Przegląd Geograficzny
2023, 95, 3, s. 237-254
https://doi.org/10.7163/PrzG.2023.3.2

Instytut Geografii i Przestrzennego Zagospodarowania
Polska Akademia Nauk

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The impact of urbanisation on local climate: a case study from Palmas, Brazil

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Abstract. The relationship between growing rates of urbanisation and city warming has been evaluated in a very large number of urban climate studies. The work detailed here has focused on remote-sensing data, looking at changes in urbanisation over time in one of the newest cities in Brazil, i.e. Palmas in the northern region of the country, which serves as capital city of Tocantins. The youngest state in Brazil, Tocantins was only founded in 1988, with the construction of Palmas as capital commencing in 1989. Measured meteorological data were used to assess local climate changes in typical years, whereas urbanisation levels, generated for stepwise increments of 10 years, were obtained from the identification of vegetated and built-up classes in satellite imagery. Results suggest that changes in local climate were not always related to ongoing urbanisation in Palmas. Equally, despite promising changes in patterns of distribution of vegetation in given areas of Palmas over time – with an increase in high NDVI levels in 2021 that would potentially ameliorate local climate – thermal benefits did not prove to be detectable at the reference meteorological station.

Keywords: urban climate, urbanization, remote sensing, historical air temperature, Brazil.

Introduction

Air-temperature changes on a local scale are frequently associated with urbanisation rates, as a number of studies on urban climate have demonstrated (Ward et al., 2016). Despite being less representative in terms of surface area (less than 0.5% of the Earth's land, Schneider et al., 2009), urban areas are commonly invoked as responsible for air-temperatures changes on the global scale, albeit with effects on scales ranging from the local to the regional or even the global asserted. Huang and Lu (2015) analysed the thermal impacts in the area of the Yangtze River Delta, which coincides with the third-largest urban agglomeration in China, concluding that urbanisation has been having a measurable effect on the observed warming of that region, and aggravating global warming.

Changes in land use and land cover can exacerbate human health problems (Zaldo-Aubanell et al., 2021), and again alter local, regional and even global climate (Huang & Lu, 2015). The scale of analysis is thus paramount in understanding climate-change impacts in urban areas, ranging from the microscale to regional climate (Gobo et al., 2018), with the latter capable of being affected by human activities at the urban level (city scale), as levels of air pollution increase, patterns of heat absorption and release change, albedo is modified – *inter alia* through widespread removal of vegetation, and so on.

The normalised difference vegetation index (NDVI) is advocated as a relevant indicator of the surface urban heat island effect, even as it also allows for intra-urban temperature comparisons, with confirmed relationships to land surface temperature (LST) (Yuan & Bauer, 2007). In the case of comparisons between field data and NDVI data obtained by remote sensing, a relationship is still seen to hold, especially under summer conditions. Bernard et al. (2017) generated an empirical model from field data collected via four different monitoring networks in France, and integrated NDVI obtained from RapidEye Satellite Imagery. In their model, they found that the impact of NDVI, due to its relationship to latent heat flux, is predominant during spring and summer. Urban greenery is among the most cited nature-based solutions to the promotion of cooling in urban areas, and the NDVI can be considered a relevant indicator of the cooling intensity (CI) attributable to, or at least associated with, urban green spaces (UGS), as shown by Zhou et al. (2023), who suggest that the NDVI is one of the critical, positively-correlated factors affecting the CI of UGS patches.

The normalised difference built-up index (NDBI) is an indicator of urbanisation and one that resembles NDVI in being obtainable through remote sensing. The two indices show opposite behavior, with LST correlations being generally positive where NDBI is concerned, and negative when it comes to NDVI – as is shown in a study investigating changes in local climate associated with rapid urbanisation in Guangzhou, China (Xiong et al., 2012). Such opposite behaviour can be explained as intense and rapid urbanisation converts naturally-vegetated, permeable surfaces into impervious built-up ones, altering local climate (Imran et al., 2022). In this paper, both indices, obtained for selected years for the city of Palmas, Brazil, will be compared to long-term field data recorded at an official meteorological station.

Domain description

The city of Palmas, capital of the youngest Brazilian state of Tocantins, was founded as relatively recently as in 1989. Palmas was located centrally within the territory of its state, with a view to socio-economic development of the region being achieved. Prior to the start of work on the state capital, this area was actually only sparsely occupied, by farms. The establishment of the capital was inspired by the foundation of Brasília as new capital of Brazil as a whole; and likewise followed a Modernist master plan. Between the end of 2001 and mid-2002, a hydroelectric power plant was constructed (*Usina Hidrelétrica de Energia Luís Eduardo Magalhães*, of 900 MW), the effect being to fill 630 km² of the surrounding area with water (Pires, 2017).

That flooding in the area, alongside other damages, led to relocation of rural and urban population, alterations in the fauna (especially the ichthyofauna), deforestation of countless areas, and the loss of natural riverbanks along the Tocantins (in part compensated for by the establishment of artificial beaches). The damage mainly afflicted the municipalities of Palmas and Porto Nacional, traditional tourist centres prior to the work on the plant.

Thus, the urban-planning proposal for Palmas was already in a position to take the pursuit of HEP plant in to account, while also foreseeing steady expansion of the city itself. However, following the trend seen in practice to characterise other planned Brazilian cities, territorial expansion actually took place in a manner diverging from the idealised urban plan, leading to vertical growth alongside urban sprawl. Resulting both from such unplanned urbanisation and the construction of the power plant, the effects of anthropisation in Palmas have proved an ideal research topic, investigated to a greater and greater extent (Pires, 2017; Silva, 2018). More specifically, by reference to data from meteorological stations and thermal comfort indices, Silva (2018) was able to verify a process of rising temperatures in the city of Palmas, not only after the construction of the plant, but also (mainly) following the onset of intensified processes of urbanisation and verticalisation in the city in the 2010s. The effects were increases in levels of thermal discomfort, also found to be reflected by perceptions present in the local population.

Pires (2017) analysed satellite imagery aided by mobile measurements in Palmas and official meteorological-station data before the establishment of the Luís Eduardo Magalhães hydroelectric plant (i.e. in 2000 and 2001), and also thereafter (in 2005, 2010 and 2014). The study referenced biophysical parameters, including satellite-imagery-based data on land surface temperature (LST). Relevant indices for existing vegetation, evapotranspiration and albedo were also obtained from satellite imagery, in order to allow for correlation analyses with LST data. Results showed that the relative increase in size of the urban area in Palmas, between the years 2000 and 2014, was of no less than 66%. The same period brought the emergence of particular hotspots in Palmas, with LSTs in the 34-38°C range, even as areas to the west of the city in the vicinity of the reservoir manifested declines in temperature of up to 3°C. A detailed analysis of stepwise buffers around the reservoir showed that, the greater the distance from the reservoir, the more marked the LST increase proved to be.

In the area evaluated in Pires's study (out to a radius of approximately 30 km from the N-S water reservoir), there was a rise in the maximum temperature of about 4°C in April (wet season) and 3°C in August (dry season). The corresponding rise in mean LST in the urban area was of 1.2°C in April and 1.5°C in August.

Research aim

The aim of the work detailed here has been to investigate the relationship between field data from an official meteorological station and city growth in Palmas, Brazil.

Methods

Detailed below is the study area, from the point of view of geographical location, climate type and observed changes in land use and land cover over time. Information is also supplied here regarding the source of field data for air temperature and the evaluation procedure, as well as the treatment of satellite images with a view to obtaining relevant data on vegetation and built-up areas.

Location

Palmas emerged from an existing rural settlement, and was tailored to become the capital of its state in line with a dedicated master plan. The growth of its local population was considerable in the 1990s, tailing off in the 2000s and stabilising after that. As of 2021, the city had an estimated 313,349 people (IBGE, 2023a), even as official data from the 1991 Census present a then population of 24,334 (IBGE, 2023b).

Palmas is located at 10.17° S and 48.33° W and has a Koeppen's Aw climate type, which corresponds to a tropical savanna or tropical wet and dry climate. The dominant biome in the region is the Brazilian tropical savanna (termed *Cerrado*), which is the second richest in Brazil in terms of biodiversity, and encompasses 204.7M ha in the central part of the country, i.e. some 23% of Brazilian territory (Sano et al., 2010; Souza et al., 2020). *Cerrado* natural vegetation consists of a mix of grasslands, scrub and woodlands. In their study mapping the Brazilian *Cerrado*, Sano et al. (2010) found that scrub is in fact the dominant remnant, covering ~75M ha, and quite well represented in the state of Tocantins, in which as of 2002 it remained practically impossible to make out croplands and pastures in satellite imagery. The *Cerrado* is one of the Brazilian biomes subject to greater pressure *vis-à-vis* its original state, and thus the forest showing the fastest annual rate of decrease between 1985 and 2017 (Souza et al., 2020).

Prevailing air-temperature conditions are invariably hot. Climatic data for Palmas (the 'Palmas TO' meteorological station at 10.17°S, 48.33°W) as obtainable from the climate re-

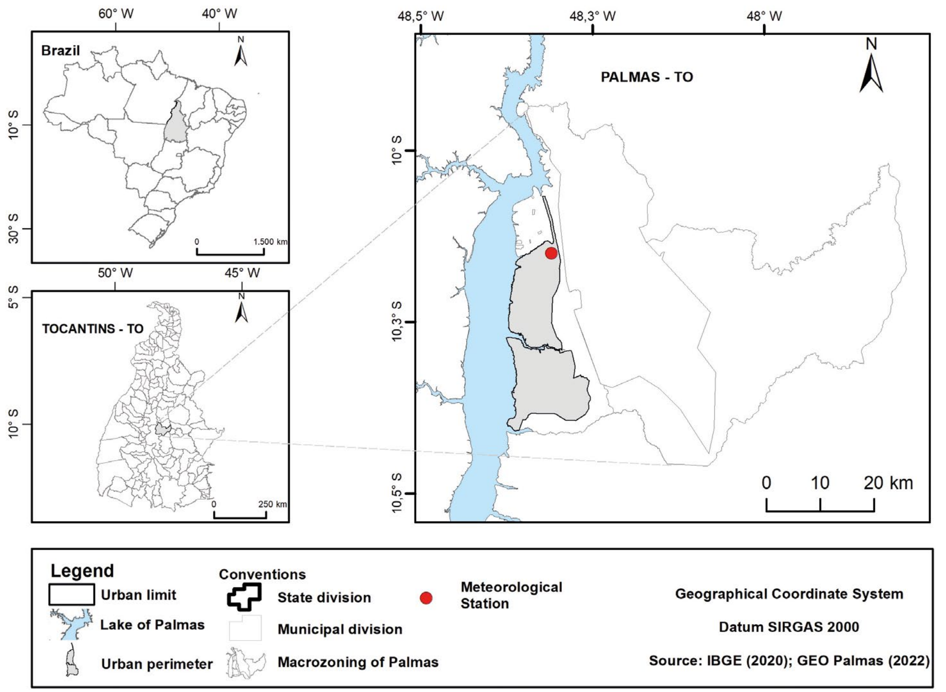


Fig. 1. Location of Palmas in Brazil
Source: IBGE (2020); GEO Palmas (2022).

pository Climate.OneBuilding.org were analysed in the CBE's Clima tool (Betti et al., 2022), based on data gathered between 2000 and 2010. Mean annual temperature was 26.8°C, with monthly means in the 25-29°C range. Ranges for the daily maxima and minima, year-round, are in turn 33-38 and 17-22°C, respectively. Daily maximum temperature and temperature fluctuation are greater in the driest months of July to September, during which daily minima tend to diminish. The Clima tool also provides as relevant output the outdoor thermal stress for a given climate. Thermal-stress conditions, expressed through values for the Universal Thermal Climate Index (UTCI; Fiala et al., 2012), and in association with a related thermal assessment scale indicate a range for Palmas TO between 'no thermal stress' during the night through to 'extreme thermal stress' in daytime in the driest months.

Population density remains rather low when compared with that in Brazil's major state capitals. Thus in 2010, Palmas had around 100 inhabitants per km^2, whereas in the same year São Paulo exhibited 7398, and Rio de Janeiro 5266 per km^2 (IBGE, 2023b). However, then, and since then, the impact of urbanisation due to the addition of impervious paved streets and other areas over time is likely to have had a profound effect on local climate.

Land-use and land-cover data for Palmas

A collaborative network formed by NGOs, universities and technology startups provides land-use and land-cover maps from 1985 onwards, by means of an online platform called *Mapbiomas* (https://mapbiomas.org/, Souza Jr. et al., 2020). This relates to Brazil's different biomes, locations and metropolitan areas. Specialists in remote sensing and vegetation mapping in partnership with *Google* are responsible for the thematic maps, based on the *Google Earth* Engine platform. Currently, the 7th version of *Mapbiomas* covers 27 classes of land use and land cover at a scale of 1:100.000, with a resolution of 30 m, on the basis of *Landsat* satellite imagery. The generated maps show a robust distribution of land-use classes from a mosaic composed of *Landsat* images that gives a general view of the area under analysis. Spatial and temporal filters are employed, as well as a verification method used to assess changes of land-use class over time. As important output, maps with land use and land cover classes and transitions between years provide surface areas (in ha) of individual classes, starting from 1985 and going through to 2021 (as was the status in June 2023).

Using the *Cobertura* (land-cover) feature in *Mapbiomas* v. 7.1, distribution within the territory of the diverse municipalities in Brazil, including Palmas, can be visualised in terms of land-cover classes, and on an annual basis. The Palmas municipality today comprises an urban area (of lesser extent) with natural biomes around it, including the reservoir. Fig. 2 shows *Mapbiomas* land-cover maps for three selected years (1985 – the first year of the *Mapbiomas* timeline, an intermediate year just before the start of work on the hydroelectric power plant, 2001, and the last in the series to date, i.e. 2021).

The growth of the urban area over time is evident (Fig. 3 gives the increase/decrease in total area pertaining to the municipality with the urban portion, and the portion covered with forests, respectively). The depletion of natural forests took place from the outset, with a drastic decrease resulting from flooding as the hydroelectric power plant had come into being by the end of 2001. The urbanisation process has been ongoing, with the steepest rise in the process characterising 1985-1997, as followed by progression at a slower pace. Regarding the area with forests, a gradual increase can be noted during the last decade.

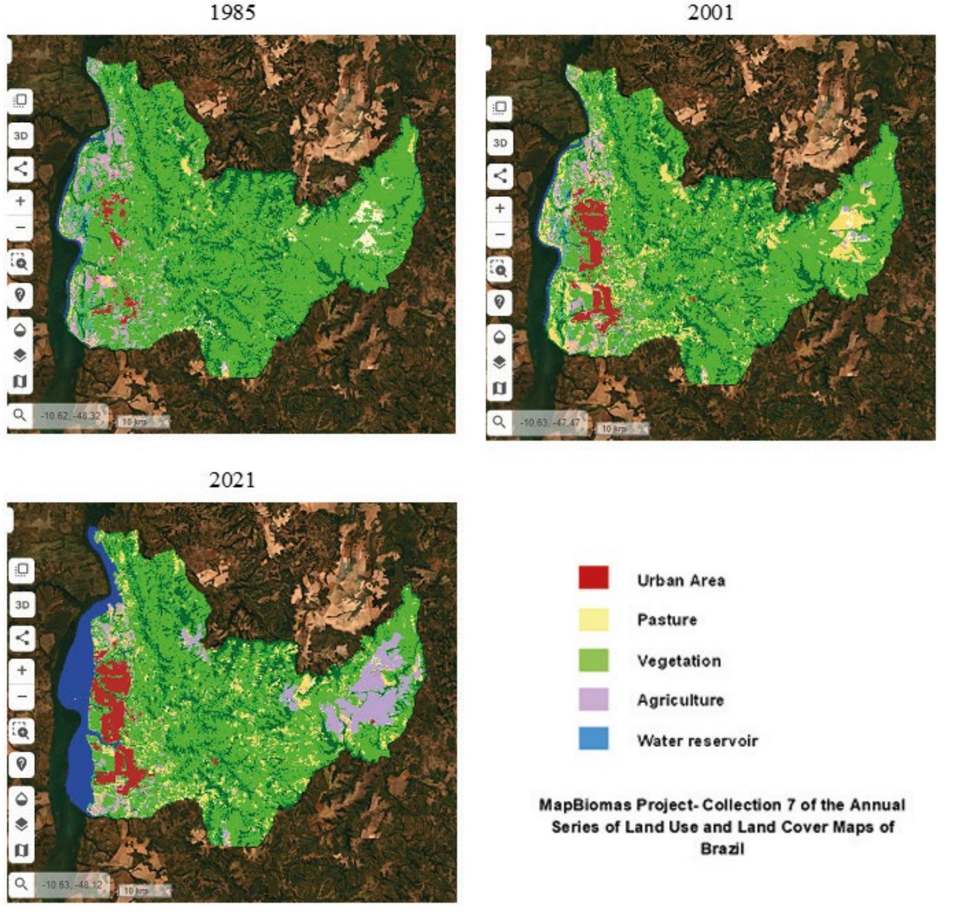


Fig. 2. The *Mapbiomas* land-cover distribution for Palmas, where the red-brown portion corresponds with the urban area, for 1985, 2001, and 2021
Source: MapBiomas Project – Collection 7 of the Annual Series of Land Use and Land Cover Maps of Brazil.

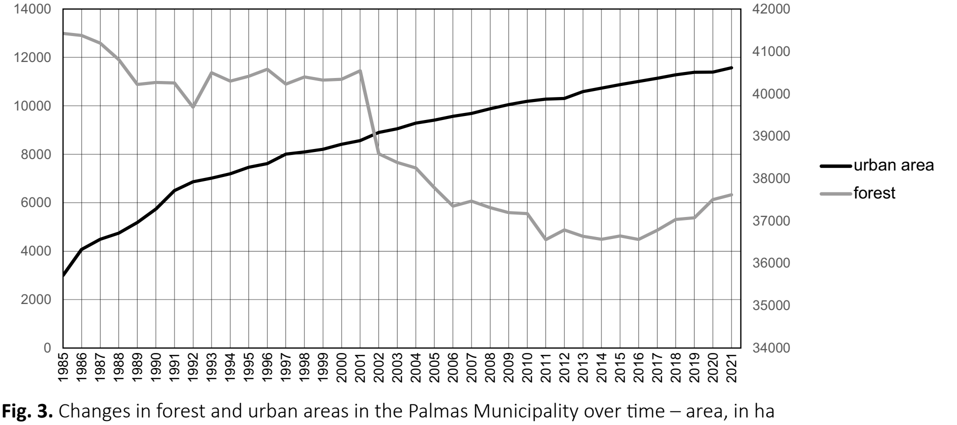


Fig. 3. Changes in forest and urban areas in the Palmas Municipality over time – area, in ha

Climate data for Palmas

Due to the unavailability of continuous hourly meteorological data for Palmas, existing data from the conventional weather station were used, from 1993 through to 2021, with three data points per day, namely at 12, 18 and 24 UTC (local time 9 am, 3 pm, 9 pm). The weather station belongs to the Brazilian Institute of Meteorology (INMET), WMO code 83003, and is located at 10.15°S, 48.31°W, close to the northern limits of the urban area, and approximately 5 km west of the reservoir (Fig. 1). Air-temperature and humidity data were extracted from the time series for our analysis. The daily average temperature was calculated as follows, after the calculation procedure suggested by INMET (2022):

$$T = \frac{\left(T_{min} + T_{max} + T_{12} + 2 \times T_{24}\right)}{5} \quad \text{(Eq. 1)}$$

Where T_{min} and T_{max} correspond to the daily minimum and maximum temperatures, and T_{12} and T_{24} to the air temperature measured at 12 and 24 UTC, respectively.

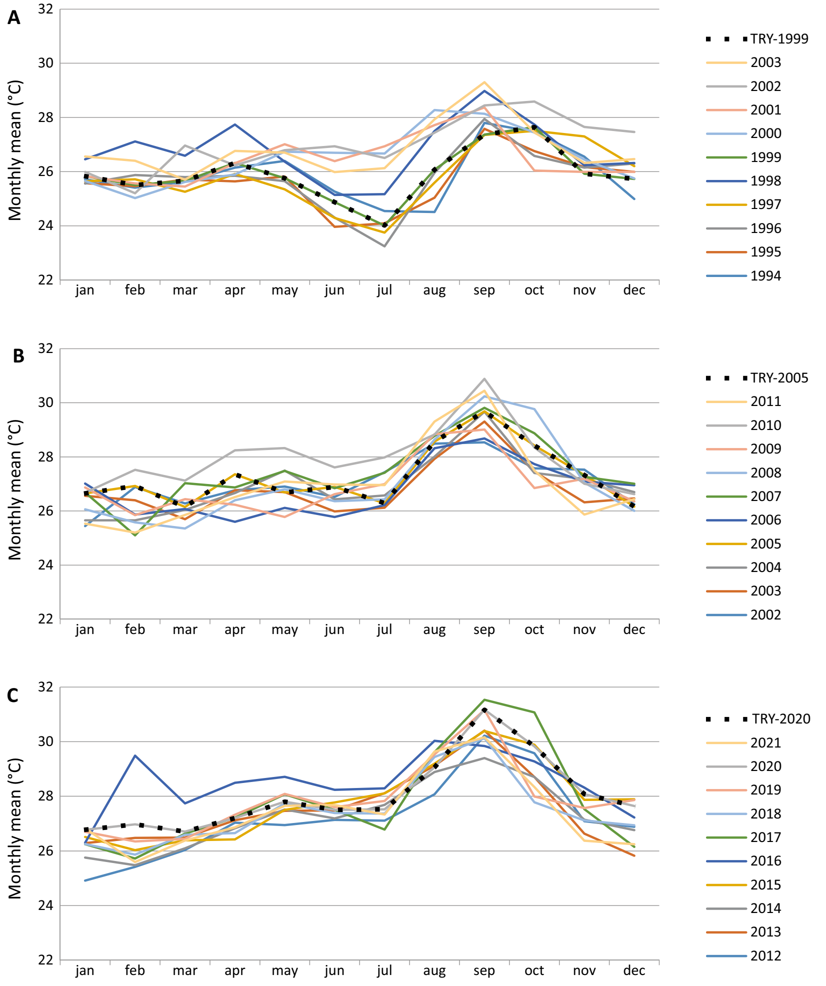
The mean daily relative humidity was obtained from:

$$RH = \frac{\left(RH_{12} + RH_{18} + 2 \times RH_{24}\right)}{4} \quad \text{(Eq. 2)}$$

Where RH_{12}, RH_{18} and RH_{24} correspond to the relative humidity at 12, 18 and 24 UTC, respectively.

Gaps in the complete series were negligible. For each calculated daily mean, missing data for any of the variables used in the calculation were annotated. For the total number of 10,288 days, from November 1993 until December 2021, 133 data points were missing, for either *T* or *RH*, thus about 1% of the total. Those gaps were solved by attributing the mean of the three previous days as an estimate, which is reasonable for the mostly invariable temperature and humidity conditions of Palmas in terms of the daily course.

To evaluate the impact of changes in urbanisation in Palmas over time, the time series was subdivided into three periods, the first 10 years of the data set (from 1994 to 2003), the last ten years of the data set (from 2012 to 2021), and a period in between, with two overlapping years with the first period (from 2002 to 2011). Instead of calculating an average year for those periods, a procedure was adopted for generating a typical year without either extreme or anomalous temperature conditions among the 10-year dataset. The Test Reference Year (TRY) procedure was employed, in line with which years that contain months with extremely high or low monthly mean temperatures are discarded, the same applying to anomalous conditions (e.g. winter months that are exceptionally warm), until one year emerges. The procedure is proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, National Climatic Data Center, 1976; Hui & Lam, 1992), and results in an actual year. Figures 4a-c represent the monthly temperature means of the TRY obtained via the ASHRAE-TRY procedure for each period over the background of the 10 years used in each case for its extraction.



Fig, 4. The TRY obtained for Palmas for each 10-year period, i.e. A – 1994-2003, B – 2002-2011, C – 2012-2021

Local climate evaluation

The comparisons between the three obtained TRYs – as potentially representing three stages to the urbanisation of Palmas – are analysed using column and whisker plots, with obtained means and distributions of air temperature and relative humidity. Thermal stress is expressed by reference to the effective temperature index (ET), as well as the sum of cooling degree-days, assuming a base temperature of 25°C as a reference for the daily relative difference (positive values only) from the average temperature to that reference. ET was calculated after Missenard (1933):

$$ET = T_{avg} - 0.4 \cdot (1 - 0.01 \cdot RH_{avg}) \times (T_{avg} - 10) \quad \text{(Eq. 3)}$$

Where T_{avg} and RH_{avg} are daily mean air temperature and humidity, respectively. The assessment scale used for thermal sensation is as given by Table 1 (Blazejczyk et al., 2012).

Table 1. Thermal assessment scale for the effective temperature index

ET (°C)	Thermal sensation category
>27	Hot
23-27	Warm
21-23	Comfortable
17-21	Fresh
9-17	Cool
1-9	Cold
<1	Very cold

Evaluation of the urbanisation rate for Palmas

Vector cartographic data were extracted from the shapefile of the urban boundaries of Palmas, made available by GEO PALMAS (https://geopalmasweb.wixsite.com/geopalmas) and by the Brazilian Institute for Geography and Statistics (IBGE, 2021), with a delimiting of the urban area. The project used the Geographic Coordinate System – GCS and the SiRGAS 2000 datum. Remote sensing was adopted for digital image processing. Images from the LANDSAT 5 (Thematic Mapper – TM sensor) and LANDSAT 8 (Operational Land Imager – OLI and Thermal Infrared Sensor – TIRS) satellites from Collection 1 Level-1 were used, acquired from the United States Geological Survey (USGS), available online (https://earthexplorer.usgs.gov/). Note that in this paper we are not using LST data, and only rely on air-temperature data from the official meteorological station. Table 2 presents the LANDSAT 5 (TM) and LANDSAT 8 (OLI) data by orbit/point and time series.

ArcGIS® 10.5 was used for the digital processing of the LANDSAT 5 and 8 images, restricting the analysis to the boundaries of the urban area of the municipality. Images were then corrected for radiance and reflectance so that two relevant indices could be obtained, namely the Normalised Difference Vegetated Index (NDVI) and the Normalised Difference Built-up Index (NDBI). Such procedures were performed after Zha et al. (2003), He et al. (2010), and Xu (2007).

Table 2. Information regarding satellite imagery for Palmas

Year	Date	Satellite/sensor	Orbit/point
1984	18/06	Landsat 05 – TM	222/67
1991	06/06	Landsat 05 – TM	
2001	17/06	Landsat 05 – TM	
2011	29/06	Landsat 05 – TM	
2021	08/06	Landsat 08 – OLI	

Results

Local climate changes

Figure 5 shows an ensemble of meteorological variables and derived indices for the three TRYs (one representative year per decade).

A warming trend with decreasing humidity (presumably due to a depletion of local vegetation) is noticeable in Palmas, with a mean increase in monthly average temperatures of 0.9°C and 0.2°C (JFM) and 2.3°C and 0.8°C (JJA), for 2005 relative to 1999, and for 2020 relative to 2005, respectively. Such warming becomes more accentuated in the dry season, between June and September; and is more evident in the daily minima. Such an effect can also be made out in the ET datasets. Most strikingly, the cooling degree-days for a Tb of 25°C show an astounding increase between 1999 and 2020, particularly during the dry months. In 1999, daily averages in July lay slightly below 25°C (monthly average 24.0°C), whereas in 2020 the monthly average was 27.5°C for that same month. Figure 6 shows the changes in thermal sensation (cf. Table 2 ranges) for the three years in Palmas.

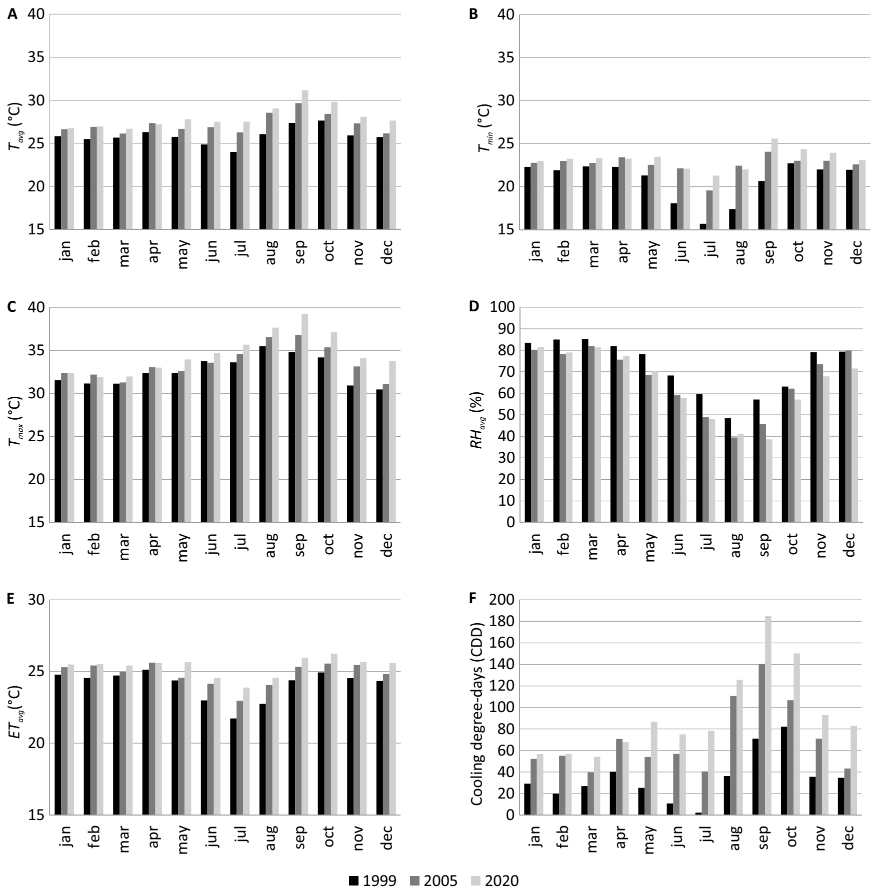


Fig. 5. Changes in: A – average, B – minimum and C – maximum temperatures, D – relative humidity, E – effective temperature, F – cooling degree-days for the three Test Reference Years in Palmas between 1994 and 2021

A rise in heat is noted, with a gradual reduction in numbers of cool and comfortable days. It should be stressed that the yearly totals are for average ET daily data. Whisker plots of the presented variables show changes in their distribution for each year (Fig. 7).

The boxplots show a consistent rise in temperature and humidity, with a similar spread of the analysed variables for the three years. The ET plot shows more evidently the gradual shift from cool conditions (still existing in 1999) to hot conditions in the two more-recent years. Note that the upper quartile and means are situated within the ET 'warm' range for the three years.

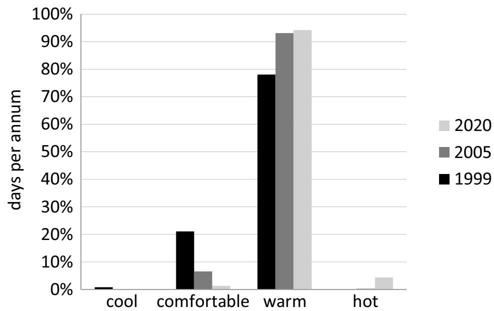


Fig. 6. Changes in predicted thermal sensation over time (ET thermal assessment)

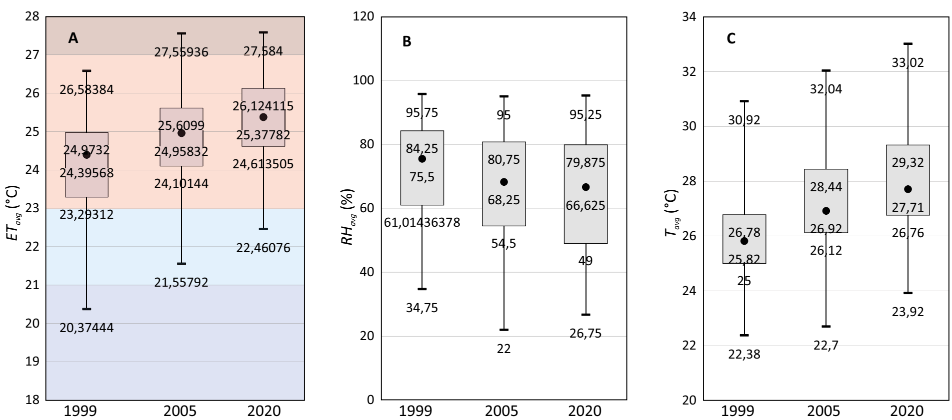


Fig. 7. Boxplot with absolute minimum, maximum and mean values, upper (Q3) and lower (Q1) quartiles for: A – average temperatures, B – relative humidity, and C – effective temperature for the three Test Reference Years in Palmas between 1994 and 2021

The urbanisation process in Palmas

From the digital processing of the *Landsat* images for the years 1984, 1991, 2001, 2011 and 2021 (in this case, allowing intervals of 10 years between digital images), the reduction of vegetation cover became evident as a direct effect of the urbanisation ongoing in Palmas over its lifetime (Fig. 8). Areas with 'very low' and 'low' levels of vegetation showed a significant increase between 1984 and 2021, of 9% and 11%, respectively, whereas portions classified as 'moderate' NDVI, with herbaceous, shrubby or secondary regeneration vegetation, suffered a reduction of 29% in the same period, being predominantly replaced by exposed or impermeable soils, the latter due to the urbanisation process.

Notably, an expansion of the areas with denser vegetation, composed of open broad-leaved forest was observed in 2021. This must be related to the implementation of green areas, with squares and gardens, planned by the municipality, which enriched the city's degree of afforestation. Thus, areas classified as having an NDVI that is 'high' (0.5-0.7) or 'very high' (0.7-1.0) showed increases of 5% and 3%, respectively, between 1984 and 2021.

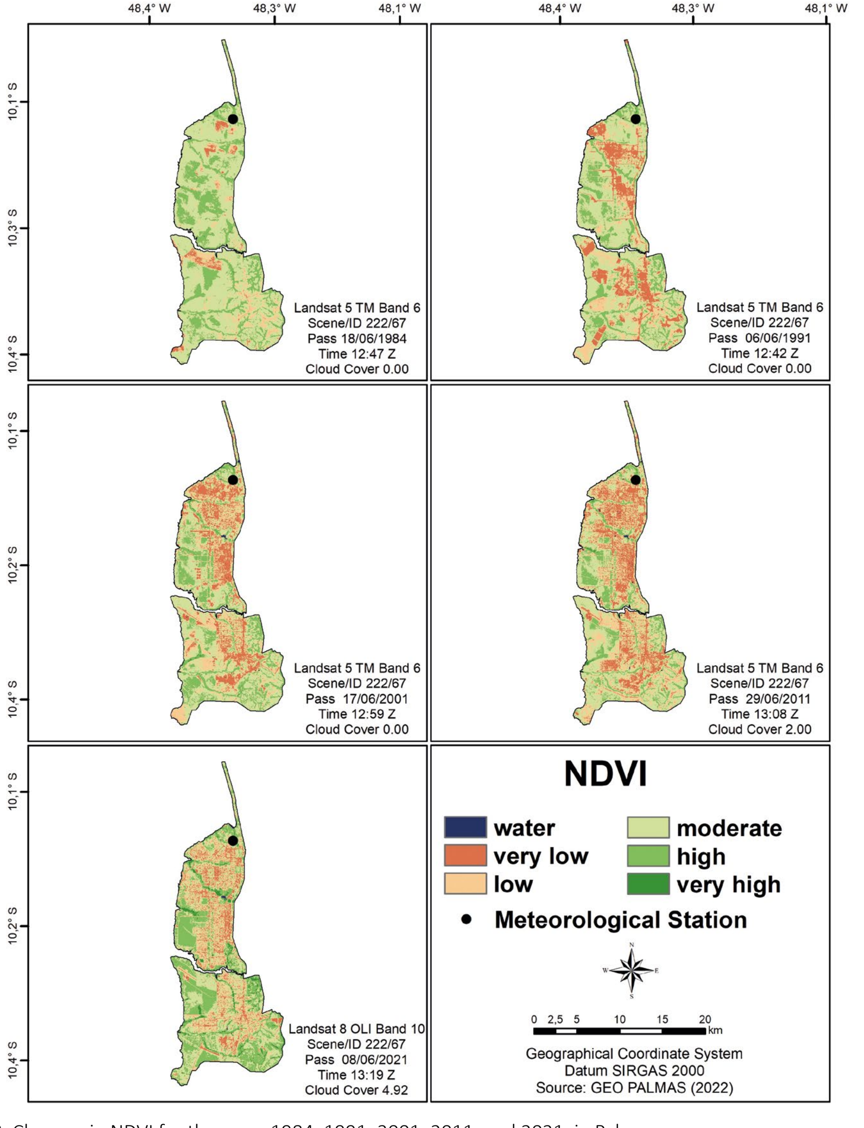


Fig. 8. Changes in NDVI for the years 1984, 1991, 2001, 2011, and 2021, in Palmas
Source: GEO Palmas (2022).

Data referring to the built-up area are in line with those for the vegetation index, only in the opposite direction (Fig. 9). This is to say that a reduction was noted in areas of open and shrubby rainforest cover, with these replaced by 'medium' or 'high' NDBI classes, as well as exposed soil. The dominant vegetation class (*Cerrado* type, with open and shrubby rainforest), which covered 58% of the city of Palmas in 1984, had been reduced by 9.5% by 2021. In turn, the areas with 'medium' and 'high' NDBI combined had achieved an increase of 5.5%. The percentage area with exposed soil also rose, with an increase of the order of 7%; and this can be related to the urbanisation process, with the formation

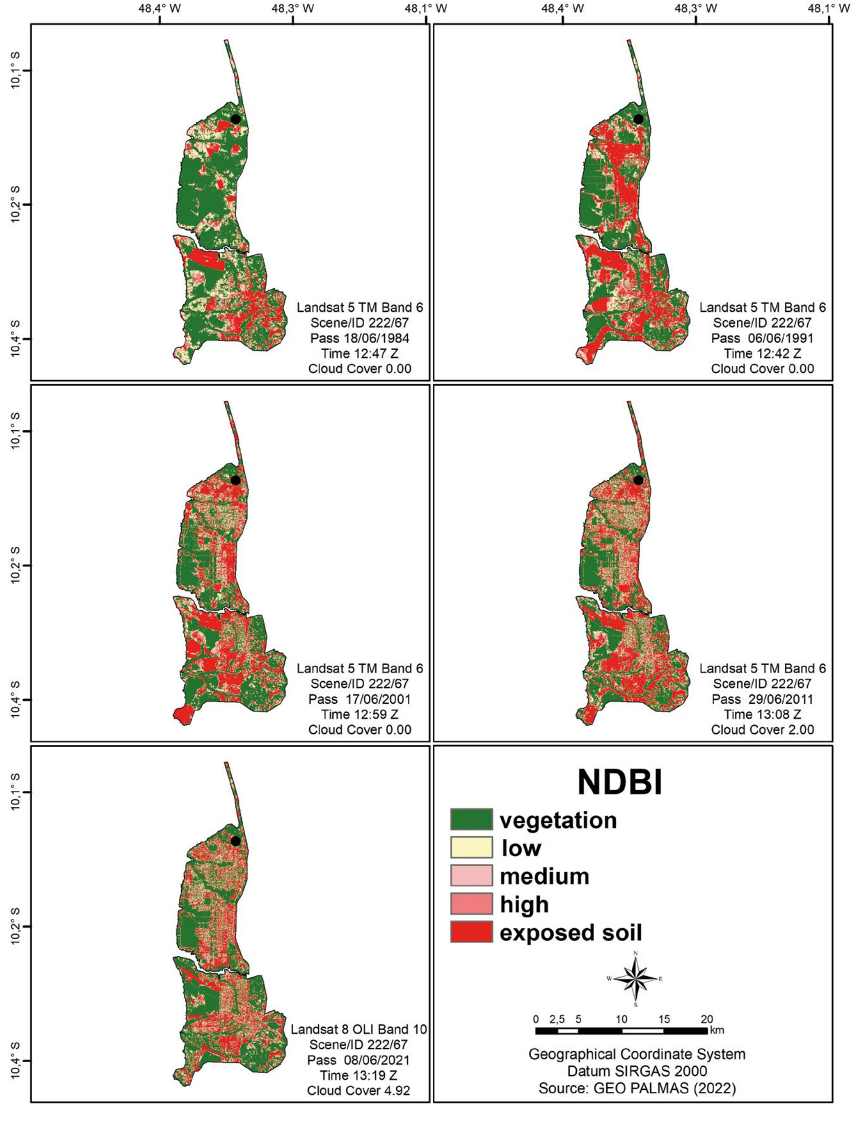


Fig. 9. Changes in NDBI in Palmas for the years 1984, 1991, 2001, 2011, and 2021
Source: GEO Palmas (2022).

of urban voids, possibly linked to real-estate speculation and the occupation of peri-urban areas forming the outskirts of Palmas, in which roads are usually left unpaved.

The development and distribution of NDVI and NDBI over time (Fig. 10) showed a first stage in which there was a progressive trend involving deforestation and overbuilding with widespread road paving, as disrupted during the last decade with the consolidation of parks and vegetated areas, which can have a rather positive effect on microclimate.

The dominant vegetation type of the area in 1981 was 'moderate' NDVI, which roughly represents the *Cerrado*-type vegetation, accounting for 63% of the total area of Palmas. In 2021, the 'moderate' NDVI class encompassed about half of that cover (34%). The 'high' and 'very high' NDVI classes showed an increase from the foundation of the city through to 2021, from 24.5 to 33%, though such improvements in terms of added vegetated areas are quite localised, and locations with very low NDVI can still be verified in the north-eastern part of the urban area. A survey conducted in 2015 on vegetation diversity in residential neighborhoods of the urbanised areas in Palmas verified a diversity higher than in other state capitals, but still only about half of that comprised native species, of which almost 90% were located in green areas, not on the streets (Pinheiro et al., 2020). A spatiotemporal evaluation of the urban greening project in Palmas during the last 30 years (through to 2018) revealed that the first stage of urbanisation of the city was accompanied by disordered planning that disregarded the protection of native species until environmental policies and legislation were put in place in 2001 (Ribeiro & Pinheiro, 2022). The remote-sensing study conducted by these authors for the urban area of Palmas showed that in 2018, original *Cerrado*-type vegetation corresponded to 37% of the area, roughly corresponding with our 'moderate' NDVI class in 2021 (34%).

NDBI development also shows a trend, albeit localised, of more vegetation being allowed to prosper, with the amount of exposed soil in the city reduced. The temporal development of Palmas thus suggests an urbanisation process responsible in the first and second decades for changes in land use and cover indeed indicative of far-reaching urbanisation, albeit with more stabilised NDVI and NDBI values between 2001 and 2011, and subsequent (last-decade) re- increases in vegetation cover, and reductions in amounts of exposed soil. Development of the city during the last decade in the direction of a stabilisation in the growth of the urbanised area was also noted by Ribeiro & Pinheiro (2022). However, in their remote-sensing study, native species and *Cerrado*-type vegetation were seen to have undergone a more-significant decrease during the first 15 years (between 1989 and 2005) and have continued under threat through to the present day.

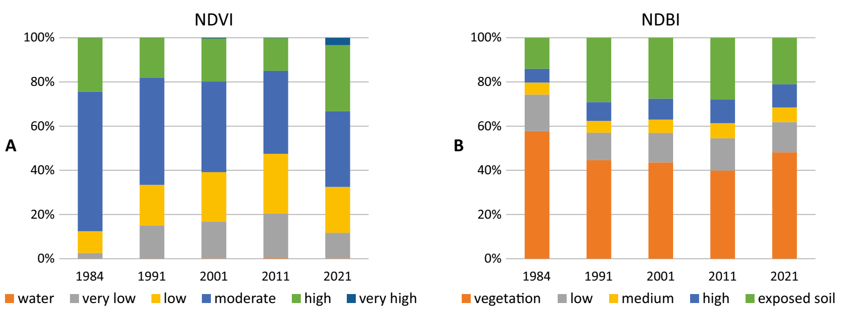


Fig. 10. Percentage changes in classes for NDVI (A) and NDBI (B) in Palmas, over four decades

Discussion

It did not prove straightforward to investigate the relationship in Palmas, Brazil, between local climatic features, expressed as a typical year (TRY) with neither climatic extremes nor anomalies on the one hand, and urbanisation indices (relating to vegetation cover and built-up areas). The obtained years for analysis of local climate variations differed with respect to time intervals, e.g. from 1999 to 2005, seven years in between, from 2005 to 2020, 15 years in between. Yet we adopted TRY for our analysis in order to reduce the chances of global atmospheric events (for example *El Niño* and *La Niña*) affecting local features of climate in particular years. As changes in local climate are set against those affecting land use and land cover, climate modifications are more obvious between the first seven years than in the sixteen years that followed, as is best illustrated in Fig. 5 for changes in ET classes for the three TRYs. The lack of existing climate data prior to 1993 hinders a close examination of impacts, due to the first stage of urbanisation of Palmas, which would have likely caused a more pronounced warming of local climate. Thus, the comparison of climate and urbanisation trends for Palmas ended up focusing in periods with potentially lesser impacts. Despite the observed warming trend in Palmas, from the turn of the century and through to 2021, positive changes in NDVI should have led to improvements in local climate. However, meteorological data from the INMET station fail to show such climate-tempering effects.

We therefore hypothesise that two concurrent might have been at play, as follows.

1) Global warming during the period of analysis might have been the major driver underpinning the verified warming of Palmas, with a lesser contribution made by modifications of the urban area, bringing about a confounding impact on local climate change.
2) Positive changes in urbanisation, e.g. with increases in the cover of vegetation and the introduction of parks and squares, were observed on a more local scale, climatically benefiting parts of the city even as hot spots were still being identified in other neighborhoods. The overall improvement in local urbanisation schemes, albeit with parts of the city neglected in this respect, reflects unequal/disparate urban development that does not promote noticeable changes in the warming trend of the city.

A possible explanation for the observed increase in vegetated areas given by the NDVI in 2021, even as air temperatures at the weather station went on rising, could be due to the overall conditions of the vegetated portion of the *Landsat* images on the days of capture (cf. Table 1). Notably, all images were obtained for June, which corresponds with the start of the dry season. A prolonged rainy season prior to the capture of the satellite image can lead to lusher vegetation, thereby confounding obtained NDVI values in a given year. Patterns of precipitation as measured by the INMET station show somewhat greater amounts of rain in 2021 and 2011, as compared with 2001; with larger amounts of rain prior to the dry season (January through to May). The NDVI is chlorophyll-sensitive and shows a strong dependence on pasture-quality parameters (particularly PMC, pasture moisture content, Serrano et al., 2022), thus vegetation vigour due to a larger amount of rain might have conveyed a somewhat exacerbated rise of certain classes of NDVI in 2021.

At any rate, the urbanisation process is still ongoing in Palmas. A recent remote-sensing study for the municipality of Palmas (Gomes et al., 2020), for the time frame 2000-2017, also showed an increase in local temperatures. Obtained NDVI for the area showed an increase over time, and the explanation advanced by the authors is that the compensatory measures due to the construction of the hydroelectric plant included afforestation. Another possible cause for the increase in vegetation over time is that urban greenery in Palmas resulting from landscape planning was still in its early stages as of 2000.

Conclusions

The present study involving the city of Palmas has shown that, whereas local climate has displayed a visible warming trend over the history of the city, modifications in urbanisation schemes and the use of greenery in specific areas of the city have not yet led to a reduction of heat-stress conditions in the local climate. The study is based on background data of a long-standing meteorological station located close to the border of the urban area of the city, which has not been subject to substantial changes in land use and land cover, and is not in a particularly hot area of the city. Results suggest that localised modifications in parts of the city did not affect background climate data over the years, and that the warming trend is ongoing. It is likely that global warming and alterations in regional climate could be at play here, and this is an issue in need of further investigation.

Among the limitations of the study is the choice of a fixed location for the analysis of local climate data, i.e. the conventional meteorological station 83003 forming part of the INMET network. Pires (2017) points out that, in Palmas, the land-use and land-cover patterns were greatly responsible for observed changes in LST, also in relation to the reservoir of the hydroelectric power plant. Station 83003 is located close to the outskirts to the north of the city. Yet, as land use and land cover (NDVI and NDBI) did not change significantly over time at that location as in other parts of the city, observed changes in meteorological data can be regarded as background data for the city as a whole.

Another limitation is related to the discrepancy between the years used in assessing NDVI and NDBI and the reference years (TRYs) used in local climate analysis. The procedure adopted to obtain a more representative year for analysis in terms of temperature, humidity and ET was considered a viable option to avoid atypical years.

Investigating the extent to which localised modifications due to the implementation of urban parks and greenery-enhancement projects potentially contribute to the mitigation of heat would require an entirely different experimental and analytical approach. Future studies should focus on changes in microclimate in specific areas of Palmas.

Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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[Wpłynęło: marzec; poprawiono: czerwiec 2023]