. Rather than focusing on individual buildings, this research evaluates the cumulative effects of area-wide development. Laboratory experiments compared existing development conditions with development permissible under then-current Toronto planning controls and with development under controls modified as recommended here.

Toronto's Climate

Canadians face greater challenges from their climate than do people who live in cities at the same latitude in Europe and Asia. Toronto, located at 43 degrees 40 minutes north latitude—the same position on the globe as the Cantabrian coast of Spain, Marseille in France, or Florence in Italy—has a winter season that lasts for six months, from November to April. During these six months the mean daily temperature hovers around 4.5 degrees Celsius. Spring comes to Toronto with some delay. During May and June the weather is generally fine; temperatures are around 18 or 19 degrees Celsius.[6] Pedestrians can expect comfortable conditions on Toronto's sidewalks and in parks, if they are sunny. In July and August, when temperatures rise above 25 degrees Celsius and the humidity measures above 55 percent on most days, people in Toronto take off jackets, seek shade, and, ideally, find a light breeze in order to stay cool. They seek such conditions at the shore of Lake Ontario or under trees in one of the parks (Figure 1).

Fall, in Canada, is world-famous but short. After two months of mild weather, winter arrives and drives people indoors or into insulated clothing.

The effect of buildings on Toronto's climate was first noticed in the late sixties, when the first stage of Toronto Downtown Centre neared completion. The buildings, designed by Mies van der Rohe and modeled after the Seagram Building in New York, were the first in Toronto's financial district to give up the street orientation, instead standing surrounded by corpo-

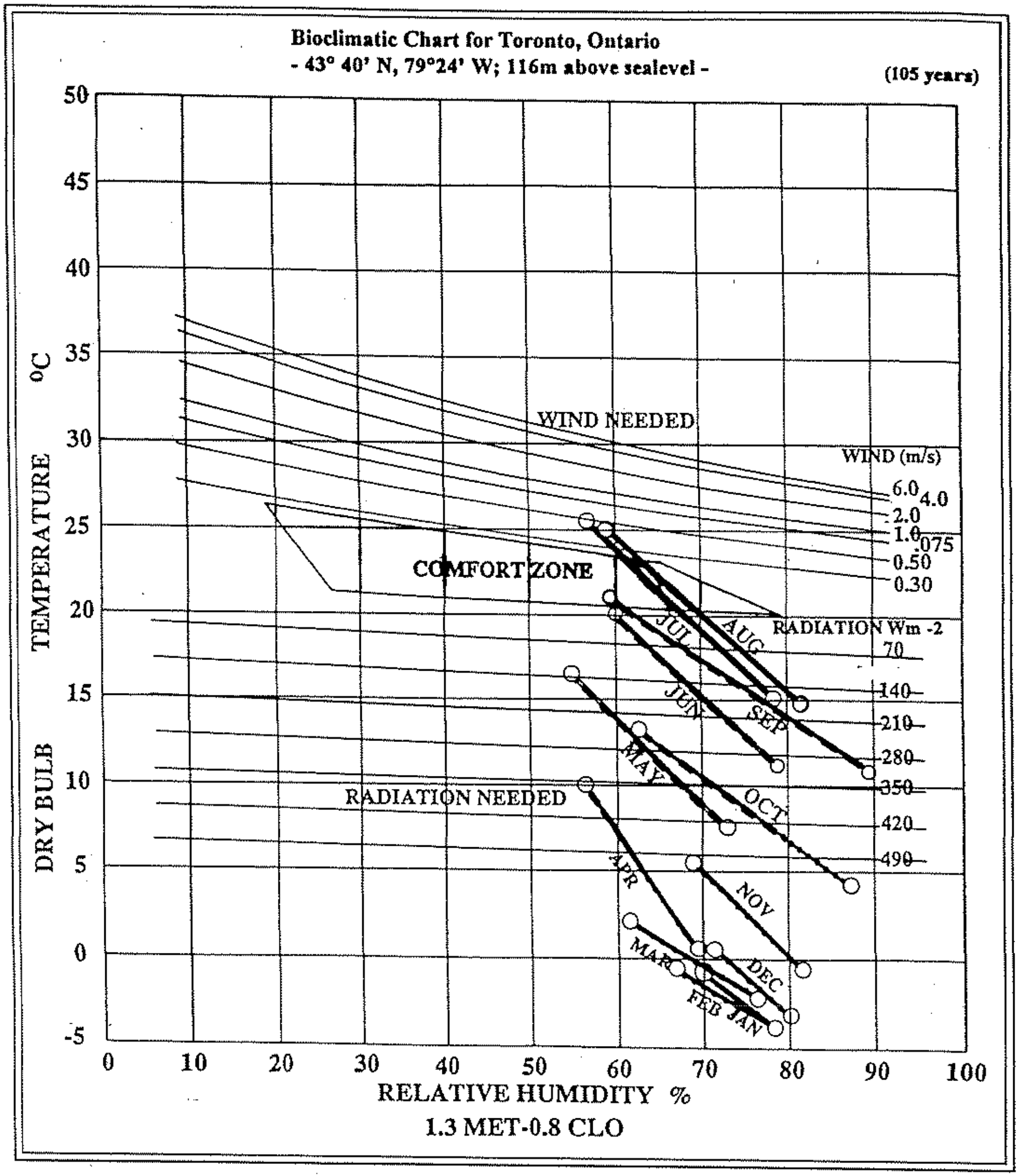


FIGURE 1. Bioclimatic chart for Toronto
The lines in the lower center of the chart connect Toronto's monthly average maximum and minimum temperature and humidity conditions. In the center of the chart, the boxed area indicates those temperature and humidity conditions under which a person leisurely walking, dressed in typical business clothing, would be comfortable in the shade. For most of the year, air temperatures are generally too low; direct sunlight is needed for comfort at this clothing level. The amount of radiation required to compensate for low air temperatures is indicated by the lines below the lower edge of the comfort zone.

rately owned, open plazas. People walking through these open plazas could not help but notice the harsh microclimate the towers created. On windy days, walkers had to brace themselves. The towers exacerbated the force of the wind.

With the Toronto Downtown Centre came the underground mall, essentially a suburban shopping mall placed underground and connected to the subway system. Now, twenty years later, nearly every downtown building can be reached through an underground network of tunnels and passages with shops, restaurants, and entrances to a clean and efficient subway system.

An office worker can leave an air-conditioned home, be dropped off from an air-conditioned car at the train station, arrive downtown, and walk underground through a well-lit shopping mall right into the underground lobby of a highrise building—without ever setting foot on a sidewalk exposed to sky. The wind chill factor reported on the radio is never experienced firsthand; the specially insulated clothing remains in the boot of the car.

Cafes serve lunch underground. After the evening rush hour, the underground stores start to close, and sections of tunnels are locked until the next workday. The population of office workers appears to be well served by the underground network. Its convenience may even contribute to the choice that sixty-one percent of Torontonians make every day to take public transport to work,[7] a percentage among North American cities second only to that in New York City.

The convenience comes at a price. Much of the street life has been taken away from the surface streets.

The Three Study Areas

In 1990, presented with the task of planning for an extension of the business district in an area located between downtown and Lake Ontario on land once covered by railroad tracks, planners asked whether it was possible to line the new streets with buildings that would not drive Torontonians underground. The planners wanted to design streets that could function instead as a pedestrian link between the existing downtown core and the lake front (Figure 2).

Along streets in other areas east of downtown but immediately adjacent, the planners envisioned a concentration of new inner-city housing with stores, designed to encourage people to walk to work in the business district (Figure 3).

Finally, in a third area, tall office towers had sprung up near the intersection of the two subway lines. This cluster of buildings, which had grown for two decades, was now approaching a lowrise neighborhood and a colorful historic district with evening entertainment, somewhat similar to sections of even more colorful Montreal (Figure 4).

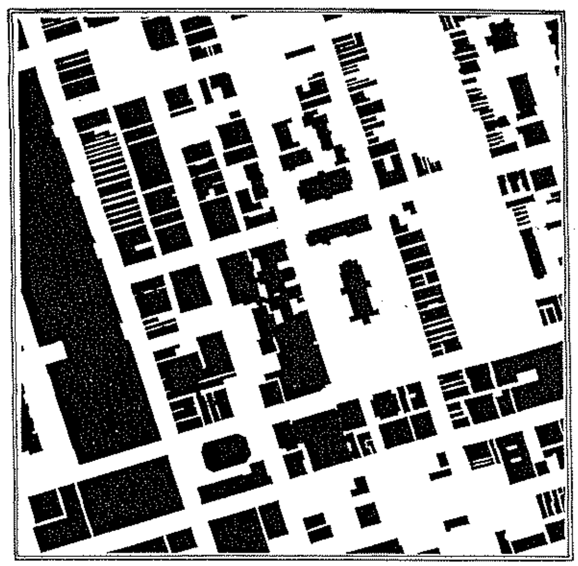


FIGURE 3. Existing building footprints, east downtown

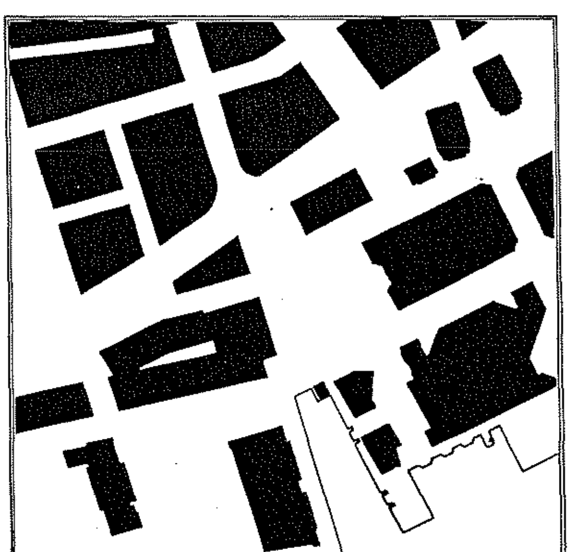


FIGURE 2. Existing and proposed building footprints, lake front

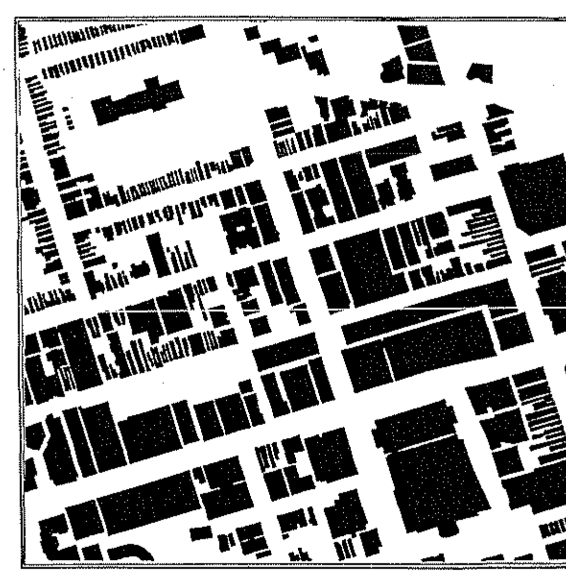


FIGURE 4. Existing building footprints, midtown, Yorkville area

These three areas were the subject of detailed studies in the laboratory. They were modeled at a large scale for wind tunnel studies and shadow analysis (Figure 5).

Wind Velocities In Toronto

The wind tunnel studies confirmed what had been measured in other cities. Winds along streets 20 meters (66 feet) in width, lined by buildings of up to four stories in height, produce shelter. Winds here are only 25 percent to 50 percent as strong as winds in the open countryside. For example, on Yorkville Avenue near the intersection of Belair Street, in a section of Toronto's Yorkville district, the average velocity of the wind is 23 percent to 52 percent of the wind velocity at the weather station, for all wind directions tested. Along this street are rows of buildings rarely exceeding four floors (Figure 6).

Two city blocks to the east from there, near the corner of Bloor and Yonge Streets, the wind velocities are 94 percent to 150 percent of those measured at the weather station (Figure 7).

Here, on days with northwest winds, the wind frequently accelerates among several highrise towers, and is deflected downward towards the sidewalks on Bloor Street. Apart from the wind's chilling effect at low temperatures, the accelerated wind speed exerts a mechanical force on pedestrians. Along the section of the Bloor Street sidewalk where wind velocities of 150 percent were measured, a modest 8 mph wind as measured at the weather station is accelerated to 12 mph, a wind speed that drives rain laterally, raises dust and paper, and disarranges people's hair. If the weather station wind is stronger than 20 mph, as it is in Toronto during the cold season, pedestrians at the foot of the high buildings begin to have difficulties walking because gusts within the 30 mph average wind exceed 44 mph, a wind speed criterion commonly accepted as the limit for people's safety.[8]

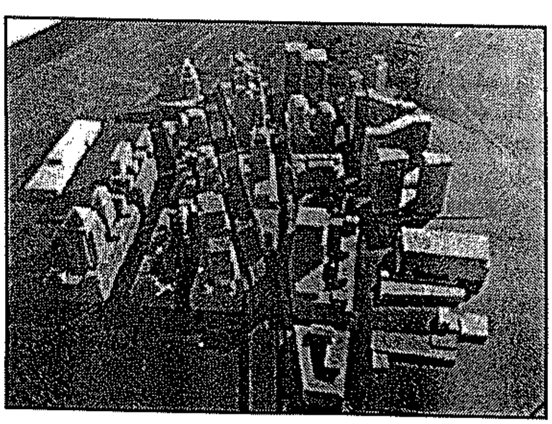


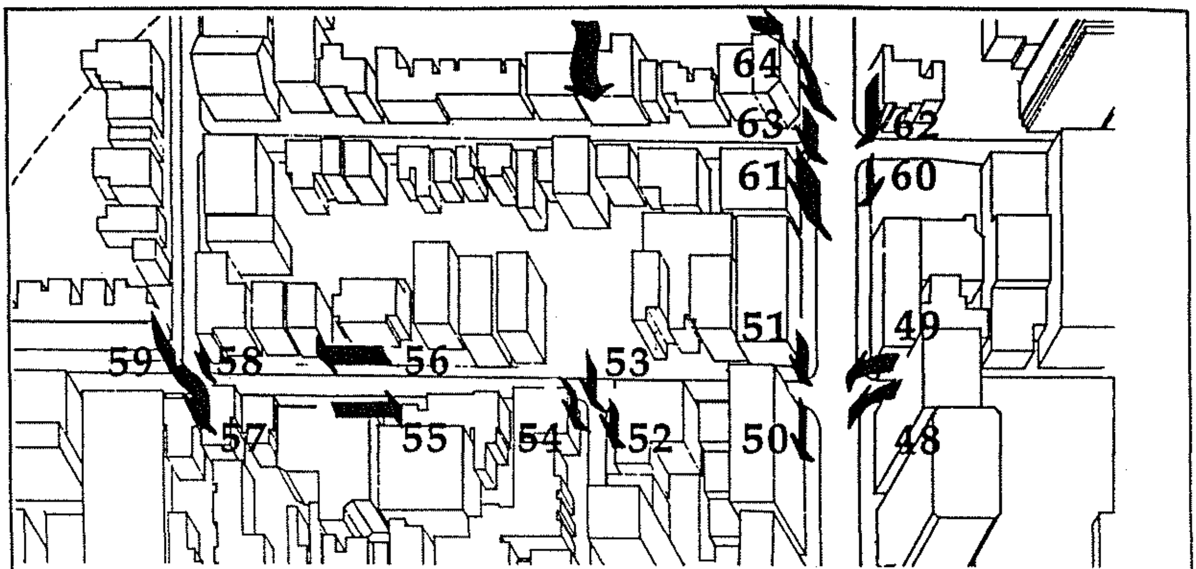
FIGURE 5. Modeling of existing, potential, and mitigated development for three Toronto areas

Standards for wind protection are still new in North American cities, but models for developing such standards exist.[9] They would, if applied consistently, change the form of cities. In a city shaped to manage wind velocities, building heights would rise less abruptly. In general, building heights would increase gradually from the heights predominant in a neighborhood, towards the city center. Building heights in downtown areas would be set similar to the contour lines of a hill, with the highest structures permitted in the center. Wherever height zones abutted, the change in height allowed would be less than half of that allowed in the adjacent higher height zone.

These general criteria, which came originally from wind tunnel experiments done by the authors with models of San Francisco and New York City, were confirmed in the testing of the three Toronto areas. In Toronto, it was observed that on future streets in the former rail yard area, lined with tall buildings up to 130 meters (433 feet) in height, a far more generous tower setback above a tower base was necessary than previously thought. Hypothetical building alternatives were constructed out of foam, and their wind conditions were compared with those of buildings possible under the then-current official plan. The hypothetical buildings were constructed with a tower base portion placed at the property lines, resulting in a height of 24 meters (80 feet) along streets that measure 40 meters (133 feet) in width. The position of the towers placed on top of the base portions was made adjustable. Only when the towers were adjusted at a 20-meter (66-foot) setback, measured from the 24-meter- (80-foot-) high street wall, could significant reductions of wind speeds be observed at street level. Less generous setback resulted in downward channeling of the wind towards the sidewalks. Thus designers of future buildings in Toronto should observe those setback rules, unless future wind tunnel studies indicate that other forms of wind blockage would provide the necessary reductions in velocity.

Sun, Wind, and Comfort

The measurement of wind provides one of six variables that affect thermal comfort for people outdoors. Solar radiation provides warmth for the human thermoregulatory system and can compensate for the body's heat loss on cold and windy days. Humidity and temperature also affect thermal comfort. At a particular sidewalk location, the occurrence of all four climate variables can be predicted from weather records, from calculations of the shade produced by buildings



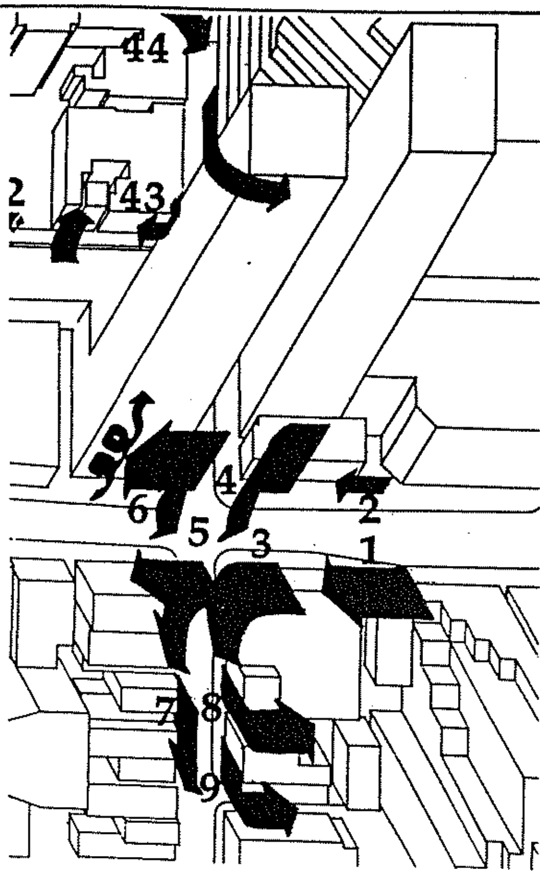
Pt. No.	Wind Ratio NW	W	SW	E
48	0.418	0.395	0.241	0.362
49	0.361	0.317	0.59	0.351
50	0.336	0.595	0.521	0.397
51	0.423	0.505	0.481	0.422
52	0.311	0.372	0.592	0.411
53	0.382	0.529	0.55	0.298
54	0.294	0.324	0.307	0.251
55	0.234	0.533	0.335	0.403

Pt. No.	Wind Ratio NW	W	SW	E
56	0.424	0.496	0.361	0.369
57	0.55	0.666	0.263	0.383
58	0.362	0.673	0.444	0.594
59	0.811	0.604	0.363	0.254
60	0.244	0.622	0.573	0.43
61	0.916	0.686	0.56	0.349
62	0.396	0.49	0.32	0.491
63	0.596	0.564	0.416	0.345
64	0.598	0.715	0.493	0.538

FIGURE 6. Yorkville area: wind velocities
Northwest wind velocity ratios in the Yorkville area of Toronto (map), and velocities for west, southwest, and east winds (table)

at specific times, and from wind tunnel measurements. For example, a prediction can be made as to whether a section of sidewalk is likely to be comfortable at a given day and time, from knowledge of the statistically typical temperature and humidity, whether the sidewalk is in the shade, and the extent to which winds over that section are accelerated or decelerated as observed in the wind tunnel. In order to relate this climate prediction to its effect on human comfort, assumptions also have to be made about the activity level of people, and about their clothing and how long they are likely to be exposed outdoors. With these data, a computer model of the human body's thermal response to the environment, which predicts comfort/discomfort for any given hour, can calculate comfort probabilities. The result of such a computation would indicate, for example, the thermal comfort of a person in a business suit leisurely strolling along a sidewalk on a spring day at lunch time. Let us assume that the air temperature measured 63°F (or 17°C) at the local weather station at that hour; that the humidity was moderate at 55 percent; and that the wind came from the west at 20 miles per hour. Along the Yorkville section of sidewalks lined with low buildings, conditions are assumed to be sunny, and wind tunnel measurements show an expected wind speed of 8 mph, or 40 percent of the 20 mph measured at the weather station. The computation shows that the person walking in the business suit would be comfortable.

If we now assume a different building configuration along a second stretch of sidewalk—for example, two highrise towers instead of the previous four-story buildings—then the sidewalk would be in the shade, and wind tunnel measurements indicate that the two towers would accelerate the northwest wind of 20 miles per hour as measured outside the city by 110 percent, or to 22 miles per hour along the sidewalk. Temperature and humidity would stay the same; so would the pedestrian's activity level and clothing. But the person in our example would now be uncomfortable, because the sidewalk would have become colder. Lack of sun combined with increased wind would make the person uncomfortable even after adding another layer of clothing. This computation may now be



Pt. No.	Wind Ratio NW	W	SW	E
1	1.088	1.163	0.149	0.898
2	0.385	0.998	0.228	1.091
3	1.105	0.617	0.253	0.52
4	1.495	1.206	0.324	0.877
5	0.941	0.832	0.206	0.441
6	1.276	0.787	0.318	0.691
7	0.768	0.661	0.354	0.704
8	0.949	0.639	0.318	0.652
9	0.775	0.526	0.41	0.716

FIGURE 7. Bloor Street area: northwest wind velocity ratios at the intersection of Bloor and Younge Streets (map), and wind velocities for west, southwest, and east winds (table)

repeated for all lunch-time periods over the entire spring season, and then for lunch periods during the other three seasons, resulting in percentages of time when pedestrians are likely to be comfortable or uncomfortable.

The Toronto Experiment

A combination of methods was used to study the effect of buildings on Toronto's climate. Methods included modeling of existing and potential development for wind tunnel experiments, and mathematical modeling of the human body's thermoregulatory system. An important step in the research was to map the results of wind tests and comfort condition modeling on seasonal maps showing the exact locations where measurements had been taken. Studying these maps, the research team analyzed the existing physical conditions in the vicinity of the measurement locations. For selected sites, they then changed the model to show potential development permitted under current planning controls, took new measurements at the identical locations, and analyzed them. The team then modeled a second set of future buildings, introducing setbacks above street facades to reduce sidewalk wind velocities and to permit sunlight into streets and open spaces. They repeated the testing of the study areas with the reconfigured future buildings in the wind tunnel and repeated the modeling of human comfort conditions, mapped the new results, and compared the net changes between existing conditions and each of the two alternative futures. The maps made it possible to analyze all comfort variables more closely, and allowed the team to determine which variables influenced comfort the most.

In winter, for example, sunlight benefits comfort, but does not alone produce sufficient warmth; sidewalks need protection from strong wind as well. Sheltered, sunny sidewalks are normally comfortable for a person in warm clothing, walking briskly.

During the spring and the fall, the pastimes of sitting on benches or leisurely strolling are comfortable only in direct sunlight. Sunlight is clearly the dominant variable, given Toronto's relatively cool air temperatures. Protection from wind, if combined with shade, will not be enough to ensure comfortable streets in those seasons. During the summer, however, shade combined with a light breeze is ideal, because of frequently hot and humid weather (Figures 8 and 9).

Streets For All Seasons

A city in a cold winter/hot summer climate like Toronto's can have comfortable streets year round. Many streets in Toronto's inner city are in fact comfortable, yet streets in the financial district are rarely so. The highrise buildings proposed for the area of the former railyards have larger floor plates than the Toronto Downtown Center does. On renderings and as models, the proposed buildings evoke the images of older highrise towers built in the 1920s, such as those located on King Street at the Imperial Bank of Commerce. In fact, though, the buildings proposed for the former railyards are far taller and have greater bulk.

Comfortable streets were a planning objective for the former railyard area. But modeling showed that

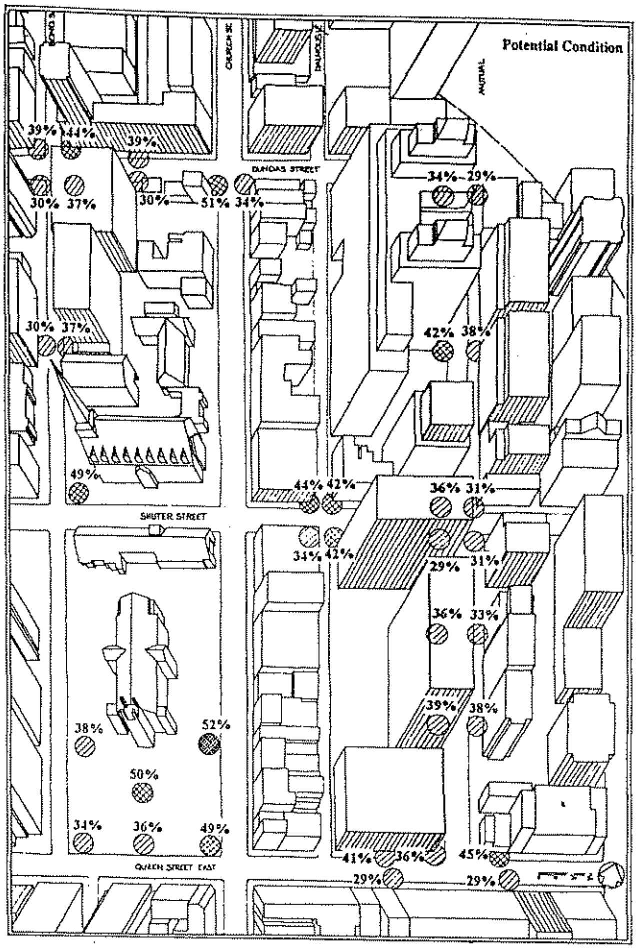


FIGURE 8. East Downtown: comfort map for potential development. Duration of comfort and percentage of time on a typical spring day

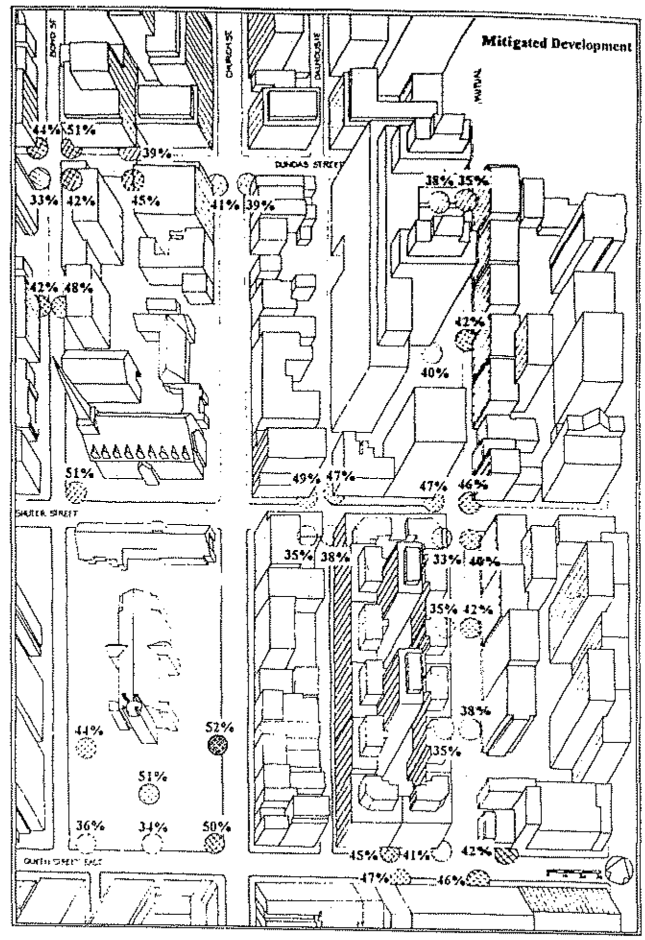


FIGURE 9. East Downtown: comfort map for mitigated development. Duration of comfort and percentage of time on a typical spring day.

the total floor area for each building, rather than being 15 times the lot area, would have to be limited to ten times the lot area. At that reduced building bulk, it would be possible to design buildings that would not create strong winds on sidewalks. The towers also could be placed to allow for three hours of sunlight during midday, from March to September, on at least one sidewalk of all streets between the existing downtown and the lake front (Figure 10).

Recommendations For New Planning Controls

The modeling in the laboratory has helped to establish building height limits and building bulk controls. The team recommended the allowable heights of new construction be set to produce three, five, or seven hours of sunlight daily from March to September. The three-hour period was considered the minimum to provide comfortable conditions around midday on commercial streets in the central district of Toronto (Figure 11).

In other downtown areas, the five-hour time window was proposed for all major pedestrian connectors, shopping streets, and historic or tourist areas. Finally, seven hours of sunlight was proposed for all residential streets on the edge of downtown. All three time windows were centered around noontime on the 21st of September. For example, a building on a north-south street 20 meters (66 feet) in width would have a street facade of 27 meters (90 feet) in height; above that height, upper floors would set back following a plane of 60 degrees. Along streets that measured 30 meters (100 feet) in width, the street facade would rise to 38 meters (124 feet).

As a result of the analysis, recommendations were made to revise the building height limits and bulk controls. Districts in Toronto limiting buildings to 30 meters in height were generally less affected by the recommended revisions than were districts that permit-

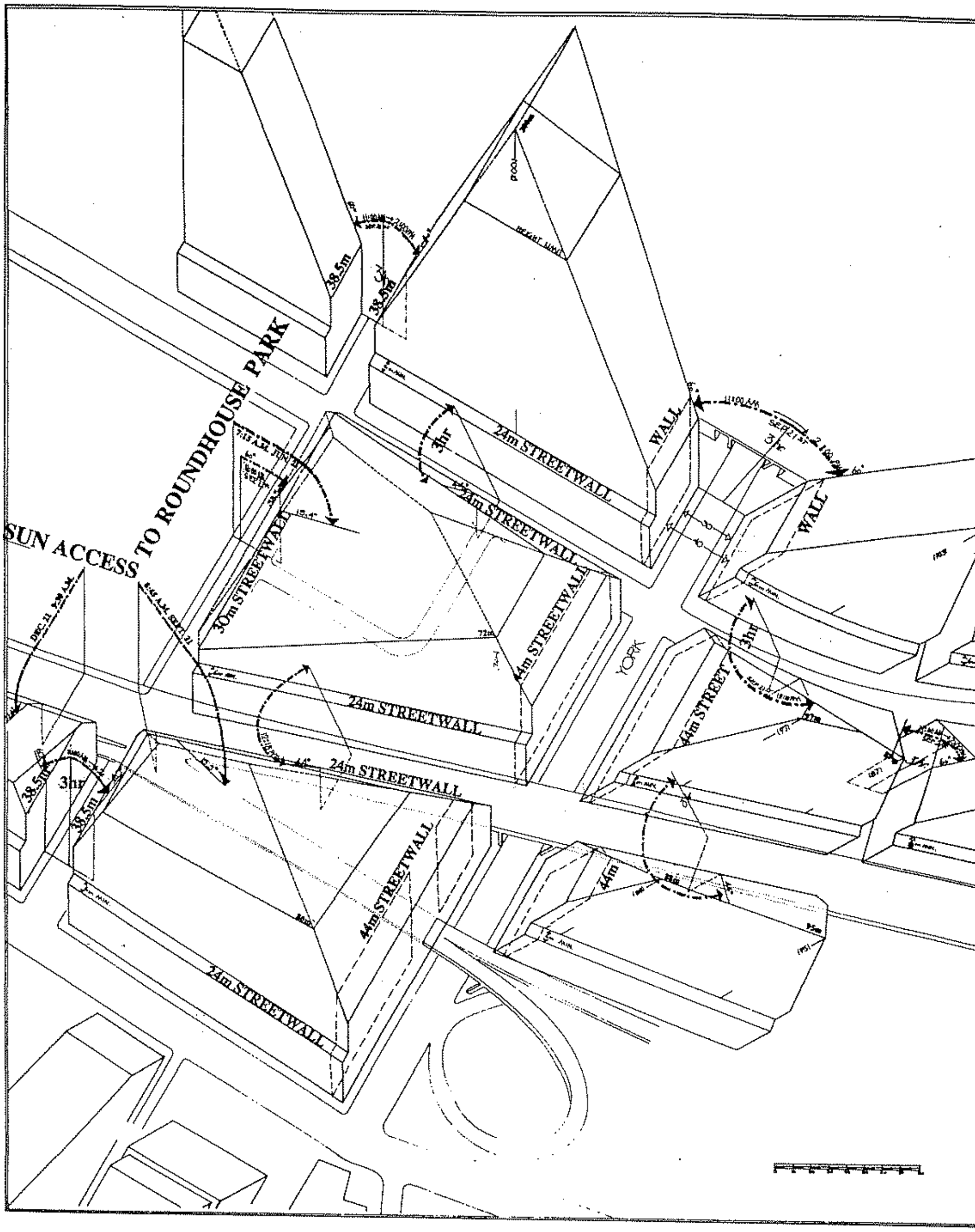


FIGURE 10. Comfort controls: allowable building height envelopes to ensure 3 hours of sunlight on at least one sidewalk of all streets during midday

ted higher structures. Likewise, districts with an allowed building bulk of up to 4 to 6 times the lot area were less affected than were districts with higher floor-area ratios (Figure 12).

The research was completed in December 1990. Toronto's city council held hearings on the recommendations, combined with hearings on various other aspects of a new plan for the center city area; and in the spring of 1993, in voting to amend the general plan, the council adopted the recommendation in part. No reduction in height limits or bulk controls took effect in the railyard area near Lake Ontario, nor along many of the streets studied to the east and north of the financial district, but reductions did

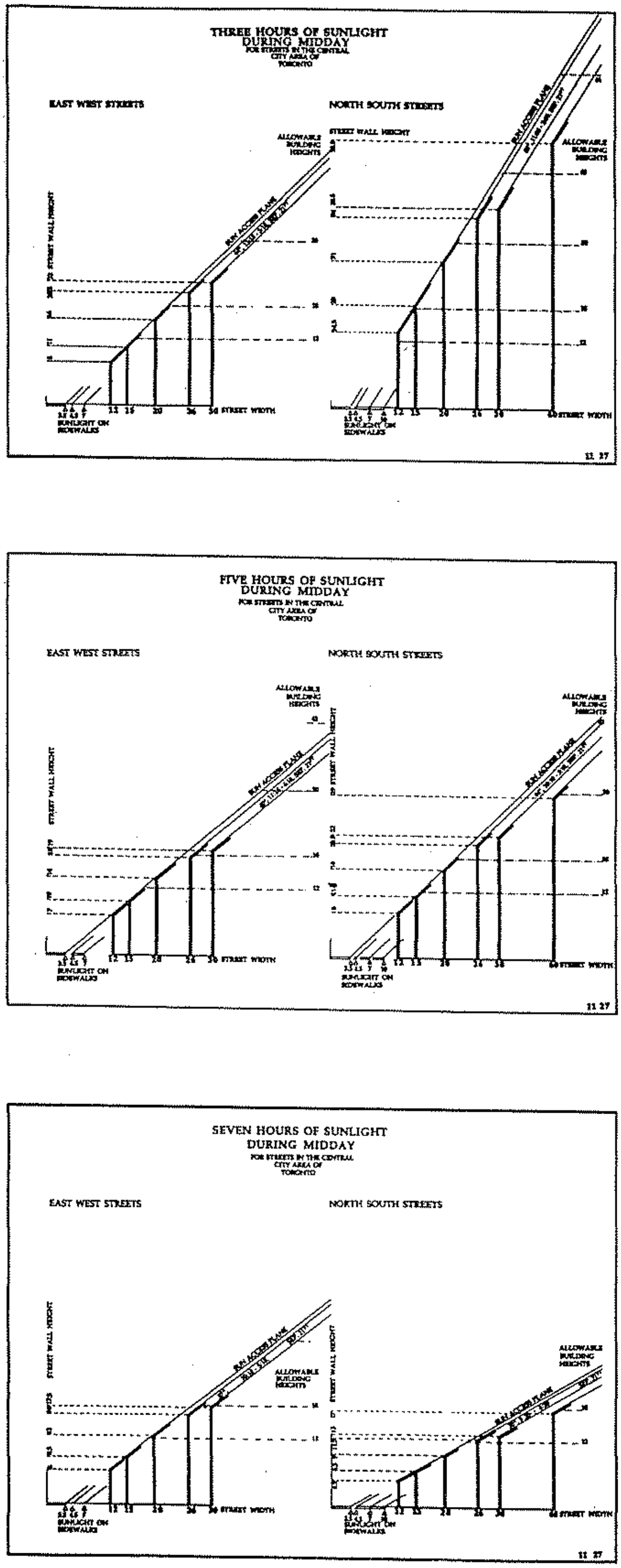


FIGURE 11. Sun access standards: for 3 hours, 5 hours, and 7 hours, encompassing midday

apply to all main streets leading from the city core area into the neighborhoods. The council also approved adoption of wind protection standards and wind tunnel testing consistent with the recommendations.

City Climate and Trees

Visitors to the city leave impressed by Toronto's many beautiful neighborhoods, which are enhanced by the significant use of street trees. At maturity, the trees easily reach across streets, creating an enclosed "roof" that improves the microclimate, especially during the summer. The same effect could be achieved along downtown streets.[10] Sun access controls would provide direct sunlight during spring and fall, when it is needed for comfort and when trees are without foliage. During the summer, Torontonians could have a choice of walking in the sun or in the shade, depending on weather conditions. On wide sidewalks like those along University Avenue, double rows of trees could be planted, turning the 50-meter- (163-foot-) wide street into a boulevard. Walking and sitting under rows of majestic maple trees would improve comfort even on hot humid days, because the shaded areas under the trees being somewhat cooler than the sunlit asphalt surfaces, and the highrise facades would produce heat exchanges, resulting in light breezes (Figure 13).

Buildings have to provide shelter during the winter. Along the new commercial streets on the former railyards, continuous arcades could run parallel to sidewalks, and instead of extended underground walkways, open arcades could shelter pedestrians from snow and rain. The sidewalks outside the arcades could be wide enough to provide sunny walks during the times when people prefer sunlight. During warm seasons, the arcades would be attractive places for outdoor restaurants. The high residential density proposed for the railyard area and the lake front, the office towers, the City's largest sports facility, and the City's main commuter rail terminal—all would bring pedestrians to the sidewalks in walking distance of the lake front: a unique opportunity to use city design so that streets are enjoyable during all seasons.

Comfort Model and Application of the Methodology in Other Cities

The mathematical comfort model (Gagge 1986) used in the Toronto experiment is briefly described as follows. The model assumes a cylindrical human body with skin layer and clothing evenly distributed over the inner core (Arens 1986). Before exposure to the environment, the body is thermally neutral. Exposure begins by reading in the four climate and two personal variables for a particular time of day and year. The

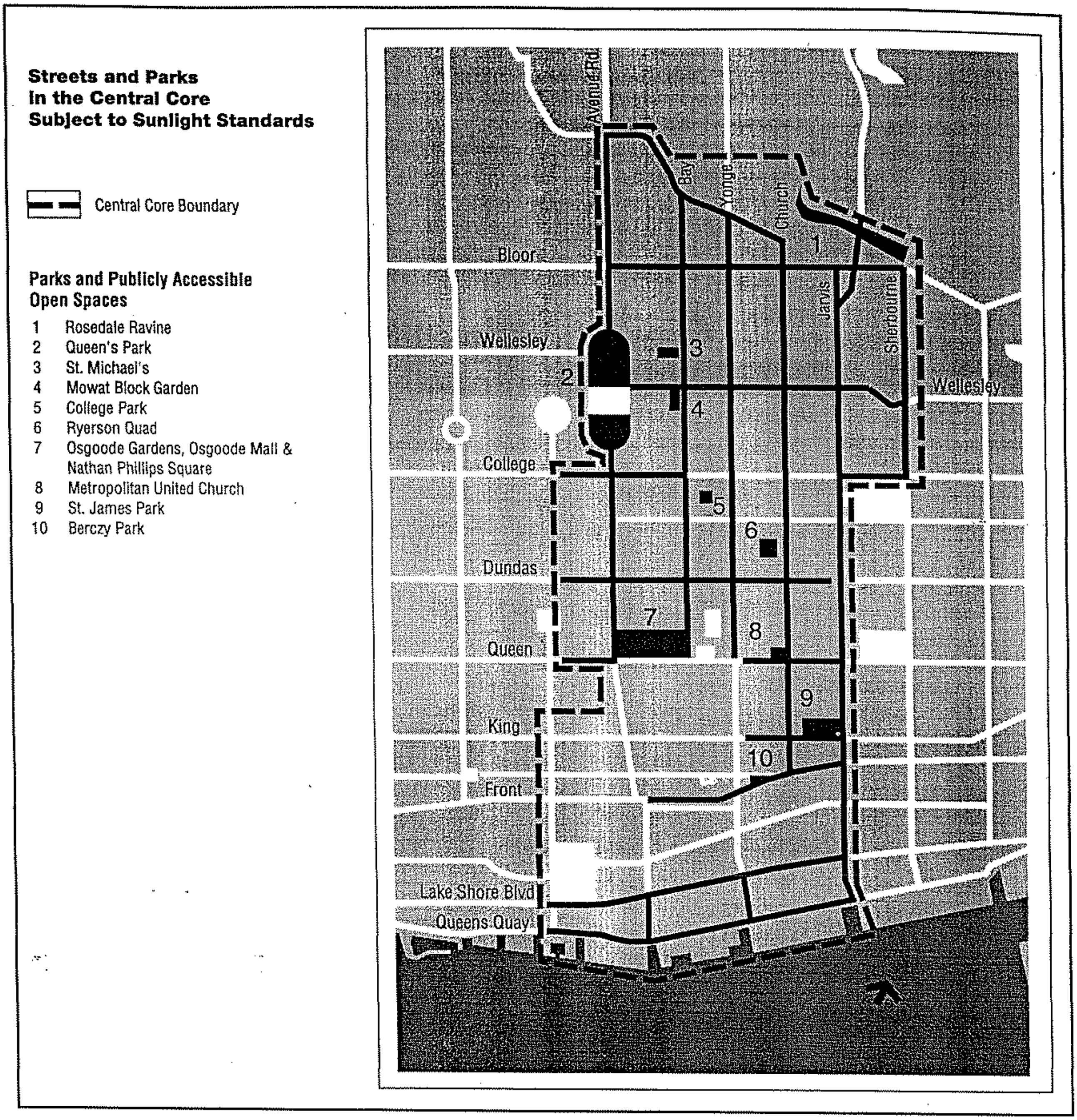


FIGURE 12. Toronto central city areas, subject to sun access standards (adopted 5/93)

model solves the body's heat balance, minute by minute, for the assumed length of time the person is exposed. At the end of the exposure, the model evaluates the new skin temperature and/or skin wettedness due to sweating. It then moves to the next hour and repeats the process. The entire year is thus assessed. Laboratory studies have provided well accepted relationships between the physiological measures (skin temperature and wetness) and thermal comfort, for indoor conditions. A condition is considered comfortable if these variables are within the limits used in the American Society of Heating, Refrigeration, and Air Conditioning Engineers' thermal environment standard (ASHRAE 1992).

Applying the computer model to the city of Toronto required careful evaluation of each variable. The first two variables, metabolic rate and clothing, are based upon our estimates of typical activities and sea-

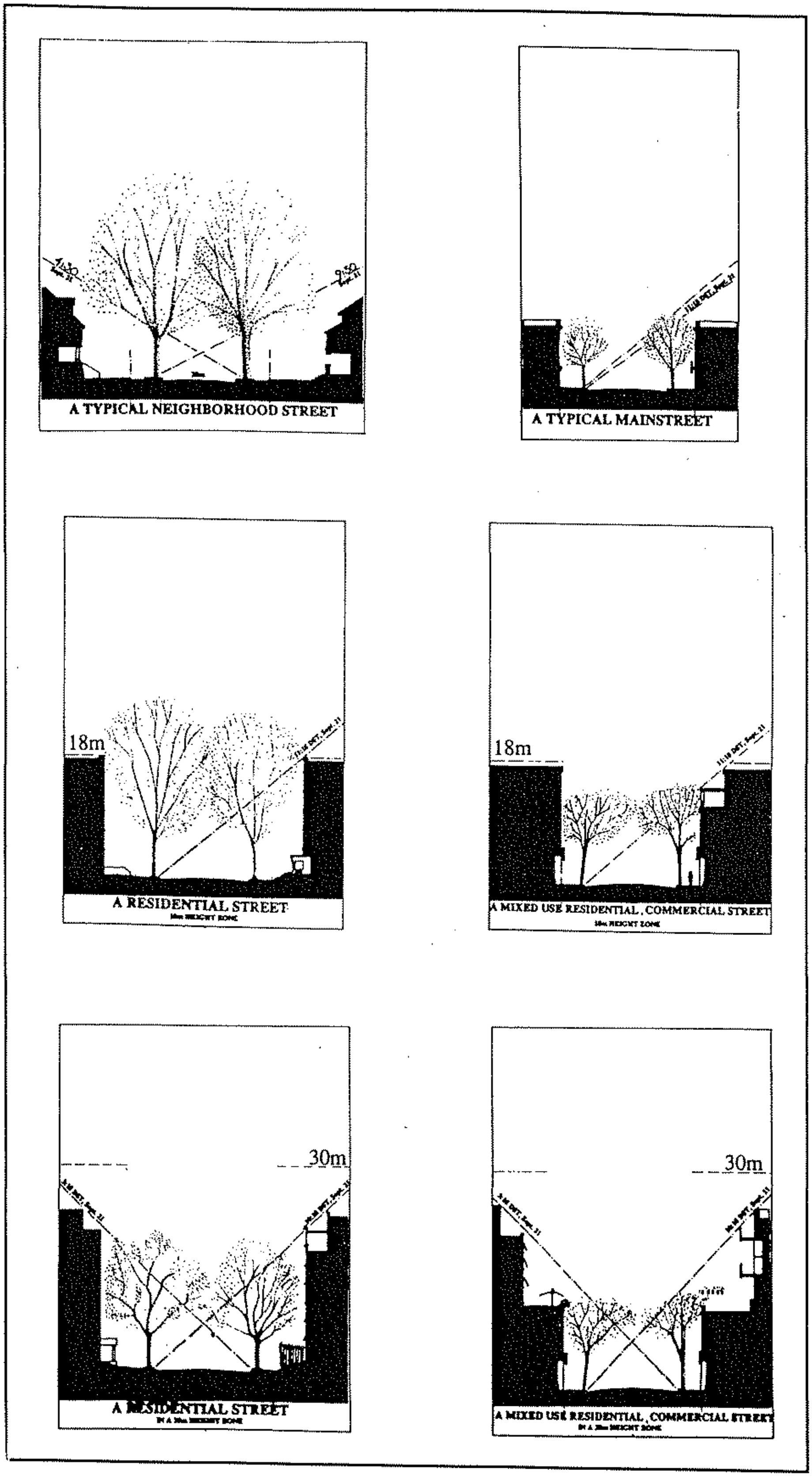


FIGURE 13. Typical street sections in height zones of 30 meters and below

sonal dress for the Toronto population. In addition, typical lengths of exposure in the outdoors were assessed and 20 minutes chosen for the variable. The four climate variables, air temperature, air velocity, solar radiation, and humidity, are the environmental conditions that people experience at street level. A standard form of hourly weather data, the "typical meteorological year," was used as a data set for the four climate variables. Local street-level air velocity was determined by adjusting the hourly wind speeds at the weather station, using the results of wind tunnel tests.

The model in its current form could not be used in an absolute sense to test compliance of individual building proposals with established standards for outdoor comfort conditions. Such standards do not exist yet, and to create them the model would have to be calibrated and validated for the Toronto population in a substantial field test. Also, administrative decisions would be necessary; for example, how does one weight the possible comfort advantages of a building proposal under summer conditions against disadvantages that it might create at other times of the year? Development of a performance standard for outdoor thermal comfort is a complex process and still the subject of research.

In its current form, the comfort model has been applied to other cities in different climate zones. In San Francisco (Bosselmann 1984), a city with a cool, windy climate, the model served to test potential developments in four downtown areas. San Francisco has become the first city in North America to adopt height limits and bulk controls, and a wind velocity standard designed to protect pedestrian comfort.

In future, the method might be applied in a city like Phoenix in the arid Arizona climate, or cities in the hot and humid climate of the southern United States and Mexico.

Likewise, as demand for larger and higher office structures increases in the capital cities of Europe and Asia, council members and administrators might want to know how planning decisions affect conditions for those who walk the streets and use the parks.

The method explained here takes us to the beginning of ordering city form: cities have first of all provided shelter, so all other activities, economic, cultural, and social, both public and private, can be conducted equitably.

AUTHORS' NOTE

This study was commissioned by the City of Toronto, Planning Development Department, Robert E. Millward, Commissioner, and was carried out between April 1990 and April 1991 under the supervision of the Architecture and Urban Design Division, City of Toronto, Marc Baraness, Director; Wendy Jacobson was the project director for the City of Toronto. The advisory group included Dr. Christopher Morgan, Gary Wright, and Thomas C. Keefe, all staff members of the Planning and Development Department. The following graduate students helped with field studies, laboratory experiments, and report graphics: James Bergdoll, Marc Fountain, David Ernest, Jane Ostermann, Kevin Gilson, Tim Mitchell, Adil Sharag-Eldin, Zhang Hui, David Lehrer, Alison Kwok, Brian Gotwals, Tom Powers, Colin Drobnis, Elaine Garrett, Kai Gutchow, Masato Matsushita, Peter Cheng, Tracy Pitt, Krystof Pavek, Claudio Cellucci, Ken DeWall, Henrik Dunker, Bruno Aletto, Mario Natarelli, and Lisa Laywine.

NOTES

1. For a review of the writings on city form and climate during Roman antiquity (Cornelius Tacitus and Marcus Vitruvius), see Joyseph Rykwert, *The Idea of a Town* (Princeton, NJ: The Princeton Press, 1976).
2. *Royal Ordinances Concerning the Laying Out of New Cities, Towns or Villages,* Archivo Nacional, Madrid, Ms. 3017, *Bulas y Cedulas para el Gobierno de las Indias,* San Lorenzo, July 3, 1573, translated by Zelia Nuttall in *The Hispanic American Historical Review* 5, 2 (May 1922): 249–54. Also see Axel Mundigo and Dora P. Crough, *The City Planning Ordinances of the Laws of the Indies Revisited, Liverpool Town Planning Review* 48 (1977): 147–68.
3. Jeffersonville, Indiana, designed 1800–1805 to induce ventilation for the prevention of disease. Thomas Jefferson, letter to C. F. C. DeVolney, Washington, February 1805. See John Reps, *Town Planning in Frontier America,* Princeton, NJ: Princeton University Press (1969): 280.
4. A summary and review of the medical research finding was prepared by the Regional Plan Association in 1929 and presented in the monograph "Sunlight and Daylight for Urban Areas," by Wayne D. Heydecker and Ernest Goodrich; it appeared in *Neighborhood and Community Planning,* Vol. 7 (New York, 1929): 142–202.
5. An account of these findings was prepared for the City of Toronto. See Peter Bosselmann, Edward Arens, Klaus Dunker, and Robert Wright, *Sun, Wind, and Pedestrian Comfort,* City of Toronto, Cityplan 91. Copies available from the City of Toronto Department of Planning and Development, (416) 392–1135.
6. "Toronto Climate Data," in *The Times Book World Weather Guide* (New York: *New York Times,* 1984).
7. "Toronto Transportation Survey, 1986," cited in *City Plan 91* (City of Toronto: June 1991).
8. There are no benches on this section of Bloor Street; however, in an area with benches or places to sit, the acceptable limit of wind velocity amounts to 7 mph. For example, winds stronger than 7 mph would make it impossible to hold a newspaper. Setting a standard to protect those times when people are likely to use the benches, a planner would have to decide on the percentage of time when wind speed should be allowed to exceed this criterion.
9. For a discussion of wind speed limits, see Edward Arens,

"On Considering Pedestrian Winds During Building Design," in *Wind Tunnel Modeling for Civil Engineering Application: Proceedings of the International Workshop on Wind Tunnel Modeling Criteria and Techniques,* ed. T. Reinhold (Cambridge, England: Cambridge University Press, 1982): 8–26; E. Arens et al., "Developing the San Francisco Wind Ordinance and its Guidelines for Compliance," *Building an Environment* 24, 4 (1989): 297–303; A. G. Davenport, "An Approach to Human Comfort Criteria for Environmental Wind Conditions," CIB/WMO Colloquia; Teaching the Teachers, Swedish National Building Award Institute (Stockholm, Sweden, 1972); J. C. R. Hunt, E. C. Poulton, and J. C. Mumford, "The Effects of Wind on People," *Building and Environment,* Vol. 11 (Pergamon Press 1976): 15–28; A. D. Penwarden, "Acceptable Wind Speeds in Towns," *Building Science,* Vol. 8 (Pergamon Press, 1973): 259–267.

10. Very few street trees exist in Toronto's downtown core area, so none of the streets modeled for wind tunnel and sunlight studies had trees. However, the effect of trees on comfort could be tested by developing physical models of a larger scale than those used for this study.

REFERENCES

Alberti, Leon Battista. 1486. *Ten Books on Architecture.* Reprinted, New York: Transatlantic Arts, 1966, Book IV, chapter 5.

Arens, E., L. Berglund, and R. Gonzales. 1986. Thermal Comfort Under Extended Range of Environmental Conditions. *ASHRAE Transactions,* Vol. 92, Pt. 1.

ASHRAE. 1992. Thermal Environmental Conditions for Human Occupancy, Standard 55-92. Atlanta: ASHRAE.

Bosselmann, Peter, et al. 1984. *Sun, Wind, and Comfort, A Study of Open Spaces and Sidewalks in Downtown San Francisco.* Monograph No. 35, Institute of Urban and Regional Development. Berkeley, CA: University of California at Berkeley.

Gagge, P., A. P. Fobelets, and L. Berglund. 1986. A Standard Predictive Index of Human Response to the Thermal Environment. *ASHRAE Transactions,* Vol. 92, Pt. 2.

Heydecker, Wayne D., and Ernest Goodrich. 1929. *Neighborhood and Community Planning,* Vol. 7. New York, 142–202.

Knowles, Ralph. *Sun Rhythm Form.* 1981. Cambridge, MA: MIT Press, 229–97.

Palladio, Andrea. 1570. *Four Books on Architecture.* Reprinted New York: Dover Publications, 1969, Third Book, chapter one.

Reps, John. 1969. *Town Planning in Frontier America.* Princeton, NJ: Princeton University Press.

Rykwert, Joseph. 1976. *The Idea of a Town.* Princeton, NJ: Princeton Press.

Tacitus, Cornelius. c. 62–65. *The Annals.* Reprinted, Chicago: Encyclopedia Britannica, Inc., 1952.

Taut, Bruno. 1977. *Architekturlehre.* Hamburg: Sozialistischer Arbeiter Verlag.

Toronto Climate Data. In *The Times Book World Weather Guide.* New York: *New York Times,* 1984.

Toronto Transportation Survey. 1986. Cited in *City Plan 91.* City of Toronto.

Vitruvius, Marcus. 30 BC. The Directions of the Streets, With Remark on the Winds. In *Ten Books of Architecture,* Chapter VI, Section 8.