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DETERMINATION OF CLIMATE VARIATION WITHIN METROPOLITAN AREAS, PHASE I SUMMARY

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ABSTRACT

The choice of climatic information for urban building analysis and design can be problematic. The climates of adjacent urban, suburban, and rural areas are known to differ. For example, the urban heat island is a well-known effect. Thus, climatic information collected from rural or suburban weather stations may not be appropriate for building design within the urban center. In response to this problem, ASHRAE Technical Committee 4.2, Weather Information, is sponsoring a two-phase project (ASHRAE Research Project 606) to develop improved methods for estimating urban climatic variables of significance to building HVAC system design. This paper summarizes the results of Phase I of this project, which includes a review of urban climate literature, identification of key urban climate parameters, identification of existing algorithms for climatic variation, identification of three urban areas for further study, and selection of a basic urban simulation model.

INTRODUCTION

Climatic information is required for building design and energy analyses. Ideally, site-specific climatic information would be available or could be collected. Realistically, however, site-specific information is rarely available, and collecting such data for a specific project is usually impractical, since the necessary data must be collected over an extended period. Most often, the building designer must use climatic information from the nearest weather station, which may not be close by and may or may not be representative of the building site.

When the building site is in a metropolitan area, the choice of climatic information presents a particular set of problems. The climates of adjacent urban, suburban, and rural areas are known to differ. These differences derive from a variety of influences, including the well-known urban heat island phenomenon. For most metropolitan areas, the nearest primary weather station is located at the metropolitan airport, which is frequently located in rural or suburban areas on the periphery of the metropolitan area. Unfortunately, climatic data collected from such a station may not be appropriate for use in designing buildings located within the urban center.

In recognition of this problem, ASHRAE Technical Committee 4.2, Weather Information, is sponsoring a two-phase project (ASHRAE Research Project 606) to develop methods for determining climatic variation within metropolitan areas and to develop improved methods for estimating urban climatic variables of significance to building HVAC system design. Phase I of this project, as defined in the work statement, consists of the following tasks:

1. Compilation of data on climatic variation within urban areas (literature review).
2. Identification of key climatic parameters—The key climatic parameters are those that show the greatest variation as a result of location within a metropolitan area, for which that variation can be most easily characterized, and which have a significant effect on building design and HVAC&R engineering.
3. Identification of existing guidelines or algorithms that can be used in predicting climatic variation.
4. Identification of three metropolitan areas for which there are sufficient data or analyses to reasonably characterize climatic variation within the metropolitan area (i.e., detect urban-rural differences).
5. Adaptation or development of a basic urban simulation model.

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Phase II will include the following tasks:

1. Collection of additional field measurements, if necessary.
2. Development and extension of algorithms for metropolitan climatic variation.
3. Incorporation of improved algorithms and relationships into the model.
4. Testing of the simulation model against reference (field) data.
5. Determination of degree of generalization possible in the model.

This paper summarizes the results of Phase I of the project.

LITERATURE REVIEW

A review of the urban climate literature was conducted, based on numerous sources of information. The World Meteorological Organization (WMO) began funding research on urban climates in the mid-1960s; its publications provide a foundation for the present effort. These include two WMO-funded literature reviews by Oke, the first (Oke 1974) citing 377 papers published between 1968 and 1973, and the second (Oke 1979a) citing 434 papers published between 1973 and 1976. Together with Chandler's earlier bibliography (1970), these references provide a fairly complete bibliography on the subject of urban climatology through the mid-1970s. Landsberg's (1981) book, *The Urban Climate*, the WMO publication on urban climatology in tropical areas (WMO 1986), and the American Meteorological Society (AMS) publication, *Modeling the Urban Boundary Layer* (AMS 1987), provide a fairly extensive, if not comprehensive, list of the more recent (post-1975) literature. In addition, approximately 600 articles on the subject of urban climatology were identified from a search of two computerized data bases.

The literature search for this review focused on the post-1975 literature. A project reference library was established consisting of more than 100 separate items, including copies of articles, workshop reports, literature reviews, reports from technical conferences, and textbooks.

The remainder of this section provides a brief review of the current state of understanding of urban climate. The reviews mentioned previously and the final report for this project provide a more comprehensive review of urban climate and should be consulted for more detailed information and references.

Descriptive Review of Urban Climate

Much of the research on urban climate distinguishes between the urban canopy layer and the urban boundary layer (Oke 1976). The urban canopy layer is the lowest portion of the atmosphere between the earth's surface and the approximate top of the urban structures. As described by Oke (1976), the urban canopy layer is a microscale concept. Urban structures are imbedded within the canopy layer, and, consequently, the urban canopy climate is dominated by the physical characteristics of those structures, particularly the type of construction materials and building geometry. The urban boundary layer (UBL) begins at the top of the canopy layer and typically increases in height from the upwind edge of the city until it reaches a capping temperature inversion separating the relatively turbulent flow below from the laminar flow above. Oke (1976) describes the UBL as a mesoscale concept; the UBL dynamics are driven from below by the energy and mass fluxes that are characteristic of an urban area, which distinguish it from the rural boundary layer. In addition, both the urban and rural boundary layers are driven by synoptic scale weather and local topographic factors.

The following sections summarize the effect of the urban environment on air pollution, long- and short-wave radiation, temperature, winds, humidity, and the urban energy balance. The descriptions apply primarily to the urban boundary layer; however, since the canopy and boundary layers share a common interface, many of the characteristics are also descriptive of the canopy layer.

Air Pollution Perhaps the earliest observations of the difference between urban and rural climate were related to air pollution. The odes of Quintus Horatius Flaccus refer to Roman smoke pollution about 24 B.C. (Neumann 1979). Various forms of coal burning were banned in London several times during the Middle Ages due to pollution problems (Landsberg 1981:3). Air pollution continues to be a major characteristic of the urban climate in most major cities to the extent that urban air pollution has become a field of study in itself, distinct from other fields of urban climate. Although urban air pollution is not a climatic characteristic of direct interest to this project, it does play an indirect role through its effect on the urban radiation budget, as described in the following section.

Long- and Short-Wave Radiation The magnitude of the attenuation of solar radiation by urban air pollution ranges from a few percent to 30 percent or higher and depends on such factors as the type of pollutant, wind direction, cloud cover, time of year, time of day, and averaging period (Landsberg 1981). In addition to reducing the amount of solar radiation reaching the surface, air pollution also changes the character of the solar radiation. For example, scattering by air pollution results in a decrease in the ratio of direct to diffuse radiation (Sprigg and Reifsnyder 1972; Wesely and Lipschutz 1976), and preferential absorption of the shorter wavelengths, particularly the ultraviolet, changes the spectral distribution of the radiation (Peterson et al. 1978). Increased heating due to absorption of solar radiation by pollution may cause a resultant increase in atmospheric long-wave radiation (Rouse et al. 1973).

Temperature After air pollution, temperature is probably the most frequently studied characteristic of urban climate. As early as 1820, Luke Howard published data indicating that the temperature in the center of London was higher than in the surrounding areas (Landsberg 1981:5). Since then, the spatial and temporal features of the urban heat island phenomenon have been documented by numerous authors (Duckworth and Sandberg 1954; Oke and East 1971; Oke 1982, 1987b).

The magnitude of the temperature difference between urban and rural areas is referred to as the heat island intensity, $\Delta T_{(u-r)}$. The heat island intensity reaches a maximum during calm, clear sky conditions, typically two to five hours after sunset (Landsberg 1981:86; Oke 1982). The temperature difference during these conditions is referred to as the maximum heat island intensity, $\Delta T_{(u-r)max}$. The heat island intensity decreases following its maximum, until it is virtually eliminated by the time the maximum temperature is reached the next day (Oke 1982).

The maximum heat island intensity is usually centered on or slightly downwind of the urban center. Some studies indicate that a daytime "cool island" occurs within high-rise portions of central business districts (Ludwig and Kealoha 1968). This effect probably results from shading from tall buildings (Oke 1974). The heat island intensity is also reduced in parks and other areas with significant vegetation.

In middle latitudes, the heat island intensity tends to be greatest during the warmer months (Chandler 1965; Lee 1979; Unwin 1980). This supports the concept that the heat island in middle latitudes is not primarily due to anthropogenic heat (Oke 1982; Landsberg 1981:91), since anthropogenic heat generation peaks in winter. The greater intensity of the warm season heat island is probably due partly to weather conditions and partly to seasonal variations in surface cover (e.g., snow in winter, more abundant vegetation in summer), solar angle of incidence, and solar attenuation by aerosols (Oke 1982). Oke et al. (1991) point out the importance of the surface conditions associated with the rural temperature measurement site in determining heat island intensity. They indicate that rural site characteristics, particularly thermal admittance, may be important determinants of the seasonal characteristics of the heat island intensity.

Oke (1982) indicates that there are fewer data available from high- and low-latitude cities than for middle latitudes. He indicates that the available data suggest that the heat islands of low-latitude cities have characteristics broadly similar to those of middle-latitude cities. At high latitudes in winter, the diurnal effect of solar radiation is greatly reduced, while the effect of diurnal anthropogenic heat generation is increased. In summer, little diurnal variation in the high-latitude heat island is expected due to increased daylight hours and reduced time for cooling at night. In spring and autumn, the high-latitude heat island characteristics are similar to those of middle-latitude cities.

The maximum heat island intensity occurs at night during clear skies with light to calm wind conditions. The heat island intensity is lessened by increased cloud cover and wind speeds, tending to disappear in cloudy and windy weather (Landsberg 1981:83). A critical wind speed above which the heat island is essentially suppressed has been postulated, and Oke and Hannell (1970) have developed an expression relating that critical wind speed to city population.

Cities are often located on coastlines, in river valleys, or near other complex topography. The associated changes in terrain elevation modify the near surface heat island effect due to the normal vertical temperature gradient, which can be augmented by cool air drainage. Significant water bodies also modify the heat island effect due to the large differences in energy balance characteristics between urban and water surfaces.

Winds The increased resistance created by the surface structures of a city impedes the mean wind flow and increases turbulence. The roughness length, z_0, is a parameter that characterizes the effect of surface resistance or drag on wind flow. Roughness lengths of 3.3 to 4.9 ft (1 to 1.5 m) and 6.6 to 13 ft (2 to 4 m) are reasonable estimates for suburban and urban centers, respectively (Oke 1979a). For comparison purposes, the roughness lengths of uncut grass and coastal seas are approximately .033 ft (.01 m) and .0033 ft (.001 m), respectively (Arya 1988:149).

The increased drag caused by the rougher urban surface usually results in reduced wind speeds near the surface. In light regional wind conditions, however, the wind speed has been observed to be greater in urban areas than in the surrounding rural areas. The most likely explanation is that weak regional winds are accelerated and turned by the pressure gradient created by the urban heat island (Oke 1979a). That is, rising air from the urban heat island results in inward flow toward the city center. This inward flow pattern is most apparent in light wind conditions and is obscured in stronger flows.

The urban surface also affects the wind direction. Steady-state winds in the boundary layer are governed by a balance between the horizontal pressure gradient force, the force due to surface friction, and a virtual force associated with Coriolis acceleration. Winds traversing urban areas encounter increased surface friction and must adjust accordingly to a new balance of forces. In strong winds, deceleration due to increased surface drag causes a decrease in the Coriolis force, which causes the wind direction to turn toward low pressure (i.e., to the left in the northern hemisphere). In light winds, however, the presence of a heat island causes an increase in the wind speed, a corresponding increase in the Coriolis force, and a resultant turn away from low pressure (i.e., to the right in the northern hemisphere) (Oke 1979a).

Microscale wind circulations are induced by individual buildings or by clusters of buildings. Channeling by pairs or rows of buildings may cause increased wind speeds. Simultaneously, sheltered areas in the lee of buildings may be relatively calm. Differences in shading within urban canyons or cross-street wind flow may induce local eddy circulations.

Complex topography and bodies of water modify the urban-induced wind flow. For example, a sea or lake breeze may superimpose its effect on the urban circulation pattern. Variations in terrain elevation may also modify the wind patterns.

Humidity Typically, urban areas are found to have lower absolute humidity during the day and higher absolute humidity at night compared to the surrounding rural areas. The lower daytime absolute humidity is thought to be caused by the reduced moisture availability at the city surface and the entrainment of drier air from the overlaying air mass into the boundary layer. The higher nighttime absolute humidity is thought to be due to reduced dewfall, increased evaporation due to higher urban temperatures, the contribution of anthropogenic moisture (Oke 1979a), or reduced eddy diffusion of water vapor. On the other hand, rural areas generally have higher relative humidity at all hours (day and night) compared to urban areas, with the exception of winter months in dry climates. In spring and summer, vegetation in rural areas acts as a moisture source due to evapotranspiration and results in increased relative and absolute humidity.

Although the previously described humidity characteristics are typical, they may vary with climate and season. For example, snow cover, dormant vegetation, arid climates, and urban irrigation may alter the relative moisture availability of rural and urban areas. In winter, higher urban temperatures and salting of city streets following snow or ice storms may cause more rapid melting and hence greater moisture availability in urban areas as compared to rural. All of these influences may alter the typical humidity characteristics described previously.

Urban Energy Balance Many of the characteristics that distinguish urban climates from rural climates are a result of the differences in the surface energy balance between the two environments. Thus, much work has been done to develop improved understanding of the urban energy balance and to identify those surface features that are most important in determining urban climate.

The energy balance at the top of the urban canopy is given by (Oke 1988):

$$Q^* + Q_F = \Delta Q_S + \Delta Q_A + Q_H + Q_E \tag{1}$$

where

Q^* = net radiation,
Q_F = anthropogenic heat flux,
ΔQ_S = net change in heat storage in the urban canopy and substrate,
ΔQ_A = net advection of heat,

TABLE 1
Summary of Typical Urban Influence on Energy Balance

Energy Balance Term	Typical Urban Effect	Reason
net radiation	decreased input by day	See Table 2.
	night above canopy: increased loss; night within urban canyon: decreased loss	
anthropogenic heat	increased	high density of space heating, transportation, industrial processes
heat storage change in surface and canopy	increased	combined effects of urban structure geometry and construction materials
advection	varies	depends on variation in surface properties
sensible turbulent heat flux	increased	reduced moisture availability, increased turbulence
latent turbulent heat flux	reduced	reduced moisture availability

Q_H = turbulent sensible heat flux, and
Q_E = turbulent latent heat flux.

The typical effects of urban areas on each of the terms in Equation 1 as described by Oke (1988), except where noted, are summarized in Table 1. The effects on individual net radiation components are summarized in Table 2.

Note that the urban effects summarized in Table 1 and Table 2 are typical and may be different in particular situations. For example, after a snowfall, moisture availability in an urban area may be greater than in the surrounding rural areas due to increased melting as a result of higher urban temperatures. This would affect both sensible and latent turbulent heat fluxes, among other factors.

KEY URBAN CLIMATE PARAMETERS

The primary goal of ASHRAE Research Project 606 is to provide improved means for estimating the urban climate variables of significance to building HVAC systems design. One of the tasks leading to this goal is to identify the key climatic parameters. The project work statement defines the key climatic parameters as those that have a significant effect on building design, that show the greatest variation as a result of location within a metropolitan area, and for which that variation can be most easily characterized. Each of these requirements is addressed in the following paragraphs.

Starting with the first requirement, a list was developed of those parameters that are currently used in building design. A distinction was made between climatic data, which are used primarily for design purposes, and time series meteorological data, which are used for energy consumption calculations. The focus of the analysis was climatic data. With this focus, the design climatic parameters identified in the *1989 ASHRAE Handbook—Fundamentals* (Chapter 24) provide a basis for the identification of the key climatic parameters. For summer, these consist of dry-bulb temperatures that have been exceeded 1%, 2.5%, and 5% of the time during the months of June through September in the northern hemisphere and the mean coincident wet-bulb temperatures; the wet-bulb temperatures that have been exceeded 1%, 2.5%, and 5% of the time during summer months; the mean daily range of dry-bulb temperature; the median of annual extreme maximum dry-bulb temperatures; and the wind direction most frequently coincident with the 2.5% dry-bulb design temperature. For winter, these consist of the values of dry-bulb temperature that have been exceeded 99% and 97.5% of the time during the months of December through February in the northern hemisphere, the wind direction occurring most frequently with the 97.5% dry-bulb winter design temperature, and the

TABLE 2
Summary of Typical Urban Influence on Net Radiation

Radiation Balance Term	Typical Urban Effect	Reason
downward short-wave radiation	reduced global, increased diffuse to direct beam ratio, reduced ultraviolet	increased scattering and absorption by pollution
upward short-wave radiation	reduced	reduced surface albedo
downward long-wave radiation	increased	increased urban air temperature, increased long-wave emission from pollution
upward long-wave radiation	above canopy viewpoint: probably increased	increased surface temperature, partially counteracted by reduced surface emissivity
	urban canyon viewpoint: decreased	decreased sky view factor (Oke 1981; Oke et al. 1991)
Net Radiation	decreased input by day	combined effect of above components
	night above canopy: increased loss; night within urban canyon: decreased loss	

TABLE 3
Typical Urban-Rural Differences of Climatic Parameters

Parameter	Comments	Typical Urban-rural Difference
dry-bulb temperature	summer maxima	+ 1-3 °C (Landsberg 1981)
	winter minima (average)	+ 1-2 °C (Landsberg 1981)
	annual mean	+ .5-3.0 °C (Landsberg 1981)
	10th percentile of difference between urban-rural minimum temperatures in winter	largest, 1.1 °C (2 °F) median, 0.0 °C (0 °F) smallest, -2.8 °C (-5 °F) (Demarrais 1975)[1]
	50th percentile of difference between urban-rural minimum temperatures in winter	largest, 3.3 °C (6 °F) median, 1.7 °C (3 °F) smallest, -1.7 °C (-3 °F) (Demarrais 1975)[1]
	90th percentile of difference between urban-rural minimum temperatures in winter	largest, 5.6 °C (10 °F) median, 3.3 °C (6 °F) smallest, .6 °C (1 °F) (Demarrais 1975)[1]
relative humidity	summer	- 8% (Landsberg 1981)
	winter	- 2% (Landsberg 1981)
	annual mean	- 6% (Landsberg 1981)
wind speed	annual mean	- 20-30% (Landsberg 1981)
	extreme gusts	- 10-20% (Landsberg 1981)
	calm	+ 5-20% (Landsberg 1981)
wind direction	light winds	± 180 °
	stronger winds	10-20° changes are common (Oke 1974)
cloud cover	time of day and season unspecified	+ 5-10% (Landsberg 1981)
solar insolation	total on horizontal surface, time of day and season unspecified	- 0-20% (Landsberg 1981)
	sunshine duration	- 5-15% (Landsberg 1981)
long-wave radiation from environment	incident on vertical surfaces from ground component only	+ 0 - 25% (Cole 1976)

[1] Percentile of urban-rural difference between minimum temperatures at 31 station pairs in 28 urban areas in 1964. Data was derived by DeMarrais (1975) from National Weather Service monthly summaries and cooperative station records. Largest, smallest, and median values from the 31 station pairs are shown. In most cities, the urban station was in the downtown business district. In some cases the urban temperatures were measured at the top of tall buildings.

mean wind speed occurring coincident with the 97.5% dry-bulb design temperature. The *Fundamentals* should be consulted for additional information on these design parameters. In addition to those climatic parameters recommended in Chapter 24 of the *Fundamentals*, other parameters may have significance to HVAC design. Cloud cover and solar insolation are of importance to passive heating system design. Long-wave radiation from the urban environment (sky, buildings, and surface) can also be a significant energy flux (Cole 1976).

The project work statement indicates that the key climatic parameters should be those that show the greatest variation as a result of location within a metropolitan area. All of the previously mentioned climatic parameters exhibit some variation within a metropolitan area. No estimates of the urban-rural differences of the specific climatic parameters listed in *Fundamentals* have been identified. Table 3 summarizes the typical urban-rural differences of climatic parameters that have been identified in the literature. Note that in most cases the characteristics of the urban environment of which the parameters are typical is not well defined. Thus, care should be taken in attempting to apply these values to any particular urban area.

The typical urban-rural differences in climatic parameters shown in Table 3 do not correspond to the potential key climatic parameters. Consequently, it is difficult to identify those parameters of significance to HVAC design that show the greatest variation within a metropolitan area. Also, the importance of each parameter to an individual engineering application is difficult to quantify. Thus, at this stage, it is not recommended that the list of potential key climatic parameters be reduced on the basis of the magnitude of their variation within a typical metropolitan area.

The key climatic parameters are to include those that are easily characterized. The section on "Urban Climate Model Selection" compares various model classes in terms

TABLE 4
Key Climatic Parameters

Parameter	Comments
dry-bulb temperature	1, 2.5, and 5 percent[2] values (summer)
	99 and 97.5 percent[3] values (winter)
	mean daily range
	median of annual extreme maximum
	median of annual extreme minima
wet-bulb temperature	mean value coincident with 1, 2.5, and 5 percent[2] dry-bulb values
	1, 2.5, and 5 percent[2] values
wind direction	most frequently coincident with the 2.5% dry-bulb summer design temperature
	most frequently coincident with the 97.5% dry-bulb winter design temperature
wind speed	average wind speed occurring coincidentally with the 97.5% dry-bulb winter design temperature
solar insolation	
long-wave radiation from environment	including sky, building, and surface components
cloud cover[1]	

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[1] Qualified entry in list of key climatic parameters. Difficulty in estimation may limit its usefulness.

[2] Values exceeded the given percentage of the time during the summer (June through September in the Northern Hemisphere).

[3] Values exceeded the given percentage of the time during the winter (December through February in the Northern Hemisphere).

of their ability to estimate climatic parameters. Table 7 summarizes the parameters that various types of model are capable of estimating. As shown in the table, all parameters except for cloud cover can be estimated to some degree by at least one model type; however, due to a lack of validation against field measurements (Ross and Oke 1988), the accuracy of the model estimates is not well defined for most urban climate models. Thus, except for cloud cover, it is difficult to evaluate the ease with which each climatic parameter can be characterized. Consequently, cloud cover is the only climatic parameter that can be objectively dropped from the list of climatic parameters based on ease of characterization. It is recommended, however, that cloud cover be retained on the list of key climatic parameters as a qualified entry so as to maintain a record of its potential significance should means of estimating it become available.

The key climatic parameters are summarized in Table 4.

SELECTED URBAN AREAS

The project work statement specifies that three metropolitan areas are to be identified "for which there are sufficient data or analyses to reasonably characterize climatic variation" within the metropolitan area. The data and analyses from those metropolitan areas are to be used during Phase II to develop and/or refine model algorithms. In order to include a broad range of urban and meteorological influences, the selected cities should represent different climatic regions. At least one metropolitan area is to be immediately adjacent to an ocean or major lake, and at least one area is to be free of ocean or lake influences.

In order to fulfill the above-stated objectives, the chosen metropolitan areas should have at least one and preferably both of the following characteristics.

- A significant amount of appropriate, good-quality data—The data must be sufficient in amount and cover a sufficient time span to adequately characterize urban climate variation within the metropolitan area. Ideally the data will span all seasons of the year and preferably more than one year. The data should also provide good areal coverage of the metropolitan area.
- A significant amount of analyses/publications—The data should have been analyzed from the viewpoint of urban climate, and a significant number of publications should be available. These analyses will provide a basic understanding of the particular metropolitan area's urban climate on which further studies in ASHRAE's program can be built.

With these characteristics in mind, a computerized search of the literature was conducted and the results examined for measurement programs and analyses that are relevant to urban climate. The results were analyzed for the primary requirements described above. Based on that investigation, the following cities were selected:

- Northeast—New York City
- Midwest—St. Louis, Missouri
- West—Vancouver, British Columbia

The studies performed in the urban areas, their period of record, and the corresponding populations of the urban areas are summarized in Table 5. The following sections describe more specific reasons for our choice of urban areas and the data and analyses that are available.

Northeast—New York City

The primary measurement program conducted in the New York metropolitan area was the New York Urban Air

TABLE 5
Summary of Studies in Selected Urban Areas

Source of Data	Period of Record	Population Growth
New York Urban Air Pollution Dynamics Program	1964-1969	15,405,000 (1960)[2] 17,035,000 (1970)[2]
Metropolitan Meteorological Experiment (METROMEX)	1971-1975	2,429,000 (1970)[3] 2,377,000 (1980)[3]
Regional Air Pollution Study (RAPS)	1974-1977	2,429,000 (1970)[3] 2,377,000 (1980)[3]
University of British Columbia	1972-present[1]	1,082,352 (1971)[4] 1,380,729 (1986)[4]

[1] See Table 6 for additional details.

[2] New York Standard Consolidated Statistical Area.

[3] St. Louis Standard Metropolitan Statistical Area.

[4] Vancouver metropolitan area.

Pollution Dynamics Program (Davidson 1967; Druyan 1968; Bornstein et al. 1976), which was conducted in 1964 to 1969. The goal of the measurement program was to collect data to be used in developing and validating "a numerical model of transport and diffusion of pollutants in a large metropolitan region" (Davidson 1967). The anemometer network consisted of 97 sites located in a 220-km (E-W direction) by 110-km (N-S direction) rectangle centered on the west side of midtown Manhattan (Bornstein and Johnson 1977). Hourly wind data were collected during 20 observational periods of three to five days duration over randomly selected periods between 1964 and 1967. The study included a point and area pollutant emissions inventory, which has been used for estimating anthropogenic heat emissions. Vertical and horizontal measurements of wet-bulb and dry-bulb temperature, pressure, and SO_2 were obtained from helicopter flights. An SO_2 emissions inventory from space-heating, hot water, and industrial sources was compiled, which has been used for estimating anthropogenic heat and moisture contributions (Clark et al. 1985). A surface network of approximately 15 fixed SO_2 stations and 3 mobile stations was operated. An SO_2 monitor was also operated in a helicopter.

Publications and analyses that have resulted from this study include studies of urban sea breeze fronts (Bornstein et al. 1978; Anderson and Bornstein 1979), urban interaction with a cold front (Gaffen and Bornstein 1988), anthropogenic moisture effects (Bornstein and Tam 1977; Clark et al. 1985), urban-rural wind velocity differences (Bornstein and Johnson 1977), and urban heat islands and mixing depths (Bornstein 1968; Leahey and Friend 1971).

Other analyses of urban climate have been performed in New York City using other data sources. These include studies of the heat island effect (DeGaetano and Shulman 1984; Oreilly et al. 1988), heat island assessment using satellite data (Price 1979), and climatic trends (Jones and Jiusto 1980).

Midwest—St. Louis, Missouri

St. Louis may be the largest source of urban meteorological data in North America. This is due to the fact that two major government-sponsored studies were performed in St. Louis in the 1970s.

The first was the Metropolitan Meteorological Experiment, METROMEX (Changnon 1981), which was conducted from 1971 to 1975. The study was designed to study inadvertent climate and weather modifications caused by the urban environment with particular attention to the effects on precipitation. The study was conducted primarily during the summer months because climatological data indicated that local rain was most affected by the urban environment during the summer. In addition to a variety of precipitation and aerosol samplers, the surface measurement network included 16 to 23 wind speed and direction sites and 16 to 32 temperature and humidity sites. The surface network was complemented by vertical measurements that included all-sky cameras; radiosonde (~4 sites) and pibal (~10 sites) releases for temperature, humidity, and airflow measurements; two tethered balloon profilers for dry- and wet-bulb temperatures, pressure, and wind speed and direction measurements in the lowest 610 meters; weather radar systems and lidar systems; an acoustic sounder; and up to 12 instrumented meteorological aircraft.

Analyses resulting from the METROMEX study include analyses of urban mixing height variation (Spangler and Dirks 1974) and urban-rural differences in the net radiation budget (White et al. 1978).

The other major study performed in St. Louis was the Regional Air Pollution Study (RAPS), which was conducted from 1974 to 1977 (Schiermeier 1978). The primary objective of this study was to provide a meteorological, air quality, and emissions data base to be used in developing, evaluating, and validating air quality simulation models. The study included a surface network of 25 stations, expeditionary studies, and an upper air sounding network. The surface network measured visibility, wind speed and direction, temperature, dew point, and selected air quality parameters at all sites. In addition, vertical temperature difference, pressure, solar radiation, turbulence, and selected air quality parameters were measured at selected surface sites. Four- to five-week expeditionary studies were conducted two to three times per year for the purpose of providing more detailed atmospheric observations. The expeditionary studies included instrumented aircraft and vehicles, airborne and surface-based lidars, mobile radiosonde and pilot balloon teams, an acoustic sounder, and laser anemometers. Vertical fluxes of momentum, sensible heat, and moisture were measured over several types of urban and rural surfaces. The flux measurements were made from four different platforms: aircraft, tethered balloons, instrumented towers, and surface and subsurface instruments. Satellite images were used to determine surface albedo and thermal emissions. Measurements were also made of solar and long-wave radiation over selected land-use types. The Upper Air Sounding Network released pilot balloons and radiosondes to measure upper air wind, temperature, and humidity. These measurements were routinely made five days a week at two sites and seven days a week at four sites during expeditionary studies.

Analyses resulting from the RAPS program include correlations of land use with meteorological anomalies (Auer 1978), urban scale variation of turbulence parameters and fluxes (Clarke 1981; Ching 1985), heat island modeling analyses (Vukovich et al. 1976; Seaman et al. 1989), urban-rural wind difference analyses (Shreffler 1979), ground heat storage parameterization (Doll et al. 1985), and the influence of advection on heat flux (Ching et al. 1983).

Other analyses performed in the St. Louis area include estimates of surface characteristics from aircraft and satellite data (Dabberdt and Davis 1978; Carlson et al. 1981) and a comparison of modeled versus measured mixing heights (Barnum and Rao 1975).

West—Vancouver, British Columbia

Data for Vancouver are derived from a number of studies of limited duration spanning more than a decade, as compared to the fewer, multi-year studies described previously for New York and St. Louis. The data collection periods for Vancouver are summarized in Table 6.

The resultant analyses and publications span a broad range. They include numerous studies of energy balance components, including rural, suburban, and canyon environments and simultaneous rural-suburban comparisons (Cleugh and Oke 1986; Oke and McCaughey 1983; Kalanda et al. 1980; Nunez and Oke 1976, 1977; Oke 1979b, 1979c, 1979d; Yap and Oke 1974). In these studies net radiation, surface heat flux, sensible heat flux, and latent heat flux are typically measured, determined by residual, or parameterized. Studies parameterizing surface heat storage have been conducted (Oke and Cleugh 1987). Heat island measurements from automobile traverses have been performed and compared to model results (Oke 1976). Water balance studies have been conducted and a water balance model developed (Grimmond et al. 1986; Grimmond and Oke 1986). Upper air data have also been collected and compared to model predictions of mixing heights during advective and subsidence conditions (Steyn and Oke 1982). More recently, a study was conducted on the spatial and temporal variability of surface energy fluxes and their relationship to variations in surface characteristics (Schmid et al. 1991). Surface characteristics, meteorological conditions, and energy balance components were compared to modeled results from three energy balance models (Ross and Oke 1988).

URBAN CLIMATE MODEL SELECTION

The project scope of work calls for the selection, development, or adaptation of an urban climate model, which is to be further developed during Phase II of the project. This section briefly reviews urban climate models and presents the one selected. The reader is referred to Bornstein (1986) for a more detailed description of urban climate models.

TABLE 6
Summary of Urban Measurement Studies in Vancouver, B.C.

Location	Period	Type of study
Vancouver	July-September, 1972	Sensible heat fluxes (Yap and Oke 1974)
Vancouver	periods of 1972-1975, including all seasons	heat island - automobile traverse (Oke 1976)
Vancouver - light industrial, residential district	July-September, 1973	Urban canyon energy balance (Nunez and Oke 1977)
Vancouver - Sunset site	August-October, 1977	Energy balance (Kalanda et al. 1980)
Vancouver - Sunset site	July - August, 1978	acoustic sounder, minisonde, tower-mounted eddy correlation, reversing psychrometer (Steyn and Oke 1982)
Vancouver - Sunset site	July - August 10, 1980	Energy balance (Ross and Oke 1988)
Vancouver suburb	January 1982-January, 1983	Urban water balance (Grimmond et al. 1986; Grimmond and Oke 1986)
Vancouver - Sunset site	July - September, 1983	Energy balance (Cleugh and Oke 1986)
Vancouver	Summer 1986	Spatial variability of energy fluxes (Schmid et al. 1991)

Statistical Models

Some of the earliest mathematical descriptions of urban climate were contained in statistical models (Oke 1974, 1979a, 1981). The general form of such models is

$$\Delta T = F(\Delta \theta / \Delta z, P \text{ or } \psi, u) \qquad (2)$$

where

ΔT = maximum diurnal heat island intensity,
$\Delta\theta/\Delta z$ = vertical gradient of potential temperature in the upwind rural area,
P = population of the city,
ψ = sky view factor, and
u = wind speed.

Note that not all of the models include all of the independent variables, and, in fact, most of the models include only a single independent variable. The function F in some cases applies only to the single urban area for which it was developed. In some cases, however, surprisingly good agreement with data from many cities is obtained from the same F function, particularly for cities within a particular geographic/cultural region (e.g., North America, Europe, etc.).

Canopy Layer Models

Canopy layer models usually deal with the energy balance in the canopy layer below the tops of the urban surface structures. The emphasis of these models is on representing the distinctive features of the urban fabric. These features include multiple reflections of long- and short-wave radiation from urban surfaces, the influence of building geometry on radiation and energy balance, and heat transfer between buildings, the earth's surface, and the atmosphere. Most canopy layer models simulate various terms of the canopy layer energy balance rather than the resultant effect on meteorological variables (Bornstein 1986). Examples of canopy layer models include Terjung and O'Rourke (1980a, 1980b), Arnfield (1982), and Johnson et al. (1991).

Advective Integral Models

An advective integral model was developed by Summers (1964) and modified by Leahey and Friend (1971) and Henderson-Sellers (1980). Sheaffer and Reiter (1988) have applied such a model to Minneapolis. The advective integral model describes the height of the urban mixing layer as a function of distance from the upwind edge of the city. The model is capable of estimating the mixed layer depth, the heat island intensity, and the concentration of a passively distributed airborne gas or aerosol.

Coupled Energy Balance and Surface/Mixed Layer Models

The coupled one-dimensional energy balance and surface/mixed layer models are often referred to in the literature simply as "energy balance models" (Bornstein 1986). These models attempt to estimate the surface temperature, the various energy fluxes at the surface, and other meteorological parameters based upon the equation for energy balance at the urban air-surface interface and empirical flux-profile relations in the surface layer, with or without feedback from the mixed layer above (Bornstein 1986). Being one-dimensional, these models cannot simulate the effects of horizontal inhomogeneity.

The earliest energy balance models (Myrup 1969; Outcalt 1972a, 1972b; Nappo 1972; Miller et al. 1972) did not provide feedback from the surface layer to the mixed layer. The temperature at the top of the surface layer was assumed constant. Later models (Bergstrom et al. 1973; Ackerman 1977; Venkatram and Viskanta 1977; Carlson and Boland 1978) include a coupling to the mixed layer.

Dynamic Differential Models

Dynamic differential models are based on numerical solutions to the basic differential equations for the conservation of momentum, heat, and moisture in the atmospheric boundary layer. Both two- and three-dimensional versions of the dynamic differential model are common in the literature. Examples include Vukovich et al. (1976), Atwater (1975), Seaman et al. (1989), and Byun and Arya (1990). Energy balance models with a coupling to the mixed layer might be considered to be one-dimensional examples of the dynamic differential class of models. Since they solve the governing equations in two- and three-dimensions, dynamic differential models are able to simulate two- and three-dimensional effects such as the urban heat island, the convergence or divergence of urban winds, and the growth of the urban boundary layer.

Urban Climate Model Selection

The different categories of urban climate models described in the preceding sections were compared in the following areas:

1. Ability to simulate the key climatic parameters.
2. Compatibility of the model with the typical resources that are expected to be available for an application. The resources considered were availability of meteorological data, availability of data on surface characteristics, computer resources, and human resources.

In reviewing the capabilities of the various models, one should recognize the inherent limitations of using models for simulating climatic variation within metropolitan areas. It is extremely difficult to specify values of the various surface characteristics, such as albedo, roughness, thermal properties, and moisture availability, for the complex urban terrain. Even the "surface" itself is not clearly defined in urban locations with a variety of building shapes and sizes, street canyons, parks, and parking areas. Input surface meteorological and upper air sounding data are often not available at the desired location. To what extent the data from the nearest meteorological station (usually an airport) might be useful will depend on the prevailing wind direction and relative locations of the particular urban site and meteorological station.

Table 7 presents a comparison of the urban climate model categories in terms of their ability to estimate the key climatic parameters. A "Y" in the table indicates that the model category is capable of estimating the parameter to some degree.

An examination of Table 7 shows that none of the model categories is capable of estimating all the key climatic parameters. The energy balance and dynamic differential categories come closest in that they are capable of estimating, at least to a limited degree, all of the parameters except cloud cover. They can estimate long-wave radiation from the sky and the ground but not from build-

TABLE 7
Model Analysis Matrix—Climatic Parameters (Y indicates parameter can be estimated to some degree by model)

Climatic Parameter	Model Class				
	Statistical	Urban Canopy	Advective Integral	Energy Balance	Dynamic Differential
minimum temperature	Y[3]		Y	Y	Y
maximum temperature				Y	Y
wet-bulb temperature			Y[4]	Y	Y
wind direction				Y[1]	Y[2]
wind speed				Y[1]	Y[2]
cloud cover					
solar insolation		Y		Y[6]	Y[6]
long-wave radiation from environment		Y		Y[5]	Y[5]

[1] Changes in wind speed and direction resulting from local adjustments to surface friction can be modeled in the mixed layer by the more sophisticated energy balance models; however, surface friction is not the only factor affecting wind speed and direction in urban areas. Changes due to advection, heat island induced convergence, two- or three-dimensional flow effects, terrain variations or surface obstructions cannot be modeled and may in many cases be the dominating factors.

[2] Two-dimensional models can simulate changes due to along-wind effects, but not due to cross-wind effects. Neither two- or three-dimensional models are currently capable of simulating changes in wind speed or direction associated with surface obstructions.

[3] Minimum temperatures can be estimated if they coincide with the maximum heat island, a situation that does not typically occur.

[4] Wet-bulb conditions can be estimated during stable upwind conditions.

[5] Long-wave radiation can be calculated from sky and ground only, not from buildings unless a canopy sub-model is included.

[6] Direct and diffuse solar insolation can be estimated. Light reflected from buildings cannot be estimated unless model is enhanced by a canopy sub-model.

ings unless enhanced with a canopy model. Similarly, they can estimate direct and diffuse solar insolation, except for that reflected from buildings. The energy balance models can estimate wind speed and direction, although they cannot include two- or three-dimensional effects. None of the models can include the effects of specific surface obstructions on wind speed or direction. The advective integral model can estimate both low temperature and wet-bulb temperature, the latter to a limited degree since stable upwind conditions must exist. The statistical models can estimate low temperatures if they are coincident with the maximum heat island conditions, a condition that does not generally exist. The urban canopy models can estimate long-wave radiation from both the sky and adjacent buildings. Urban canopy models are limited in their capability of estimating other variables, since those variables are typically inputs to the models rather than outputs. Based on the number of key climatic parameters that they can estimate, the energy balance and dynamic differential models are the preferred model categories.

Although both the energy balance and dynamic differential models are capable of estimating the same number of key climatic parameters, there are differences in the accuracy and completeness that can be expected from each. The energy balance models, being one-dimensional, cannot simulate effects due to urban heterogeneity. Thus, certain known urban climate effects cannot be modeled by energy balance models, including:

- topographic effects—climatic effects due to hills and valleys cannot be treated;
- heat-island-induced wind flows—the elevated temperature centered on urban areas encourages a net convergence of air toward the center of the urban area, and this effect modifies the regional wind field and can induce its own convergent wind flow during light wind conditions;
- surface inhomogeneities—the modification of an air mass due to advection from one surface type to another cannot be estimated, although some models incorporate an ability to estimate the effects of mixed-layer advection if suitable estimates of advection are available (Ackerman 1977).

Table 8 presents a comparison of the urban climate model categories in terms of the resources required for the simulation of climatic variation within metropolitan areas. In the following analysis, emphasis is placed on the energy balance and dynamic differential models, since they are capable of estimating the largest number of key climatic variables.

A comparison of the resources required by the energy balance and dynamic differential categories indicates that the dynamic differential models require significantly greater resources in each of the resource categories.

- Meteorological data—The dynamic differential models provide the most benefit when provided with initial and boundary condition data in either two or three dimensions, although with suitable assumptions they can be used with less data. The energy balance models require such data in only one dimension.
- Surface data—The dynamic differential models require data on surface characteristics either along an upwind vector or on a two-dimensional surface grid. The energy balance model requires surface characteristics at the building site and possibly the meteorological data collection site.

TABLE 8
Model Analysis Matrix—Required Resources

Resource Compatibility	Model Type				
	Statistical	Urban Canopy	Advective Integral	Energy Balance	Dynamic Differential
meteorological data	1	2	2	2	3
surface data	1	3	3	2	3
computer	1	2	2	2	3
human resources	1	2	2	2	3

1 - Least resources required.

2 - Intermediate resources required.

3 - Most resources required.

- Computer—The dynamic differential models require significantly greater computer resources, although they may be capable of execution on personal computers, particularly the two-dimensional models. The energy balance models are easily capable of execution on a personal computer.
- Human technical resources—The dynamic differential models require technical personnel with extensive experience and knowledge of modeling techniques. Dynamic differential models are typically used for research applications where such expertise is available. The energy balance models are simpler to run than the dynamic differential models and have been used in instructional situations. Although energy balance models are simpler to run, they are nonetheless complex models and they do require that the user be experienced in their use.

In summary, the dynamic differential models require significantly greater resources than the energy balance models. The critical resources are surface data and human technical resources. The requirement to collect surface data along an upwind vector or on a two-dimensional surface grid, although feasible, is judged to require more effort than is justified for a first-generation modeling approach. The dynamic differential models also require technical personnel with extensive experience in applying such models. Such experience will not typically be available for ASHRAE applications. Thus, the resource requirements favor the choice of an energy balance model for ASHRAE urban climate simulation applications. This would also be consistent with the project goal of identifying a "first generation prototype" of a quantitative simulation model for engineering applications. The selected energy balance model can be tested and refined during Phase II. If two- and three-dimensional effects prove to be critically important, then additional model development resources, including the use of a dynamical differential model or the addition of an advective integral model in certain situations, might be justified.

Note that the energy balance class of model is selected on the basis of its ability to estimate most of the key climatic parameters to some degree and its compatibility with expected resources. This does not necessarily indicate, however, that another class of model may not be more appropriate for particular applications. For example, the energy balance models identified do not estimate long-wave radiation fluxes from surrounding buildings. For applications for which estimation of those fluxes is critical, an urban canopy model, such as that of Terjung and O'Rourke (1980a, 1980b), would be preferable. As another example, coupled energy balance and surface/mixed layer models are capable of estimating wind speed. However, a simpler algorithm, such as that used by Arens et al. (1985) in their SITECLIMATE model, might be preferable if wind speed is the only variable of interest and if a less rigorous approach is acceptable.

As mentioned above, the energy balance models are divided into two classes: those with a dynamic link to the mixed layer and those without such a link. There is evidence (Carlson and Boland 1978) that a dynamic link to the mixed layer is necessary to estimate the amplitude and phase lag of the temperature after the solar noon. Therefore, energy balance models with a link to the mixed layer were the primary focus of model selection.

Those energy balance models with a link to the mixed layer include Bergstrom and Viskanta (1973), Zdunkowski et al. (1976), Torrance and Shum (1976), Ackerman (1977), Venkatram and Viskanta (1977), and Carlson and Boland (1978).

Intercomparisons of urban climate models are rare. Todhunter and Terjung (1988) compared the energy fluxes estimated by the energy balance models of Carlson and Boland (1978) and Outcault (1972a, 1972b) and the urban canopy model of Terjung and O'Rourke (1980a, 1980b). In general, the comparison indicated that the urban canopy model gave the more realistic energy fluxes, followed in order by the models of Carlson and Boland and of Outcault. Although the urban canopy model was judged most realistic, it requires urban climate parameters such as temperature as inputs, rather than producing them as outputs, and it is thus inappropriate for the ASHRAE application, except for radiative fluxes.

Ross and Oke (1988) compared the energy balance models of Carlson and Boland (1978), Ackerman (1977), and a modified version of Myrup's (1969) energy balance model to data from Vancouver, B.C. The results indicated that the models of Ackerman and Carlson tend to give more realistic estimates of surface energy fluxes and temperature than did Myrup's model. Overall, the relative superiority of Ackerman and Carlson's models is difficult to judge from this study. This is primarily due to the differences in the two models' methods of characterizing surface moisture and the resultant difficulty in objectively assigning surface moisture parameters.

The model of Carlson and Boland was selected as most appropriate for the urban climate simulation model for the following reasons:

- The model has been enhanced with a vegetative canopy submodel (Taconet et al. 1986a, 1986b; Carlson et al. 1990), which simulates a surface composed of a combination of vegetation and bare soil. This may prove useful for sites with significant vegetation. Although other such models exist (Taconet et al. 1986a, 1986b), the Carlson and Boland model is the only model identified with a vegetative canopy submodel that has been applied to the urban climate, although the submodel itself has not.
- The bare soil model includes aspects of a general canopy model, which may simplify the insertion of an urban canopy submodel if that should eventually be found necessary.

- The model developers are enhancing the model with technical refinements and ease-of-use features.
- The model has been used in conjunction with satellite measurements of surface temperature to estimate surface properties, such as moisture availability and thermal inertia, in the St. Louis and Los Angeles urban areas (Carlson et al. 1981). This capability may prove useful in addressing the difficult problem of characterizing urban surface properties.
- In the few model intercomparisons, mentioned previously, that have been performed in urban environments, the performance of the Carlson and Boland model appears to be at least comparable to the other energy balance models in the intercomparisons.

PHASE II RECOMMENDATIONS

The previously described model of Carlson and Boland (1978) will need further improvements before it can be used operationally for estimating climatic variations in specified metropolitan areas. A recent evaluation of this and other energy balance models has pointed out the severe limitations of such models for practical applications (Ross and Oke 1988). These limitations are due to a lack of validation against field measurements and difficulty in specifying the surface properties of urban areas. Similar limitations also apply to the dynamic differential models. The following recommendations are made for guiding the Phase II improvements.

As a first step in the model development and refinement process, ASHRAE's goals for acceptable accuracy for the key urban climate design parameters should be determined. These goals should be used in Phase II to judge the adequacy of the model estimates and to identify those input parameter estimates and model features that require improvement.

Most of the so-called urban climate models are not really climate models in the sense that they can readily give desired climatic variable statistics for any specified urban location. Except for the purely empirical relations (statistical models) for some readily available climatic variables, such as the urban heat island intensity, the identified models are actually urban canopy, surface layer, or boundary layer models for short-term (order of an hour) averages of near surface meteorological variables and surface energy fluxes. In order to get the desired climatological information, such models must be run for extended periods of simulation time with the historical surface or upper air sounding data as inputs. Thus, compatibility with expected resources is particularly important. The selected urban climate model was chosen to be as simple as possible, consistent with the need to treat the important factors that affect urban climate. Nevertheless, the model may prove too complex to model the extended periods required to provide operational estimates of urban climate. Therefore, as part of Phase II, simplifications to the modeling process may be necessary. These simplifications fall into two categories:

- Simplification of the urban climate model itself—Simplifications may be identified that allow the model to be executed on multiple years of data with fewer resources.
- Development of a parameterized model—The parameterized model would not explicitly model many of the urban climate processes to the level of detail that the selected urban climate model does. Consequently, it would be more efficient. Instead, it would incorporate parameters that characterize those processes. The parameters in the model could be determined by executing the complete urban climate model for a sufficient number of conditions to adequately determine the parameters. The parameterized model would then be used to efficiently model the multiple years of data required to estimate climatic variables.

  Models that express the heat island intensity as a function of wind speed (see, for example, Oke [1976]) or rural temperature gradient (see, for example, Ludwig [1968]) may provide a useful starting point for developing such a parameterized model. Sheaffer and Reiter (1988) have found that the temporal change in temperature at a rural site can be usefully related to the rural temperature gradient. They consequently used rural temperature changes as input to an advective model for predicting heat island intensity. Ludwig (1968) has suggested that rural temperature changes may be directly related to heat island intensity, without invoking advective arguments. Thus, the temporal change in the reference temperature should be considered as an independent variable in a parameterized model.

Thus, as part of the model development process, potential model simplifications or a parameterized model should be considered.

The selected urban climate model and any parameterized models should be validated against the selected urban data bases. Statistics describing the accuracy of the models' estimates for the key climatic parameters (Table 4) should be developed. These statistics of accuracy should be compared to the project goals and should be used to judge the adequacy of the models' estimates and to identify those input parameters and model features that require improvement.

The selected urban data bases were chosen primarily due to the detailed, research-oriented data that have been collected there. Due to the research nature of those data bases, they are particularly well suited for analyzing model behavior in detail and for developing model refinements. As in all model development and validation projects, care should be taken to perform final model validation on a separate data set, independent of the data set used to develop the model refinements. This helps to ensure that the model has not been inadvertently "tuned" to the particular characteristics of the data. This is particularly important for model components that include empirically determined parameters. Therefore, during Phase II, the data bases for each city should be segregated into separate model refinement and final validation data sets. If additional confidence in the model's estimates is desired or if the three identified data bases provide insufficient data for an independent, final validation data set, the model should be validated against additional data from other cities. Since those additional data will be used primarily for model validation purposes, the data need not be research oriented and may, for example, include National Weather Service (NWS) data from urban stations.

The most promising and cost-effective areas for model improvement should be identified. Improvements in the model's capability can be achieved in two areas: improvements in the accuracy and representativeness of input parameters and improvements in model algorithms. In order to utilize model development resources most effectively, the model input parameters and/or algorithms should be identified that will yield the greatest improvement in model performance for the resources expended. Existing studies have identified certain model input parameters and model algorithms that hold potential for significant improvement. The following paragraphs outline some of those input parameters and model algorithms that should be considered for improvement in Phase II.

Model sensitivity studies indicate that moisture availability (Carlson and Boland 1978; Ross and Oke 1988; Seaman et al. 1989) and thermal admittance (Carlson and Boland 1978; Ross and Oke 1988; Oke et al. 1991) are key model parameters. Oke et al. (1991) point out the importance of the thermal admittance of the rural site that is used as a reference for the heat island intensity. As a result, model accuracy is limited by the fact that these parameters are quite difficult to estimate (Ross and Oke 1988; Oke 1988). Thus, improved methods of estimating surface moisture availability and thermal admittance should be evaluated. Oke (1988) describes the potential of a technique developed by Carlson et al. (1981) for estimating these parameters using satellite data. Oke points out, however, that such approaches may be biased by the fact that the surface seen by satellites includes roof surfaces, which have relatively low thermal admittance. Carlson (personal communication) has suggested the possibility of using near surface (screen-level) measurements of temperature in a similar manner to estimate moisture availability and thermal admittance. Although this approach does not provide the broad areal coverage of the satellite technique, it does provide an objective estimate of surface properties that is implicitly tailored to the model's requirements. Since near surface measurements would be used, this approach also has the advantage of giving estimates that are more characteristic of the urban canopy. Therefore, this approach should be considered as a tool for testing or calibrating more operationally useful surface property estimation techniques.

Oke (1981), Yamashita et al. (1986), and Oke et al. (1991) indicate that urban geometry, particularly the sky view factor, is an important factor in determining the nocturnal urban heat island intensity. Thus, the necessity of including the effects of urban geometry within an urban canopy submodel should be considered.

One-dimensional energy balance models do not estimate advective effects. There is evidence (Oke 1976) that advective effects are relatively unimportant in determining the formation of the urban canopy heat island near the heat island core. On the other hand, Sheaffer and Reiter (1988) show evidence of advective effects on urban-rural temperature differences at four peripheral urban sites. Thus, the model's lack of simulation of advective effects should be evaluated for its importance to ASHRAE applications.

Ross and Oke (1988) compared the models of Carlson and Boland (1978), Myrup (1969), and Ackerman (1977). They found that Ackerman's model gave more realistic diurnal temperature variations than did the model of Carlson and Boland; however, the Ackerman model was tested with a constant, site-specific Bowen ratio, which in reality is found to be variable. Since temperature variations are important to ASHRAE applications, this characteristic should be evaluated during Phase II.

No additional field measurements are recommended at this time. Significant urban data bases currently exist, and model validation and refinement should proceed with those data sources until specific data deficiencies are identified.

CONCLUSIONS

Existing urban climate models suffer from serious limitations for application to practical problems (Ross and Oke 1988). These limitations are the result of two primary problems: a lack of validation against field measurements and difficulty in specifying the surface properties of urban areas.

These problems are of direct relevance to ASHRAE's application. The difficulty in specifying urban surface properties makes application of the models difficult and limits the accuracy of the resulting model estimates. The lack of validation against field measurements limits the usefulness of the model results since the accuracy of the model estimates are not well established.

As a result of these problems, urban climate models are currently of limited use in fulfilling ASHRAE's needs for estimating urban climate design parameters. Phase II of ASHRAE's urban climate project should be directed toward resolving these problems.

The following tasks are recommended for Phase II of this project:

1. ASHRAE should determine accuracy goals for the key climatic design parameters.
2. In order to simplify the model's operational application, model simplifications or a parameterized model should be evaluated and considered for implementation, within the constraints of accuracy goals.
3. The urban climate simulation model and any parameterized models should be compared to measurements from

the selected urban data bases. The model's accuracy at estimating the key climatic design parameters should be determined.

4. Final model validation should be performed on separate data sets, independent of the model refinement data sets.
5. The model's accuracy at estimating the key climatic design parameters should be compared to ASHRAE's goals for accuracy, and the results should be used to guide the model's further development.
6. Existing studies indicate that the following model refinements should be considered in Phase II:
   a. improvement of moisture availability estimation techniques;
   b. improvement of thermal admittance estimation techniques;
   c. implementation of an urban canopy submodel, particularly including the effects of urban geometry and surface thermal properties;
   d. evaluation of effects of advection on model estimates;
   e. evaluation of diurnal variation of near surface temperature.
7. No additional field measurements are recommended at this time. This should be reevaluated as specific data deficiencies are identified during Phase II.

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