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 Hawaiʻi. 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, to identify local potentially-impacted communities in light of projected global hotspots where combinations of heat and humidity are making conditions intolerable. Are these potentially-impacted areas key for food, resource production, or shipping for Hawaiʻi? How will heat-induced human displacement affect Hawaiʻi? This document describes the physical nature of atmospheric and marine heat in Hawaiʻi and provides accounts of how other cities have managed urban heat, the successes and lessons learned, and possible directions that will provide the maximum benefit for C&C services and communities. Past and present efforts to manage urban heat in the City and County of Honolulu are reviewed.

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RECOMMENDATIONS

Based on research, the Commission recommends that the C&C consider the following:

1. 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 and life-saving measure and to establish successful practices.
2. 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 O‘ahu 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 consequences 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.
3. 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.
    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. Collect more heat information.
    a. Develop a climate sensor system.
    b. Urban form will change over time which may affect urban heat. Collecting data on these changes can inform analysis of the impact that urban changes have on heat issues.
    c. Conduct high-granularity heat surveys 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 the data gaps preventing development of a cooling action plan.
    e. Survey actions taken by other communities to mitigate heat risk and evaluate for adoption.
5. 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 with resilient energy systems and grid integration regionally, locally, and in specific building design.
    c. Require that residential buildings, especially older buildings, be retro-fitted with sufficient emergency power to avoid stranding residents without cooling, running water, elevator capacity and other power-dependent assets.
    d. Require new buildings (commercial and residential), to incorporate climate responsive design strategies based on the key stressors to the City and County of Honolulu.
6. Develop a cool-streets and cool-roofs/walls program that emphasizes:
    a. Green and cool 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. Open urban spaces that include water features (blue space) and shaded gathering areas.
7. Use census data to identify underserved and low-income communities that are at risk of heat stress and shock.
    a. Prioritize heat resiliency steps in these communities.

FINDINGS

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

1. Since 1950, temperatures across the Hawaiian Islands have risen by about 2°F, with a sharp increase in warming over the last decade.
    a. Temperatures in Honolulu have increased by 2.6°F since 1950 and have consistently been above the 1951–1980 average since 1975.[1]
2. The Commission has identified heat stress and heat shocks as climate change- and extreme weather-related hazards.
    a. Extreme heat in Hawai‘i to date has been associated with the development of marine heat waves in regional waters.[2]
    b. Changes in local winds exacerbate rising heat.[3]
    c. Increasing sea surface temperatures[4] and air temperature[5] result in rising heat stress.
    d. 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.[6]
    e. The record high temperature for Honolulu was set on August 31, 2019 at 95^{o}F (35^{o}C).[7]
3. Urban heat waves are strongly associated with socio-economic impacts.[8]
    a. Globally, from 1983 to 2016, urban extreme heat exposure increased nearly 200%, affecting 1.7 billion people.
    b. 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.[9]
4. To date, the City has taken several steps with regard to managing urban heat.
    a. The O‘ahu Resilience Strategy (2019)[10] identifies:
        i. Action #32 “Deploy sustainable roof systems to manage urban heat and rainfall” and
        ii. Action #33 “Keep O‘ahu cool by maintaining and enhancing the community forest”.
    b. Between 2010 and 2013, Honolulu lost nearly 5% of its total urban tree canopy.[11]
        i. 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.[12]
    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).[13] The maximum heat index (see “Heat Index” Appendix I) recorded was 107.3°F (41.2^{o}C), and the data identified several localized heat islands.[14] The aim of the campaign was to improve understanding of how urban heat varies across neighborhoods and how local landscape features can affect temperatures.

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[1] Stevens, L.E., R. Frankson, K.E. Kunkel, P.-S. Chu, and W. Sweet (2022) Hawai'i State Climate Summary 2022. NOAA Technical Report NESDIS 150-HI. NOAA/NESDIS, Silver Spring, MD, 5 pp.

[2] www.washingtonpost.com/weather/2019/09/26/inside-hawaiis-wild-summer-broken-high-temperature-records/

[3] 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

[4] 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

[5] 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.

[6] 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

[7] https://www.washingtonpost.com/weather/2019/09/26/inside-hawaiis-wild-summer-broken-high-temperature-records/

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[10] O‘ahu Resilience Strategy (2019) https://resilientoahu.org/resilience-strategy

[11] Urban Tree Canopy Assessment, https://smarttreespacific.org/projects/honolulu-urban-tree-canopy-assessment/

[12] Honolulu Resilience Office, Tree Program, https://resilientoahu.org/trees

[13] Honolulu Heat Watch Report (2019) https://drive.google.com/file/d/1tHSMOETsOv-_PAb10OYtAv7iIer8StLu/view

[14] Oahu Community Heat Map, https://www.arcgis.com/apps/View/index.html?appid=ff1b73d836074cf6b2aca420fffbd930

5. The experiences of other urban areas provide guidance on practices that are effective in mitigating heat stress and heat shocks. These established best-practices 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 reduces both direct heat and carbon emissions. See "Green Space", Appendix I.
    b. Shade Structures. Traditional architecture in hot countries has often made use of structures such as arcades, colonnades, large umbrellas, pergolas, and awnings. Including shade as a fundamental architecture component in city design is an effective way to cool urban areas and make them more livable.
    c. Green Roofs and Walls. Green roofs insulate buildings from heat, and also cool the air through evapotranspiration. The Oasia Hotel in Singapore[15] is a 27-story high-rise tower 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. See "Green Space", Appendix I.
    d. Cool Roofs and Walls – Darker colors absorb heat, so increasing the reflectivity of buildings can reduce heat. The NYC Cool roofs program[16] 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, and may be best reserved for parking lots or streets with less 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 –some traditional buildings place a fountain at the center of a shaded courtyard. See "Blue Space", Appendix I.
    g. Intentional Design – 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.
6. 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.
    a. Long-term modeling of more reflective urban surfaces found a sustained global cooling effect of 0.01–0.07°C. 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.[17]
7. Global warming has caused surface air temperature to rise over 1^{o}C (1.8^{o}F) above the pre-industrial average surface temperature.[18]
    a. Updated national pledges under the UNFCCC[19] only cut greenhouse gas emissions 7.5% by 2030, leaving a 34% probability of staying below 2^{o}C (3.6^{o}F) and a 1.5% probability of staying below 2.7^{o}C (2^{o}F).[20]

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[15] Building of the Week: Oasia Hotal, Singapore, https://earthbound.report/2018/09/14/building-of-the-week-oasia-hotel-singapore/

[16] NYC CoolRoofs, https://www1.nyc.gov/nycbusiness/article/nyc-coolroofs

[17] Samset, B.H., Zhou, C., Fuglestvedt, J.S. et al. (2022) Earlier emergence of a temperature response to mitigation by filtering annual variability. Nat Commun 13, 1578. https://doi.org/10.1038/s41467-022-29247-y

[18] GISTEMP Team (2022) GISS Surface Temperature Analysis (GISTEMP), version 4. NASA Goddard Institute for Space Studies. Dataset accessed 20YY-MM-DD at https://data.giss.nasa.gov/gistemp/. See also, Samset, B.H., Zhou, C., Fuglestvedt, J.S. et al. (2022) Earlier emergence of a temperature response to mitigation by filtering annual variability. Nat Commun 13, 1578. https://doi.org/10.1038/s41467-022-29247-y

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[20] Ou, Y., et al. (2021) Can updated climate pledges limit warming well below 2oC? *Science*, 5 Nov, v. 374, Iss. 6568, DOI:10.1126/science.abl8976

   b. On-the-ground policies to limit greenhouse gas emissions are insufficient and advancing slowly.[21] End-of-century global warming is projected to cause air temperature to rise 2.0 to 3.6°C (median 2.7°C, 5°F) above pre-industrial levels.[22]
   c. Under-reporting[23] of emissions and decreasing natural carbon sinks[24] suggest that global temperatures will be even higher.

8. The ocean is getting warmer, acidifying, and decreasing in dissolved oxygen content.[25]
   a. For the year 2019, 57% of the global ocean surface recorded extreme heat, which was comparatively rare (approximately 2%) during 1850-1870.
   b. With continued warming, marine heatwaves (see "Marine Heatwave" Appendix I) will intensify, occur more often, persist for longer periods of time, and extend over larger regions.[26]
   c. Marine heatwaves have occurred in all of Earth's ocean basins over the past two decades, with severe negative impacts on marine organisms and ecosystems.
      i. For example, in Hawai'i, widespread coral bleaching and mortality occurred during the summers of 2014 and 2015.[27]
   d. The occurrence probabilities of the duration, intensity, and cumulative intensity of most documented, large, and impactful marine heatwaves have already increased more than 20-fold as a result of anthropogenic climate change.
   e. From 1925 to 2016, global average marine heatwaves frequency and duration increased by 34% and 17%, respectively, resulting in a 54% increase in annual marine heatwaves days globally.[28]
9. Under current global emission reduction pledges, children born in 2020 will experience 7.5 times as many heatwaves (30 vs 4 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 versus those born decades earlier.[29]
10. Climate change is causing a rise in the global 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)[30] exceeding 10°C (18°F) above ambient temperatures.[31] This can cause serious impacts to cooling energy consumption, peak electricity demand, heat related mortality and morbidity, urban environmental quality, local vulnerability, and comfort.
    a. In 2016, Honolulu experienced 24 days of record-setting heat that compelled the local energy utility to issue emergency conservation to reduce threats to the electrical grid.[32]
    b. In 2019, an O'ahu, community heat assessment found many neighborhoods with afternoon heat indices between 100°F and 107°F.[33]
11. Studies show that over 25% of the U.S. population experienced heat-related symptoms during the summer of 2020.

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[21] 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

[22] Ibid.

[23] 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/

[24] 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

[25] Cheng, L., et al. (2020) Record-setting ocean warmth continued in 2019. Advances in Atmospheric Sciences, 37(2), 137–142. DOI: 10.1007/s00376-020-9283-7; Johnson, G. C., & Lyman, J. M. (2020) Warming trends increasingly dominate Global Ocean. Nature Climate Change, 10(8), 757–761. DOI: 10.1038/s41558-020-0822-0

[26] Gruber, N., Boyd, P. W., Frölicher, T. L., & Vogt, M. (2021) Biogeochemical extremes and compound events in the Ocean. Nature, 600(7889), 395–407. DOI: 10.1038/s41586-021-03981-7

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[31] 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

[32] Keener, V., et al. (2018)

[33] https://www.arcgis.com/apps/View/index.html?appid=ff1b73d836074cf6b2aca420fffbd930

    a. Among all socio-economic groups, those who were most impacted 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).[34]

12. Extreme heat can trigger fatal heat exhaustion or heat stroke, which occur when a person's body cannot cool itself enough.[35]
    a. Heat stress can also kill by exacerbating underlying conditions, such as cardiovascular or respiratory disease, but also suicide and several types of injury.[36]
    b. Heat waves are a leading cause of weather-related deaths in the United States, killing more than 600 people each year.[37]
    c. Older adults, young children, and people with chronic conditions face the highest risk.[38]
    d. 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.[39]
    e. For pregnant women, extreme heat exposure is linked to more preterm births and poorer pregnancy outcomes, including low birth weight and infant death.[40]
    f. Extreme heat can make some mental health conditions worse.[41]
    g. 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.[42]
13. 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.
    a. Deaths vary geographically but are of the order of dozens to hundreds of deaths per year in many locations.[43]
14. Climate change is causing heat to rise globally[44] and locally.[45] Model projections identify geographic regions where heat joins with other stressors to cause community displacement.
    a. 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.[46]
15. By 2050, models project that 68% of the world's population will live in urban areas.[47] 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 (7.2°F), larger than regional warming, by the end of the century.[48]
    a. As Honolulu's urban population rises, more communities will be at risk from heat stress unless mitigating actions are taken.

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[34] 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

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[39] Ibid.

[40] Ibid.

[41] Ibid.

[42] Ibid.

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3. Since 2018, the Miami Shade project has documented how hot Miami actually is. Florida International University students, faculty, and Miami-Dade citizens have deployed heat-sensing iButtons around the county in areas residents are most likely to congregate.[49]

INTRODUCTION

It is unequivocal that human influence has rapidly warmed and changed the atmosphere, ocean and land.[50] The scale of post-industrial changes across the climate system as a whole and in different indicator variables are unprecedented over many centuries to many thousands of years. Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and their attribution to human influence, has strengthened.

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".[51] Trends on Oahu, and Hawaiʻi at large,[52] show that air temperature is increasing at both sea-level and at elevation,[53] with 2019 the hottest year on record, and is projected to continue to rise.[54] 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.[55]

2. In 2014, Shanghai, China set a goal to add 400,000 m^2 of green roofs and walls by 2016 and 2 million m^2 by 2020. Authorities estimate the green roofs can reduce power consumption by 6 million kwh, prevent 920,000 tons of rainfall from entering the sewer system, and absorb 170 tons of air pollutants annually in the city.[56]

3. Tweny-one parks were studied in Addis Ababa, Ethiopia for their efficiency in mitigating the urban heat island effect. The cooling intensity of parks was found on average to be approximately 7°F (0.2 to 12°F) and the maximum cooling distance of a park was estimated to be 735 ft. Researchers determined the park's cooling effect is mainly determined by species group, canopy cover, size and shape of the parks.[57]

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.[58] 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.[59] As the potentially most-affected regions are among the

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poorest in the world, where adaptive capacity is low, building community resilience and adaptation potential in those areas should be a priority alongside climate mitigation.

Heat and Human Communities – Extreme heat threatens human communities. Research has established a positive relationship between temperature and mortality, and its effects are exacerbated in highly vulnerable communities. This includes low-income, Indigenous, and isolated island communities.[60] Furthermore, every additional increment of global warming increases the intensity and frequency of hot extremes, including heatwaves.[61] 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 °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°C warming. Considering that current GHG emissions put humanity on a pathway to over 3 °C of warming (see Appendix IV), the global health and socio-economic risks are potentially catastrophic.[62]

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.[63] 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)[64] exceeding 10°C above ambient temperatures.[65] This can cause serious impacts to cooling energy consumption, peak electricity demand, heat related mortality and morbidity, urban environmental quality, local vulnerability, and comfort.

Heat, Health, and 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, racial and ethnic minorities accounted for almost 65% of all heat-related hospitalizations between 2001 to 2010 in a U.S. nationwide study. The same communities experienced higher mean costs of heat-related hospitalizations compared to whites.[66] Differences in costs based on income, insurance, and gender were also significant. These results suggest that these populations are suffering disproportionately from health inequity, thus, they could shoulder greater disease and financial burdens due to climate change. Unprecedented climates will

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[60] 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

[61] 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., et al. (eds.)]. In Press.

[62] Schmeltz, M.T., et al. (2016) Economic Burden of Hospitalizations for Heat-Related Illnesses in the United States, 2001-2010. International journal of environmental research and public health, 13(9), 894. https://doi.org/10.3390/ijerph13090894

[63] 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

[64] 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.

[65] 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

[66] Schmeltz, M.T., Petkova, E. P., & Gamble, J. L. (2016).

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.[67]

The increasing intensity, duration, and frequency of heat waves due to human-caused climate change puts historically underserved populations in a heightened state of risk, as studies observe that vulnerable communities—especially those within urban areas in the United States—are disproportionately exposed to extreme heat.[68] The historical practice of "redlining," refusing home loans or insurance to whole neighborhoods based on a racially motivated perception of safety for investment, has been compared with present-day summertime intra-urban land surface temperature anomalies at 108 U.S. locations. Results reveal that 94% of studied areas display consistent city-scale patterns of elevated land surface temperatures in formerly redlined areas relative to their non-redlined neighbors by as much as 12.6°F. Regionally, Southeast and Western cities display the greatest differences while Midwest cities display the least. Nationally, land surface temperatures in redlined areas are approximately 4.7°F warmer than in non-redlined areas. While these trends are partly attributable to the relative preponderance of impervious land cover to tree canopy in these areas, other factors may also be driving these differences. Historical housing policies may, in fact, be directly responsible for disproportionate exposure to current heat events.

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.[69] An extra 0.5 °C of global warming, from 1.5 to 2 °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.

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.[70] 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). 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.[71]

Since 1991, empirical data from 732 locations in 43 countries reveal that global warming is responsible for significant warm-season heat disease and morbidity.[72] 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.

Heat illness is a commonly encountered health problem in the Hawaiian Islands. Year-round warm temperatures, proximity to the equator, and high humidity combined with many opportunities for outdoor activities put many individuals at risk. Heat stroke is a persistent and potentially lethal event. Treatment has shown that the method used for cooling is not crucial, instead the speed of cooling and transport to advanced medical care is more important in determining patient outcome.[73] The recognized complications of heat stroke are numerous and in the worst-case

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[67] Mora C., et al. (2013) The projected timing of climate departure from recent variability. Nature. Oct 10;502(7470):183-7. doi: 10.1038/nature12540. PMID: 24108050.

[68] Hoffman, J.S., et al. (2020) The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 U.S. urban areas, Climate, 8(1), 12, https://doi.org/10.3390/cli8010012

[69] Benz, S.A., and Burney, J.A. (2021) widespread race and class disparities in surface urban heat extremes across the United States, Earth's Future, 13 July, https://doi.org/10.1029/2021EF002016

[70] 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

[71] Ibid.

[72] Vicedo-Cabrera et al. (2021) The burden of heat-related mortality attributable to recent human-induced climate change. Nat. Clim. Chang.

[73] Gordon S. (2014) Heat illness in Hawai'i. Hawaii J Med Public Health. 2014 Nov;73(11 Suppl 2):33-6. PMID: 25478301; PMCID: PMC4244899.

scenario it can result in multiorgan failure. Thorough laboratory assessment as well as electrocardiogram and chest X-ray should be performed upon arrival to a higher level of care to avoid missing complications. Medical care is largely aimed at supportive therapy with cooling and intravenous crystalloids, with the goal of maintaining normal vital signs and preventing organ damage.

4. Washington, D.C. Smart roof program for city buildings. At current deployment rates, the Smart Roof program will reduce estimated life cycle GHG emissions by 20,000 metric tons and save the District US$33 million over 20 years. The use of coatings to restore and extend the life of functioning roofs reduced capital requirements by 75% and generated 224 new local jobs.

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.[74] As Honolulu's urban population rises,[75] more communities will be at risk from heat stress unless mitigating actions are taken. Globally recognized environmental problems– 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. 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^{o}C (7.2^{o}F)—larger than regional warming—by the end of the century.

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.[76] In the US, the heat island effect increases daytime temperatures 1-7°F and nighttime temperatures 2-5°F compared to outlying areas. 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.

Heat Shock: Heat Waves – Heat waves are prolonged periods of excessive heat associated with atmosphere-related heat stress.[82] In 2019, extreme heat was the most common cause of death among all weather-related disasters in the US.[83] Hot and humid environments reduce the efficiency in which the human body can cool itself

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[74] 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

[75] https://www.staradvertiser.com/2021/08/13/hawaii-news/honolulus-population-tops-1-million/

[76] United States Environmental Protection Agency (2021)

[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] 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

[83] 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

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. Additionally, heat negatively affects power generation and transmission, and when coupled with increased power usage, increases the risk of power outages. 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 1**).[84]

5. In 2021, Honolulu's Resilience Office measured the tree canopy and ground vegetation effect on heat index. Tree canopies and ground vegetation were found to have a cooler heat index than the surrounding environment, but only an average of 1°F difference between low and high levels of greenery. Higher tree canopy and ground vegetation were found to mitigate heat more during peak times of day (by 3.27°F and 1.26°F, respectively). Ground vegetation had both a greater efficiency and stronger relationship to reducing the heat index when compared to tree canopy.[85]

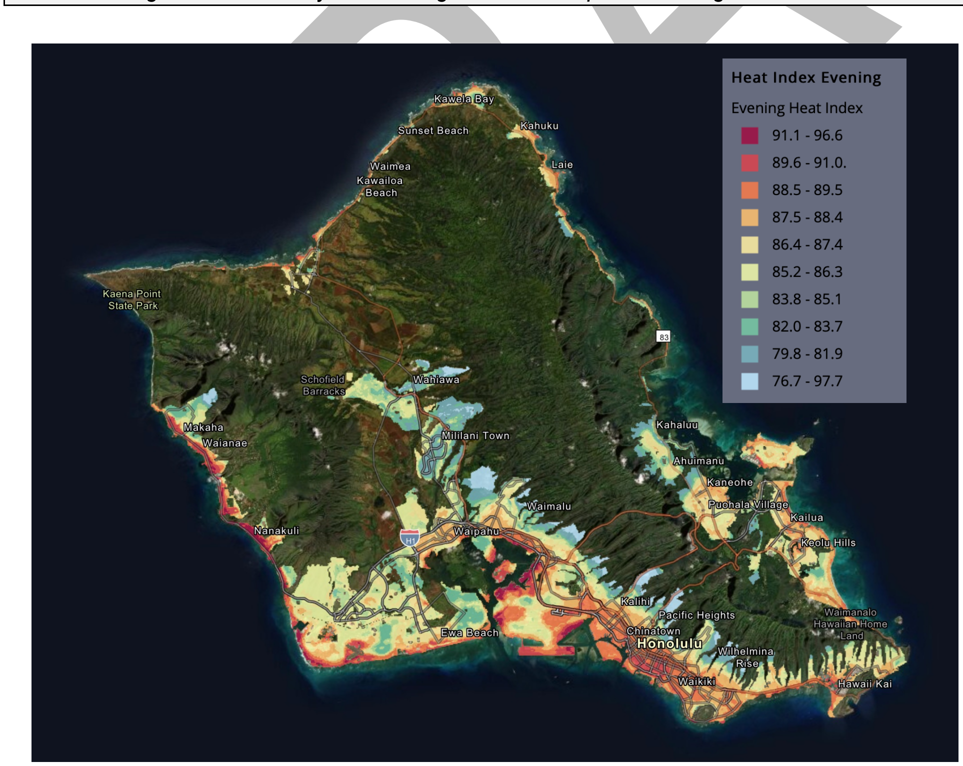

***Figure 1.** Evening heat index, O‘ahu, Saturday, Aug. 31, 2019. (figure Oahu Heat Vulnerabiity map series)*[86]

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[84] CAPA Strategies. (2019). Heat Watch Report: Honolulu, HI. OSF. https://osf.io/ekamd/

[85] Siddarth, U. (2021). Measuring the effects of tree canopy and ground vegetation on heat index. Office of Climate Change, Sustainability and Resiliency-Trees. https://resilientoahu.org/trees

[86] https://cchnl.maps.arcgis.com/apps/MapSeries/index.html?appid=81a93d637086418f9118d8740a7e8f3c

Heat negatively affects the amount and rate of power generation and transmission, and when coupled with increased power usage for space cooling, increases the risk of power outages.[87] Heat waves can also damage transportation infrastructure, building materials, and are exacerbated by urban heat islands.[88] On O’ahu, extreme heat can increase the vulnerability of a community. O’ahu’s social vulnerability[89] 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.[90] Doctors at Queens Medical Hospital noticed an increase in patients suffering from dehydration or acute heat injuries.[91]

A number of O'ahu's programs and policies include heat strategies–mainly urban trees, and climate plans and principles. **Table 1** is a summary of O’ahu’s current heat-related strategies.

Table 1. Summary of City heat mitigation and adaptation efforts

Effort	Description
Office of Climate Change, Sustainability and Resilience	This program focuses on providing tree and heat related data for O’ahu. Tree data includes location and physical and biological characteristics of city tree stock.
Resolution 18-055 (2018); Mayor’s directive No. 20-14 (2020); Office of Resilience: 100,000 Trees O’ahu map	Tree planting: Expand the City’s urban tree canopy to 35% by 2035; plant 100,000 trees by 2025.
Urban Tree Plan (2019)	Describes the benefits of trees, sets goals and a vision for the urban tree canopy in Honolulu.[92]
Community Forester position, Division of Urban Forestry (2019)	Promote collaboration amongst sectors, educate the public on importance of trees, oversee some tree planting goals and initiatives.[93]
O’ahu Resilience Strategy (2019)	Action 14; Action 18; Action 22; Action 28; Action 32; Action 33.
City and County of Honolulu Climate Adaptation Background Research (2020)	Climate resilience guidance for developers and landowners in Honolulu’s TOD and other urban areas vulnerable to SLR. Provides information and best practices for adapting building sites and structures to climate change related hazards including heat. (SSFM Interntl & Arup, 2020)
City and County of Honolulu Climate Adaptation Design Principles for Urban Development (2020)	Design principles for policy in TOD and other areas. Identifies recommended tools and best practices to consider in designing building sites and structures to be resilient to SLR, flooding, extreme heat, and rising groundwater. (SSFM International & Arup, 2020)

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[87] 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

[88] Zuo, J., et al. (2015)

[89] https://www.atsdr.cdc.gov/placeandhealth/svi/index.html

[90] 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/

[91] 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/

[92] https://www.honolulu.gov/rep/site/dpr/duf_docs/Urban_Tree_Plan_Final_Draft.pdf p.4

[93] https://www.honolulu.gov/parks/hbg/community-forestry.html

Heat data	Heat Watch Report: Honolulu, HI (2019); O’ahu Heat Vulnerability Series
Green Roofs	O’ahu Resilience Strategy (2019). Action 33; Honolulu Climate Change Adaptation Design Principles for Urban Development.
Cool Roofs	O’ahu Resilience Strategy (2019). Action 32; Ordinance No. 20-10. Sec. 21-4.90 Sunlight reflection regulations. “No building wall shall contain a reflective surface for more than 30% of surface area.” (Ord. 99-12)
Cooling with seawater	O’ahu Resilience Strategy (2019). Action 22. [Note: No longer active.]

HEAT MITIGATION 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. Blue spaces and green spaces provide multiple ecosystem services that are considered essential nature-based approaches for alleviating climate-change impacts in cities.[94] Cities can address rising air temperatures by adopting a package of measures (**Figure 2**), including:

1. Passive, nonmechanical cooling solutions, such as:
    a. Cool 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).
    c. Building orientation and interior use programming – Orient buildings to take advantage of inherent shading from surrounding buildings and vegetation, wind patterns, and locate interior use spaces based on hours of use, degree of habitation (i.e. storage versus office) and façade solar radiation exposure.
    d. Optimizing Exterior Wall Performance – Increase thermal insulation and glazing performance to reduce interior temperatures.
    e. Shade horizontal surfaces – Increase the projection factor at the street level or at open gathering spaces by providing shade in the form of architectural canopies or awnings, freestanding shade structures or tree canopies.
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 shading openings (doors and windows) and encouraging air flow through interior spaces (use of operable windows and ceiling fans).
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.

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[94] Filho, W. L., Icaza, L. E., Emanche, V. O., & Al-Amin, A. Q. (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

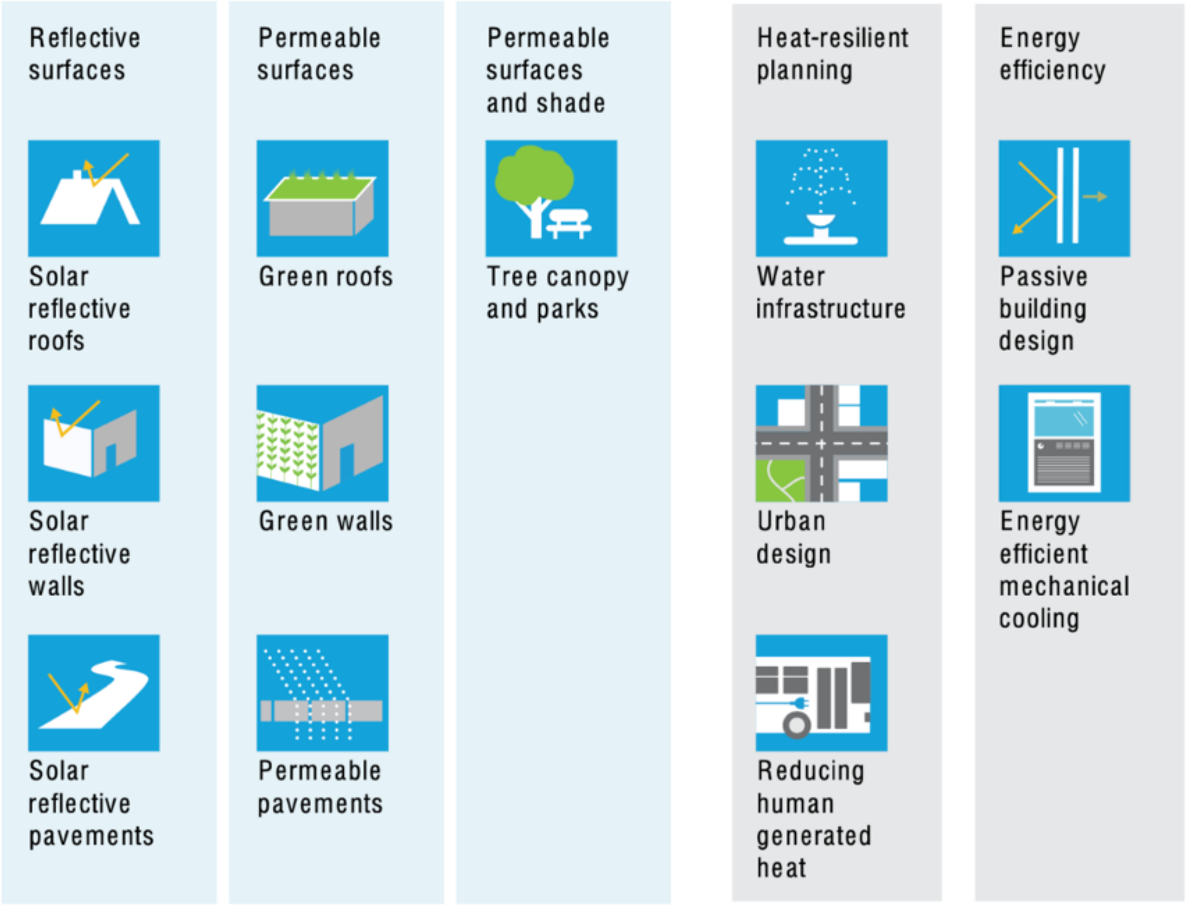

Figure 2. *Commonly used urban cooling solutions.*[95]

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

Reflective Surfaces – Cool surfaces (roofs, walls, pavements) decrease the demand on the electrical grid by lowering the need for air-conditioning during peak energy demand periods on high temperature and summer days.[96] This by-effect decreases GHG emissions from power plants and thereby indirectly mitigates 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 immediately mitigate warming by reducing the amount of heat that is transmitted from Earth's surface and trapped in the atmosphere.

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.[97]

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[95] Ibid.

[96] Cool Roofs, Heat Island Group, Berkley Lab, https://heatisland.lbl.gov/coolscience/cool-roofs

[97] Filho, W. L., Icaza, L. E., Emanche, V. O., & Al-Amin, A. Q. (2017)

Roofs typically make up 25–30% of an average city's urban surfaces. Roofs may be either steep sloped (slopes greater and 2:12) or nearly flat (slopes less than 2:12). There are a wide variety of highly reflective roofing products available today in nearly every roof surface type used 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, such as a fluid applied elastomeric coating, to increase the solar reflectance of an existing, functional roof. Coatings are typically applied to a functional roof to improve water resistance or to extend its useful life.

Cool roof surfaces are commonly created by selecting a roof color with an aged solar reflectance index (SRI) value greater than 32 for steep slopes and 75 for low slopes[98] and or a product certified with the Cool Roof Council (CRRC). White roof colors traditionally reflect more solar energy in the visible spectrum, 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 roofs can come in a wide variety of colors; not just white, so it is important to confirm the reflective performance by reviewing the SRI value and associated certifications. Cool roof colors are installed on both steep-sloped and low-sloped roofs and are available in an array of conventional building materials such as asphalt shingle, standing and corrugated metal, clay and concrete tile, and single-ply membrane.

Exterior walls are often protected by roof overhangs reducing solar exposure but are typically constructed with less insulation than a roof which makes walls susceptible to increase urban heat and interior temperatures.[99] The cool roof theory is easily applied to vertical surfaces through the use of light-colored (i.e. light color pigmented paints often with solar reflectance of 0.61 and a thermal emittance of 0.75).[100] Cool wall products are typically opaque materials which can be common building materials such as light pigmented paints, stones, stucco, and green walls. 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 topcoat to the pavement: Cool pavement coatings are light-colored topical surface treatments that increase pavement solar reflectance.

There are several 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

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[98] Heat Island Reduction, LEED BD+C New Construction LEEDv4.1, USGBC, https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-data-cent-5?return=/credits/New%20Construction/v4.1

[99] Cool Walls, Heat Island Group, Berkley Lab, https://heatisland.lbl.gov/coolscience/cool-walls

[100] Heat Island Mitigation with Cool Walls, LEED BD+C New Construction LEEDv4.1, https://www.usgbc.org/credits/SSpc154-v4.1?return=/credits/New%20Construction/v4.1

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.

6. *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 new formula, 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.*[101]

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 II) – Vegetation uses plants to decrease air temperature and mean radiant temperature through evapotranspiration and shading.[102] 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.[103] 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

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[101] ESMAP (2020)

[102] 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

[103] Wong, N.H., et al. (2021)

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.[104] Building structure, waterproofing treatments, plant water requirements, plant selection and reduced thermal comfort from increased humidity should be considered[105]. 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.[106] Surface temperatures of rooftop gardens were found to be much lower than hard surfaces, and dependent on the density Leaf Area Index of plants.[107] 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).[108] Authorities in Shanghai, China, estimate that green roofs can reduce power consumption by 6 million kwh, prevent 920,000 tons of rainfall from entering the sewer system, and absorb 170 tons of air pollutants annually in the city.[109]

Ventilation and Urban Design – Creating comfortable microclimates in urban settings is critical to mitigate future extreme heat conditions. The relationship between buildings – scale, form, size, height and distance, can directly influence temperature, solar exposure and wind flow.

1. Urban street canyon or the space between buildings is an aspect ratio of building height to street width that determines the degree of air flow and associated temperature around buildings. Various wind patterns are formed in an urban street canyon depending on the shape and width. Narrow canyons, commonly created when the building height is greater than the street width, can channelize wind at high velocities creating unpleasant conditions at the ground level, whereas wider canyons flanked by buildings of various heights interrupt wind flow to create various wind patterns and eddies around buildings. Non-uniformed building heights typically encourage the best air flow.
2. Orienting buildings and streets 20 to 30 degrees to prevailing winds in a staggered pattern encourages good air flow between buildings and streets versus parallel organized buildings and streets. Staggered patterns have few straight through streets and when paired with greater permeability, creates opportunity for multiple breezeways through a neighborhood (**Figure 3**).
3. Increasing porousness at borders through change in wind pressure encourages greater air movement through neighborhoods. Permeability is typically created by increasing the frontage width between a building and street (i.e. urban plaza and open green space), but as cities become more dense, permeability can pertain to specific building design. Taller buildings can increase permeability by carving out open space at the mid-level, or depending on the density, tier building heights to create roof levels from low to high. Urban permeability is also created by clustering low rise buildings adjacent to taller buildings as it increases upward and downward air flow between the various building heights.

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[104] ESMAP (2020)

[105] Ibid.

[106] 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

[107] Wong et al. (2003)

[108] ESMAP (2020)

[109] Ibid.

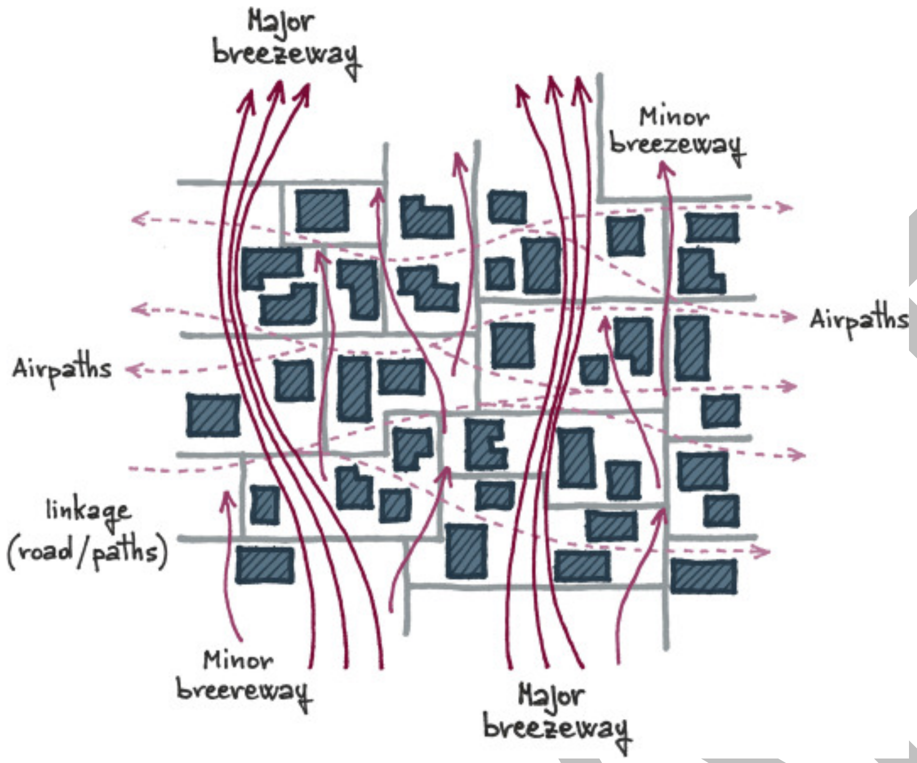

__Figure 3.__ Various breezeway options through a neighborhood created by increased permeability and staggered building and street patterns.[110]

Water features – Water bodies decrease air temperature and increase humidity by absorbing or transporting heat.[111] This takes the form of rivers, ponds, and dispersed water systems (fountains). Water has an average cooling effect of 2-5°F to a range of 100 ft. Water bodies are more effective with a large surface area or when the water is flowing or dispersed. Examples of blue infrastructure cooling in Lahore, Pakistan, where urban vegetation and water ponds have resulted in higher levels of thermal comfort for their local communities.[112] In Shanghai, China, areas located within 30 to 70 ft from the Huansha artificial water body are characterized with higher levels of thermal comfort.

Information Systems – Heat warning systems reduce heat related health effects by providing useful information and inputs for decision-making during a heat wave period.[113] The effectiveness of heat warning systems is determined by the awareness of the public and its consequences, communication measures and socio-demographic factors. 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. New York's Urban Heat Island Task Force invested in urban heat data needs in response to the rapidly rising city temperatures.[114] The result was Cool Neighborhoods, a $100 million commitment to transforming three of its most heat vulnerable neighborhoods. Paris, France deployed a heat resiliency initiative to ensure every Parisian is within a 7-minute walk of a "cool island" by 2020.

Resilient Building Codes and Guidelines – Building codes exist to ensure a minimum level of life safety protection for building inhabitants from external climate conditions. With growing evidence that future climatic driven events will increase building risk, building codes must factor future climate scenarios and weather conditions to ensure buildings continue to buffer external environmental conditions and hazard risks. Discussion on defining climate resilient

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[110] Federico M. Butera (2018) 1.3 - Sustainable Neighborhood Design in Tropical Climates, Urban Energy Transition (Second Edition), Elsevier, p. 51-73

[111] Nasrollahi et al. (2020); Kleerekoper et al. (2012)

[112] Nasrollahi et al., 2020.

[113] Zuo et al., 2015

[114] ESMAP, 2020.

buildings and the associated minimum levels of building performance in code is growing globally, and cities such as New York City developed a Climate Resiliency Design Guideline in September 2020 to address climate responsiveness for city facilities. The guideline is intended to compliment current building code by providing a framework for professionals (architects, engineers, planners) to incorporate future climate and science-based evidence to the design of climate resilient buildings (**Figure 4**).

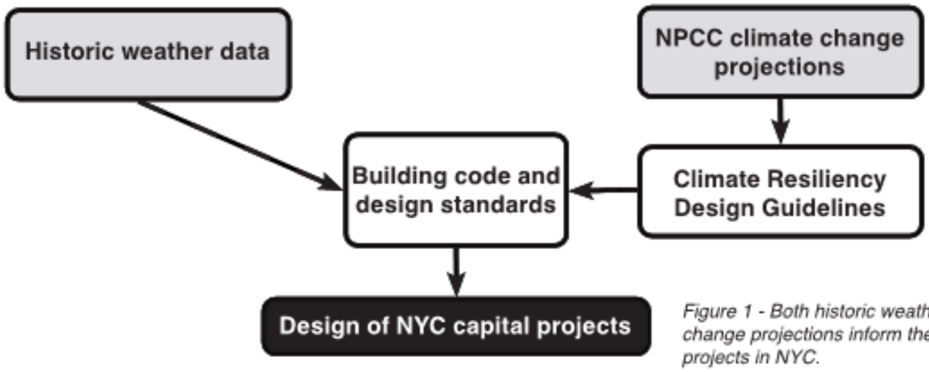
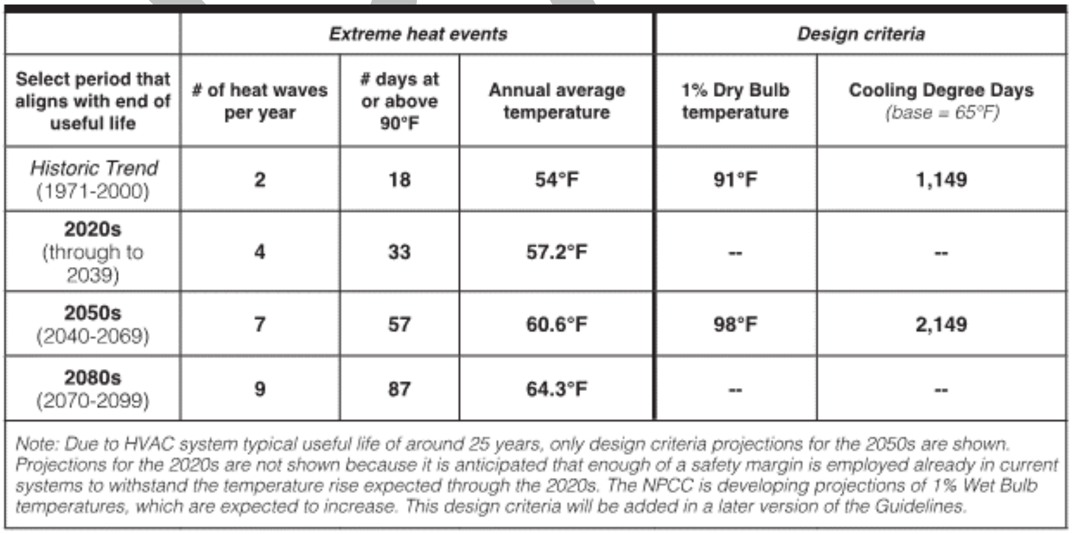


Figure 1 - Both historic weather data and climate change projections inform the design of capital projects in NYC.

Figure 4. *Flow Chart illustrating how future climate information and the Climate Resiliency Design Guidelines impact building code.*[115]

In response to urban heat, the Climate Resiliency Guideline discusses the synergy between future dry bulb temperature, increase in the number of cooling degree days (compares the number of warm days over 65ºF over the mean[116]) and HVAC system time horizons in a simple table (**Figure 5**) to guide decision-making for designers. As outdoor temperatures rise, this increases the demand on cooling loads, energy use, hardware performance, and overall system durability. Tropical climates such as Hawaii are even more susceptible to short equipment life as designer must also factor corrosion impacts from salt laden air in addition to impacts from increased heat.



	Extreme heat events			*Design criteria*	
Select period that aligns with end of useful life	**# of heat waves per year**	**# days at or above 90°F**	**Annual average temperature**	**1% Dry Bulb temperature**	**Cooling Degree Days** *(base = 65°F)*
Historic Trend (1971-2000)	**2**	**18**	**54°F**	**91°F**	**1,149**
2020s (through to 2039)	**4**	**33**	**57.2°F**	--	--
2050s (2040-2069)	**7**	**57**	**60.6°F**	**98°F**	**2,149**
2080s (2070-2099)	**9**	**87**	**64.3°F**	--	--

Note: Due to HVAC system typical useful life of around 25 years, only design criteria projections for the 2050s are shown. Projections for the 2020s are not shown because it is anticipated that enough of a safety margin is employed already in current systems to withstand the temperature rise expected through the 2020s. The NPCC is developing projections of 1% Wet Bulb temperatures, which are expected to increase. This design criteria will be added in a later version of the Guidelines.

Figure 5. *Current and projected extreme heat events and design criteria. Example of impacts to number of cooling days trended against end-of-life targets for HVAC systems.*[117]

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[115] Climate Resiliency Design Guidelines, New York City Mayor's Office of Resiliency, September 2020, 5

[116] Units and calculators explained, U.S. Energy Information Administration, https://www.eia.gov/energyexplained/units-and-calculators/degree-days.php#:~:text=Cooling%20degree%20days%20(CDD)%20are,two%20days%20is%2033%20CDD, 5 May 2022.

[117] Climate Resiliency Design Guidelines, New York City Mayor's Office of Resiliency, September 2020, 15

7. The Cool Neighborhoods NYC program aims to keep communities safe in extreme heat. One strategy is "Be a Buddy NYC", a community-led preparedness model promoting social cohesion. Social service, community organizations, and volunteers become "buddies" to vulnerable New Yorkers. This network is deployed in emergencies to contact vulnerable individuals (NYC Mayor's Office of Recovery and Resiliency, 2017, p. 24).

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, and heat stress impacts will increase as global and local air temperatures continue to rise. 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.[118] 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.
5. Urban designs 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.
6. 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 all cases, especially in the tropical climate found in Hawai‘i.

8. During the 2021 Pacific Northwest heat wave, temperatures rose above 100°F. Multnomah County staff set up cooling centers-buildings with books, beds, chairs, charging areas, food, and air conditioning. Bus fares were waived for those headed to cooling centers, an emergency operations center was activated, and public library hours were extended.

ACKNOWLEDGEMENTS

Many thanks to Ryan Ringuette, Honolulu Climate Commission members, and Dr. Vivek Shandas, Professor at Portland State University for their assistance in various stages of this project.

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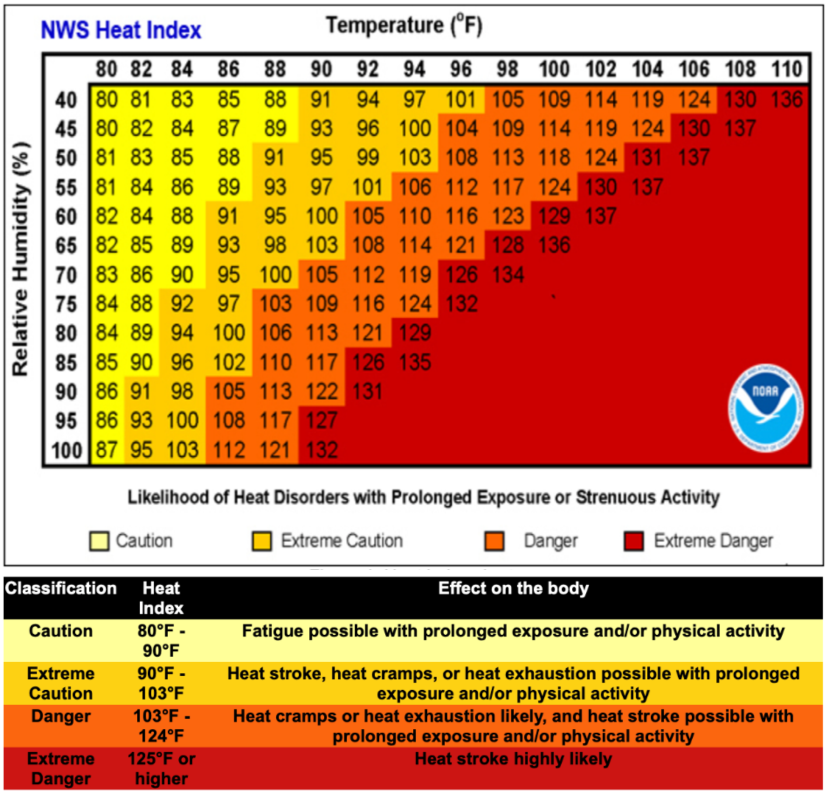
[118] Santamouris, M. (2020)

Appendix I – Glossary of heat terms

Wet Bulb Temperature - The wet bulb temperature (TW) is used as an indicator of dangerous, heat-humidity combinations.[119] 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).[120] 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.[121]

Heat Index - The heat index is a measure of both relative humidity and air temperature.[122] 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.[123] The National Weather service has established a warning system based on the heat index (**Figure I-1**).



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 I-1. *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)*[124]

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[119] Wet-bulb Temperature, Wikipedia, https://en.wikipedia.org/wiki/Wet-bulb_temperature

[120] Ibid.

[121] 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

[122] National Weather Service, What is the Heat Index? https://www.weather.gov/ama/heatindex

[123] Ibid.

[124] National Weather Service Heat Index, https://www.weather.gov/ama/heatindex

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.[125] Surface heat islands tend to be most intense during the day when the sun is shining.

Atmospheric Heat Islands - Atmospheric heat islands form as a result of warmer air in urban areas compared to cooler air in outlying areas.[126] Atmospheric heat islands vary much less in intensity than surface heat islands.

Blue Spaces - Blue space (also referred to as blue infrastructure) in urban planning and design comprises all the areas dominated by surface waterbodies or watercourses. In conjunction with greenspace (parks, gardens, etc. specifically: urban open space), it may help in reducing the risks of heat-related illness from high urban temperatures.

Green Spaces - In land-use planning, urban green space is open-space areas reserved for parks and other "green spaces", including plant life, water features -also referred to as blue spaces- and other kinds of natural environment. Most urban open spaces are green spaces, but occasionally include other kinds of open areas.

Marine Heatwave (MHW) – A marine heatwave is defined as a coherent area of extreme warm sea surface temperature (SST) that persists for days to months.

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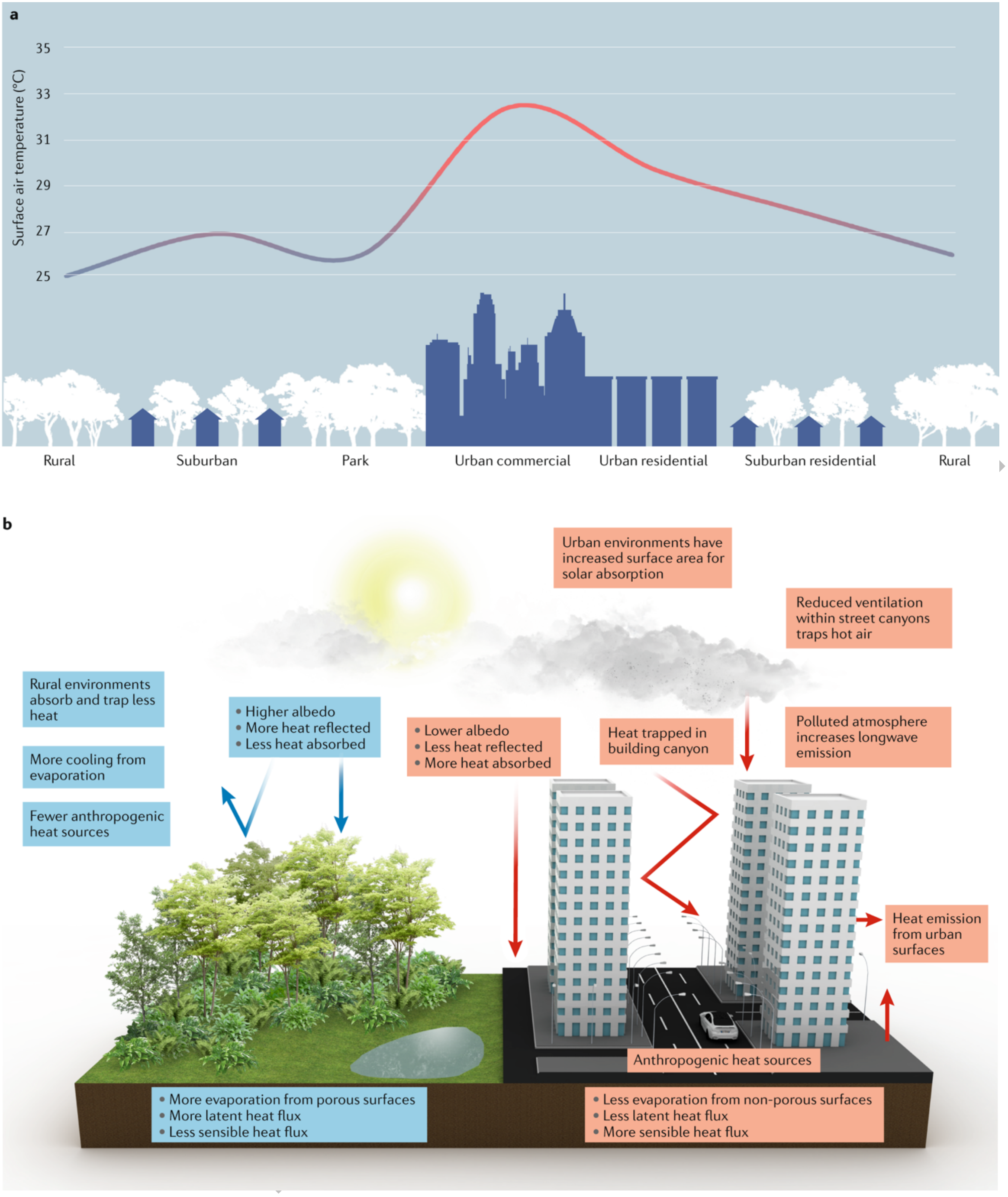
[125] Hibbard et al. (2017) Changes in land cover and terrestrial biogeochemistry. In Climate Science Special Report: Fourth National Climate Assessment, v. I, U.S. Global Change Research Program, Washington.

[126] United States Environmental Protection Agency, 2021

APPENDIX II - Renderings of urban heat and cooling solutions from Wong et al. (2021).[127]



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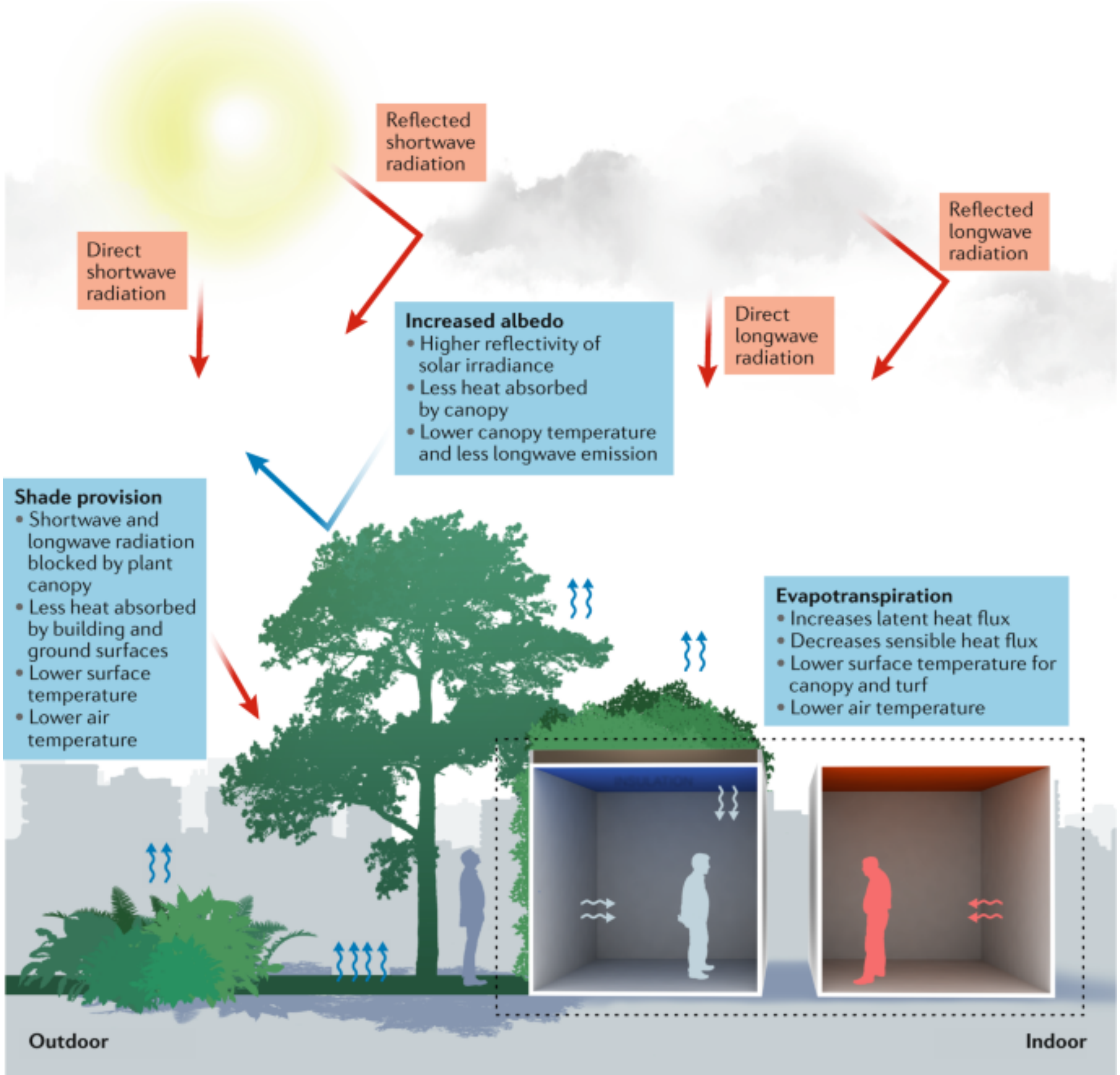
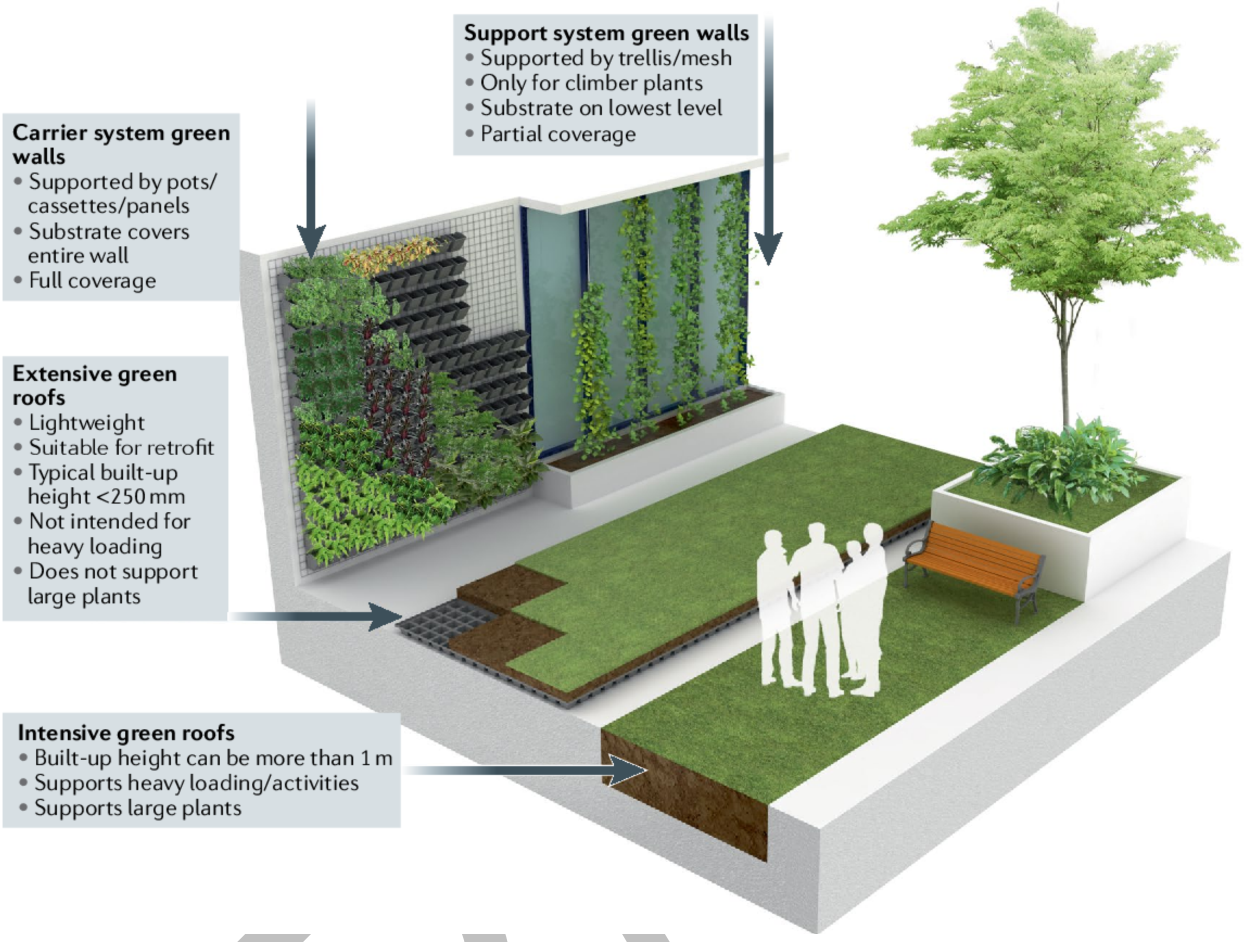
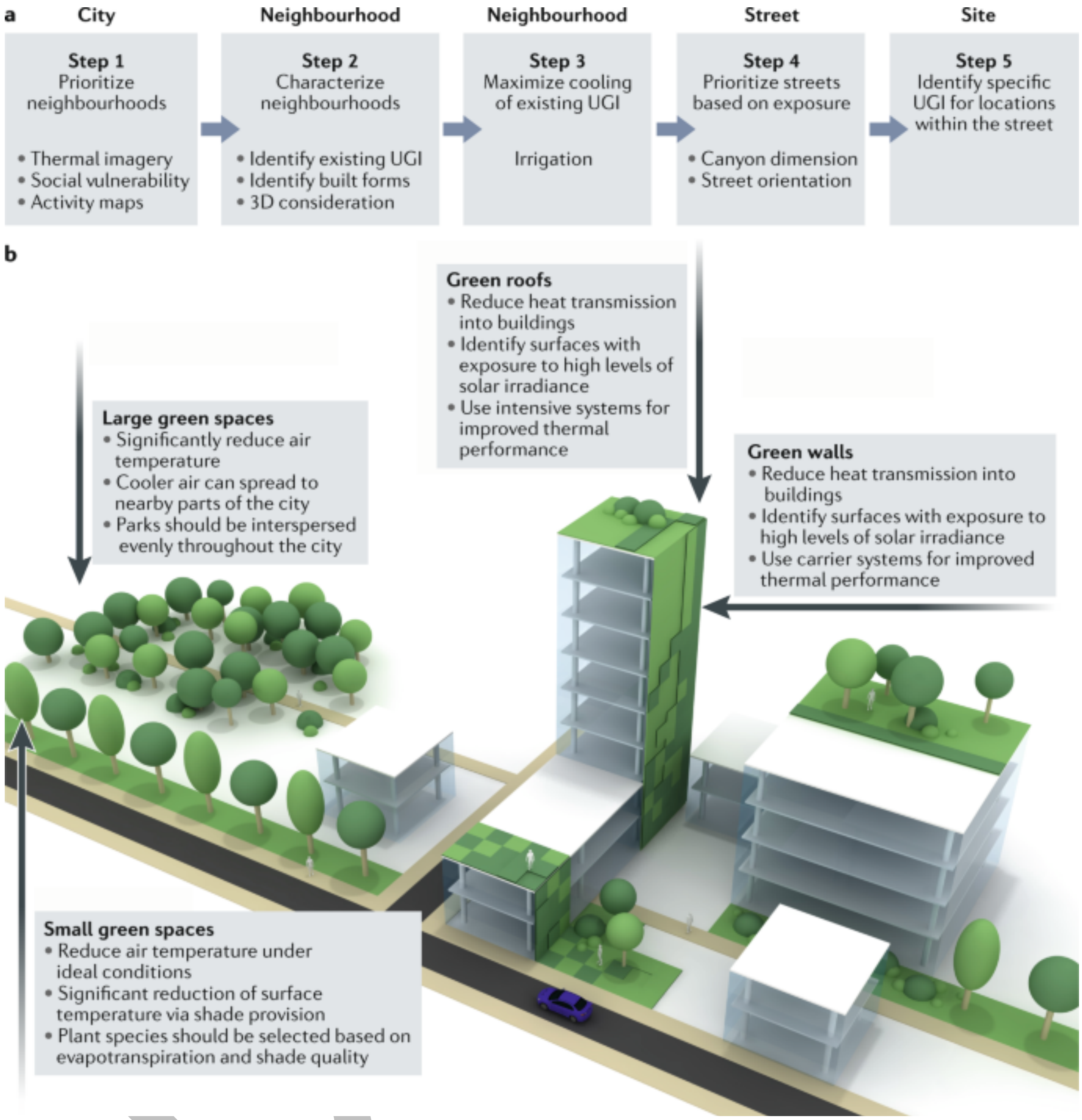
[127] Wong, N.H., Tan, C.L., Kolokotsa, D.D. et al. (2021) Greenery as a mitigation and adaptation strategy to urban heat. Nat Rev Earth Environ 2, 166–181. https://doi.org/10.1038/s43017-020-00129-5



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).*

APPENDIX III - Heat related organizations

1. Arsht-Rockefeller Foundation Resilience Center
    a. https://www.atlanticcouncil.org/programs/adrienne-arsht-rockefeller-foundation-resilience-center/
    b. The Adrienne Arsht-Rockefeller Foundation Resilience Center (Arsht-Rock) is driven to action by the critical need to address the widespread and intensifying consequences of climate change and related risks — threatening our communities, natural ecosystems, economic development, and political stability. We pledge to reach one billion people around the world with resilience solutions to climate change by 2030.
2. CAPA Strategies
    a. https://www.capastrategies.com
    b. CAPA Strategies, LLC provides data analytics and decision support tools to communities worldwide. Our model is rooted in innovative research and an ever-growing network of experts, researchers, and concerned community members. We seek to provide accessible data acquisition and analysis tools and methods, poignant data-based insights, and community-based strategies to move toward an equitable and adapted future.
3. Centers for Disease Control and Prevention (CDC)
    a. https://www.cdc.gov/about/organization/mission.htm
    b. CDC works 24/7 to protect America from health, safety and security threats, both foreign and in the U.S. Whether diseases start at home or abroad, are chronic or acute, curable or preventable, human error or deliberate attack, CDC fights disease and supports communities and citizens to do the same.
    c. CDC increases the health security of our nation. As the nation's health protection agency, CDC saves lives and protects people from health threats. To accomplish our mission, CDC conducts critical science and provides health information that protects our nation against expensive and dangerous health threats, and responds when these arise.
4. Cool Roof Rating Council
    a. https://coolroofs.org
    b. The Cool Roof Rating Council is a 501(c)(3) nonprofit organization that develops fair, accurate, and credible methods for evaluating and labeling the radiative properties of roofing and exterior wall products.
5. Environmental Protection Agency (EPA)
    a. https://www.epa.gov/aboutepa/our-mission-and-what-we-do#:~:text=The%20mission%20of%20EPA%20is%20to%20protect%20human%20health%20and%20the%20environment.
    b. The mission of EPA is to protect human health and the environment.
6. Global Cool Cities Alliance
    a. https://globalcoolcities.org/
    b. Global Cool Cities Alliance (GCCA) launched in 2010 to accelerate a world-wide transition to cooler, healthier cities. Its mission is to advance urban heat island mitigation policies and programs to promote more efficient and comfortable buildings, healthier and more resilient cities, and to cancel some of the warming effects of climate change through global cooling. Increasing the solar reflectance of urban surfaces such as roofs and roads is a cost-effective strategy to achieve these goals.
    c. The GCCA approach is to cultivate partnerships with cities and other stakeholders to give them the tools and support they need to identify successful policies and programs, adapt them for each city's unique characteristics, and connect with experts and partners to help with implementation. We work with companies and governments to help grow new markets for technologies and materials.

We also link the diverse world of experts and researchers who study urban heat islands and cool materials.

7. The Cool Coalition
    a. https://coolcoalition.org/wp-content/uploads/2020/04/Cool-Coalition-Brochure-1.pdf
    b. The Cool Coalition is a global multi-stakeholder network that connects a wide range of key actors from government, cities, international organizations, businesses, finance, academia, and civil society groups to facilitate knowledge exchange, advocacy and joint action towards a rapid global transition to efficient and climate-friendly cooling. The Cool Coalition promotes an 'reduce-shift-improve-protect' holistic and cross-sectoral approach to meet the cooling needs of both industrialized and developing countries through urban form, better building design, energy efficiency, renewables, and thermal storage while phasing down HFCs.
8. The Cool Cities Network (through the C40)
    a. https://www.c40.org/networks/cool_cities
    b. Knowledge sharing and collaboration among C40 cities to reduce impact of urban heat island effect. Works with the Global Cool Cities Alliance. C40-network of the world's megacities committed to addressing climate change. C40 supports cities to collaborate effectively, share knowledge and drive meaningful, measurable and sustainable action on climate change. 97 affiliated cities: steering committee, innovator city, megacity, observer city.
9. National Integrated Heat Health Information System
    a. https://nihhis.cpo.noaa.gov/
    b. NIHHIS is an integrated information system that builds understanding of the problem of extreme heat, defines demand for climate services that enhance societal resilience, develops science-based products and services from a sustained climate science research program, and improves capacity, communication, and societal understanding of the problem in order to reduce morbidity and mortality due to extreme heat. NIHHIS is a jointly developed system by the Centers for Disease Control and Prevention (CDC) and the National Oceanic and Atmospheric Administration.
10. National Weather Service
    a. https://alerts.weather.gov/cap/hi.php?x=1
    b. The National Weather Service provides watches, warnings or advisories for Hawaii.

Appendix IV – Discussion of global warming and the rise of marine and terrestrial heat

Progress in Mitigating Emissions

Updated national pledges under the UNFCCC only cut greenhouse gas (GHG) emissions 7.5% by 2030, resulting in a 34% probability of staying below an average global temperature rise of 2°C and a 1.5% probability of staying below 1.5°C by 2100.[128] On-the-ground policies to limit greenhouse gas emissions are advancing at a snail's pace.[129] At current levels of mitigation, end-of-century global warming is estimated to reach 2.0 to 3.6°C (median 2.7°C) above pre-industrial levels. However, under-reporting of emissions and decreases in natural carbon sinks suggest that global temperature rise may be even higher. On average, global emissions are underreported 23%[130] with 70%[131] under-reporting of methane emissions alone. Projected warming may underestimate future increases in 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.[132] New studies[133] report that the loss of global carbon sequestration 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.

Intolerable Heat

For thousands of years, human communities have existed within a relatively narrow range of climate variables characterized by mean annual temperatures (MAT) around 13°C (55.4°F). 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°F) meaning that a substantial part of humanity will be exposed to mean annual temperatures warmer than nearly anywhere today. 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 IV-1**).[134]

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[128] Ou, Y., et al. (2021)
[129] Climate Action Tracker (2021)
[130] Mooney, C., et al. (Nov. 7, 2021)
[131] 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
[132] 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
[133] 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. Nature Sustainability, https://doi.org/10.1038/s41893-022-00854-3
[134] Xu, Chi et al. (2020). Future of the human climate niche. *PNAS*, https://doi.org/10.1073/pnas.1910114117

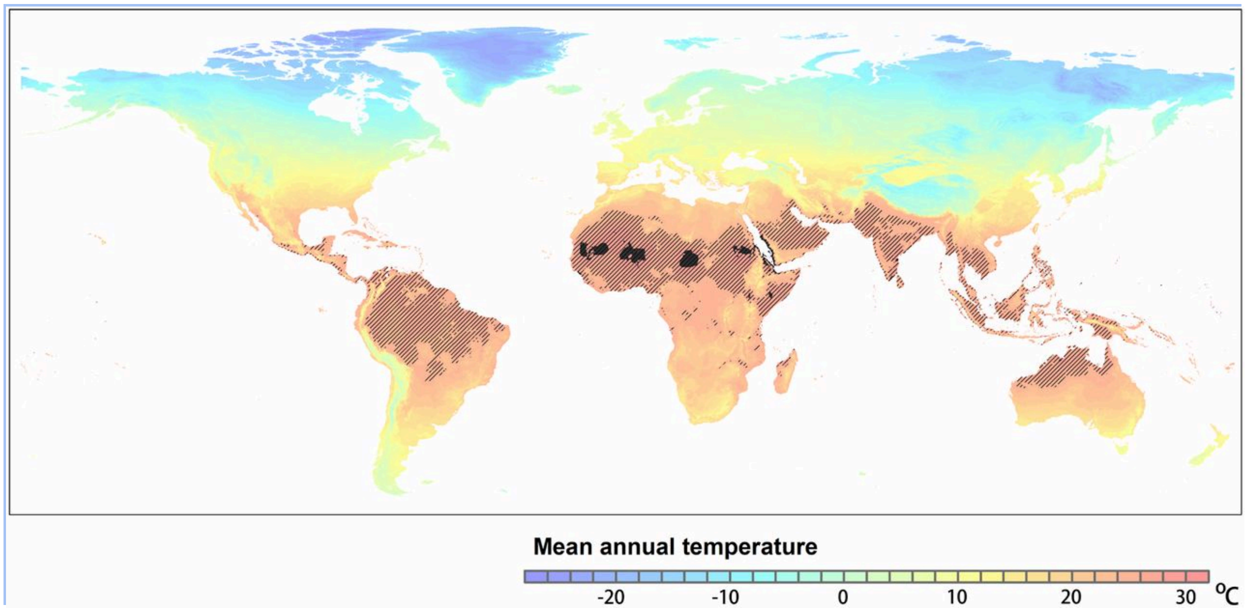

Figure IV-1. *Expansion of extremely hot regions in a business-as-usual climate scenario. Today, mean annual temperatures (MATs) >29°C (84.2°F) are restricted to the small dark areas in the Sahara region (0.8% of global land area). With continued emissions these conditions are projected to occur throughout the shaded area (19% of global land area) by 2070, currently home to 3.5 billion people. Background colors represent current MATs.*[135]

Marine Heat

More than 90% of the excess heat trapped by anthropogenic GHG emissions is stored in the world's oceans, where it accumulates and drives a rise in ocean temperature.[136] For the year 2019, 57% of the global ocean surface recorded extreme heat, which was comparatively rare (only 2%) during the period of 1850-1870.[137] A marine heatwave (MHW) is defined as a coherent area of extreme warm sea surface temperature (SST) that persists for days to months. With continued warming, MHW's will intensify, occur more often, persist for longer periods of time, and extend over larger regions.[138]

Marine heatwaves have occurred in all of Earth's ocean basins over the past two decades, with severe negative impacts on marine organisms and ecosystems.[139] The occurrence probabilities of the duration, intensity, and cumulative intensity of most documented, large, and impactful MHWs have already increased more than 20-fold as a result of anthropogenic climate change.[140] From 1925 to 2016, global average MHW frequency and duration increased by 34% and 17%, respectively, resulting in a 54% increase in annual MHW days globally.[141] These impacts extend across the Pacific[142] and are projected to grow in frequency and magnitude.

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Ocean deoxygenation (i.e., loss of dissolved oxygen) due to climate change can result in negative impacts to the marine environment.[143] Under the RCP8.5 high-emissions scenario, more than 72% of the global ocean is projected to experience emerging deoxygenation throughout the water column before 2080.[144] Temperature is a fundamental driver of change in marine systems, with restructuring of communities in the most rapidly warming areas.[145]

Ocean temperature variability is a fundamental component of Earth's climate system, and extremes in this variability affect the health of marine ecosystems around the world.[146] Multiple regions in the Pacific, Atlantic and Indian Oceans are particularly vulnerable to MHW intensification. This is due to the co-existence of high levels of biodiversity, a prevalence of species found at their warm range edges, and concurrent non-climatic human impacts.[147] The effects of marine heatwaves can reverberate up the food chain.[148] Declines in maximum catch potential exceeding 50% from late-20th century levels under RCP8.5 are projected by 2100 for the exclusive economic zones of most islands in the central and western Pacific.[149]

For example, in late 2013, a huge patch of unusually warm ocean water, roughly one-third the size of the contiguous United States, formed in the Gulf of Alaska and began to spread. Cod numbers plunged by 70% in 2 years, essentially erasing a fishery worth $100 million annually.[150] Warm, low-nutrient water in the Northwest Pacific devastated phytoplankton growth. Then, Chinook salmon populations plunged, and as many as one million seabirds died in the Gulf of Alaska. Marine heatwaves have also caused massive amounts of coral bleaching in reefs around the world over the past several decades (Figure IV-2).[151] Widespread coral bleaching and mortality occurred during the summers of 2014 and 2015 in Hawai‘i and during 2013, 2014, and 2016 in Guam and the Commonwealth of the Northern Mariana Islands.[152] Impacts varied by location and species, but the 2015 bleaching event resulted in an average mortality of 50% of the coral cover in western Hawai‘i. Coral losses exceeded 90% at the remote and pristine equatorial reef of Jarvis Island.

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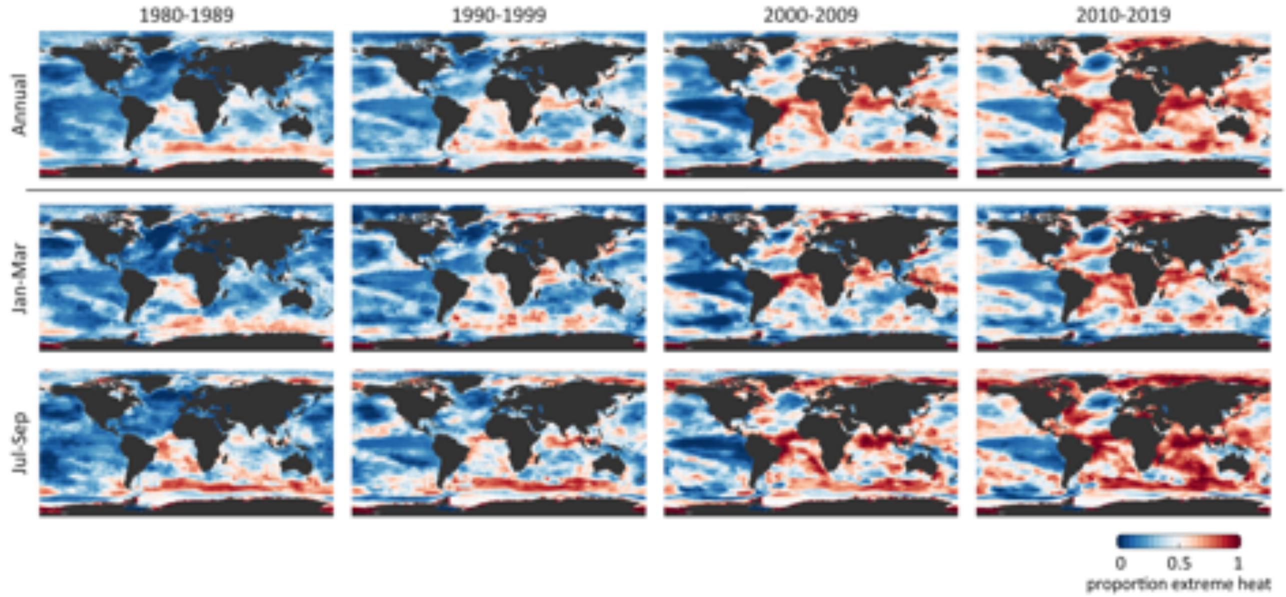

Figure IV-2. *Decadal evolution of frequency of extreme marine heat from 1980–2019. Extreme heat defined as exceeding the localized (1 ˚× 1 ˚), monthly, 98th percentile of sea surface temperatures (SST) observed during 1870–1919, averaged from HadISSTv1.1 and COBESSTv2 products. Extreme heat, resolved for boreal winter (Jan-Mar) and summer (Jul-Sep), accumulates steadily over time beginning in the Southern, South Atlantic, and Indian basins. Regions of the mid North Atlantic and eastern South Pacific indicate a low occurrence.*[153]

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