Urban climate adaptation: an interdisciplinary research experience empowering architecture and urbanism education

La adaptación al cambio climático: una experiencia de investigación interdisciplinar que potencia la formación en arquitectura y urbanismo

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Abstract

The world's cities are growing in size and number. At the same time, the global climate change rises global average temperatures as well as increase weather extreme events. Sao Paulo, the 5th urbanized region in the world, has currently more than 21 million inhabitants and recent studies alert for the increased frequency of extreme climate/weather events in the city. In this context, this work presents an interdisciplinary research experience, based at the Architecture and Urbanism school in partnership with the Atmospheric Sciences' Department, approaching the interdependencies between urban morphology, green infrastructure, and microclimate in São Paulo, aiming to discuss planning, urban and building design alternatives to counterbalance urban warming effects in a subtropical changing climate. The research team, led by an architecture researcher and an associate researcher from atmospheric sciences, includes a post-doc researcher, graduate and undergraduate students, engaging architecture, urban design, planning, and meteorology dealing with the role of planning, urban and building design for climate change adaptation. This paper briefly summarizes what we have learnt with remote sensing, measurements and numerical simulation encompassing the metropolitan, the neighbourhood and the building scales and discuss the results of an interdisciplinary research empowering architectural education in different levels.

Keywords: architectural education; building design; interdisciplinary research; urban climate adaptation; urban design

Resumen

Las ciudades del mundo están creciendo en tamaño y número. Al mismo tiempo, el cambio climático global eleva las temperaturas medias del planeta y aumenta los fenómenos meteorológicos extremos. Sao Paulo, la quinta región urbanizada del mundo, tiene actualmente más de 21 millones de habitantes y estudios recientes alertan sobre el aumento de la frecuencia de los eventos climáticos/ meteorológicos extremos en la ciudad. En este contexto, este trabajo presenta una experiencia de investigación interdisciplinaria, basada en la escuela de Arquitectura y Urbanismo en colaboración con el Departamento de Ciencias Atmosféricas, que aborda las interdependencias entre la morfología urbana, la infraestructura verde y el microclima en Sao Paulo, con el objetivo de discutir alternativas de planificación, diseño urbano y de edificios para contrarrestar los efectos del calentamiento urbano en un clima subtropical cambiante. El equipo de investigación, dirigido por un investigador de arquitectura y un investigador asociado de ciencias atmosféricas, incluye un investigador postdoctoral, estudiantes de grado y de posgrado, que se dedican a la arquitectura, el diseño urbano, la planificación y la meteorología y que tratan el papel de la planificación, el diseño urbano y de edificios para la adaptación al cambio climático. Este artículo resume brevemente lo que hemos aprendido con la teledetección, las mediciones y la simulación numérica, abarcando las escalas metropolitanas, de barrio y de edificio, y discute los resultados de una investigación interdisciplinaria que potencia la educación arquitectónica en diferentes niveles.

Palabras clave: adaptación al clima urbano; diseño urbano; diseño de edificios; enseñanza de la arquitectura; investigación interdisciplinar;

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Introduction

This paper describes an interdisciplinary research experience based at the Architecture and Urbanism school in partnership with the Atmospheric Sciences' Department, empowering architectural education. On the one hand, the research scope approaches the interdependencies between urban morphology, green infrastructure and microclimate in São Paulo, Brazil, aiming to discuss planning, urban and building design alternatives to counterbalance urban warming effects in a subtropical changing climate. The research team, led by an architecture researcher and an associate researcher from atmospheric sciences, includes a post-doc researcher, graduate and undergraduate students from the architecture school.

On the other hand, experiences in thermal comfort are ongoing at the atmospheric sciences disciplines inside of the Biometeorology area. There is a very well-known literature dealing with thermal comfort and its impact on human health, including research developed for the local context, such as Gonçalves et al. (2007), Batista et al. (2016) and Diniz et al., (2020) for the São Paulo Metropolitan Area.

The research context

In 2018, 55% of the world's population lived in urban settlements and it is expected to rise to 60% in 2030. One in five people worldwide lives in a city with more than 1 million inhabitants. The world's cities are growing in size and number. In 2016, there were 31 megacities globally, 33 in 2018 and their number is projected to rise to 43 by 2030 (UN, 2019). Brazil surpassed 84% of urban population in 2010 (IBGE, 2011).

At the same time, the global climate change is a phenomenon of shift in global climate patterns, rising global average temperatures as well as increasing weather extreme events, particularly heat waves. The Intergovernmental Panel on Climate Change - IPCC, an international body that compiles worldwide studies on climate change, indicates, in its five previous reports (IPCC, 2014), both the climate change intensification as well as the increasing certainty about the human actions' role.

In a clear sign of continuing long-term climate change, the Copernicus Climate Change Service[1] reveals that globally 2020 was tied with the previous warmest year 2016, making it the sixth in a series of exceptionally warm years starting in 2015, and 2011-2020 the warmest decade recorded. 2020 was 0.6 ºC warmer than the standard 1981-2010 reference period and around 1.25 ºC above the 1850-1900 pre-industrial period, and this makes the last six years the warmest six on record. Europe saw its warmest year on record at 1.6 ºC above the 1981-2010 reference period, and 0.4 ºC above 2019, the previous warmest year.

The global climate change is a phenomenon of shift in global climate patterns, rising global average temperatures as well as increasing weather extreme events. The Intergovernmental Panel on Climate Change special report, Global Warming of 1.5 ºC (IPCC, 2018), states that climate models project robust differences in regional climate characteristics between present-day and global warming of 1.5 ºC, and between 1.5 ºC and 2 ºC. These differences include increases in mean temperature in most land and ocean regions (high confidence), hot extremes in most inhabited regions (high confidence), heavy precipitation in several regions (medium confidence), and the probability of drought and precipitation deficits in some regions (medium confidence). Most adaptation needs will be lower for global warming of 1.5 ºC compared to 2 ºC(high confidence). There is a wide range of adaptation options that can reduce the risks of climate change (high confidence). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5 ºC, with associated losses (medium confidence). Pathways limiting global warming to that threshold 1.5 ºC with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (high confidence). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (medium confidence). Limiting to 1,5 ºC is not impossible, but requires unprecedented efforts in all sectors, with a whole mitigation portfolio for each one of the sectors; to achieve this, 2050 CO^2 emissions should be zero, but there are also residual emissions to be considered. Besides that, climate and Sustainable Development Goals - SDG are linked, and limiting to 1,5 ºC helps to achieve other SDG. Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5 ºC, although trade-offs are possible (high confidence).

In 2019, the GEO6 Report (UN Environment, 2019) concluded that, at present the world is not on track to meet the SDGs by 2030 or 2050. Urgent action is required now as any delay in climate action increases the cost of achieving the goals of the Paris Agreement, or reversing our progress and at some point, will make them impossible. While urbanization is happening at an unprecedented level globally, the report says it can present an opportunity to increase citizens' well-being while decreasing their environmental footprint through improved governance, land-use planning and green infrastructure. Furthermore, strategic investment in rural areas would reduce pressure for people to migrate.

There is an important need to limit the potential negative sustainability impacts of drivers of population, economic development and climate change. Whether these three drivers serve as catalysts of positive (rather than negative) transformative response in the form of social equity, environmental resilience, and poverty eradication is likely to be determined by uncertain long-term impacts of drivers of urbanization and technology (UN Environment, 2019).

The five drivers raised by the GEO6 Report —population growth and demographics, urbanization, economic development, new technological forces, and climate change— have led to an unprecedented expansion of wealth for many but have also left many behind and could produce trouble for the future. The previous report, GEO-5, referred to two drivers – population and economic development – to which GEO-6 adds three more, urbanization (previously covered under population), technology and climate change. In this assessment, urbanization and climate change are added as independent drivers because of their importance in socioeconomic change. Urbanization has been going on throughout history, but its pace, scale and impact have accelerated sharply in recent decades. As such, it is included independently as a fourth driver (UN Environment, 2019).

In urban areas, the land use and the heat residues emissions by mechanical systems are playing a more significant role in ongoing warming trends than greenhouse gas emissions (Stone, 2012). Heat islands can increase discomfort and potentially raise the threat of heat stress and mortality in tropical climates as well as during the warmer seasons at temperate zones and heighten the cost of air conditioning and the demand for energy (Stewart; Oke, 2012).

1 Copernicus: 2020 warmest year on record for Europe; globally, 2020 ties with 2016 for warmest year recorded. In: https://climate.copernicus.eu/copernicus-2020-warmest-year-record-europe-globally-2020-ties-2016-warmest-year-recorded. Press release in 8th January 2021.

Considering the IPCC´s climate scenarios, both from the IPCC Special Report 1,5 ºC (IPCC, 2018) and the latest AR6 cycle (IPCC, 2021; 2022), for the urban scale, the increase of urban vegetation cover is seen as an effective strategy to cooling cities and save energy due to the decreased demand for air conditioning. Particularly in urban centers, urban growth typically decreases space for green areas and the urban environment creates obstacles to planting of new trees. These include soil compaction, lack of space for roots, overhead and underground provision of services, such as electric cables and other urban infrastructures, and the lack of adequate management of trees. Consequences of neglecting green and water infrastructure —factors that modulate urban climate— are evident: recurrent and severe flooding, excessive heating of urban surfaces, low air quality and an increase in urban heating, particularly daytime urban heat island in the tropics, among other factors (Emmanuel, 2005). The situation is worse in high-density cities, where land is scarce and there is little provision of space for the incorporation of urban greenery such as urban parks and landscaping. Land-use pressures and overheated property markets limit the potential for large-scale green infrastructure (ONG, 2012). The integration of greenery in buildings and dense urban spaces faces many constraints (Chen, Y., Wong, N.H., 2006), despite some cases of success, such as Singapore, with the adoption of Green Plot Ratio by local legislation (ONG, 2002), increasing green infrastructure in parallel to the built density, adding shading and moisture to the urban environment.

In addition, both global and local urban heating phenomena can potentially influence the thermal building performance. The associated urban heat island and the global warming increases the cities surface temperature, which negatively impacts environmental and social balance (Santamouris, 2014), affecting energy consumption for cooling, emissions and human health and comfort.

Climate and urban context in Sao Paulo

São Paulo is a sprawling megacity with 39 municipalities. It is the 4th urbanized region in the world with almost 22 million inhabitants, the biggest Latin-American megacity (UN, 2019). Sao Paulo Metropolitan Area (SPMA) is located at 46.6 OW longitude and 23.5 OS latitude, characterized by a subtropical climate, with annual mild temperatures, with average of 19-20 ºC nowadays, hot and wet summers and milder and drier winters.

The warming pattern has changed, not just globally, but also at the regional scale, including South America (Sánchez E. et al., 2015). Recent studies alert for the increased frequency of extreme events in the city such as heat waves (Batista, et al., 2016; Nobre, et al., 2010; Marengo, 2006; Diniz et al., 2020). The data from the Meteorological Station of Parque Estadual das Fontes do Ipiranga (IAG/USP, s.d) reveals a progressive rising in air temperatures, which started in 1933; there was an increase in annual average temperature of approximately 3 ºC, from 16-17 ºC to 19-20 ºC, and respective relative decrease of air humidity. There were heat wave events in January and February during the years 2014 and 2015, being the absolute maximum 37,7 ºC occurred in October 2020 (IAG/USP, s.d). Temperatures over 36 ºC became common after 2014, which has occured as often as 13 times. There were 14 heat wave events during 2014, three times higher than the previous record (Batista et al., 2016). More recent projections from Diniz et al. (2020) have shown that the heat wave-related excess mortality will be increased by a factor of three times to twelve times, while duration and intensity will be also higher. Its impact on elderly mortality will increase, mainly from cardiovascular diseases in women (up to 587 deaths per 100.000 inhabitants per year).

From 2010 to 2020, the mean temperatures were higher than the previous bases from 1961-1990 and 1981-2010, at the IAG/USP Meteorological Station (IAG/USP, s.d.). Despite that 2016 was the coolest year among the later ones, there

Table 1 Annual mean air temperatures and their records for the period 2010-2020, in Sao Paulo. The anomaly was based on the mean air temperature in relation to the period 1981-2010

Source: Authors, over meteorological data (IAG/USP, s.d.).

	Annual mean air temperature	Anomaly based on the absolute maximum temperature 1981-2010	Absolute air temperature	Anomaly based on the absolute maximum temperature 1932-2012
2010	19,5	0,18	34,6	-1,0
2011	19,1	-0,15	34,7	-0,9
2012	19,9	0,61	35,9	0,3
2013	19,3	0,03	35,2	-0,4
2014	20,1	0,81	37,2	1,6
2015	20,3	1,09	36,4	0,8
2016	19,6	0,31	36,7	1,1
2017	19,7	0,42	36,1	0,6
2018	19,7	0,39	35,0	-0,6
2019	20,2	0,93	36,6	1,0
2020	19,6	0,36	37,7	2,1

were 100 days with temperatures higher than 30 ºC (the average is 49 days), particularly from mid-March to the end of April. The years of 2015 and 2019 were the second and third warmest years since 1933, being overpassed only by the year of 2002, the record. The years of 2014, 2017 2018 and 2020 also presented temperatures above normal, from 0.3 to 0.8 ºC positive anomaly. Concerning daily maximum temperature records, from 2014 to 2020, a plenty of them were broken. Before 2014, 35.9 ºC (during the year of 2012) was the absolute record. After 2014, that record was broken twenty times, being present in all years, but 2017. That also means the effect of urban heat island acting together with global warming, as it is shown in Table 1.

Sao Paulo is characterized by a heterogeneous urban structure, caused by the rapid growth of the city during the 20th century. High-rises are found everywhere in the city and contrasts with poor informal settlements spread all over the metropolitan area. In Sao Paulo deforestation has occurred since the early stages of urban development due to illegal and legal allotments, however no updated official monitoring is available. The lack of information about the vegetation dynamics in SPMR can be related both to technical restrictions from the local technical staff and to suspicious political and economic interests influencing urban planning decision-making processes in the local government (Ferreira, 2015). It must be noted that the São Paulo megacity has not grown in the last decades as much, therefore, the last years of temperature increase can be attributed to global warming.

Besides the urban scale, the Brazilian Panel on Climate Change - PBMC states that the building sector is increasing its energy consumption both in Brazil and all around the world (PBMC, 2016). According to data from the Brazilian Energy Research Company, energy consumption in buildings (commercial, residential, and public sector) is responsible for a significant portion of the energy generated in Brazil, more than 15 % of total energy consumption and circa 50 % of electricity consumption, being half of this in the residential sector (Brasil, 2020a; 2020b).

In the global scenario, buildings account for about 32 % of global energy demand from a variety of sources, which has motivated cities worldwide to adopt more rigorous urban and building regulations, as well as more efficient energy consumption policies. In Brazil, unlike countries in higher latitudes, the cooling demand is significantly higher than the heating one. The estimated electricity consumption for air conditioners in the residential sector has more than tripled in the last 12 years. The household air conditioner ownership increased by 9.0 % per year between 2005 and 2017, influenced mainly by the growth of sales of new appliances between 2010 and 2015 (Brasil, 2018).

During the heatwave events, such as the one during the year of 2014, the energy demand tends to be even greater. An example is the heatwave that took place in São Paulo in January and February 2014, when there was a 4.9 % energy consumption increase during January and 8.6 % during February, if compared to the same months in 2013. Mostly was due to the increase in the purchase and use of air conditioning in that period, especially by the residential sector (Brasil, 2014). Once the air conditioning is installed, the equipment will be used whenever there is a temperature increase (Wu & Pett, 2006), which means that consumption patterns probably will not return to what they used to be previously.

After periods of low economic growth in Brazil, which characterized the 1980s and part of the 1990s, economic stability and the rise in average family income created the conditions to supply part of a suppressed demand for thermal comfort, as expressed by the increase of electricity consumption due to the use of air conditioners in the country. The energy consumption for thermal comfort is the fastest growing end-use in Brazil. Considering only the residential sector, the ownership of air conditioners more than doubled from 2005 and 2017, and the demand are expected to increase in a near future. The estimated electricity consumption for air conditioners in the residential sector has more than tripled in the last 12 years (Brasil, 2018).

It was verified that, for the São Paulo weather conditions, residential buildings that use traditional construction systems and were built around the 1970's tend to respond reasonably well to the current and projected future climate changes, operating in passive mode and keeping most of the year under comfortable conditions, according to the ASHRAE-55 (2020) adaptive comfort model. The gradual increase of hours in warmer conditions, out of the comfort zone, and the discomfort intensity can be considered unavoidable, and it was simulated around 270 % discomfort increase in the housing units studied, highlighting the summer period and the heat waves (Alves et al., 2016).

In addition to the traditional residential buildings, there is a large stock of new residential ones in São Paulo, especially built from 2007 to 2014 due to a real estate market boom in the city. Being driven by market issues, the real estate production is remarked by the distance between professional practice and architecture research and it over values the aesthetic while other issues, as functionality and performance, do not play such an important role. On the one hand, glass facades, less thermal mass and poor natural ventilation design are used in wealthy and fancy new high-rise residential buildings, with big apartments, for residents that can afford air conditioning for thermal comfort. On the other hand, these building design strategies are imitated by middle-class buildings, which are much smaller, and they are spreading very fast all over the city.

The city of Sao Paulo has in force three laws for its urban planning and development: The Master Plan (2014), the Zoning Law (2016) and the Building Code (2017) (Sao Paulo, s.d.). As recently updated texts, it was expected that they could express the integration of its contents pointing at contemporary urban issues such as managing energy efficiency and providing buildings with quality and comfort to the users. What happens instead are several mismatches between their contents. On the opposite of the worldwide trend, São Paulo city laws have been losing, over the last century and the update process, almost all the performance construction requirements, which influence the environmental quality of buildings (Tsuda, 2018).

Methodology

Under this urban and climate context, this project deals with the role of planning, urban and building design for climate change adaptation,

Figure 1. Microclimate monitoring (on the right):on the right, two nearby locations in Sao Paulo downtown, close to Paulista Avenue below, on the left, the urban block/below, on the right, the urban park in a densely built and high-rise area

Source: authors, (2016).

including occasional heat waves or for the projected IPCC AR-5 scenarios. For this purpose, a research team was based at the Architecture and Urbanism school in partnership with the Atmospheric Sciences' Department approaching the interdependencies between urban morphology, green infrastructure, and microclimate in São Paulo, aiming to discuss urban and building design alternatives to counterbalance urban warming effects in a subtropical changing climate.

The research group encompasses a principal investigator at the Architecture and Urbanism school, an associate researcher from the Atmospheric Sciences Department, a post-doc researcher and Architecture students from different levels: 4 PhDs and 2 Master candidates, 4 Diploma students and 6 undergraduates as scientific initiation researchers, from 2nd to 5th year students.

The research group was formed aiming to involve Architecture students at different levels of their education in training around common themes. All research topics involve graduate and undergraduate students working together, in theoretical, experimental, public policies and/or design issues. In some cases, the undergraduate students started as scientific initiation in the laboratory, continued for the Diploma and later apply for the graduate courses. In this case, the 4 PhD candidates did the Master in the same group, as well as the post-doc researcher for Master and PhD, consolidating a long-term research commitment with environment and energy issues.

The research topics were organized in three different scales: 1) metropolitan scale, mainly studying the impact of vegetation loss increasing land surface temperature, due to the lack of shading and humidity, at various temporal and spatial scales, combining satellite thermal images from 2002 to 2017 (Modis), vegetation indices and mapping techniques, exploring daytime and nighttime effects and relating these results to the urban morphology, feeding other investigations in the group; 2) neighbourhood scale, subdivided into 2.1) the impact of vegetation on urban microclimate, encompassing urban parks, street trees and green walls; and 2.2) the role of the density of built form on local microclimate, concerning urban geometry and materiality; 3) building scale, regarding building's thermal performance and comfort, highlighting the new stock of residential buildings that emerged during the real estate boom in the last years in Sao Paulo. The neighbourhood and building scales are carried out through local measurements and numerical modelling, mainly with ENVI-met and TAS/EDSL.

Vertical interactions in the group were encouraged, e.g., green issues are addressed in metropolitan, neighbourhood and building scales (green walls), besides public policies, encompassing researchers and students in all levels of formation, including design proposals by the four Diploma students.

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Figure 2 - Fieldwork to measure surface temperature with a thermographic camera, air, temperature, and air humidity in different locations and leaf area index with the canopy analyzer

Source: authors, (2016).

Figure 3. Indoor measurements in apartment buildings

Source: authors, (2016).

Horizontal interactions among different themes were encouraged also, e.g., the density studies subgroup discussing with the green infrastructure subgroup, aiming to counterbalance built density with climate amenities in the city, one of the big challenges to be explored and answered. The in situ urban climate and building thermal performance measurements were planned, as far as possible, aiming to optimize human and equipment resources, at the same time, coinciding urban and building scale data gathering to evaluate the results simultaneously.

The reference station from IAG/USP gathers all climatological data in an hourly basis since 1933, giving a long-term overview from a suburban location. The thermal satellite images for the metropolitan area were analyzed for a 15 year's period, from 2002 to 2017. At the neighbourhood (figure 1 and 2) and building's scale (figure 3) it was possible to coincide both measurements in April 2016, on an hourly basis, considered sufficient to calibrate both models, due to very stable weather condition during that period.

Simultaneously, as far as possible, depending on climate stability, instruments and people availability, parallel measurements (fig.2) were carried out to gather local data related to: 1) surface temperature with a thermographic camera, at the same time as a Landsat pass, for comparison; 2) leaf area index of local species; 3) building facades, paving and vegetation surface temperature, to be compared with ENVI-met modelling results; 4) indoor measurements of air temperature and humidity, wind speed and globe temperature in residential buildings, to calibrate a building energy simulation model, in this particular case, TAS/EDSL (fig.3).

In a regular basis, smaller groups' meetings were carried out for 1) discussing theoretical issues, 2) for training features of new software versions encompassing modelling, parametrization, visualization of results; 3) for planning common activities including workshops and fieldwork and 4) for presentation and discussion of partial results, most of the time, exchanging the findings among the team members.

For the urban and building scales, the research methods encompass: 1) data raising and/or mapping to identify study areas; 2) development of fieldwork plans according to the resources and constraints of the models adopted; 3) primary data collection in urban scale for soil, vegetation and atmosphere at ground level, to be obtained by surface microclimatic measurements coupled with remote sensing (RS) data and geographic information systems (SIGs), and also by measurements at the building scale; 4) modelling of the study areas, for the urban scale using ENVI-met, and for the building scale using Thermal Analysis Software – TAS/EDSL; 5) calibration of the models between measured and simulated data (Shinzato et al, 2019; Alves et al, 2016; 2021); 6) development of parametric studies and selection of the best strategies from simulation results for current and future climate scenarios. Therefore, starting from the metropolitan information, using thermal satellite images and other available mapping techniques, besides microclimate data at pedestrian level, the purpose was to focus in interest areas and develop parametric studies to select the best strategies using model simulation.

Results

Results of the project[2] include the impacts of density, vegetation and urban surfaces in microclimate, the effects of adaptation strategies to climate change for urban areas and buildings, in current and future climates, as well as applications in urban and building design and public policies. The outcomes can be better understood organized in three scales: metropolitan, neighbourhood and building scale.

Metropolitan scale: land surface temperatures as a function of vegetation suppression in spatial and temporal scales

Results are shown starting from the metropolitan scale, aiming to quantify the impact of vegetation loss in the urban microclimate and to contribute for public policies in the São Paulo Metropolitan Region (SPMR). Temporal variations of the land surface temperature and vegetation indices, obtained by MODIS satellite images from 2002 to 2017 were analysed. Urban morphology was mapped using the WUDAPT-Local Climate Zones (LCZ) approach. LCZ maps for 2003 and 2017 were generated to verify whether changes in LST and/or vegetation cover can be explained by changes in urban morphology. The year of 2016 was chosen for the entire procedure, due to a very stable weather condition coinciding with the in-situ measurements period. Daytime and nighttime land surface temperature (LST) and the Normalized Vegetation Index (NDVI) derived from 2016 Aqua/MODIS satellite images were computed for the SPMR (Ferreira & Duarte, 2019; Ferreira, 2019).

There is a strong negative linear correlation between LST and NDVI, both for daytime and nighttime. LST-NDVI correlation is strongest during summer, when LSTs are higher, and the vegetation cover more vigorous (Figure 4). During daytime LCZ 1 showed lower temperatures than LCZ 3. Since NDVI values of these two zones are similar, shadows may have lowered LST. The combination of vegetation cover shaded by buildings may explain the lowest daytime LST of LCZ 4. The open arrangement of LCZ 4 and 6 also enables urban ventilation, which may have an influence both in diurnal and nocturnal LST. During nighttime, the daily heat storage and the lack of open spaces may contribute to LCZ 1 higher LST values. Results showed that ventilation, building shadows and vegetation cover have a key role in LST for SPMR (Ferreira & Duarte, 2019; Ferreira, 2019).

Neighborhood scale: green infrastructure and built density

Green infrastructure studies on ENVI-met V.4 Science model were intensified after the Albero tool, a new resource for modelling and parametrization of trees available as part of ENVI-met; therefore, a 3D parametrization of Brazilian trees was carried out with Albero based on leaf

2 Results from the project, encompassing researchers and students in all levels of education, including design proposals by the four Diploma students, can be found at https://www.researchgate.net/project/The-role-of-planning-urban-and-building-design-for-climate-adaptation-in-the-microscale-Contributions-to-an-interdisciplinary-approach. Forthcoming publications are continuously updated in the same platform.

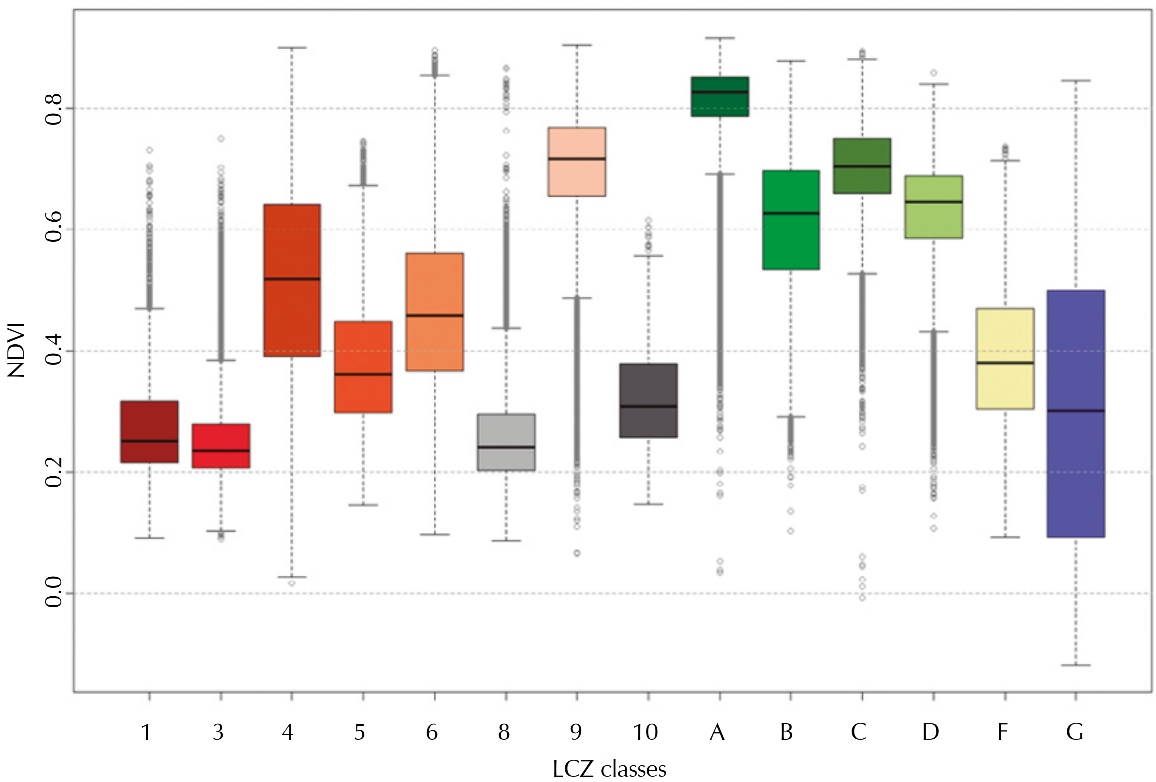

Figure 4. Boxplot with NDVI by LCZ. The bottom of the box indicates the first quartile and the top of the box, the third quartile. The line within the box indicates the median

Source: Ferreira, Duarte (2019)

density in local field measurements (Shinzato et al., 2019). The full-forcing feature was also important to better calibrate São Paulo's microclimatic conditions, coupling in situ and simulation results. Different scenarios were simulated, considering an urban park and its surroundings. The new areas with vegetation were incorporated gradually in order to verify the local microclimate effect including street trees, trees inside the blocks (Shinzato et al., 2018) and green walls (Silva, 2018; Silva & Duarte, 2018).

Building scale: thermal performance and comfort under an urban and changing climate

Before the in-situ measurements and simulation, the building scale investigation started at the intersection of two factors: the local real estate housing typical production, mainly multifamily apartment buildings, from 2005 to 2014 in Sao Paulo - a Real Estate boom period (Longarine & Duarte, 2017) and the changing warming climate, registered by the reference meteorological station in the suburbs. In parallel to this Real Estate boom period, and in contrast to the worldwide trend, the local building code have been losing since the 20th century, along several updating processes, many construction requirements, which influence the environmental quality of buildings. The justification for some of these changes was on the fact that the approval processes for building construction were simplified, dismissing the need to detail internal spaces, to speeding up the city hall clearance, a worrying path for planning a more energy efficient future (Tsuda, 2019; Tsuda & Duarte, 2018).

Inside this context, the research focused on the building thermal performance simulation looking for the assessment of the different weather scenarios and the parameters related to construction and building use, influencing indoor thermal performance and human comfort. At the building scale, this study combined simulations and in-situ data collection. Measurements were carried out simultaneously in five apartment buildings. Substantial differences in thermal performance were found, attributed to the building design, building components and materials, solar orientation, openings, and shading, as well as to the occupation pattern, especially regarding ventilation rate. Results demonstrate that: a) more space or more openings do not guarantee a better thermal performance; b) balcony glazing can be positive or negative, depending on solar orientation and opening hours; c) thermal performance depends in large amount of the user operation of openings (Alves, 2019; Alves et al., 2021).

Another challenge is the consideration of the urban heat island (UHI) effect, considering both the climate change and the local urban warming. For this purpose, an UHI effect, locally measured (Gusson & Duarte, 2018; Alves et al., 2021), was coupled to the climatic data in the current and future scenarios, IPCC RCP 8.5 AR-5, for the simulation with TAS/EDSL.

Discussion

For the metropolitan scale, higher daytime and nighttime surface temperature were found at the urbanized areas, compared to their less urbanized surroundings; however, the urbanized area is not homogeneous. Areas with higher vegetation indexes and/or higher buildings have lower surface temperatures compared to other urban typologies in the daytime period, and areas with high buildings and low vegetation indexes have higher nighttime surface temperature, a figure compatible with the surface heat island pattern. Regarding areas with high rise buildings and high vegetation indices, existent only in wealthy neighbourhoods in Sao Paulo, the buildings are more spaced, and the nighttime surface temperatures are lower compared to the high-rise compact morphology found at downtown, not only because of green but also due to the higher sky view factor for the longwave radiation loss during nighttime. The areas that presented extensive vegetation losses and urban interventions, such as pavement, showed an increase in surface temperature. The results also reveal the role of urban design in surface thermal dynamics, encompassing building heights and spacing (the ratio of street width to building height), open spaces, green infrastructure, and buildings' thermal mass, indicating the potential, and consequently the responsibility, of urban and building design in the development of strategies for mitigation and adaptation to urban warming phenomena, especially in a scenario of climate change and extreme events (Ferreira, 2019).

For the neighbourhood scale, regarding the urban form, both geometry and urban materials were investigated separately. Results suggest that urban geometry determines the neighbourhood microclimate conditions, but surface finishes raise questions for the conflict between more reflective materials for the buildings' interior and the outside urban environment (Gusson, 2020; Gusson et al., 2020).

One of the main aims of the São Paulo Masterplan and its current land-use regulation is to increase population density along the city's main transport axes, optimizing the occupation of the areas around the train stations, subway lines and bus corridors (Sao Paulo, s.d.). At the same time, there are no predictive studies of the real impact of the proposed densification over the urban microclimate.

In principle, densifying affects the climate within the Urban Canopy Layer - UCL through the storage of heat, in the urban fabric during nighttime. This storage depends on the materiality of the urban surfaces, on urban geometry and on the sky-view factor (SVF). During daytime, mutual shading generated by adjacent buildings plays an important role in decreasing surface temperatures (Gusson, 2020; Gusson et al., 2020).

For the building scale, simulation results show that the balcony is positive when it assumes several configuration possibilities, varying also for different solar orientations and mutual shading from the surrounding buildings in such a dense urban environment like Sao Paulo, acting and being occupied as a transitional environment in fact and not as an indoor room, during the day and during the night; in this way it can be a vector of the best operating practices in the search for thermal comfort. Elements allowing the opening operation, especially the ones connected to the balcony, namely external glazing, door between balcony and living room and external shading elements, must be available to be operated by the user, who must be able to perceive the best possible operation and perform it (Alves, 2019; Alves et al., 2021).

Conclusions

This paper summarizes an interdisciplinary research experience between architecture, urbanism and meteorology empowering architects' education in different levels. Teamwork dynamics were detailed, exemplifying vertical and horizontal interactions among different scales, themes, and students' formation levels. The vertical interactions among researchers, graduate and undergraduate students allow the Diploma students to develop building and urban design proposals, informed by the latest research developments in the group. Currently, research goes forward following a close cooperation between Architecture and Urbanism and Meteorology courses.

Research methods were briefly presented, as well as some results on what we have learnt with remote sensing, microclimatic measurements and numerical simulation in the metropolitan, neighbourhood and building scales, for current and future climate scenarios. The research results in a sprawling megacity as Sao Paulo suggests that urban density seems to be a better solution for urban climate adaptation, but it is possible only side by side with urban amenities, creating small oasis spread all over the city, in transition spaces, taking the benefits of green, cool surfaces, weak winds and mutual building shading. For now, São Paulo is going to the opposite direction, more and more air conditioning dependent, with a local building code failing to establish any thermal and energy performance requirement and lacking good quality urban spaces in most parts of the city. Therefore, this project results' can subsidy proposals for future revisions of the local masterplan, zoning law and building code, that should be more aligned with overheating issues, related to climate change and urban heating phenomena, as many other urban ordinances in different cities and climates.

To conclude, aligned with the final statement of IPCC Cities (2018), "the science we need for the cities we want", the decision process should be based on scientific evidence. In the built environment, the scientific development and the adaptation plans related to planning, urban and building design can follow the recently launched AR6 cycle (IPCC 2021; 2022), aiming the "Special Report on Cities", included in the IPCC agenda for the forthcoming years, in AR7 cycle. In the Brazilian context, with a huge diversity between scales and social and economic development of our cities, an important challenge is to balance the urban density needed, instead of urban sprawl, relating climate actions to the Sustainable Development Goals (SDG), side by side with climate amenities in urban and building scales, including energy efficiency, mobility, urban ecosystem services and nature-based solutions. For that, urban and building professionals with different backgrounds and skills must be trained to work in interdisciplinary teams in close collaboration, with the aim of creating a balanced urban ecosystem facing the challenges of current and future climate scenarios.

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Denise Helena Silva Duarte and Fábio Luiz Teixeira Gonçalves coordinated and vice-coordinated, respectively, this research group during the funded project FAPESP and are responsible for the conceptualization, data gathering, analysis and conclusions, as well as for the writing and final revision of this paper.

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