Impact of Increasing the Height of Tel Aviv Buildings on Pedestrian Comfort and Building Energy Efficiency

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ABSTRACT: This study examines the potential effects of adding several additional floors to existing buildings on the microclimate of Tel Aviv streets, and hence on pedestrian thermal sensation and on energy consumption for space conditioning. The research employs computer simulation, using three numerical models: First, the Canyon Air Temperature (CAT) model is used to generate site-specific weather data from time-series measured at a meteorological station in the region, accounting for urban geometry, materials and surrounding hydrological conditions. These data are used as inputs for assessing:

a) Pedestrian thermal comfort, using the Index of Thermal Stress (ITS), which estimates pedestrian thermal sensation under warm conditions based on radiative and convective exchange, as well as humidity and physiological responses, and is calculated as the evaporation rate in terms of equivalent latent heat which is required to maintain thermal equilibrium.

b) Building energy performance, using ENERGYui, a graphic user interface for EnergyPlus. ENERGYui was developed to generate building energy efficiency labels according to the Israeli building standard IS 5282.

The paper reports on the effect of different building heights in N-S oriented street canyons. Results suggest that deeper streets are likely to create more intense nocturnal heat islands. However, the total number of hours in which a pedestrian is likely to experience thermal stress is reduced in deeper N-S canyons, creating a net positive effect. Additionally, building energy modelling shows that elevated air temperature plays less of a role in energy efficiency than do other aspects such as the proportion of building envelope exposed to the sky and mutual shading by adjacent buildings, making taller buildings more economical under the conditions simulated.

Keywords: Urban density; radiant exchange; canyon aspect ratio; computer modelling

INTRODUCTION

Israel lies along the Dead Sea Transform, with earthquakes of magnitudes between 6 and 7.2 occurring in the region on average every 80-100 years. Many of the existing buildings in Tel Aviv's older neighbourhoods suffer from structural weaknesses and might collapse in the event of a major earthquake, of which there is a high probability. To mitigate potential damage, the Israeli Ministry of Interior created a National Guideline Plan (NGP 38) [1] which facilitates the renovation of unsafe buildings planned or constructed before the implementation of a more demanding construction code, IS 413 [2]. The plan promotes construction of additional storeys in existing buildings undergoing reinforcement, thus providing a financial incentive and a suitable regulatory framework. The number of renovations under NGP 38 has steadily increased with each successive revision, particularly in the densely populated centre of the country. If plan implementation becomes widespread, it could mean substantially deeper street canyons in older parts of many cities in Israel. However, the increase in urban density, although desirable in many respects, may also be expected to exacerbate the urban heat island.

It has been noted that canyon geometry affects the microclimate within, creating and defining the magnitude of urban heat islands (UHI) [3-4]. Many studies link thermal stress to higher air temperature prevailing in cities, but several emphasize the importance of the combined effect of shading, humidity and wind speed in addition [5-6]. Likewise, some studies claim UHIs necessarily lead to increased building energy demand [7-9] – but others show that this too may be affected by mutual shadowing among adjacent buildings [10], so that the same factors that lead to the creation of UHIs may also counteract their effects.

This paper will use numerical modelling to examine the effect on pedestrian comfort and building energy consumption resulting from widespread implementation of NGP 38, which will lead to substantial increases in urban density, and specifically to much deeper street canyons.

METHODOLOGY

The first stage of the study is a simulation of microclimate changes in a canyon due to increased building height altering the aspect ratio (H/W). The canyon air temperature (CAT) model [11] predicts conditions in an UC, creating an altered typical meteorological year (TMY) file for urban street canyons of varying geometry. The information is then used as input for the second stage - an analysis using the Index of Thermal Stress (ITS) [12] to gauge the respective discomfort during different hours of the day. The same altered TMY data are used as input for ENERGYui [13], an interface for the EnergyPlus building thermal simulation software [14], which rates building energy efficiency according to Israeli standards. EnergyPlus simulates building energy requirements for acclimatization based on inputs including building materials, geometry and designated function, as well as solar angles and meteorological data.

The Canyon Air Temperature model (CAT)

The CAT model uses meteorological data from a nearby representative weather station to generate time series of local-scale meteorological parameters at an urban street canyon. The transformation is based on a complete surface energy balance at the two sites: In addition to a 2.5-dimensional analysis of radiant exchange accounting for short and long-wave fluxes, it incorporates several elements of the LUMPS [15] parameterization scheme, including moisture advection from nearby vegetation and bodies of water [16]. The effect of turbulent mixing in different stability regimes is estimated by means of an empirical correlation established using site data from Adelaide and Goteborg.

Index of Thermal Stress (ITS)

The ITS is a measure of the rate at which the human body must secrete sweat in order to maintain thermal equilibrium under warm conditions, in response to both metabolic heat production and heat exchange with the environment [17]. It is defined as the ratio between the rate of sweat evaporation required for thermal equilibrium and a cooling efficiency that is estimated by an empirical relationship that accounts for the humidity of the air, wind speed and the insulation value of the clothing. To obtain the ITS, a full energy balance must be evaluated for the pedestrian, approximated by a rotationally symmetrical standing body: The calculation includes short-wave radiation (direct, diffuse and reflected from adjacent surfaces, as well as reflected from the skin); long-wave radiation (received from the sky and from terrestrial surfaces, and emitted by the skin); and convection with the surrounding air. The level of pedestrian thermal stress yielded by the ITS is given in watts (W), and values of the index may be correlated with categories of subjective thermal sensation ranging from "comfortable" to "very hot" based on threshold values that were recently validated and refined using observational data [18].

EnergyPlus and ENERGYui

EnergyPlus simulates a building's thermal load based on a description of its physical make-up and mechanical systems. The program calculates heating and cooling loads necessary to maintain an input temperature or temperature range. EnergyPlus is built upon DOE-2.1E and IBLAST, combining their functions and standardizing the programming language for improved model usage and flexibility. EnergyPlus is an extremely flexible and capable simulation tool [19]; it provides a detailed breakdown of consumption according to sources; and it is accepted as an aid in achieving compliance for numerous green building standards including LEED and BREEAM.

ENERGYui is one of a number of graphical user interfaces for EnergyPlus. It compares thermal loads of simulated residential or office buildings with the Israeli Standard 5282 - Energy Performance for Buildings. Outputs are represented as an efficiency rating for a building as well as each individual apartment and a break-down of thermal loads. It was developed at the Technion – Israel Institute of Technology, and is accepted as a tool towards achieving an energy rating under IS 5282.

Simulation parameters

The study area, about 350m from the sea (32° 4'17"N, 34°46'2"E), comprises typical streets in the older neighbourhoods of Tel Aviv, which are about 15m wide and flanked by 2-3 storey buildings. Streets are arranged in a grid parallel to the beach, approximately N-S, and perpendicular to it. The neighbourhood has little vegetation, and there are no trees to provide shade for pedestrians. The albedo of building walls is estimated at 0.4, and the road surface at 0.15.

The modifications to the existing urban matrix assumed an increase in building height up to 8 storeys – but no other changes to street geometry or materials.

The CAT simulations were run using data from the nearest meteorological station (at Bet Dagan, about 7.3km inland, 32°0'28"N, 34°48'52"E) as input. Modified TMY files were generated for each of the urban scenarios, for both N-S and E-W oriented streets, comprising 8760 hourly values. These were used as inputs for the ENERGYui simulation of building energy performance.

Additionally, CAT provided inputs for the ITS model, including surface temperatures for building walls and street pavement; air DBT; RH; and wind speed at pedestrian level. Since summer weather in Tel Aviv is very stable and there are few changes from day to day, comfort analysis was carried out for only one, typical, summer day (July 6).

Energy consumption was simulated for an H-shaped apartment building commonly constructed in Israel pre-1980, comprised of 4 apartments per floor, each of about 84 sq. m in floor area. This building was chosen for several reasons:

- It represents a building typology found very frequently in Israel, in some areas making up the majority of the urban fabric.
- It was built before the enforcement of seismic building codes and is therefore a candidate for renovation and expansion under NGP 38.
- The window/wall ratios are very similar for each facade of the building (0.11 and 0.12).

A simulation of the building's thermal loads was carried out for a variety of building heights, from one 3-meter storey to eight storeys, in order to simulate the effects of canyon aspect ratio on building efficiency. Additional floors were assumed to have the same thermal characteristics as the existing structure, to simplify the analysis. Analysis of the effects of upgrades to the building stock during the construction process, though quite likely in practice, was beyond the scope of the present study.

ENERGYui is capable of accounting for self-shading by building elements such as balconies, but it does not account for shading by adjacent buildings. To achieve a more accurate measure of solar radiation to glazed surfaces, an unheated built space in the shape of eight identical buildings with one narrow attachment at the first floor level was added to the model to simulate shading by adjacent buildings. The heights of these buildings were altered to match the height of the simulated building. In order to assess the impact of urban microclimate on building efficiency, the model was run twice for each building height: first with inputs from the meteorological station; then again with a TMY file modified by the CAT model.

SIMULATION RESULTS

The following section will first provide results of the street canyon microclimate simulation, followed by illustration of the implementation of these data in thermal comfort and building energy calculations.

CAT output

The output of the CAT model represents the combined effect of proximity to the sea and differences in surface cover and geometry between the Bet Dagan weather station and the city of Tel Aviv.

Temperatures for a typical summer day (July 6th) were plotted (Figure 1). As we can see from the graph, increasing canyon depth has a direct effect on air temperature. Built surfaces store heat during the day and re-radiate it back into the canyon at night as long wave radiation. As canyons become deeper the sky view factor (SVF) becomes smaller, allowing less long wave radiation to escape at night to the atmosphere. The maximum predicted heat island intensity is nearly 5°C, shortly before dawn, but mid-day differences in air temperature are very small.

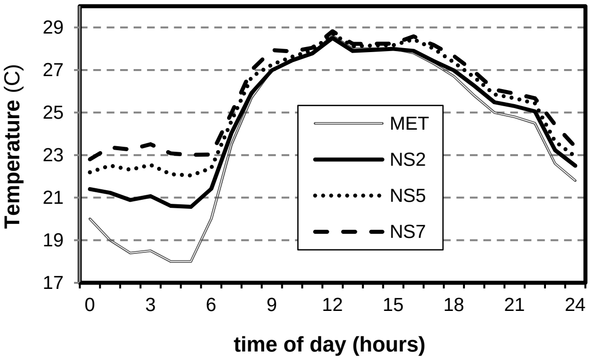

Figure 1: Dry bulb temperature at the weather station (MET) and predicted temperatures for a N-S street canyon flanked by buildings of 2, 5 and 7 storeys.

Additional heat trapping occurs due to the reduced wind speed which is a result of increased surface roughness in built areas. Figure 2 shows the effect of aspect ratio on wind speed in the canyon. Concurrent wind speed at the reference (rural) meteorological station was minimal at night, increasing gradually to maximum values of as much as 6 m/s.

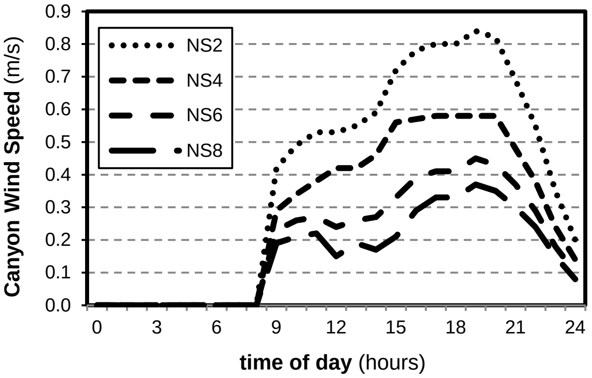

Figure 2: Wind speed at pedestrian height (1.5m) in a N-S street canyon 15m wide flanked by buildings of different heights (2-8 storeys).

Wind speed in the city of Tel Aviv is reduced substantially due to the overall aerodynamic roughness of the urban surface, but there is a further, localized effect as deeper street canyons experience lower wind speed at street level. In warm, humid conditions such as those prevailing in Tel Aviv during summer, this reduction in air speed reduces the effectiveness of sweat as a cooling mechanism, leading to greater pedestrian thermal stress.

Effect of aspect ratio on pedestrian thermal stress

In Figure 3 we see the contribution of various sources to the total energy fluxes on a pedestrian in a street canyon 2 storeys tall (top) and 7 storeys tall (bottom). The greatest change is in direct shortwave radiation, since in a deeper canyon this is blocked for much of the day by high canyon walls, and long wave radiation fluxes, as less is emitted to the sky and more is emitted from surrounding surfaces in a deeper canyon. Convective heat release in a deeper canyon is smaller due to lower wind speeds decreasing sweat efficiency.

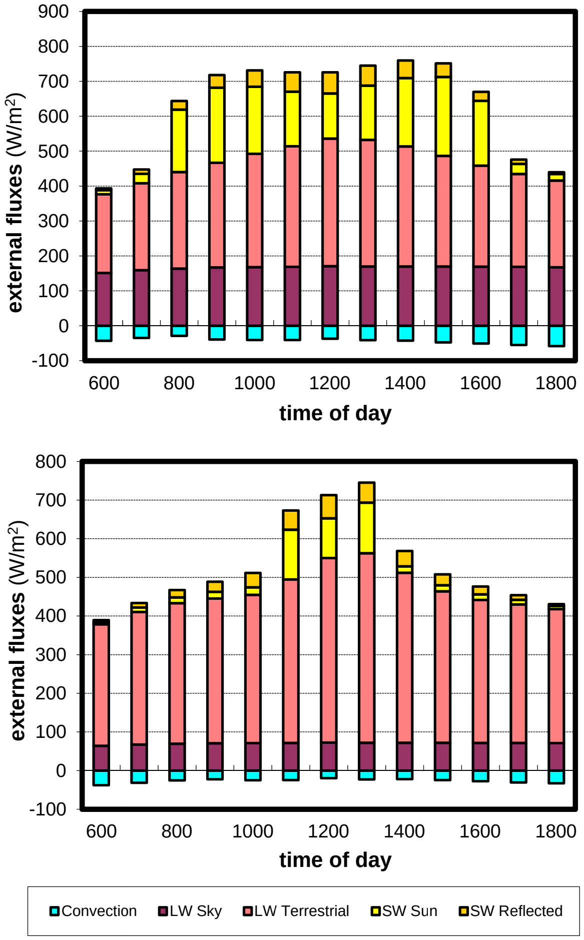

Figure 3: Breakdown of fluxes causing thermal stress on a pedestrian in a N-S canyon with 2-storey buildings (top) and 7 storeys (bottom).

Figure 4 displays the total thermal stress (watts) on a person in the centre of a 15m wide street flanked by buildings of 2, 4 and 6 floors. While a pedestrian in the deeper canyon will experience a higher maximum thermal stress, experiencing conditions rated as 'hot', it is only for a short period during the middle of the day that this value is reached.

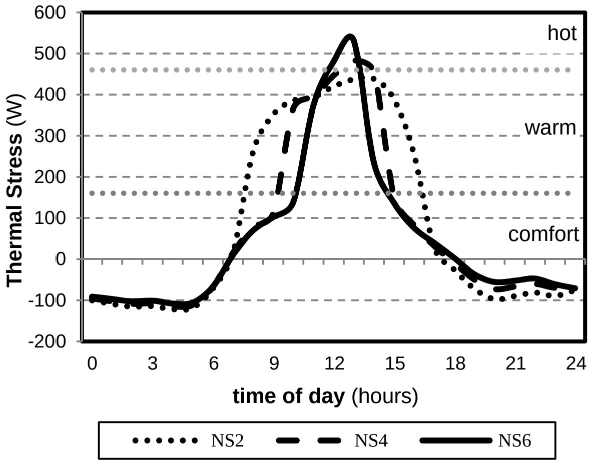

Figure 4: Pedestrian thermal stress (W) for a N-S street canyon of 2, 4 and 6 storeys. ITS categories: <160W "comfortable" (ITS=4); 160-460W "warm"(ITS=5); 460-760W "hot" (ITS=6); >760 "very hot"(ITS=7).

Figure 5 is a representation of the hourly distribution of thermal stress in N-S street canyons of different heights, from 1 to 8 storeys, as indicated by the ITS. Although deeper canyons may cause more intense thermal stress for two hours during the heat of the day than that experienced in shallower streets, the total time a person feels discomfort in such streets is considerably shorter than in wider street canyons.

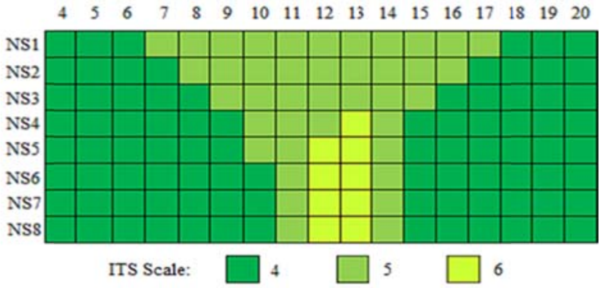

Figure 5: Hourly measures of thermal stress by experienced by a pedestrian in a N-S street flanked by buildings of different height. The ITS scale: 4 – comfortable; 5 – warm; 6 – hot; 7 – very hot.

Effect of the street canyon aspect ratio on building thermal performance

There are various factors affecting the energy efficiency of the modelled buildings, including: variation in surface-to-volume ratio of buildings of different height; the relative effect of the top floor which is exposed to the sky; the proportion of glazed surface which is shaded by nearby buildings; and the outdoor microclimatic conditions which are altered by the surrounding building geometry.

Looking at Figure 6, it becomes evident that the 7-storey building is more energy-efficient than the shorter buildings, as measured by its specific energy consumption (W/m^2/year).

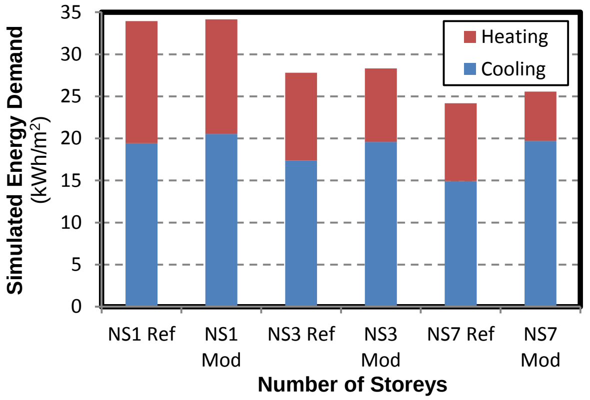

Figure 6: Simulated energy demand for heating and cooling buildings on a N-S canyon for 1, 3, 5 and 7 storeys. Results compare buildings simulated with TMY data from a nearby reference site (ref) and with those simulated with TMY modified to account for site conditions according to different density scenarios (mod).

Additionally, we see that although CAT predicts the formation of substantial nocturnal heat islands, which increase in magnitude as building height increases, the increase in summer cooling loads is offset by decreased winter heating loads. While the difference grows with building height, the largest variation between simulations using reference and modified weather data is ~1.4 kWh/m^2 over the course of a year. Table 1 shows the breakdown of energy consumption for each floor of a 5-storey building modelled using both climate inputs from the meteorological site and CAT-modified data for the urban canyon.

Table 1: Heating, cooling and total loads for each floor of a 5 storey building on a N-S oriented canyon. Simulations using reference data from the meteorological site (left) and modified data for the urban canyon (right).

	using Bet Dagan TMY			using modified TMY		
Storey	Cooling	Heating	Total	Cooling	Heating	Total
1	8.7	7.6	29.2	11.1	5.6	29.5
2	14.4	7.6	34.7	18.0	5.1	35.9
3	14.8	7.3	34.9	18.4	4.9	36.0
4	15.5	6.8	35.0	19.0	4.4	36.3
5	25.8	16.5	55.0	29.9	13.3	55.9
average	15.8	9.1	37.8	19.3	6.6	38.7

The data shown for each floor are the average for 4 apartments, which display some variance among themselves due to different orientations. The smallest total loads can be seen for the ground floor, which has the thermal mass of the ground beneath it keeping temperatures relatively stable. The greatest total loads are for the top floor, which is exposed to the sky above and to the air on four sides. The middle storeys all have very similar energy requirements.

DISCUSSION AND CONCLUSIONS

This paper presented a series of simulations modelling hypothetical modifications to the built environment in a Mediterranean city, manifested in increasing urban density by addition of floors to existing buildings. The goals were to create a comprehensive image of thermal exchanges in a Tel Aviv street and to generate recommendations regarding the effects of changes to building geometry which are likely to take place in coming years, based on computer simulations.

Through a coupled simulation using CAT and ITS, we see that deeper canyons (simulated aspect ratio of up to H/W=1.6) result in greater maximum thermal stress - but only for a short period in the middle of the day when the sun is near its zenith. Thermal stress throughout the rest of the day is considerably reduced in deep canyons which block much of the solar radiation from reaching pedestrians. In fact, total hours of thermal discomfort are reduced from 11 to 4 when the canyon aspect ratio is increased from H/W=0.2 to H/W=1.2 (by increasing the number of floors from 1 to 6).

Through a series of simulations using the ENERGYui interface for EnergyPlus, it is evident that taller buildings are more efficient in terms of indoor acclimatization than are lower buildings (up to 8 storeys). This is attributed largely to differences in the total number of floors not in direct exchange with the sky: The roof is exposed to high radiant loads in summer and is most exposed to wind at winter, so it is a thermal weak point in the building envelope, especially considering the current standard of thermal insulation: The energy consumption of the top floor is ~55 kWh/m^2/year, compared to ~35 for an intermediate level floor.

It should also be noted that building properties and mutual shading by adjacent buildings outweigh the thermal consequences of adding extra floors: In Tel Aviv, the increase in summer cooling resulting from stronger urban heat islands is in any case offset by the reduction in winter heating.

The model accounts for the reduced solar gains in winter as well as in summer but assigns a fixed lighting schedule. Deeper canyons are in fact going to allow less sunlight: however, Israel is a sunny country, so this is less of an issue than in many other locations. The effect is most likely marginal in our case.

Buildings were only modelled under conditions where all surrounding buildings were of the same height, so mutual shading increased along with building height. Additional complexity resulting from varied building height, such as altered wind patterns and changes to the radiation balance of the street and to mutual shading from adjacent buildings, was likewise unaccounted for. Pollution dispersion within the canyon is a complex issue beyond the scope of this research, particularly between medium aspect ratios (0.5-1.0), [20]. However, as a general rule, pollution concentration in the canyon tends to increase with aspect ratio.

The simulated buildings are of fairly low thermal performance, reflecting accepted practice at the time of their construction over 30 years ago: In particular, external walls and roofs are poorly insulated. Better construction is likely to yield even smaller differences among buildings of different heights, especially if roof insulation is improved.

Translation of these results to the energy consumption of buildings in other climates/latitudes, with larger window/wall ratios, different window shading patterns or of different construction materials (i.e. lightweight timbre frames) should be done with much care, and requires further research. The energy consumption of office buildings is likewise unaccounted for in this study.

Finally, the results presented here reflect the most likely outcome of the application of the NGP 38 construction policy in Tel Aviv. The effects of differences in moisture availability between the reference site and the city site were not distinguished from the effects of building geometry in this paper, as the simulations reproduced their combined effect. The separate effects of the two factors and the implications of using of non-localized TMY data for certification purposes will be examined in a future publication.

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