URBAN HEAT – GUIDANCE DOCUMENT

City and County of Honolulu Climate Change Commission April, 2022

PURPOSE

Pursuant to the Revised Charter of Honolulu ("RCH") Section 6-107(h), the City & County of Honolulu ("City") Climate Change Commission ("Commission") is charged with gathering the latest science and information on climate change impacts to Hawai'i. It provides advice and recommendations to the mayor, City Council, and executive departments as they draft policy and engage in planning for future climate scenarios as well as reduce Honolulu's contribution to global greenhouse gas emissions.

The purpose of this document is to provide a set of findings and recommendations to the City on managing heat stress and heat shocks (heat waves) to augment City decision-making; for example, in light of projected global hotspots where combinations of heat and humidity are making conditions intolerable. Are these areas of key food and resource production and shipping for Hawai'i? How will human displacement where heat plays a role affect Hawai'i? This document describes the physical nature of atmospheric and marine heat in Hawai'i and provides accounts of how other cities have managed urban heat, the successes and lessons learned, and directions of maximum return. Past and present efforts to manage the problem in the City and County of Honolulu are reviewed. The majority of this information is contained in appendices that supplement a primary narrative focused on Commission recommendations.

FINDINGS

The Commission has conducted research on the problem of urban heat. The Commission finds the following:

1. Updated national pledges under the UNFCCC only cut greenhouse gas emissions 7.5% by 2030, leaving a 34% probability of staying below 2^{o}C and a 1.5% probability of staying below 1.5^{o}C.[1] However, on-the-ground policies to limit greenhouse gas emissions are advancing at a snail's pace.[2] End of century global warming is estimated to reach 2.0 to 3.6^{o}C (median 2.7^{o}C) above pre-industrial levels.[3] Under-reporting[4] of emissions and decreases in natural carbon sinks,[5] suggest global temperatures will be even higher.
2. Under current emissions pledges, children born in 2020, versus those born decades earlier, will experience 7.5 times as many heatwaves (4 vs 30 heat waves), 3.6 times as many droughts, 3 times as many crop failures, 2.8 times as many river floods, and 2 times as many wildfires.[6]
3. Climate change is causing a rise in the frequency and magnitude of extreme heat (heat waves). Heat waves can interact synergistically with the urban heat island effect to create localized overheating (urban heating)[7] exceeding 10^{o}C above ambient temperatures.[8] This can cause serious impacts to cooling energy consumption, peak electricity demand, heat related mortality and morbidity, urban environmental quality, local vulnerability, and comfort.

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[1] Ou, Y., et al. (2021) Can updated climate pledges limit warming well below 2oC? Science, 5Nov, v374, Iss.6568, DOI:10.1126/science.abl8976
[2] Climate Action Tracker (2021) Glasgow's 2030 credibility gap: net zero's lip service to climate action, https://climateactiontracker.org/documents/997/CAT_2021-11-09_Briefing_Global-Update_Glasgow2030CredibilityGap.pdf
[3] Ibid.
[4] Mooney, C., et al. (Nov. 7, 2021) Countries' climate pledges built on flawed data, Post investigation finds; Washington Post, https://www.washingtonpost.com/climate-environment/interactive/2021/greenhouse-gas-emissions-pledges-data/
[5] Duffy, K.A., et al. (2021) How close are we to the temperature tipping point of the terrestrial biosphere? Science Advances, v.7no.3, DOI: 10.1126/sciadv.aay1052
[6] Thiery, W., et al. (2021) Intergenerational inequities in exposure to climate extremes, Science, 26 Sept, v. 374, Iss. 6564, p. 158-160, https://www.science.org/doi/10.1126/science.abi7339
[7] Bao-Jie He, et al. (2022) Perception, physiological and psychological impacts, adaptive awareness and knowledge, and climate justice under urban heat: A study in extremely hot-humid Chongqing, China, Sustainable Cities and Society, v. 79, 103685, ISSN 2210-6707, https://doi.org/10.1016/j.scs.2022.103685.
[8] Santamouris, M. (2020) Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change, Energy and Buildings, ISSN: 0378-7788, Vol: 207, https://doi.org/10.1016/j.enbuild.2019.109482

4. Studies show that over 25% of the U.S. population experienced heat-related symptoms during the summer of 2020 and that among all socio-economic groups, those who were most vulnerable were women, those in low-income households, unemployed or on furlough, and people who identify as Hispanic or Latino or as other non-white census categories (including Asian, American Indian or Alaska Native, Native Hawaiian or other Pacific Islander, and multi-racial US residents).[9]
5. Extreme heat can trigger fatal heat exhaustion or heat stroke, which occur when a person's body cannot cool itself enough.[10] Heat stress can also kill by exacerbating underlying conditions, such as cardiovascular or respiratory disease, but also suicide and several types of injury.[11]
    a. Heat waves are a leading cause of weather-related deaths in the United States, killing more than 600 people each year.[12]
    b. Older adults, young children, and people with chronic conditions face the highest risk.[13]
    c. People who work outdoors or in hot conditions are at special risk of heat stress, as are people who don't have access to air conditioning or cooling facilities.[14]
    d. For pregnant women, extreme heat exposure is linked to more preterm births and poorer pregnancy outcomes, including low birth weight and infant death.[15]
    e. Extreme heat can make some mental health conditions worse.[16]
    f. Anyone can be affected by extreme heat, especially during strenuous activity. Some medicines increase this risk by affecting the body's ability to regulate temperature.[17]
6. Studies find that 37.0% (range 20.5–76.3%) of global warm-season heat-related deaths can be attributed to anthropogenic climate change and that increased mortality is evident on every continent. Deaths vary geographically but are of the order of dozens to hundreds of deaths per year in many locations.[18]
7. Climate change is causing heat to rise globally[19] and locally. Model projections identify geographic regions where heat joins with other stressors to cause community displacement. Among these are South and East Asia, North Africa and the Middle East, Eastern Europe, Central America and the U.S. Southwest, and portions of Australia and the Pacific.[20]
8. By 2050, models project that 68% of the world's population will live in urban areas.[21] Cities in the U.S., Middle East, northern Central Asia, northeastern China and inland South America and Africa are estimated to experience substantial warming of more than 4°C, larger than regional warming, by the end of the century.[22]
9. In Southwest North America the period from 2000 to 2021 was the driest 22-year span in at least 1,200 years. This appears to be just the beginning of a more extreme trend toward megadrought as global warming continues.[23]
10. The Commission has identified heat stress and heat shocks as climate change related extreme weather-related hazards. Extreme heat in Hawaiʻi to date has been associated with the development of marine heat

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[9] Wilhelmi, O.V., et al. (2021) Compounding hazards and intersecting vulnerabilities: experiences and responses to extreme heat during COVID-19, *Environ. Res. Lett.*, v.16, no. 8, https://iopscience.iop.org/article/10.1088/1748-9326/ac1760
[10] Mora, C., et al. (2017) Twenty-seven ways a heat wave can kill you: Deadly heat in the era of climate change, Circulation: Cardiovascular Quality and Outcomes, v. 10, No. 11, https://doi.org/10.1161/CIRCOUTCOMES.117.004233
[11] The Lancet (2021) Health in a world of extreme heat, Editorial, v. 398, Iss.10301, p. 641, https://doi.org/10.1016/S0140-6736(21)01860-2
[12] National Academies of Sciences, Engineering, and Medicine 2016. Attribution of Extreme Weather Events in the Context of Climate Change. Washington, DC: The National Academies Press. https://doi.org/10.17226/21852.
[13] Ibid.
[14] Ibid.
[15] Ibid.
[16] Ibid.
[17] Ibid.
[18] Vicedo-Cabrera, A.M., et al. (2021) The burden of heat-related mortality attributable to recent human-induced climate change. Nat. Clim. Chang. 11, 492–500. https://doi.org/10.1038/s41558-021-01058-x
[19] https://www.washingtonpost.com/weather/2019/09/26/inside-hawaiis-wild-summer-broken-high-temperature-records/
[20] Clement, V., et al. (2021) Groundswell Pt 2: Acting on Internal Climate Migration. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/36248 License: CC BY 3.0 IGO
[21] Ritchie, H., Roser, M. (2018) Urbanization, Published online at OurWorldInData.org. https://ourworldindata.org/urbanization#what-share-of-people-will-live-in-urban-areas-in-the-future
[22] Zhao, L., et al. (2021) Global multi-model projections of local urban climates. Nat. Clim. Chang. 11, 152–157. https://doi.org/10.1038/s41558-020-00958-8
[23] Williams, A.P., Cook, B.I. & Smerdon, J.E. (2022) Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. Nat. Clim. Chang. 12, 232–234. https://doi.org/10.1038/s41558-022-01290-z

waves in regional waters[24] and not from atmospheric heat domes such as the Western North America heat wave in June-July 2021.[25]

   a. Changes in local winds exacerbate rising heat.[26]
   b. Increasing sea surface temperatures[27] and air temperature[28] result in rising heat stress.
   c. In 2019 a marine heat wave developed in regional waters of the North Central Pacific leading to over 300 temperature records set in Hawai‘i between May and September.[29]
   d. The record high temperature for Honolulu was set on August 31, 2019 at 95^{o}F.[30]

11. Urban O‘ahu may experience intolerable levels of heat by mid-century and mitigation steps should be undertaken sooner rather than later as a cost-savings measure and in order to establish successful practices.
12. Urban heat waves are strongly associated with socio-economic impacts.[31] Globally, from 1983 to 2016, urban extreme heat exposure increased nearly 200%, affecting 1.7 billion people. Total urban warming elevated exposure rates 52% above population growth alone. However, complex exposure patterns highlight an urgent need for locally tailored adaptations and early warning systems.[32]
13. To date, the City has taken several steps with regard to managing urban heat.
    a. The O‘ahu Resilience Strategy (2019)[33] identifies Action #32 “Deploy sustainable roof systems to manage urban heat and rainfall” and Action #33 “Keep O‘ahu cool by maintaining and enhancing the community forest”.
    b. Between 2010 and 2013 Honolulu lost nearly 5% of the total urban tree canopy.[34] In response, the Resilience Office is working towards a goal of planting 100,000 trees by 2025 across O‘ahu and is committed to increasing the urban tree canopy to 35% by 2035.[35]
    c. On August 31st, 2019, volunteers traversed ten study areas across Honolulu and collected a total of 77,456 measurements of temperature and humidity (heat index).[36] The maximum heat index recorded was 107.3°F, and the data identified several localized heat islands.[37] The aim of the campaign was to improve understanding of how urban heat varies across neighborhoods and how local landscape features can affect temperatures.
14. Experiences by other urban areas provide guidance on practices that are effective in mitigating heat stress and heat shocks. These are now established practices that have shown success in mitigating urban heat.
    a. Trees. Trees produce shade, but they also cool the air through transpiration. A building shaded by trees has lower air conditioning costs, which also reduces both direct heat and carbon emissions.
    b. Shade Structures. Traditional architecture in hot countries has often made use of arcades, colonnades, large umbrellas, pergolas, awnings, and more. Including shade as a fundamental architecture component in city design is an effective way to cool urban areas and make them more livable.

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[24] www.washingtonpost.com/weather/2019/09/26/inside-hawaiis-wild-summer-broken-high-temperature-records/
[25] https://en.wikipedia.org/wiki/2021_Western_North_America_heat_wave
[26] Garza, J. A., P.-S. Chu, C. W. Norton, and T. A. Schroeder (2012), Changes of the prevailing trade winds over the islands of Hawaii and the North Pacific, J. Geophys. Res., 117, D11109, doi:10.1029/2011JD016888
[27] Cheng, L., Abraham, J., Trenberth, K.E., et al. (2022) Another Record: Ocean Warming Continues through 2021 despite La Niña Conditions. Adv. Atmos. Sci. https://doi.org/10.1007/s00376-022-1461-3
[28] McKenzie, M.M., Giambelluca, T.W., & Diaz, H.F. 2019. Temperature Trends in Hawai‘i: A Century of Change, 1917–2016. International Journal of Climatology, 39(10): 3987-4001, doi: 10.1002/joc.6053.
[29] WASHINGTON POST, HAWAII GOES 20 DAYS IN A ROW SETTING A HEAT RECORD DURING ITS HOTTEST SUMMER EVER: HTTPS://WWW.PENNLIVE.COM/NATION-WORLD/2019/09/HAWAII-GOES-20-DAYS-IN-A-ROW-SETTING-A-HEAT-RECORD-DURING-ITS-HOTTEST-SUMMER-EVER.HTML
[30] https://www.washingtonpost.com/weather/2019/09/26/inside-hawaiis-wild-summer-broken-high-temperature-records/
[31] Popovich, N., and Flavelle, C. (2019) Summer in the city is hot, but some neighborhoods suffer more, New York Times, Aug. 9, https://www.nytimes.com/interactive/2019/08/09/climate/city-heat-islands.html
[32] Tuholske, C., et al. (2021) Global urban population exposure to extreme heat, PNAS, 118 (41), https://doi.org/10.1073/pnas.2024792118
[33] O‘ahu Resilience Strategy (2019) https://resilientoahu.org/resilience-strategy
[34] Urban Tree Canopy Assessment, https://smarttreespacific.org/projects/honolulu-urban-tree-canopy-assessment/
[35] Honolulu Resilience Office, Tree Program, https://resilientoahu.org/trees
[36] Honolulu Heat Watch Report (2019) https://drive.google.com/file/d/1tHSMOETsOv-_PAb10OYtAv7iler8StLu/view
[37] Oahu Community Heat Map, https://www.arcgis.com/apps/View/index.html?appid=ff1b73d836074cf6b2aca420fffbd930

c. Green Roofs and Walls. Green roofs insulate buildings from heat, and also cool the air through evapotranspiration. The Oasia Hotel in Singapore[38] is a 27-story high-rise tower that has been clad in aluminum mesh so that climbing plants can grow on it. This living external cover shades the building and keeps it cool, while enhancing biodiversity in the urban area.
d. Painting Roofs White – Darker colors absorb heat, so increasing the reflectivity of buildings can reduce heat. Some hot parts of the world have always known this, which is why there are so many white cars in tropical countries, and white buildings in Greece. The NYC Cool roofs program[39] has painted over 10 million square feet of roof over the last ten years.
e. Cooler Streets and Pavements – Inspired by white roofs, some municipalities have experimented with painting whole streets white. Some say this doesn't work, because people walking the streets feel the heat reflected back at them off the ground – a problem that doesn't occur on rooftops. Other studies suggest it can make a significant difference to heat overall, so perhaps it's best reserved for parking lots or streets that don't have high foot traffic.
f. Water Features – Water features can help to cool a city. Canals and ponds have a limited effect, but moving water creates spray and has cooling power – this is why some traditional buildings place a fountain at the center of a shaded courtyard.
g. Design Out Heat – Research on urban heat informs many styles of new development. A variety of building heights encourages better air flow, passive cooling techniques can be incorporated into new buildings to minimize air conditioning, and shade can be planned as a key element from the start. Cities may need to tweak planning regulations to encourage cooler buildings and streets, and avoid the need for retrofitting measures later.

RECOMMENDATIONS

Based on research, the Commission recommends the following:

1. The City should create a public education and outreach program to increase heat awareness. This should include:
    a. Explicitly include and define heat language in city efforts that mitigate the effects of heat.
    b. Create a *cooling action plan* that leverages the Honolulu Climate Action Plan and Oʻahu Resilience Strategy.
    c. Develop and promulgate individual and family heat preparedness plans.
    d. Develop a series of Public Service Announcements to raise awareness of the rising threat of dangerous heat, medical and health aspects of heat, protective actions to mitigate heat risk, and C&C resources relevant to mitigating heat risk.
    e. Engage with communities on all heat mitigation actions to develop a high level of awareness.
2. The City should collect more heat information.
    a. Develop a climate sensor system.
    b. Urban form will change over time which may affect urban heat. Capture the changes that happen over time.
    c. Run heat surveys of high granularity in specific areas where urban heat puts residents at risk.
    d. Create a heat data collection plan that identifies what types of heat data are available and that identifies data gaps preventing development of a cooling action plan.
    e. Survey actions taken by other communities to mitigate heat risk and evaluate for adoption.
3. The City should develop a comprehensive plan for emergency heat response.
    a. Identify and map cooling center locations. Leverage cooling centers/resilience hubs for emergency cooling during heat waves.

[38] Building of the Week: Oasia Hotal, Singapore, https://earthbound.report/2018/09/14/building-of-the-week-oasia-hotel-singapore/
[39] NYC CoolRoofs, https://www1.nyc.gov/nycbusiness/article/nyc-coolroofs

   b. Create an extreme heat warning system with triggering criteria, extreme weather action plans for departments and the public, and coordinate with the National Weather Service and relevant state agencies.
4. The City should develop heat resilience building guidelines and codes.
   a. Create a network of heat resilience centers in existing and new/future building stock.
   b. Mitigate against the potential of black-outs and brown-outs during heat waves through building energy systems.
   c. Require that residential buildings, especially older buildings, have sufficient emergency power to avoid stranding residents and to provide reliable cooling.
5. The City should develop a cool streets and cool-roofs programs that emphasizes:
   a. Green and white roofs,
   b. Strategically placed white surfaces at street-level,
   c. Extensive shade structures using architectural elements, awnings and large umbrellas, tree canopy and green tunnels, and other forms of shade,
   d. Water features and shaded gathering places.
6. The City should use census data to identify underserved and low-income communities that are at risk of heat stress and shock. Apply heat resiliency steps in these communities early.

INTRODUCTION

It is unequivocal that human influence has warmed the atmosphere, ocean and land.[40] Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years.[41] Human-induced climate change is already affecting many weather and climate extremes in every region across the globe.[42] Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, their attribution to human influence, has strengthened.[43] According to the Intergovernmental Panel on Climate Change (IPCC), it is virtually certain that “there have been increases in the intensity and duration of heatwaves and in the number of heatwave days at the global scale”.[44] As the impacts of heat directly increase with the level of warming, food and water security, human health, and community wellbeing are all at risk.[45]

Progress in Mitigating Emissions - Updated national pledges under the UNFCCC only cut greenhouse gas (GHG) emissions 7.5% by 2030, leaving a 34% probability of staying below 2^{o}C and a 1.5% probability of staying below 1.5^{o}C.[46] However, on-the-ground policies to limit greenhouse gas emissions are advancing at a snail’s pace.[47] At current levels of mitigation, end of century global warming is estimated to reach 2.0 to 3.6^{o}C (median 2.7^{o}C) above pre-industrial levels.[48] However, under-reporting of emissions and decreases in natural carbon sinks, suggest global temperatures may be even higher. On average, global emissions are underreported 23%[49] with 70%[50] under-

[40] IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.
[41] Ibid.
[42] Ibid.
[43] Ibid.
[44] Ibid.
[45] Guy, K. et al. (2020) A Security Threat Assessment of Global Climate Change: How Likely Warming Scenarios Indicate a Catastrophic Security Future. Product of the National Security, Military, and Intelligence Panel on Climate Change. Edited by Femia, Francesco and Werrell, Caitlin. The Center for Climate and Security, an institute of the Council on Strategic Risks. Washington, DC. February 2020. https://climateandsecurity.org/a-security-threat-assessment-of-global-climate-change/
[46] Ou, Y., et al. (2021) Can updated climate pledges limit warming well below 2oC? Science, 5Nov, v374, Iss.6568, DOI:10.1126/science.abl8976
[47] Climate Action Tracker (2021) Glasgow’s 2030 credibility gap: net zero’s lip service to climate action, https://climateactiontracker.org/documents/997/CAT_2021-11-09_Briefing_Global-Update_Glasgow2030CredibilityGap.pdf
[48] Ibid.
[49] Mooney, C., et al. (Nov. 7, 2021) Countries’ climate pledges built on flawed data, Post investigation finds; Washington Post, https://www.washingtonpost.com/climate-environment/interactive/2021/greenhouse-gas-emissions-pledges-data/
[50] International Energy Agency (2022) Methane emissions from the energy sector are 70% higher than official figures: https://www.iea.org/news/methane-emissions-from-the-energy-sector-are-70-higher-than-official-figures

reporting of methane emissions alone. Projected warming, consequently, generally represent underestimates of future temperature. In addition, the terrestrial biome, historically responsible for sequestering about 30% of anthropogenic carbon dioxide emissions, has already neared, and temporarily crossed, a photosynthetic thermal maximum beyond which the terrestrial carbon sink will grow increasingly unstable. Models project this sink potentially losing 50% capacity by 2040.[51] New studies[52] report that global carbon loss from forests has doubled in only 20 years. The acceleration and high rate of loss suggests that existing strategies to reduce forest loss are not successful.

HEAT AND CLIMATE CHANGE

For thousands of years, human communities have concentrated under a relatively narrow range of climate variables characterized by mean annual temperatures (MAT) around 13^{o}C (55.4^{o}F).[53] This distribution reflects a temperature niche related to fundamental bounds on food and water security. Under continued greenhouse gas emissions this century, approximately one third of the global population is projected to experience MAT >29°C (84.2^{o}F) meaning that a substantial part of humanity will be exposed to mean annual temperatures warmer than nearly anywhere today.[54] Today this MAT accounts for only 0.8% of Earth's land surface, mostly concentrated in the Sahara. However, with continued warming, the area subjected to these deadly heat conditions will expand to incude about one-fifth of global land (**Figure 1**).

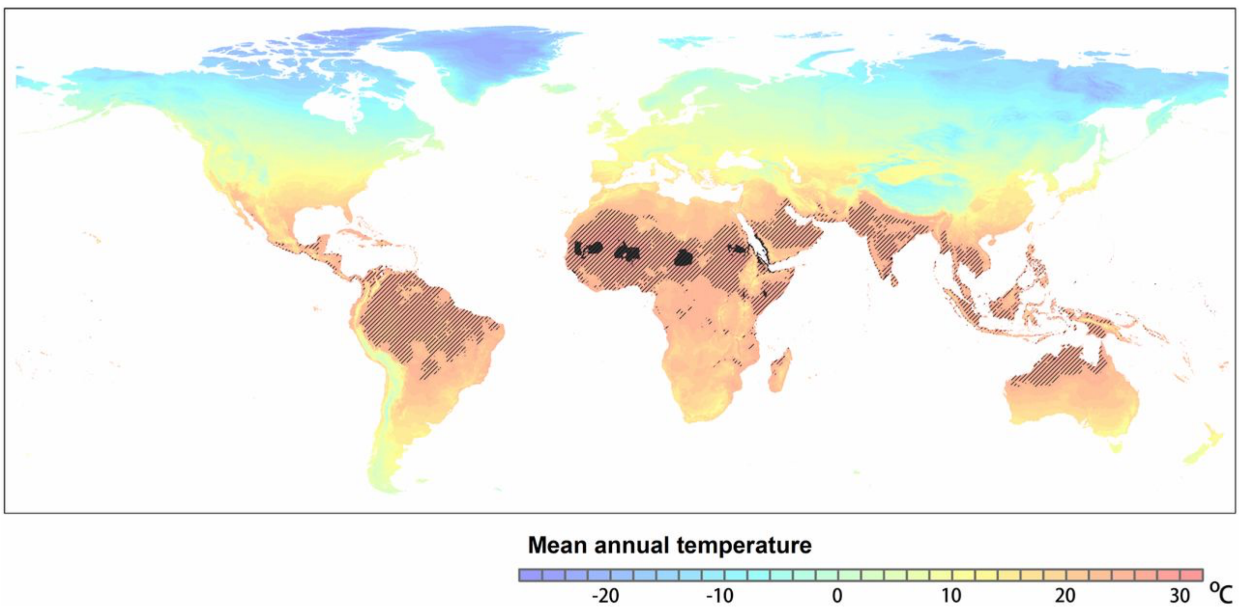

Figure 1. *Expansion of extremely hot regions in a business-as-usual climate scenario. In the current climate, mean annual temperatures (MATs) >29°C (84.2^{o}F) are restricted to the small dark areas in the Sahara region (0.8% of global land area). With continued emissions, these conditions are projected to occur throughout the shaded area (19% of global land area) by 2070, potentially home to 3.5 billion people. Background colors represent current MATs. (Xu et al., 2020)*

[51] Duffy, K.A., et al. (2021) How close are we to the temperature tipping point of the terrestrial biosphere? Science Advances, v.7no.3, DOI: 10.1126/sciadv.aay1052

[52] Feng, Y., Zeng, Z., Searchinger, T.D. et al. (2022) Doubling of annual forest carbon loss over the tropics during the early twenty-first century. Nat Sustain. https://doi.org/10.1038/s41893-022-00854-3

[53] Xu, Chi et al. (2020). Future of the human climate niche. PNAS, https://doi.org/10.1073/pnas.1910114117

[54] Ibid.

Security Concerns - The Institute for Economics and Peace projects that by mid-century 1.2 billion people will be displaced from their homes due to climate change related weather extremes, including heat.[55] The world's least resilient countries, when faced with ecological breakdowns, are more likely to experience civil unrest, political instability, social fragmentation and economic collapse.[56] As the potentially most affected regions are among the poorest in the world, where adaptive capacity is low, enhancing human development in those areas should be a priority alongside climate mitigation.

Heat and Human Communities - Extreme heat threatens human communities. Research has established a positive temperature-mortality relationship, and its effects are exacerbated in highly vulnerable communities. This includes low-income communities, Indigenous communities, and isolated island communities.[57] Furthermore, every additional increment of global warming increases the intensity and frequency of hot extremes, including heatwaves.[58] In the Middle East and North Africa a business-as-usual emission pathway indicates that in the second half of this century unprecedented "super- and ultra-extreme" heatwave conditions will emerge. These events involve excessively high temperatures (56 ^{o}C and higher) and will be of extended duration (several weeks), being potentially life-threatening for humans.

Warming air contributes to the intensity of heatwaves, and increases the chances of very hot days and nights. Studies indicate that 74% of the world's population will be exposed to deadly heat waves by 2100 if GHG emissions continue to rise at current rates. Even if emissions are aggressively reduced, it is expected that 48% of the world's human population will be affected. With large socioeconomic differences within and among countries, heat waves could exacerbate global disparities in health, especially given the diminished resources available to many developing nations. In the last decade, there has been >2300% increase in the loss of human life from heat waves as a result of about 1^{o}C warming. Considering that current GHG emissions put humanity on a pathway to over 3 ^{o}C of warming, the global health and socio-economic risks are potentially catastrophic.

Under current emissions pledges, children born in 2020, versus those born decades earlier, will experience 7.5 times as many heatwaves (4 vs 30 heat waves), 3.6 times as many droughts, 3 times as many crop failures, 2.8 times as many river floods, and 2 times as many wildfires.[59] Climate change is causing a rise in the frequency and magnitude of extreme heat (heat waves). Heat waves can interact synergistically with the urban heat island effect to create localized overheating (urban heating)[60] exceeding 10^{o}C above ambient temperatures.[61] This can cause serious impacts to cooling energy consumption, peak electricity demand, heat related mortality and morbidity, urban environmental quality, local vulnerability, and comfort.

Impact Disparities - The most serious health impacts of a heat wave are often associated with high temperatures at night, which is usually the daily minimum. The human body needs to cool off at night, especially after a hot day. If the air stays too warm at night, the body faces extra strain as the heart pumps harder to try to regulate body temperature. Understanding how heat waves affect morbidity and mortality, as well as the associated economic costs, is essential for characterizing the human health impacts of extreme heat under a changing climate. For example, many studies have previously shown that the elderly in a society are among the most vulnerable to heat waves. Additionally, the mean costs of heat-related hospitalizations were higher among racial/ethnic minorities compared to whites, who accounted for almost 65% of all heat-related hospitalizations. Differences in costs based on income, insurance, and gender were also significant. These results suggest that these populations are suffering disproportionately from

[55] Institute for Economics & Peace (IEP) (2020) Ecological Threat Register 2020: Understanding Ecological Threats, Resilience and Peace, Sydney, September.
[56] Ibid.
[57] Anderson, G.B., et al (2013) Methods to calculate the heat index as an exposure metric in environmental health research, Environmental Health Perspectives, 121:10, https://doi.org/10.1289/ehp.1206273
[58] IPCC (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.
[59] Thiery, W., et al. (2021) Intergenerational inequities in exposure to climate extremes, Science, 26 Sept, v. 374, Iss. 6564, p. 158-160, https://www.science.org/doi/10.1126/science.abi7339
[60] Bao-Jie He, et al. (2022) Perception, physiological and psychological impacts, adaptive awareness and knowledge, and climate justice under urban heat: A study in extremely hot-humid Chongqing, China, Sustainable Cities and Society, v. 79, 103685, ISSN 2210-6707, https://doi.org/10.1016/j.scs.2022.103685.
[61] Santamouris, M. (2020) Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change, Energy and Buildings, ISSN: 0378-7788, Vol: 207, https://doi.org/10.1016/j.enbuild.2019.109482

health inequity, thus, they could shoulder greater disease and financial burdens due to climate change. Unprecedented climates will occur earliest in the tropics and among low-income countries, highlighting the vulnerability of global biodiversity and the limited governmental capacity to respond to the impacts of climate change.

Drawing on urban temperature anomalies during extreme summer surface temperature events from all 1,056 US counties with more than 10 developed census tracts, the poorest tracts (and those with lowest average education levels) within a county are significantly hotter than the richest (and more educated) neighborhoods for 76% of these counties (54% for education). For 71% of all counties the significant racial urban heat disparities persist even when adjusting for income. An extra 0.5 ^{o}C of global warming, from 1.5 to 2 ^{o}C, would impose the earliest and severest heat-related consequences on the least-developed regions. Lower-income regions have reduced adaptative capacity to warming, which compounds the impacts of higher heatwave exposure.

Heat and Health - A study regarding the compounding effect of the COVID-19 pandemic on extreme heat vulnerability revealed that over 25% of the US population experienced heat-related symptoms during the summer of 2020.[62] Among all socio-economic groups, those who were most vulnerable were women, those in low-income households, unemployed or on furlough, and people who identify as Hispanic or as other non-white census categories (including Asian, American Indian, Native Hawaiian or other Pacific Islander, and multi-racial US residents).[63] The study findings indicate that for millions of people, the intersection of two health hazards—extreme heat and coronavirus SARS-CoV2—amplified existing systemic vulnerabilities and expanded the demographic range of people vulnerable to heat stress.[64]

Since 1991, empirical data from 732 locations in 43 countries reveal that global warming is responsible for significant warm-season heat disease and morbidity.[65] Across all study countries, researchers found that 37.0% (range 20.5–76.3%) of warm-season heat-related deaths can be attributed to anthropogenic climate change and that increased mortality is evident on every continent. Heat-related health impacts varied geographically but were of the order of dozens to hundreds of deaths per year in many locations. Researchers found an urgent need for more ambitious mitigation and adaptation strategies to minimize the public health impacts of climate change.

Wet Bulb Temperature - The wet bulb temperature (TW) is used as an indicator of dangerous, heat-humidity combinations.[66] Even heat-adapted people cannot carry out normal outdoor activities past a TW of 32°C (90°F). The theoretical limit to human survival for more than a few hours in the shade, even with unlimited water, is a TW of 35°C (95°F).[67] Studies show that extreme humid heat overall has more than doubled in frequency since 1979 and that TW will regularly exceed 35°C on land with less than 2.5°C of global warming since the preindustrial period—a level that may be reached in the next several decades.[68]

Heat Index - The heat index is a measure of both relative humidity and air temperature.[69] As air temperature and relative humidity increase, the heat index also increases. Heat indices meeting or exceeding 103°F threaten human health and can result in dangerous heat disorders.[70] The National Weather service has established a warning system based on the heat index (**Figure 2**).

[62] Wilhelmi, O.V., et al. (2021) Compounding hazards and intersecting vulnerabilities: experiences and responses to extreme heat during COVID-19, Environ. Res. Lett., v.16, no. 8, https://iopscience.iop.org/article/10.1088/1748-9326/ac1760
[63] Ibid.
[64] Ibid.
[65] Vicedo-Cabrera et al. (2021) The burden of heat-related mortality attributable to recent human-induced climate change. Nat. Clim. Chang.
[66] Wet-bulb Temperature, Wikipedia, https://en.wikipedia.org/wiki/Wet-bulb_temperature
[67] Ibid.
[68] Raymond, C., et al. (2020) the emergence of heat and humidity too severe for human tolerance, ScienceAdvances, v. 6, no. 19, https://doi.org/10.1126/sciadv.aaw1838
[69] National Weather Service, What is the Heat Index? https://www.weather.gov/ama/heatindex
[70] Ibid.

NWS Heat Index — Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution | Extreme Caution | Danger | Extreme Danger

Classification	Heat Index	Effect on the body
Caution	80°F - 90°F	Fatigue possible with prolonged exposure and/or physical activity
Extreme Caution	90°F - 103°F	Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity
Danger	103°F - 124°F	Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity
Extreme Danger	125°F or higher	Heat stroke highly likely

Figure 2. *National Weather Service (NWS) Heat Index. The NWS has developed a warning system based on the effect of heat and humidity on the human body. In order to determine the heat index using this chart, you need to know the air temperature and the relative humidity. For example, if the air temperature is 100°F and the relative humidity is 55%, the heat index will be 124°F, the upper limit of the NWS Danger classification. At this level of humid heat, "Heat cramps or heat exhaustion are likely, and heat stroke is possible with prolonged exposure and/or physical activitiy." The Heat Index is developed for shady locations. If you are exposed to direct sunlight, the index can be increased by up to 15°F. (figure from NWS)*[71]

Urban Heat - Researchers combined climate modelling and data-driven approaches to provide global multi-model projections of urban climates over the twenty-first century. Today, more than 50% of the world's population resides in an urban area, and this is projected to increase to 70% by 2050.[72] Globally recognized environmental problems–

[71] National Weather Service Heat Index, https://www.weather.gov/ama/heatindex
[72] Zhao, L., et al. (2021) Global multi-model projections of local urban climates. *Nat. Clim. Chang*. 11, 152–157. https://doi.org/10.1038/s41558-020-00958-8

such as heat stress, water scarcity, air pollution and energy security – are amplified in built areas through the uniqueness of urban climates and high population density.[73] Under a high-emissions scenario, cities in the United States, Middle East, northern Central Asia, northeastern China and inland South America and Africa are estimated to experience substantial warming of more than 4°C (7.2°F)—larger than regional warming—by the end of the century.[74]

HEAT AND CITIES

The Honolulu Climate Change Commission has characterized heat impact both as a stress (urban heat islands) and as a shock (heat waves). Heat shocks and stressors have health, economic, environmental, and equity impacts.

In an urban context, heat is especially acute in areas where temperatures are higher relative to their surroundings, these are called heat islands.[75] In the US, the heat island effect increases daytime temperatures 1-7°F and nighttime temperatures 2-5°F compared to outlying areas.[76] These urban heat islands (UHI) are caused by changing surface albedo (from vegetative to impervious surfaces of lower solar radiance), and by reducing circulation via urban form.[77] UHI's are not limited by their conditions as they can occur during day or night, in small and large cities, in suburban areas, in both hemispheres, and during any season.[78] UHI's can increase energy consumption (and increase emissions of air pollutants and GHG's), compromise human health and comfort, and impair water quality.[79] They can exacerbate heat waves,[80] as well as reduce economic output and productivity. [81] Heat islands can be further broken down into surface heat islands and atmospheric heat islands.

Surface Heat Islands - Surface heat islands form because urban surfaces such as roadways and rooftops absorb and emit heat to a greater extent than most natural surfaces. On a warm day with a temperature of 91°F, conventional roofing materials may reach as high as 60°F warmer than air temperatures.[82] Surface heat islands tend to be most intense during the day when the sun is shining.

Atmospheric Heat Islands - Atmospheric heat islands form in cities as a result of warmer air in urban areas compared to cooler air in outlying areas.[83] Atmospheric heat islands vary much less in intensity than surface heat islands.

Heat Shock: Heat Waves - Generally, heat waves are prolonged periods of excessive heat usually associated with atmosphere-related heat stress.[84] In 2019, extreme heat was the most common cause of death among all weather-related disasters in the US.[85] Hot and humid environments reduce the efficiency in which the human body can cool itself through evaporative cooling (i.e. sweating). Health impacts range from sunburn, heat stress and heat exhaustion to kidney failure and heart attacks, and can lead to increased emergency admission, ambulance call outs, and increased morbidity and mortality.[86] Additionally, heat negatively affects power generation and transmission, and

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[73] Ibid.
[74] Ibid.
[75] United States Environmental Protection Agency (2021)
[76] Ibid.
[77] Kleerekoper, L., et al. (2012). How to make a city climate-proof, addressing the urban heat island effect. Resources, Conservation and Recycling, 64, 30-38. Elsevier. doi:10.1016/j.resconrec.2011.06.004; Manoli, G., et al. (2020) Seasonal hysteresis of surface urban heat islands. PNAS, 117(13), 7082-7089. doi.org/10.1073/pnas.1917554117; Filho, W. L., et al. (2017). An Evidence-Based Review of Impacts, Strategies and Tools to Mitigate Urban Heat Islands. International Journal of Environmental Research and Public Health, 14(12), 1-29. MDPI. https://doi.org/10.3390/ijerph14121600
[78] United States Environmental Protection Agency (2021)
[79] Santamouris, M. (2020) Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Energy and Buildings, v. 207, https://doi.org/10.1016/j.enbuild.2019.109482
[80] Filho et al. (2017)
[81] United States Environmental Protection Agency (2021)
[82] Hibbard et al. (2017) Changes in land cover and terrestrial biogeochemistry. In Climate Science Special Report: Fourth National Climate Assessment, v. I, U.S. Global Change Research Program, Washington.
[83] United States Environmental Protection Agency, 2021
[84] Zuo, J., et al. (2015) Impacts of heat waves and corresponding measures: a review. Journal of Cleaner Production, 92(2015), 1-12. Elsevier. https://doi.org/10.1016/j.jclepro.2014.12.078
[85] NWS (2021) Summary of Natural Hazard Statistics for 2019 in the United States. Weather Related Fatality and Injury Statistics. Retrieved March 15, 2022, https://www.weather.gov/hazstat/Weather%20Related%20Fatality%20and%20Injury%20Statistics
[86] Ibid.

when coupled with increased power usage, increases the risk of power outages.[87] Heat waves also damage transport infrastructure and building materials – resulting in significant urban financial costs– and are exacerbated by UHI’s.

The June 2021 heat waves in Oregon, Washington and British Columbia shattered temperature records and killed hundreds of people; mainly those who were older, homebound and socially isolated, and those unwilling or unable to get to cooling centers. In Portland, a call center designed to provide information about cooling centers went unstaffed during part of the peak heat, and the light-rail train was shut down to reduce strain on the power grid. Unaccustomed to dealing with heat, many in the Pacific Northwest region do not have air conditioning.

Heat and Honolulu - According to the 2010 Census, 944,982 people resided in urban areas on O‘ahu, which represents 99.1% of O‘ahu's population. On August 31, 2019, volunteers collected temperature and humidity measurements in the morning, afternoon, and evening of Honolulu as part of the Urban Heat Watch program. The maximum heat index recorded was 107.3°F, with a highest heat index differential of 22.3°F. Data from this day was used to produce urban heat maps to improve undeerstanding how heat varies across neighborhoods and how local landscape features can affect temperatures (**Figure 3**).[88]

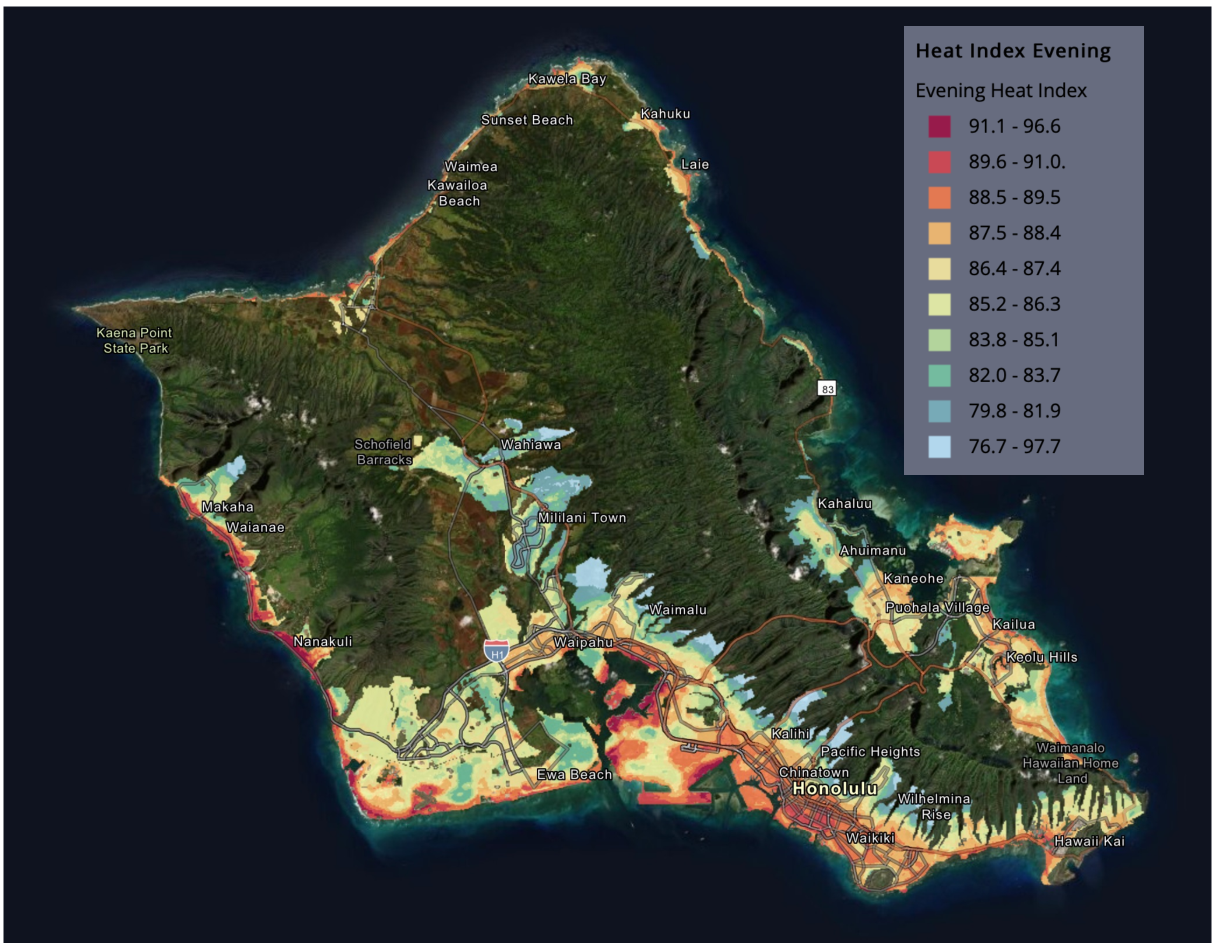

Figure 3. Evening heat index, O‘ahu, Saturday, Aug. 31, 2019. (figure Oahu Heat Vulnerabiity map series)[89]

[87] Ibid.
[88] CAPA Strategies. (2019). Heat Watch Report: Honolulu, HI. OSF. https://osf.io/ekamd/
[89] https://cchnl.maps.arcgis.com/apps/MapSeries/index.html?appid=81a93d637086418f9118d8740a7e8f3c

On O'ahu, extreme heat can increase the vulnerability of a community. O'ahu's social vulnerability[90] score of 0.6053 indicates a moderate-to-high level of vulnerability to shocks and stresses. In 2019, the national weather service recorded a record high of 91°F in Honolulu breaking the previous record of 90°F set in 1995. During this heat wave, 27 records were either set or matched in May in Honolulu, Kahului, Hilo, and Lihue.[91] Doctors at Queens Medical Hospital noticed an increase in patients suffering from dehydration or acute heat injuries.[92]

Heat negatively affects power generation and transmission, and when coupled with increased power usage for space cooling, increases the risk of power outages.[93] Heat waves can also damage transportation infrastructure, building materials, and are exacerbated by urban heat islands.[94]

HEAT STRATEGIES

Physical infrastructure and information systems can be used to reduce the impacts of urban heat. Cooler cities result in positive impacts on human health, air quality, productivity, student learning, tourism, public safety, energy use, energy expenditures, and quality of life. Cities can address rising air temperatures by adopting a package of measures (**Figure 4**), including:

1. Passive, nonmechanical cooling solutions, such as:
    a. Reflective Surfaces - Urban roofs, walls, and pavements that reflect, rather than absorb solar radiation
    b. Permeable Surfaces - Expanded vegetated cover and tree canopy (shading, green roofs/walls, and permeable paving).
2. Heat-resiliency planning, such as:
    a. Natural and man-made water features (water infrastructure)
    b. Urban planning that minimizes heat buildup and retention (urban design)
    c. Passive cooling designs for buildings, such as increased thermal insulation (passive building design).
3. Energy-efficient cooling solutions, such as:
    a. Energy-efficient cooling technologies and climate-friendly centralized cooling applications, including district cooling
    b. Fewer polluting vehicles and more public transportation.

[90] https://www.atsdr.cdc.gov/placeandhealth/svi/index.html
[91] The Associated Press. (2019, June 20). Hawaii heat wave continues to break June temperature records. Hawaii News Now. https://www.hawaiinewsnow.com/2019/06/20/hawaii-heat-wave-continues-break-june-temperature-records/
[92] KHON2. (2019, June 17). Doctors notice increase in patients with heat related injuries. KHON2. Retrieved March 3, 2022, from https://www.khon2.com/local-news/doctors-notice-increase-in-patients-with-heat-related-injuries/
[93] Zuo, J., et al. (2015); Primer for Cool Cities: Reducing Excessive Urban Heat – With a Focus on Passive Measures, Energy Sector Management Assistance Program (ESMAP); Knowledge series 031/20. Washington, D.C.: World Bank Group.http://documents.worldbank.org/curated/en/605601595393390081/Primer-for-Cool-Cities-Reducing-Excessive-Urban-Heat-With-a-Focus-on-Passive-Measures
[94] Zuo, J., et al. (2015)

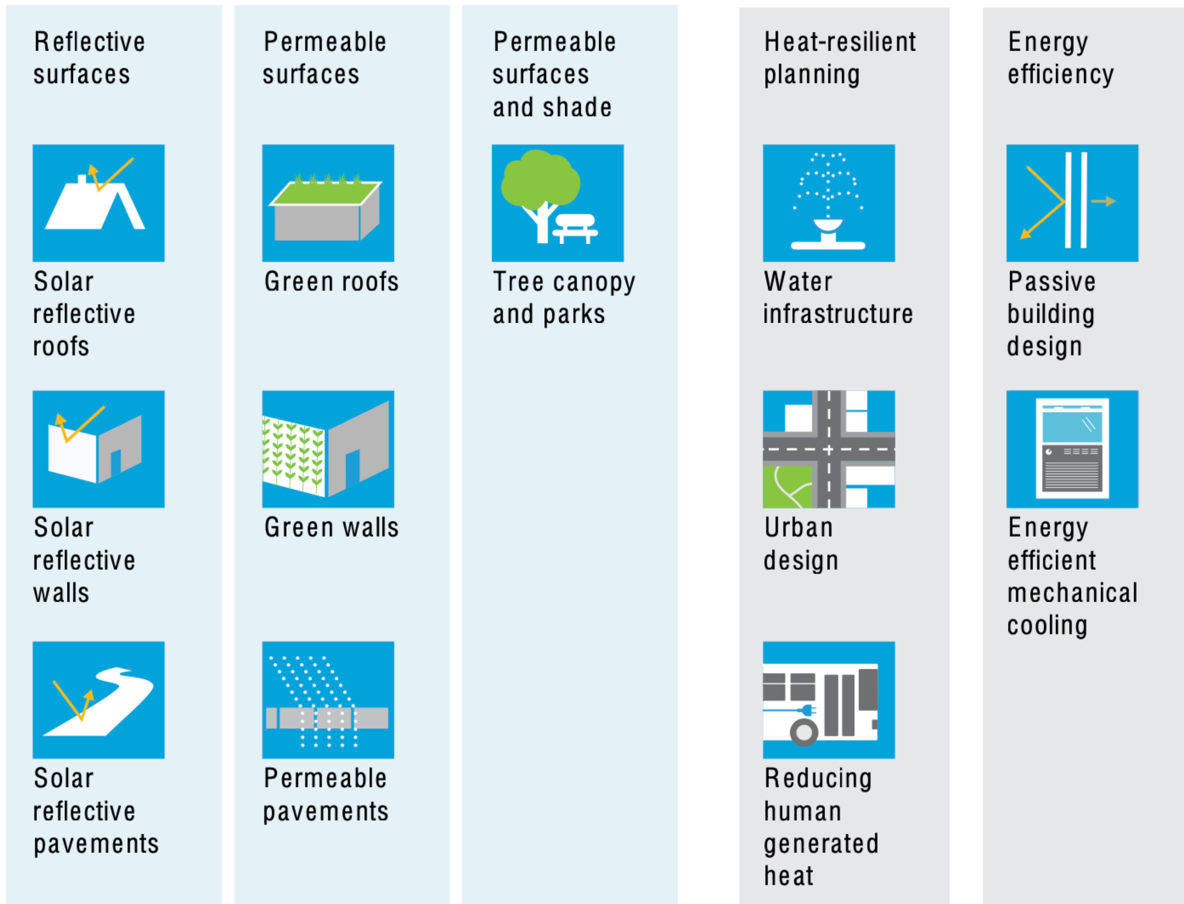

Figure 4. *Commonly used urban cooling solutions.*

The following sections concentrate on the use of reflective surfaces and permeable infrastructure, water features, and information systems.

Reflective Surfaces - By reducing the electricity needed for air-conditioning, reflective surfaces (roofs, walls, pavements) decrease GHG emissions from power plants and thereby indirectly mitigate global warming. But the larger and more direct cooling benefit of reflective surfaces is that they reflect, rather than absorb, most incoming sunlight. So instead of heating up and warming not only the surrounding air but also the atmosphere, reflective surfaces return sunlight back through the atmosphere and out into space, starting from the moment they are installed. A large-scale shift toward reflective surfaces could therefore immediately mitigate warming by reducing the amount of heat that is transmitted from Earth's surface and trapped in the atmosphere.[95]

The use of more reflective surfaces in hot cities around the world could cancel the warming effect of 44–57 billion metric tons of emitted carbon dioxide, up to 75% above current annual global emissions of carbon dioxide. Long-term modeling of more reflective urban surfaces found a sustained global cooling effect of 0.01–0.07°C. Another study estimated that increasing the reflectance of land surfaces (e.g., by converting to highly reflective roofs only) could offset as much as 30% of greenhouse warming and therefore slow climate change.[96]

Roofs typically make up 25–30% of an average city's urban surfaces. Roofs may be either steep sloped or nearly flat. There are a wide variety of highly reflective roofing products available today in nearly every roof surface type used

95 Ibid.
96 Ibid.

worldwide. Most changes to roof solar reflectance will occur when a new roof or a replacement roof is installed. At these times, it is much easier to design for and choose a cool option. There are also options to use coatings to increase the solar reflectance of an existing, functional roof. Coatings are typically applied to a functional roof to waterproof it or to extend its useful life.

Cool surfaces are commonly created by lightening roof color to reflect more solar energy in the visible spectrum (e.g., a white roof rather than a dark roof). However, slightly less than 50% of solar energy is contained in the visible spectrum. The vast majority of the remaining solar energy is in the near infrared spectrum that is invisible to the naked eye. Certain pigment technologies known as cool colors take advantage of that fact to allow colored surfaces (i.e., red, green, blue, grey) to be more highly reflective than traditional pigments would allow. Cool colors are most often used on steep-sloped roofs, where the roof is more noticeable and aesthetics are an issue. Cool colored roofing products are available for conventional roofing materials such as tile, asphalt shingle, coatings, and metal.

Cool walls are very similar to cool roofs but applied to vertical building surfaces. There are many light-colored, cool wall products available commercially worldwide, and they tend to stay clean and reflective over time. Cool walls mitigate urban heat islands like cool roofs. Simulations predict that increasing wall solar reflectance throughout Los Angeles County would lower daily average outside air temperature in the “urban canyon” between buildings by about 0.4°F during the hot summer month of July.

Pavements cover approximately 40% of a city’s surfaces. Of that amount, roads generally cover 45%, parking lots 40%, and sidewalks 15%. Paved space may take up more urban surface than any land use type and cool pavements could be a major potential contributor to urban cooling strategies. Most pavement can be classified into the two basic types: Asphalt cement pavements and concrete. Similar to roofs and walls, pavements that are darker in color have higher surface temperatures than lighter colored materials and can also raise air temperatures. Both pavement types have options for lightening the surface color to increase solar reflectance. There are three common methods for lightening a paved surface, including:

1. Transition from dark asphalt to concrete materials: Switching to concrete will lighten the pavement, though the difference in solar reflectance shrinks as both materials age.
2. Substitute dark aggregate used in the asphalt pavement mix for lighter colored aggregate: Over time, the dark asphalt binder wears down and reveals more of the aggregate color. Lighter aggregate choices would lighten the color of the aged asphalt surface compared to a darker colored aggregate. The effect of aggregate color can be immediate if a clear binder such as resin is used instead of bitumen.22
3. Apply a light-colored, reflective top coat to the pavement: Cool pavement coatings are light-colored topical surface treatments that increase pavement solar reflectance.

There are a number of benefits unique to solar reflective pavements. Lighter-colored pavement surfaces are cooler than dark surfaces. Particularly for asphalt pavements, cooler surface temperatures lengthen pavement life and delay rutting. One study performed a Heavy Vehicle Simulation where a standard axle load was driven back and forth over a surface at 7 km per hour and found that an asphalt pavement surface maintained at 127°F rutted to the point of pavement failure after 20,000 repetitions. A pavement maintained at 107°F rutted to the point of failure after 270,000 repetitions, a more than 10-fold extension of pavement life.

Lighter-colored pavements may reduce energy demand for streetlighting by 30% compared to darker pavements, though the energy saving will be lower in places where already efficient LED lighting is used. Light-colored pavements may also improve safety by improving visibility at night in city streets, especially where there are pedestrians and cyclists.

Los Angeles has undertaken one of the largest and long-standing **cool pavement evaluations** in the world. In 2015, the Los Angeles Bureau of Street Services, Parks and Recreation Department, and the city’s materials testing laboratory partnered to test a cool pavement coating on a portion of a parking lot at a recreation facility. The surface of the paved area in the pilot study remained 10°F cooler than the surrounding black asphalt. The pilot study was expanded to 15 city blocks (1 block in each of the city’s legislative districts). The city, working with the manufacturers, identified opportunities to improve the durability and application of the coating product. In 2018, the original pilot areas were recoated with a newly formulated coating, which has performed well over the last two years. The city is now in the process of identifying an entire neighborhood of roadways to coat to evaluate the effect on local air temperatures. The city has also developed a testbed for other cool pavement technologies (located at the Los Angeles Cleantech Incubator). Major public transportation hubs in neighborhoods with a high risk of heat stress have also been targeted for demonstrations of an integrated set of urban passive cooling solutions, including cool pavement, water fountains, and enhanced shade.[97]

However, because pavements are more visible than roofs and potentially interact more directly with buildings and pedestrians than most roofs, caution is advised in the elaboration and implementation of pavement strategies to ensure that unintended consequences are minimized. Generally, the solutions available today are most appropriate for paved areas with light vehicle or pedestrian traffic with shading present.

Green infrastructure (see Appendix I) - Vegetation uses plants to decrease air temperature and mean radiant temperature through evapotranspiration and shading.[98] Vegetation also modifies wind flow, filters pollution, and reduces runoff, which assists in indirectly cooling the environment. Green infrastructure takes the form of green roofs, green walls, trees, street vegetation, and parks. The absence of vegetation in urban areas contributes to the establishment of the urban heat island, markedly increasing thermal stress for residents, driving morbidity and mortality.

Mitigation strategies are needed to reduce urban heat, particularly against a background of urbanization, anthropogenic warming and increasing frequency and intensity of heatwaves. Green infrastructure acts to cool the urban environment through shade provision and evapotranspiration. Typically, greenery on the ground reduces peak surface temperature by 3.6–16.2°F, while green roofs and green walls reduce surface temperature by ~30°F, also providing added thermal insulation for the building envelope. However, cooling potential varies markedly, depending on the scale of interest (city or building level), greenery extent (park shape and size), plant selection and plant placement. Urban planners must, therefore, optimize design to maximize mitigation benefits, for example, by interspersing parks throughout a city, allocating more trees than lawn space and using multiple strategies in areas where most cooling is required.

Covering a roof or wall with vegetation cools the building and the surrounding urban environment through the evapotranspiration of the leaves, conversion of heat into latent heat by evaporation from the soil, and prevention of the absorption of short-wave radiation by low albedo materials through shading. Vegetation also provides insulation, reducing indoor heat in the summer and retaining heat in cooler conditions.

Green roofs come at a steeper cost than regular roofing, but stormwater management and longer roof life can cause green roofs to have a net economic benefit.[99] Building structure, plant water requirements, plant selection and reduced thermal comfort from increased humidity should be considered[100]. Regular maintenance is necessary and water requirements should also be considered.

Green roofs reduce the energy consumption in buildings; however, they do little to improve outdoor thermal comfort, especially at the pedestrian level.[101] Surface temperatures of rooftop gardens were found to be much lower than hard surfaces, and dependent on the density Leaf Area Index of plants.[102] Modeling 30% of total roof area with green roofs in Adelaide, Australia was found to reduce surface temperatures by 0.1°F and reduce electricity consumption by 2.56 (W/m^2/day).[103] Authorities in Shanghai, China, estimate that green roofs can reduce power consumption by 6 million

[97] ESMAP (2020)
[98] Wong, N.H., et al. (2021) Greenery as a mitigation and adaptation strategy to urban heat. Nat Rev Earth Environ 2, 166–181, https://doi.org/10.1038/s43017-020-00129-5
[99] ESMAP (2020)
[100] Ibid.
[101] Nasrollahi, N., et al. (2020) Heat-Mitigation Strategies to Improve Pedestrian Thermal Comfort in Urban Environments: A Review. *Sustainability*, 12(23), 1-23. https://www.mdpi.com/2071-1050/12/23/10000
[102] Wong et al. (2003)
[103] ESMAP (2020)

kwh, prevent 920,000 tons of rainfall from entering the sewer system, and absorb 170 tons of air pollutants annually in the city.[104]

Water features - Water bodies decrease air temperature and increase humidity by absorbing or transporting heat.[105] This takes the form of rivers, ponds, and dispersed water systems (fountains). Water has an average cooling effect of 2-5°F to an extent of about 100 ft. Water bodies are more effective when they have a large surface area or when the water is flowing or dispersed.[106] Examples of blue infrastructure cooling can be seen in Lahore, Pakistan, where urban vegetation and water ponds have resulted in higher levels of thermal comfort for their local communities.[107] In Shanghai, China, areas located within 30 to 70 ft from the Huansha artificial water body are characterized with higher levels of thermal comfort also.[108]

Information Systems - Heat warning systems reduce heat related health effects by providing useful information and inputs for decision-making during a heat wave period.[109] The effectiveness of heat warning systems are determined by the awareness of the public and its consequences, communication measures and socio-demographic factors.[110] Such systems should take into account local conditions, and be simple and reliable. However, passive dissemination of heat avoidance advice is likely to be ineffective by itself.[111] New York Urban Heat Island Task Force invested in urban heat data needs in response to the rapidly rising city temperatures.[112] The result was Cool Neighborhoods, a $100 million commitment to transforming three of its most heat vulnerable neighborhoods.[113] Paris, France deployed a heat resiliency initiative to ensure every Parisian is within a 7-minute walk of a “cool island” by 2020.[114]

SUMMARY

Urban areas will experience excess heat and heat island effects in unique ways depending on location, size, shape, built environment, construction practices, existing land cover, climate and meteorological conditions, and other factors. Cooling solutions should be tailored accordingly. For example, solutions that may be highly effective in an arid environment such as Southern California may not be as effective in the humid marine setting of urban Honolulu.

A comprehensive review of studies evaluating the effectiveness of urban cooling strategies found that city-scale solutions meaningfully reduce urban air temperatures.[115] Findings include:

1. Average outdoor air temperatures can be reduced by 0.54°F per 0.10 increase in solar reflectivity (e.g., increasing the number of cool roofs, walls, and pavements) across a city. Peak outdoor air temperature decreases by up to 1.6°F per each 0.10 increase in solar reflectivity.
2. The deployment of green roofs at a city-scale can reduce air temperatures by 0.54 – 5.4°F.
3. Street-tree deployment at scale has a cooling effect of between 0.72 – 5.4°F, with the greatest cooling effect occurring within 100 ft of a tree.
4. Waste heat from active mechanical cooling (particularly vapor compression technologies) adds between 1.8°F and 3.6°F to nighttime air temperatures in cities where mechanical cooling is common. Thus, efforts to improve efficiency and reduce the need to operate mechanical cooling equipment can have a direct effect on urban air temperatures.

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104 Ibid.
105 Nasrollahi et al. (2020); Kleerekoper et al. (2012)
106 Ibid.
107 Nasrollahi et al., 2020.
108 Ibid.
109 Zuo et al., 2015
110 Ibid.
111 Ibid.
112 ESMAP, 2020.
113 Ibid.
114 Ibid.
115 Santamouris, M. (2020)

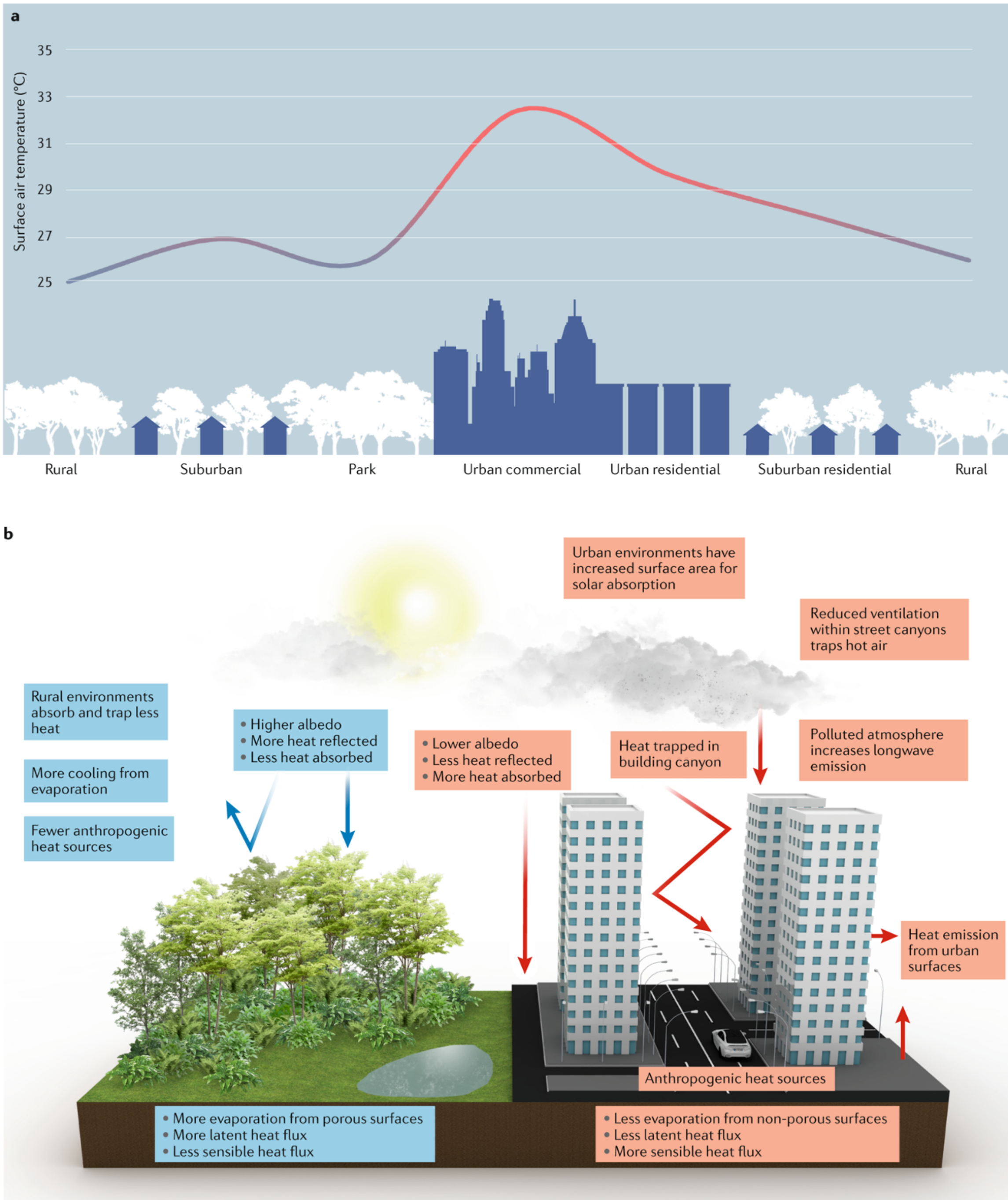
5. Urban design choices that maximize natural wind flows and minimize trapped heat can help cities stay cooler. For example, an increase in windspeed of 5 feet per second reduced air temperatures in Singapore by 3.6°F.

Indoor air temperatures can also be lowered by adopting urban cooling strategies. A pilot study outside of Ahmedabad, India, found that air temperatures inside a small home with a solar reflective metal roof were 4.5–6.3°F lower than an identical home with an uncoated metal roof. Passive, nonmechanical cooling in buildings (for example, improved natural ventilation, good shading devices, and a green roof for insulation) can deliver thermal comfort while significantly reducing a building's cooling load and the waste heat generated by active mechanical cooling. Studies show that passive cooling in buildings can reduce energy consumption by up to 23.6%.

Adopting cooling solutions will generate benefits in practically all cases, especially in the tropical climate found in Hawai'i.

APPENDIX 1

Renderings of urban heat and cooling solutions.[116]



The urban heat island effect. *a. A typical urban heat island profile showing higher air temperature in built-up areas and lower temperature in rural areas with more greenery coverage. b. Factors contributing to the urban heat island effect highlighting significant changes in heat and air movement when rural land is urbanized. Red boxes indicate warming mechanisms and blue boxes indicate cooling mechanisms.*

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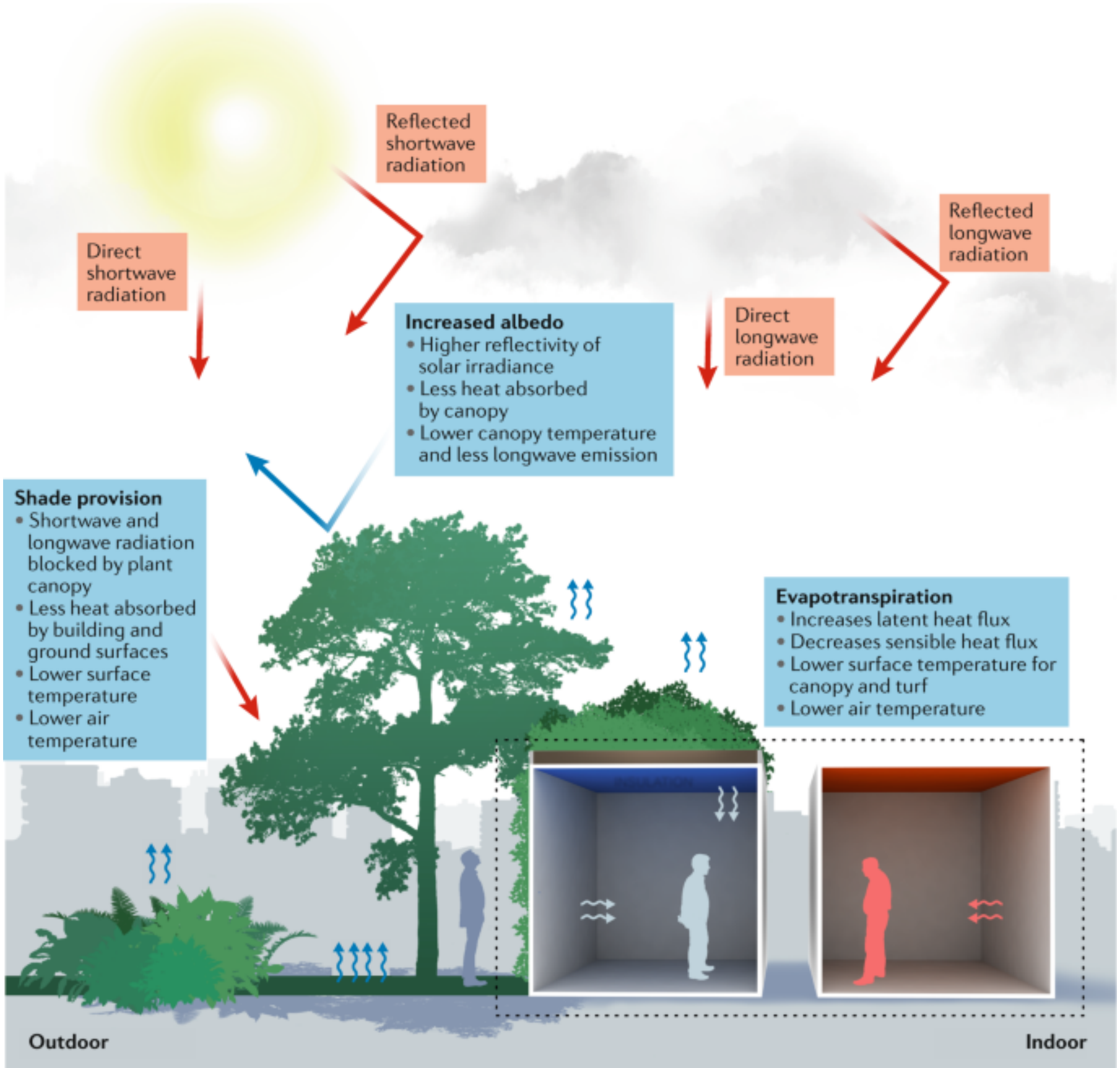
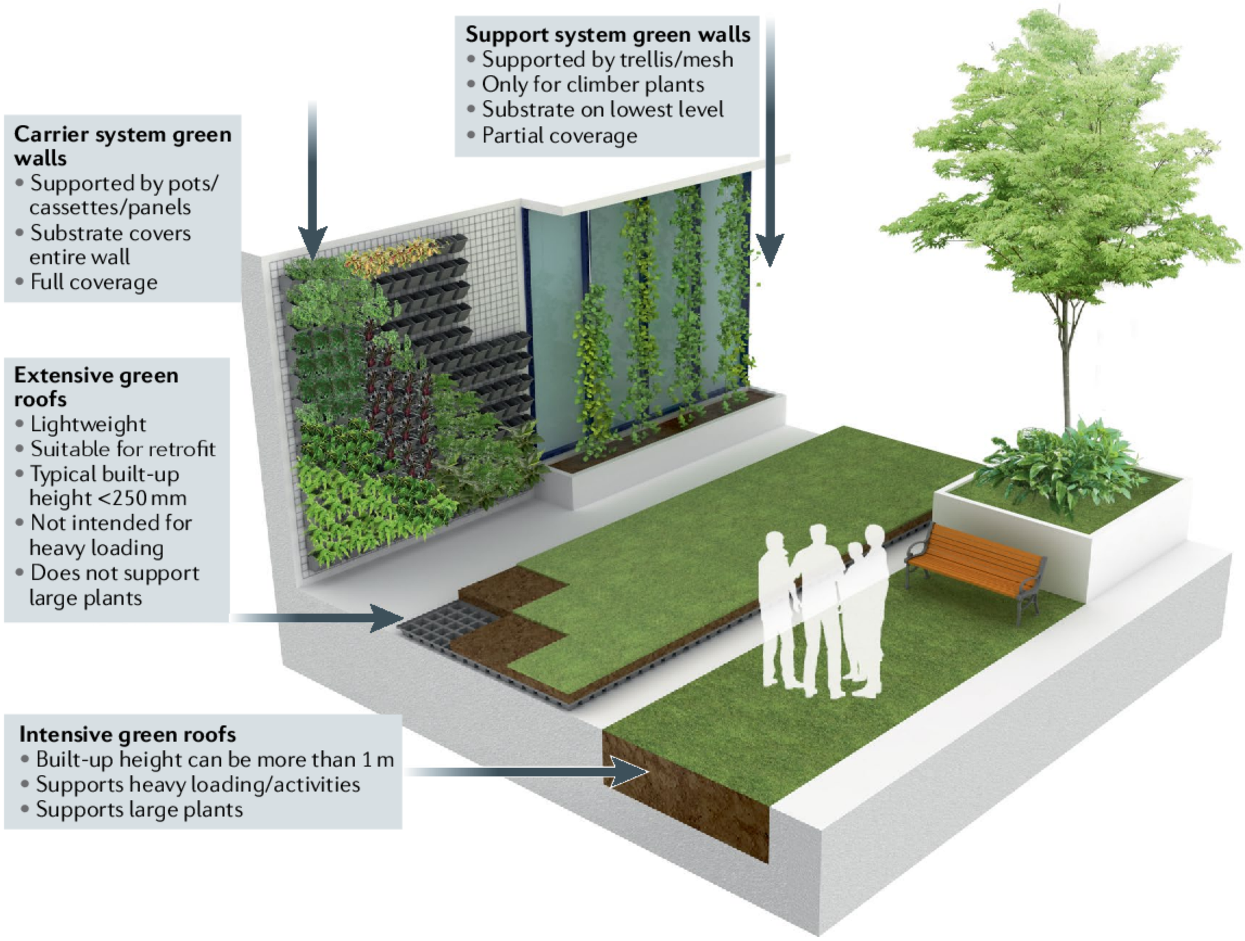
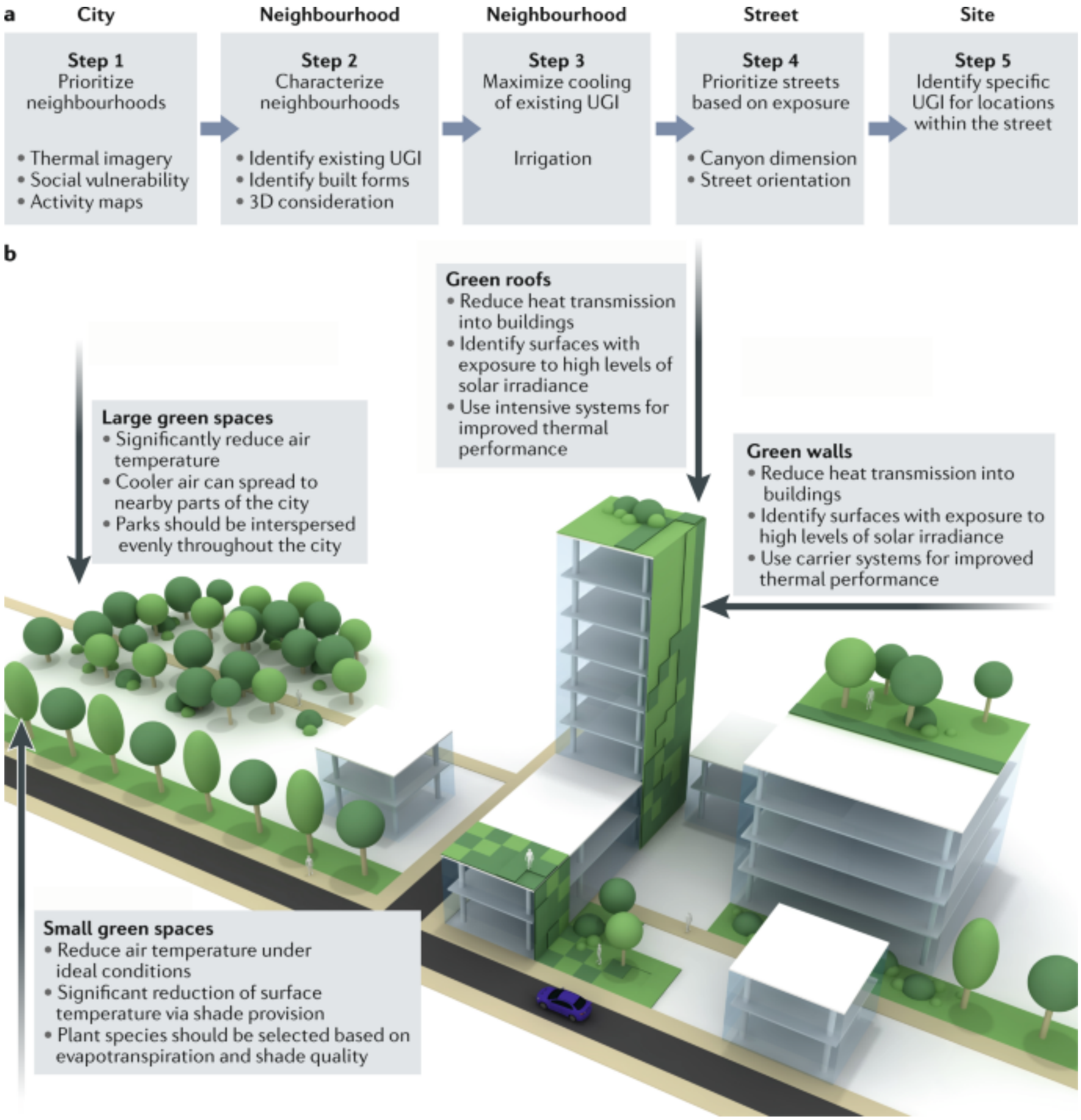
[116] Wong, N.H., Tan, C.L., Kolokotsa, D.D. et al. (2021) Greenery as a mitigation and adaptation strategy to urban heat. Nat Rev Earth Environ 2, 166–181. https://doi.org/10.1038/s43017-020-00129-5



Greenery-related cooling mechanisms in the urban environment. *Urban greenery acts to modify shade provision, evapotranspiration, and albedo. The combination of these three mechanisms reduces sensible heat gain, thereby, lowering heat gain and surface temperature. Red boxes indicate warming mechanisms and blue boxes indicate cooling mechanisms.*



Types of greenery on buildings. *Different options for vertical and rooftop greenery, including support system green walls, carrier system green walls, extensive green roofs and intensive green roofs.*



Translation of greenery research into design. *a. Proposed framework for implementing greenery at different scales. b. A summary of cooling benefits of urban greenery, (UGI – urban green infrastructure).*