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Urban Climates and Climate Change

The design of our cities amplifies climate change and adds to the risks most Australians will experience in the future.

The majority of Australians live in an urban environment, making cities critical in our climate change response.

Urban climatology involves understanding how the compounding impacts of urbanisation and climate change affect our local weather and climate.

Introduction

Urban areas are home to the majority of the world's population. In Australia, over 90 percent of the population live in cities with 87 percent living within just 50km of the coast. As the climate crisis threatens our nation's environment, economy and society, we need to focus on urban environments and their unique interaction with weather and climate.

Cities are a major source of greenhouse gases and respond differently to climate change compared to their natural surroundings. Any response to the climate crisis must include consideration of the local climate in cities, i.e., the urban climate. The choices we make when designing our cities can help reduce negative climate impacts, improve urban climate and create healthier more resilient cities.

The urban environment (Figure 1) is a combination of the:

- **built environment**, all human-made structures and spaces in cities including buildings, roads, and infrastructure that support daily life,
- **natural environment**, such as parks, rivers, trees, and bare land, and
- **inhabitants**, the people who live there and their activities.

All aspects of the urban environment face multiple environmental and health-related challenges, such as rising temperatures and extreme rainfall leading to flooding, all of which significantly impact our quality of life. Studying how urban environments affect and are affected by climate is central to our appreciation of the broader effects of weather and climate on our lives and society.

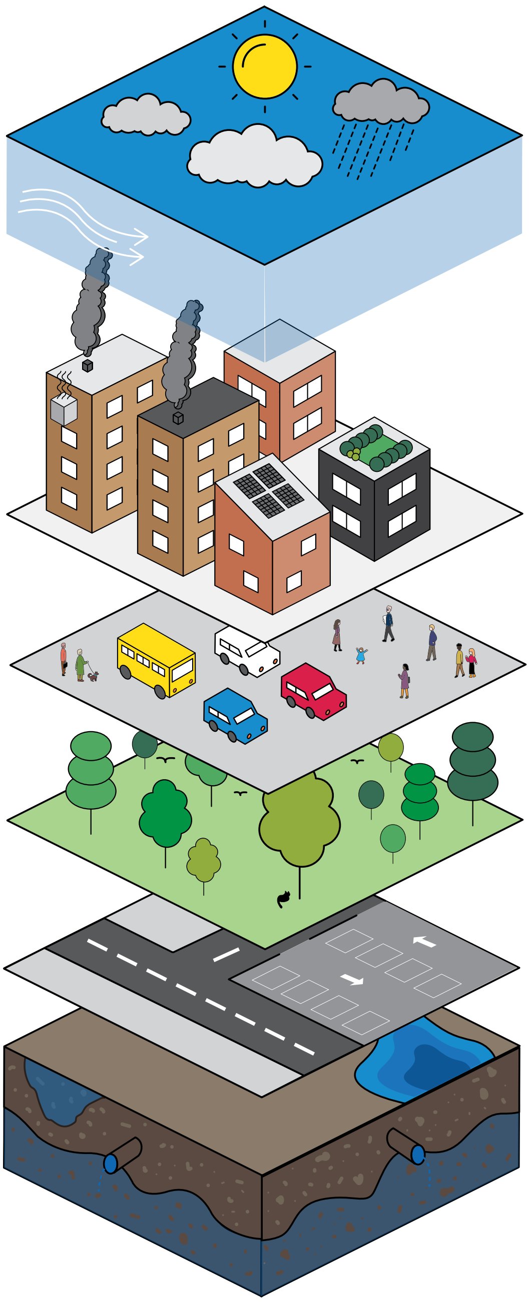
Figure 1: Urban environments have a diversity in their form, fabric, and function.
Source from left: Katoomba, NSW - Martin David, Melbourne, VIC - Josh Chiodo, Brisbane QLD - Marcus Lenk.

What is urban climatology?

Urban climatology involves understanding the compounding impacts of urbanisation and climate change on our local weather and climate.

Cities represent one of the most extreme cases of human modification of our natural landscapes. Urbanisation replaces the natural environment with dense concentrations of pavement, buildings, and other materials that absorb and retain heat, while also increasing impermeable surfaces that cannot retain water. Urbanisation causes substantial environmental impacts as shown in Figure 2, compared to the rural surroundings.

An understanding of urban climates requires an appreciation of the urban system (Figure 2) as well as the geographical characteristics such as the latitude (e.g.tropical or alpine), topography (e.g. mountainous or flat plains) and distance to large water bodies (e.g. proximity to the sea). The same city design in a different geographic location will have a different urban climate.



Why study urban climatology?

Understanding the two-way interaction between cities and climate change is crucial for informing decisions on how to build better future cities, improve current ones and prepare for current and future climate risks. By studying the urban climate, we can develop strategies to mitigate the adverse effects of urbanisation and climate change, ensuring that our cities remain sustainable, resilient and livable for our growing urban populations.

Urban climatology not only reveals how much hotter cities are compared to rural areas but can also provide detailed maps showing hotspots of climate challenges (such as heat and air quality) within different parts of a city. By using both modelling and observations, urban climatology can also show how the design and planning of cities contribute to urban climate challenges or, conversely, how they can be used to mitigate the impacts on people.

Figure 2: Different layers of the urban environment (such as buildings, trees, people, and soil) interact with each other and the regional conditions to create our urban climates.
Source: Georgina Harmer, ARC Centre of Excellence for Climate Extremes.

Aspects of urban climatology

Changing land use and land cover by urbanisation can greatly impact the surrounding weather and climate. It can influence weather patterns, temperature (Figure 3a), the formation of storms (Figure 3b), humidity and winds. These impacts can significantly vary between cities, depending on their geographical location, background climate and local urbanisation characteristics.

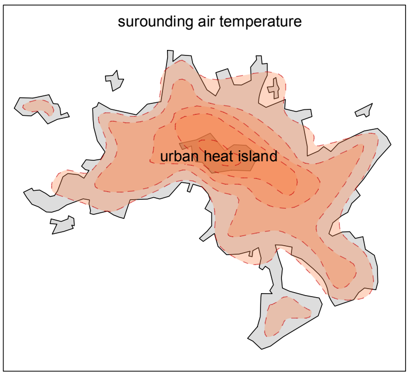
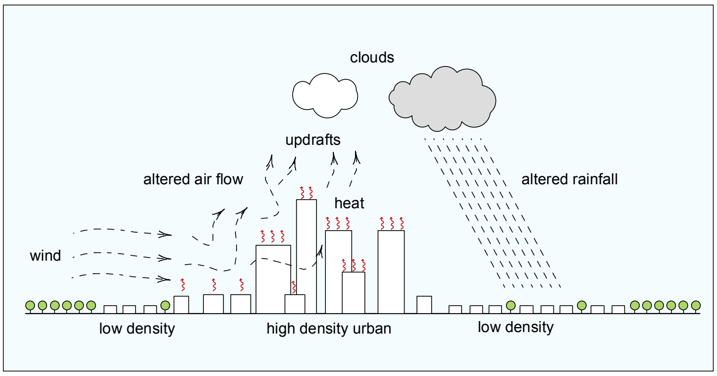


Figure 3: a) Air temperature can be higher over built-up urban areas (gray patches) than the surrounding non-urban regions (white areas). This "urban heat island" (UHI) varies by city, neighbourhood and time of day.



b) Buildings in urban areas alter wind flow patterns. Dense urban areas are often warmer than surrounding areas. Together they can lead to updrafts that affect cloud formation, and in some cases alter rainfall patterns, particularly downwind of the city.

Temperature

Urbanisation influences the climate in many ways, with the 'urban heat island effect' being one of the clearest examples of inadvertent climate modification due to cities (Figure 4). The term refers to the characteristic where cities tend to be hotter than rural, or non-urbanised surroundings, effectively creating an island of heat. The magnitude of an urban heat island will vary across a city, as the form, fabric and function of neighbourhoods vary. From highrise central business districts to suburban single-family housing, or to industrial regions, the temperature can vary from street to street. Urban-induced heat can originate from many different sources including:

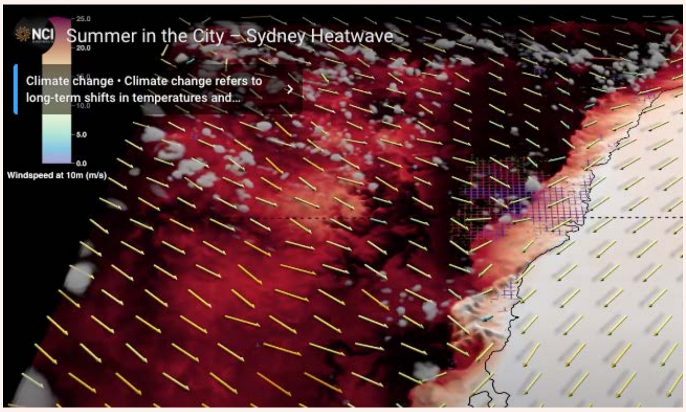
- **Dark surfaces:** urban materials like asphalt and dark tiled roofs absorb more energy from the sun (i.e. have lower albedo) than lighter materials like vegetation, white roofs or light concrete which reflect energy (Figure 4). Traditional architecture in hot parts of the world (e.g. the Mediterranean or the Middle East) often incorporate features such as white-washed walls and roofs, reflecting heat and keeping urban areas cooler.
- **Urban materials retaining heat:** roads, pavements and buildings all have the ability to retain heat for longer than natural landscapes (i.e., higher heat capacity). After a hot day, a building will sometimes be warm to the touch even after the sunset or when the air has cooled down. Conversely, heavy urban materials also take longer to warm up, so they may provide a cooling benefit until around midday.
- **Urban geometry trapping heat:** the complex geometry of buildings can stop heat from escaping into the sky, trapping heat within the city for longer than would happen in an open environment. A built-up area can be hotter than an open park space.
- **Heat from human activities:** this can include heat released by transport (like car or bus engines and exhausts), heating and cooling systems in buildings and crowded spaces filled with people. We call this anthropogenic heat.
- **Reduced vegetation:** trees provide shade, but also draw water from the soil which evaporates from leaves, reducing local air temperatures. A neighbourhood without trees will likely be hotter than a naturally vegetated area, or a well-vegetated urban area.

These factors on average result in warmer urban areas (see Research box 1, 2). The effect is greatest at night when rural areas cool down at a much faster rate than cities. This can have significant health impacts during heatwaves as our bodies may not have the opportunity to cool down overnight. On the other hand, urban areas may be cooler than surrounding rural areas before midday, because of building shadowing and slower warming rates.

Figure 4: The left is a traditional suburb in Australia. On the right is a more modern neighbourhood with black roofs and roads, very little vegetation (and possible synthetic turf) and little space for ventilation all maximising the land covered by built/impervious materials. Source: left: https://westernweekender.com.au/2024/02/no-more-backyards-penrith-council-to-reject-state-governments-housing-plans/ Right: Aerial image of Caddens, NSW, taken from Nearmap, showing rows of houses with black roofs (2023).

Research box 1: Urban heat amplification in Sydney from local flows

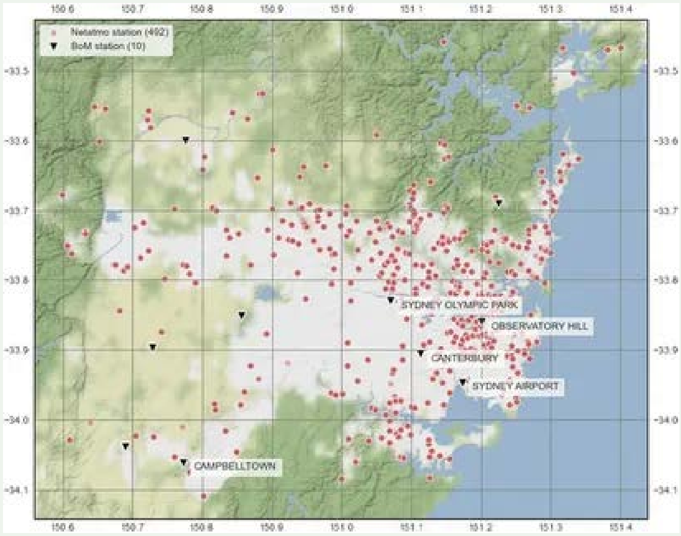
By using climate models that include the effects of a city, researchers ran simulations over Sydney's complex built environment to understand how urban heat interacts with sea breezes during heatwaves. They found that heatwaves often start with hot continental flow over the Blue Mountains moving into Sydney and getting trapped. The urban environment on average adds about 1°C of heat to the lower atmosphere, but during heatwaves, the Western Suburbs can be up to 15°C hotter than other areas of the city which have the benefit of the sea breeze.



Hirsch et al. (2021). Resolving the influence of local flows on urban heat amplification during heatwaves.doi.org/10.1088/1748-9326/ac0377

Research box 2: Crowdsourced weather sensors can provide important urban climate information

Sydney's air temperature can vary considerably across the city but measuring this variation can be challenging as traditional weather sensors are few and far between. Researchers used crowdsourced weather sensors from over 500 citizens to collect detailed data in real time. They found Sydney's geography, particularly the distance from the coast, is the most critical factor of temperature differences within the city. Land use and surface types also affect temperatures: areas with more vegetation, such as parks, tend to be cooler at night, while areas with more buildings and roads remain warmer. The research demonstrates the usefulness of crowdsourced sensors for improving our understanding of temperature variation across urban environments.



Potgieter et al. (2021). Combining High-Resolution Land Use Data With Crowdsourced Air Temperature to Investigate Intra-Urban Microclimate. doi.org/10.3389/fenvs.2021.720323

Precipitation and storms

Cities can influence the intensity and path of storms and rainfall in cities. Dense urban areas are warmer and "rougher" (i.e. more uneven) than non-urban areas influencing updrafts and the formation of clouds and rain. The result is spatial differences in rainfall events and rainfall amounts that would not occur without urbanisation. Urban areas can influence the formation and intensity of storms, and even the path of a storm which can split around a city.

Once the rain has fallen, the urbanised environment changes the flow of water. The replacement of natural surfaces with impervious urbanised surfaces, such as concrete footpaths, influences rainfall runoff. These surfaces interrupt the water cycle and can result in flooding during extreme rainfall events if the capacity of drainage is exceeded (Figure 5).

Figure 5: A petrol station in St Lucia, Brisbane floods after heavy rains in March 2022. Source: Grace Koo, Unsplash. https://unsplash.com/photos/a-flooded-gas-station-with-cars-parked-in-it-BPuQpkYqacI

Winds and airflow

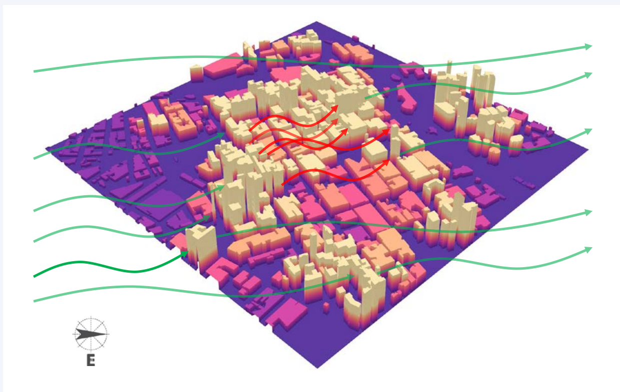
The wind has a unique pattern in the urban environment. Airflow over cities responds to the structural forms, the street network and the small-scale (microscale) effects of buildings, trees and even the effect of moving vehicles. These structures are often rigid bodies that block and divert the incoming flow of air, leading to reduced wind speeds and potential stagnation of heat and poor air quality in some areas. Conversely, the arrangement of tall buildings and narrow streets can create wind tunnels, channeling and intensifying wind flow, resulting in higher wind speeds in gaps between buildings. Both effects – reduced airflow due to obstructions and intensified winds in wind tunnels – highlight the complex interaction between urban design and wind patterns, which impacts air quality, comfort and climate resilience in cities (see Research box 3).

How airflow responds to urban layouts also varies with meteorological conditions, such as seasonal changes and daily variations, as well as the city's geography. Many cities rely on the comfort and cleanliness provided by natural breezes, such as cold air drainage down slopes or valleys and sea or lake breezes. Poor placement of large buildings can obstruct these beneficial breezes, impacting the overall comfort and air quality of the area (Figure 6).

Figure 6: Flow displacement over high-rise buildings in Panama City Beach, United States. Wind is from the ocean. Source: Oke, T. R., Mills, G., Christen, A., & Voogt, J. A. (2017). Urban climates. Cambridge university press. (Photo Credit: J. R. Hott, Panhandle Helicopters; with permission).

Research box 3: Wind patterns over cities

Neighbourhood factors such as building shapes, heights, and street orientations have a significant impact on air flow and wind patterns in a city. Researchers used very high-resolution models (1 metre) to investigate new methods to incorporate wind effects into city-scale models. They found that wind patterns are strongly influenced by street connectivity. Connected streets aligned with prevailing winds result in higher wind speeds and better ventilation, improving heat and air quality. The researchers established new methods that quantify how effectively winds move through an area, which can be integrated into larger models for entire cities.



Lu et al. (2023). Novel geometric parameters for assessing flow over realistic versus idealized urban arrays. doi/full/10.1029/2022MS003287

Air quality

Poor air quality is often a feature of the urban atmosphere, and can have significant impacts on human health. Globally, more than 7 million people a year die due to poor air quality. Australia is one of only seven countries that meet the World Health Organization (WHO) guideline limits, however smoke from hazard reduction burns and summer bushfires can lead to dangerously poor air quality when atmospheric conditions trap smoke in cities (Figure7).

In cities, vehicles introduce heat, moisture, noise and numerous air pollutants into the atmosphere. A street with buildings on both sides can trap air flow and limit the dispersion of pollutants. Not only does this increase pollutants on the streets, polluted air can enter nearby buildings, impacting indoor air quality and affecting the comfort and health of residents. Air pollutants also influence the amount of sunlight that reaches a city, by scattering, reflecting or absorbing it, and can influence the formation of clouds and rainfall. While air pollution is not exclusive to urban areas, the high concentration of emissions and the large populations, combined with these unique urban meteorological conditions make it a problem for cities.

Figure 7: Sydney is blanketed by a thick layer of hazardous smoke. Source: https://www.sbs.com.au/language/korean/en/podcast-episode/sydneys-air-quality-rated-11-times-higher-than-threshold-for-hazardous-levels/tnqgzyie5 via Twitter @DrDallasG

Cities and climate change: a two-way impact

There is a dynamic, two-way interaction between cities and climate that influences climate extremes and high-impact weather events such as heatwaves and flooding.

Cities are already facing increased exposure to climate extremes due to their high concentration of people and their locations – often at low elevations, near coasts, or within river basins. This combination makes urban areas particularly vulnerable to extreme climate events, such as projected sea-level rise, heatwaves and more intense precipitation.

Just as the climate impacts urban environments, cities themselves play a significant role in shaping regional and global climates. Although urban areas cover only 3-4% of the Earth's landmass, they are associated with intense resource use and directly generate more than 50% of the emissions contributing to anthropogenic global climate change. Regionally, cities exacerbate several existing hazards, with their impacts extending well beyond their physical boundaries:

- Urbanisation alters the water cycle, generating increased precipitation over and downwind of cities, and increasing surface runoff intensity.
- There is a compounding effect between heatwaves and urban heat, where the combined heat experienced in cities exceeds the sum of its parts.

Cities therefore are central to managing climate change. Effective policy responses to projected climate changes are crucial for urban communities. Mitigation actions, such as improving the energy efficiency of urban infrastructures and processes, are vital for reducing net emissions. At the same time, adaptation measures must focus on ensuring that cities and their inhabitants can manage and thrive as the climate evolves.

Incorporating cities into climate models

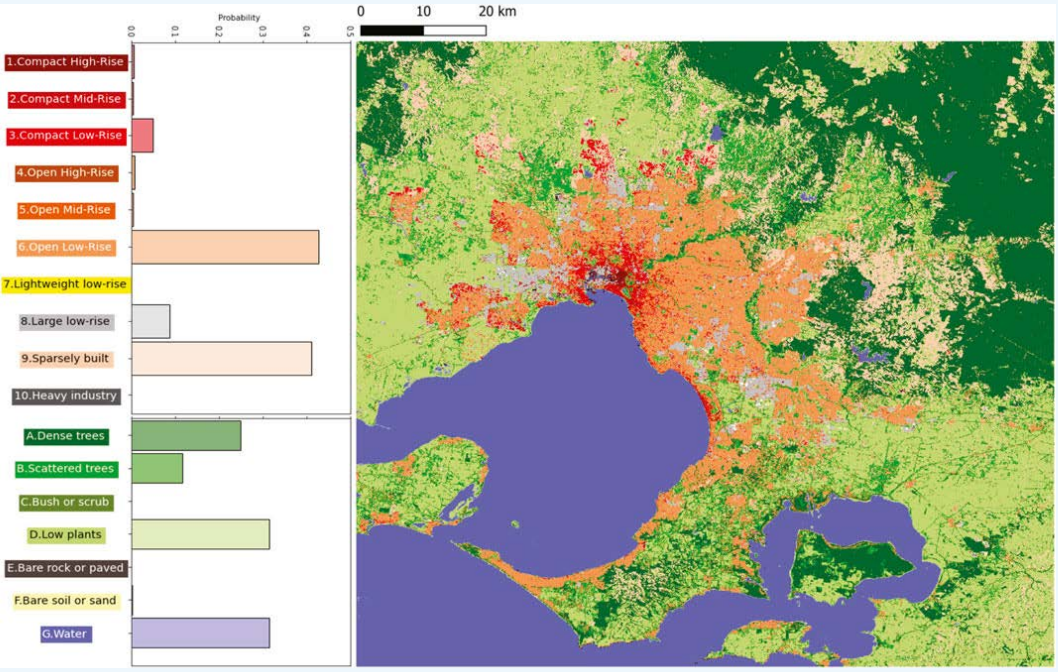
Despite the critical role of cities, most climate models still fail to capture urban environments well. Some climate projections produced by Australia overlook urban areas altogether. Even international models (used by the IPCC for example) have more than 70% of major Australian cities and towns represented as ocean grids. Moreover, some regional models treat all Australian cities as either soil cover or concrete slabs, which doesn't reflect the true complexity of urban environments (see Research box 4).

In addition, we lack some of the necessary data to assess urban impacts properly. This gap limits our understanding of how our cities will be impacted by climate change. To improve our urban climate models, we need systematic and comprehensive observation networks across Australia, focusing on relevant urban factors like temperature, airflow, air quality and water. Currently, urban observations are sparse, inconsistent, or short-term, making it hard to get accurate data suitable for our cities (see Research box 5).

Modelling remains our main tool for exploring how various strategies for urban landscape design might impact on extremes of weather and climate. To tailor these models to Australian cities, urban-scale processes need to be integrated into our national modelling capabilities.

Research box 4: Incorporating dynamic city characteristics into climate models

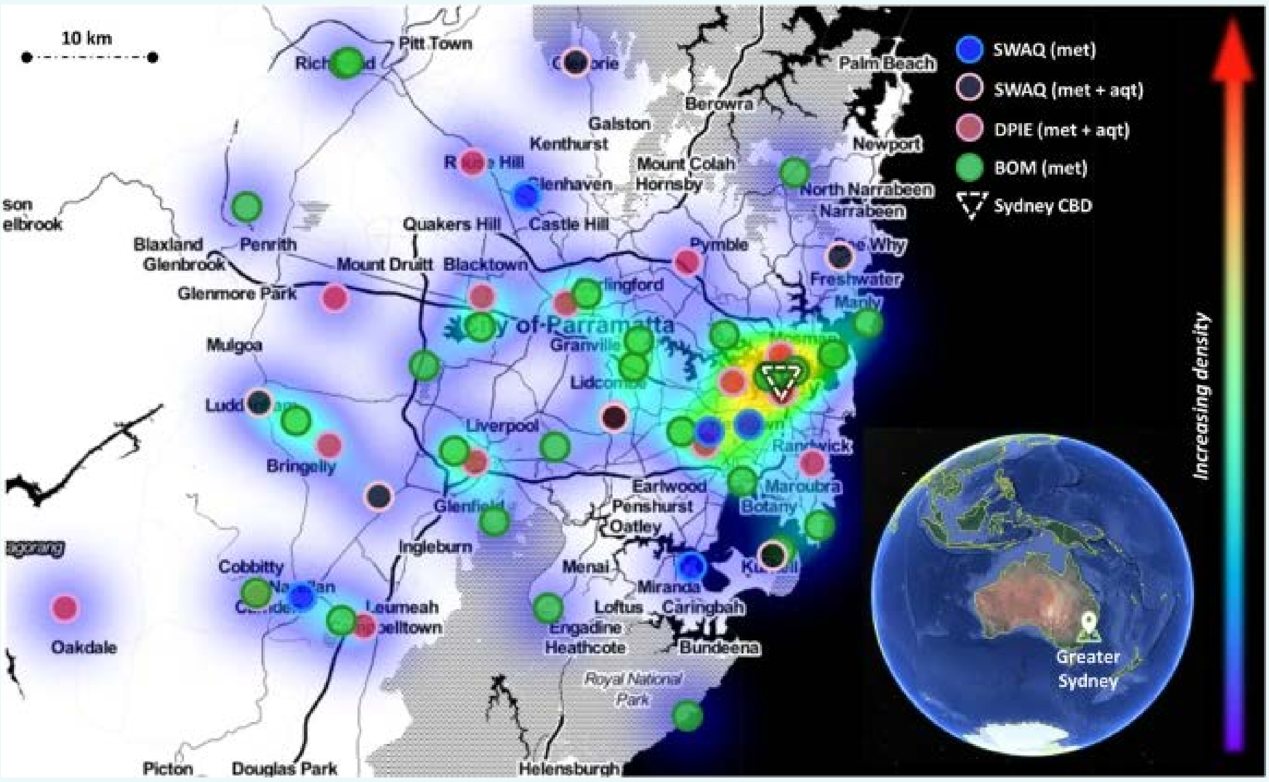
New datasets are becoming available which describe the three-dimensional details of cities at a scale of less than 1 metre resolution, capturing individual buildings and trees across large areas. Researchers created methods to convert this detailed city data into a format that can be understood by climate models. This allowed researchers to model the urban climate at local and regional scales with unparalleled accuracy, marking significant progress in urban climate modelling. The datasets are available publicly for Sydney.



Lipson. (2022). A Transformation in City-Descriptive Input Data for Urban Climate Models doi.org/10.3389/fenvs.2022.866398

Research box 5: Training our citizen scientists: a citizen-centred urban network for weather and air quality in Australian schools

Schools Weather and Air Quality (SWAQ) is a citizen science project that places meteorology and air quality sensors in schools across Sydney to collect data for urban climate, meteorology, and air quality research. The project provided a pilot for how citizen science could potentially enhance monitoring networks, increase STEM engagement and give the public more agency in their daily decision-making through access to localised, high temporal-resolution weather and air quality data. The data collected is being used both in scientific urban climate research and in curriculum-aligned classroom activities.



Ulpiani et al. (2022). A citizen centred urban network for weather and air quality in Australian schools. doi.org/10.1038/s41597-022-01205-9

Conclusion

Cities are living, breathing entities that not only house people but also embody some of the most complex dynamics in our economy, culture and politics. While climate has historically played a significant role in shaping urban environments, its influence has diminished with modern design and technology. It's time to restore that balance. Cities are at the epicenter of many climate challenges but also they are the nexus of opportunity. There is now the opportunity to make a change to our cities to the advantage of all who live there.

The more we understand the science of urban climate, and enable different sectors to implement this science in their practice, the better we can make resilient cities and communities.

Written by

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