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Abstract:

New York City (NYC) faces many challenges in coming decades due to climate change and its interactions with social vulnerabilities and uneven urban development patterns and processes. This New York City Panel on Climate Change (NPCC) report contributes to the Panel's mandate to advise the city on climate change and provide timely climate risk information that can inform flexible and equitable adaptation pathways that enhance resilience to climate change. This report presents up-to-date scientific information as well as updated sea level rise projections of record. We also present a new methodology related to climate extremes and describe new methods for developing the next generation of climate projections for the New York metropolitan region. Future work by the Panel should compare the temperature and precipitation projections presented in this report with a subset of models to determine the potential impact and relevance of the "hot model" problem. NPCC4 expects to establish new projections-of-record for precipitation and temperature in 2024 based on this comparison and additional analysis. Nevertheless, the temperature and precipitation projections presented in this report may be useful for NYC stakeholders in the interim as they rely on the newest generation of global climate models.

Keywords:
climate change, climate risk, climate science, New York City, adaptation, NPCC4

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1 Chapter Summary

While providing an informative context on how to frame and contextualize climate risks, it often remains challenging for municipal stakeholders to obtain practical advice and insights on how to assess climate risks on a local scale from the Intergovernmental Panel on Climate Change (IPCC) reports alone (Viner et al., 2020). The New York City Panel on Climate Change (NPCC) was formed in 2009 and codified in New York City Local Law 42 of 2012 with a mandate to provide an authoritative and actionable source of scientific information on future climate change and its potential impacts. A key task of the NPCC is to provide up to date climate projections (i.e. "projections of record") for use by the City of New York and its agencies in climate-related decision making (C. Rosenzweig & Solecki, 2019). As mandated by Local Law 42, the Panel[1] is expected to make recommendations regarding the near-, intermediate- and long-term quantitative and qualitative climate change projections for the City after the release of an assessment report by the Intergovernmental Panel on Climate Change. This NPCC report fulfills this expectation following the 2021 publication of the climate science report of Working Group 1 of the Sixth IPCC Assessment (Masson-Delmotte et al., 2021).

1.1 Key Messages

Key Message 1: *Sea level is projected to rise for centuries and remain elevated for thousands of years. Glaciers and ice sheets combined are now the dominant contributors to global mean sea level rise (GMSLR). In the future, the cryosphere contributions will dominate, especially in higher GMSLR scenarios. Changes in ocean circulation, such as the Atlantic Meridional Overturning Circulation may also play an increasing role in the future. Coastal locations in the NYC metropolitan region continue to experience higher rates of relative sea level rise as compared to the global mean, a trend that is generally expected to continue into the future. Projected sea level rise for NYC will exacerbate the destructive hazards posed by storm surges and cause more frequent high-tide flooding. Although many improvements have been made to protect neighborhoods and secure critical infrastructure in future floods, many neighborhoods remain vulnerable to coastal flooding. More research is needed on both the baseline storm surge hazard as well as its potential future changes.*

Key Message 2: *Surface and air temperature varies throughout NYC as a function of time of day, season, and the underlying characteristics of the built environment. The number of days with minimum temperatures below freezing has been steadily declining since 1900. The total number of hot days in the city is expected to increase as this century progresses. The frequency and duration of heat waves are also expected to increase. In general, the projected changes in precipitation are small relative to year-to-year variability. Average annual precipitation in NYC is projected to increase by approximately 2 to 7 percent by the 2030s, 4 to 11 percent by the 2050s and 7 to 17 percent by the 2080s (all relative to a 1981-2010 baseline period). Although the increase in total annual precipitation is projected to be relatively small, global climate models project somewhat larger increases in the frequency of extreme precipitation events.*

Key Message 3: *The largest recorded drought in the New York metropolitan region occurred during the 1960s. This event serves as a critical benchmark to evaluate potential impacts of extreme drought and vulnerability to low water availability in the region, with current water management practices designed around that event. Since the 1960s drought of the record, several smaller droughts have had measurable impacts. Consideration of water management under drought currently relies on estimates of imbalances between annual supply and evaporative losses, but droughts are manifestation of the non-linear interaction between supply and demand as the climate risks faced by water users vary over time and by sector of use. There is a need for more comprehensive assessment of drought vulnerability that accounts for projected changes in cross-sectoral demand as well as projected climate impacts.*

[1] The Panel is currently led by a team of four co-chairs who possess a broad spectrum of disciplinary expertise including climate science, demography, civil and environmental engineering, geography, vulnerability analysis, global change, architecture, and urban planning. Both the full NPCC and its leadership team were selected to ensure a diversity of backgrounds, research disciplines, and fields of technical practice.

2 Introduction

This report builds on and updates the sea level rise projections developed by the second New York City Panel on Climate Change (NPCC2) (Horton, Little, et al., 2015) as well as the third Panel (NPCC3) (González et al., 2019). It also draws upon climate projections that are under development in the on-going New York State Climate Impacts Assessment (New York State Energy Research and Development Authority, 2024). The main climate hazards and stressors described in this report of the fourth iteration of NPCC (NPCC4) include: (1) Sea Level Rise and Storm Surge; (2) Inland and Coastal Flooding; (3) Average and Extreme Temperature; and (4) Extreme Precipitation and Drought.

Climate risk is a function of the changing characteristics of the climate system and socioeconomic change as well as changes in norms and values. As in previous NPCC assessments, NPCC4 makes use of definitions, measurements, baselines, and scenarios to represent how the magnitude, duration, and frequency of climate hazards[2] may change in the future. NPCC4 follows a risk management approach that explicitly recognizes the temporally evolving nature of risk components (Viner et al., 2020). This approach can be summarized as R = H x E x V; R = Risk on an asset, system, population (e.g. socially marginalized groups, NYC residents), individual or location being the product of variables: H = hazard, E = exposure, and V = vulnerability (Figure 1).

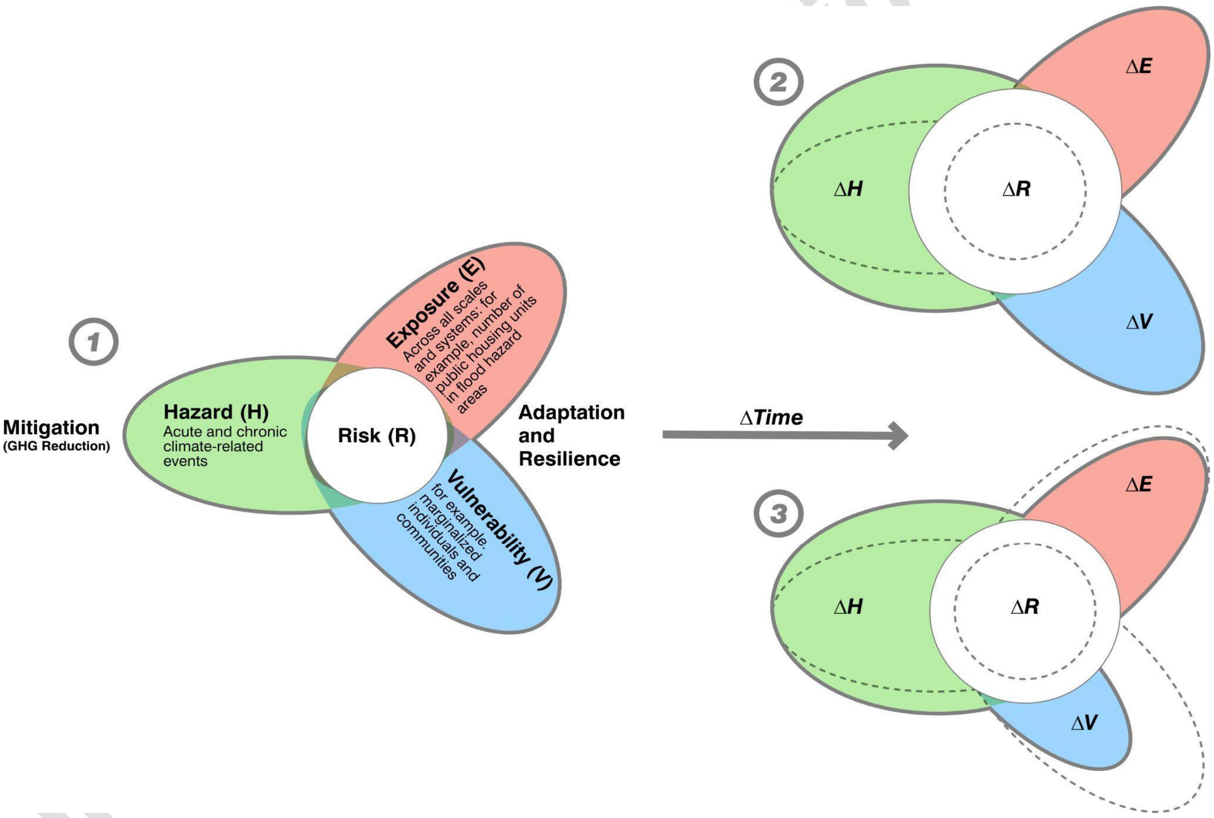

Figure 1. The impact of the dynamic components of climate risk (R) on its temporal evolution. Graphic 1 shows the baseline condition. Graphic 2 shows the impact of sluggish climate mitigation on the magnitude of the hazard (H) and the subsequent increase in climate risk. Graphic 3 shows that even with the implementation of climate adaptation and resilience strategies that reduce vulnerability (V) and exposure (E), climate risk may increase if the magnitude of the hazard continues to increase (adapted from Viner et al., 2020).

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[2] A climate hazard is a weather or climate state such as a heat wave, flood, high wind, heavy rain, ice, snow, and drought that can cause harm and damage to people, property, infrastructure, land, and ecosystems. Climate hazards can be expressed in quantified measures, such as flood height in feet, wind speed in miles per hour, and inches of rain, ice, or snowfall that are reached or exceeded in a given period of time.

"Based on climate analyses, regional and global trends, and a review of scientific literature", NPCC confirms which climate projections of temperature, precipitation, sea level rise, and coastal flooding (i.e. projections of record) are most appropriate for use in resiliency planning for the city and region (C. Rosenzweig & Solecki, 2019). In this work, we present co-developed climate projections that translate global climate model (GCM[3]) outputs under a range of future emissions scenarios into climate risk assessments associated with different climate stressors and hazards at the urban scale. Given that the scenarios and narratives utilized by IPCC are associated with spatial scales that are much larger than cities like NYC, we aim to address an important urban adaptation gap by presenting an approach for incorporating the local sociocultural context and equity considerations into urban climate risk assessment through co-production with local stakeholders (Coggins et al., 2021).

This report presents up-to-date climate risk and scientific information as well as updated sea level rise projections of record, which are used by the city to inform resilience planning and investment and is one of the primary functions of the NPCC. We also present a new methodology related to climate extremes and describe new methods for developing the next generation of climate projections for the New York metropolitan region. NPCC4 expects to establish new projections of record for precipitation and temperature in 2024. The temperature and precipitation projections presented in this report are intended to be used as interim products. Recommendations for developing additional projections of record and future work are included in the Conclusions and Recommendations section.

2.1 Future Scenarios

The representative concentration pathways (RCPs) identify plausible futures for greenhouse gas concentrations and other radiative forcings (i.e., differences between incoming and outgoing energy in the Earth's atmosphere) that are used in future projections of sea level, temperature and precipitation (van Vuuren et al., 2011). The shared socio-economic pathways (SSPs) describe alternative future socio-economic and demographic visions consistent with the RCPs (O'Neill et al., 2020) across the globe through 2100 (Figure 2) (Eyring et al., 2016). Because socioeconomic and demographic change drive alternative land use, energy use, transit and other key sectors, they are used to develop emissions scenarios. Each SSP is consistent with the RCPs and multiple radiative forcing targets based on the timing and spatial distribution of development pathways. There are a total of five major SSP narratives (representing nominally pathways that are associated with "sustainability" [SSP1], "middle of the road" or "business as usual" [SSP2], "regional-rivalry" [SSP3], "inequality"[SSP4], and "fossil-fuel development" [SSP5][4]) and nine total narratives (i.e., because more than one RCP may be consistent with an SSP).

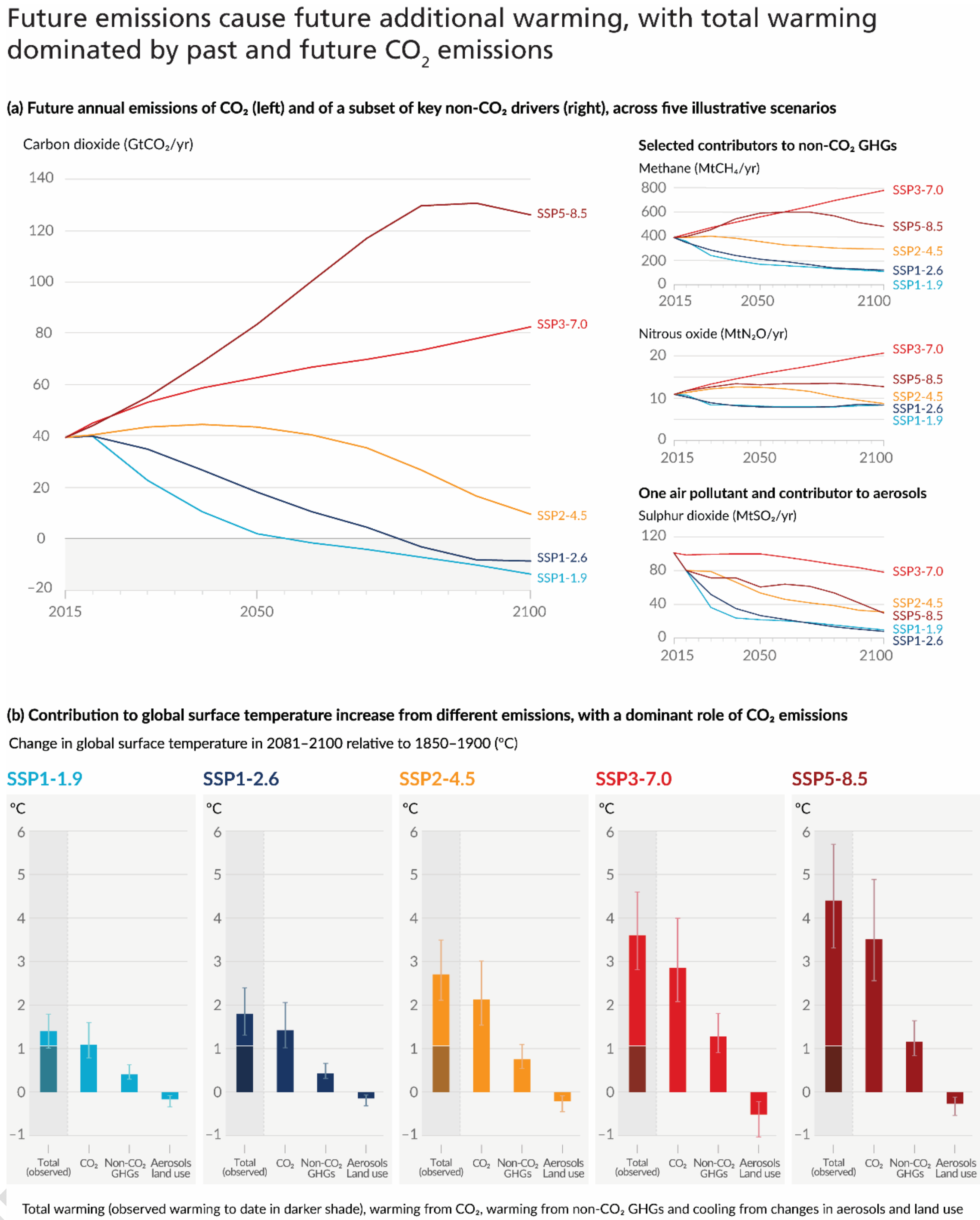
This report uses two emissions scenarios (i.e. SSP2-4.5 and SSP5-8.5) for three important reasons. First, using these scenarios allows for the Panel to build on the 2010, 2015, and 2019 NPCC reports as NPCC4 carries out its work across multiple years and working groups. SSP2-4.5 and SSP5-8.5 are consistent with the two emissions scenarios that drive the climate projections previously developed by NPCC2 and NPCC3; this allows for a sustained assessment approach where municipal stakeholders can more readily compare new climate projections with earlier climate projections that were co-developed with less advanced GCMs. This approach facilitates the relevance, credibility, and legitimacy of Panel outputs and activities. Second, SSP5-8.5 remains useful as a complement to SSP2-4.5 when determining a range of plausible outcomes for risk management that represent a "short-to-medium term mean scenario and a longer-term tail-risk scenario" (See Appendix B for further discussion on tail risk) (Serinaldi et al., 2015; Srikrishnan et al., 2022; Yu et al., 2020). While IPCC (2022) suggests that policies implemented by the end of 2020 point to late-century cumulative emissions that are closer to SSP2-4.5 than SSP5-8.5, to date the Global North has failed to rapidly transition away from fossil fuels in the manner that international agreements[5] call for (Hickel & Slamersak, 2022) and this may ultimately lead to reduced implementation (or commitment walk-back) in the Global South (Armstrong & McLaren, 2022; Sultana, 2022). In addition, "there is extremely limited evidence on the aggregate effects of climate laws on climate outcomes" (although there is a broader literature assessing climate policies) (Dubash et al., 2022) and there have been multiple climate policy walk-backs in the Global North since 2020 (e.g. the U.K.'s shift to delay a prohibition on the sale of new gasoline and diesel cars). Further, geopolitical shocks

[3] A GCM is a mathematical representation of the behavior of the Earth's climate system over time that can be used to estimate the sensitivity of the climate system to changes in atmospheric concentrations of greenhouse gasses (GHGs) and aerosols. Each model simulates physical exchanges among the ocean, atmosphere, land, and ice (C. Rosenzweig et al., 2013)

[4] Note that RCP 8.5 is only plausible under SSP5. These short-hand nicknames for the SSPs come from global scenario development and are not necessarily describe the associated local conditions in U.S. or New York City.

[5] The Paris Agreement calls for a just transition, to ensure that global emissions decline fast enough to keep global warming below 2·0°C, and to pursue sustainable development and poverty reduction. The agreement also enshrines the principle of common but differentiated responsibility, which acknowledges that wealthy countries have an obligation to decarbonise faster than other countries, given their disproportionate contributions to historical emissions.

such as climate change-associated conflicts (Bowles et al., 2015) as well as pandemics (Marani et al., 2021; Zakeri et al., 2022) have the potential to slow progress towards a transition away from fossil fuels and "RCP8.5 is in close agreement with historical total cumulative CO2 emissions" (i.e. within 1%) (Schwalm et al., 2020). Third, the publicly available National Aeronautics and Space Administration (NASA)/IPCC Sea Level Projection Tool (Fox-Kemper et al., 2021; Garner et al., 2021; Kopp et al., 2023) includes "low confidence" sea level projections for SSP5-8.5 that account for the potential impact of deeply uncertain ice sheet processes and extend beyond 2100. NPCC4 utilizes SSP5-8.5-*low confidence* sea level projections along with SSP2-4.5-*medium confidence* and SSP5-8.5-*medium confidence* projections as an actionable and prudent way to explicitly account for deeply uncertain, high consequence events that disproportionately impact socially vulnerable and marginalized NYC residents (Faber, 2015; Martinich et al., 2013; Singh et al., 2015; Tate et al., 2021).



The five scenarios are SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5.

Panel (a) Annual anthropogenic (human-caused) emissions over the 2015–2100 period. Shown are emissions trajectories for carbon dioxide (CO2) from all sectors (GtCO2/yr) (left graph) and for a subset of three key non-CO2 drivers considered in the scenarios: methane (CH4, MtCH4/yr, top-right graph); nitrous oxide (N2O, MtN2O/yr, middle-right graph); and sulphur dioxide (SO2, MtSO2/yr, bottom-right graph, contributing to anthropogenic aerosols in panel (b).

Figure 2. Future global anthropogenic emissions of key drivers of climate change and warming contributions by groups of drivers for five scenarios: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (Masson-Delmotte et al., 2021).

2.2 Sustained Assessment and Co-Production

While the IPCC assessment reports act as a standard for many scientists and practitioners when working on matters relating to climate change, equitable urban adaptation requires meaningful engagement with local stakeholders to ensure that there are mechanisms and procedures to incorporate local knowledge and values into risk assessments (Barnett et al., 2014; Broadbent et al., 2022; Foster et al., 2019; Moss et al., 2019). Further, equitable urban adaptation also requires that the voices of low-income, marginalized and vulnerable communities (i.e. the communities most likely to bear the brunt of adverse climate impacts) be centered in order to imagine futures associated with equitable outcomes and their corresponding pathways (Fitzgerald, 2022; Swanson, 2021). NPCC4 organized a series of workshops focused on climate science and racial equity that complemented the continuous co-production activities (e.g. Climate Knowledge Exchange or CKE[6]) that the Panel engages in with the Mayor's Office of Climate and Environmental Justice (MOCEJ) and other local stakeholders in order to further incorporate the local sociocultural context and equity considerations into updated climate projections and other NPCC processes and outputs (City of New York, 2022). As of this writing, CKE activities continue to address gaps in knowledge and research and needs of local stakeholders.

MOCEJ, the NPCC Climate Science and Projections Working Group, and partners, organized a two-day virtual NYC Climate Science and Projections Workshop in 2022. The purpose of the workshop was to bring together city agencies, state partners, NPCC members, and other key stakeholders, to: present on the latest climate science and projections for NYC; share how the city is using climate projections; determine how climate projections can be further refined and/or customized to improve decision-making; and identify additional climate analyses that are needed and/or would be useful for NYC. The workshop consisted of presentations, followed by discussions (see Figure 3) via breakout rooms and interactive tools. The feedback and discussion during the workshop has been instrumental in helping to shape the 4th NPCC Assessment. This report aims to meaningfully respond to two key action items that came out of the workshop: NPCC4 should (1) conduct data-driven analyses to determine the extent to which the Panel should utilize global climate models (GCMs) associated with the Coupled Model Intercomparison Project Phase 6 (CMIP6) that project rises in global temperature by the end of the century that might be larger than that supported by other evidence and (2) utilize sea level rise projections that are publicly available through the National Aeronautics and Space Administration (NASA)/IPCC Sea Level Projection Tool to present a broad range of plausible outcomes.

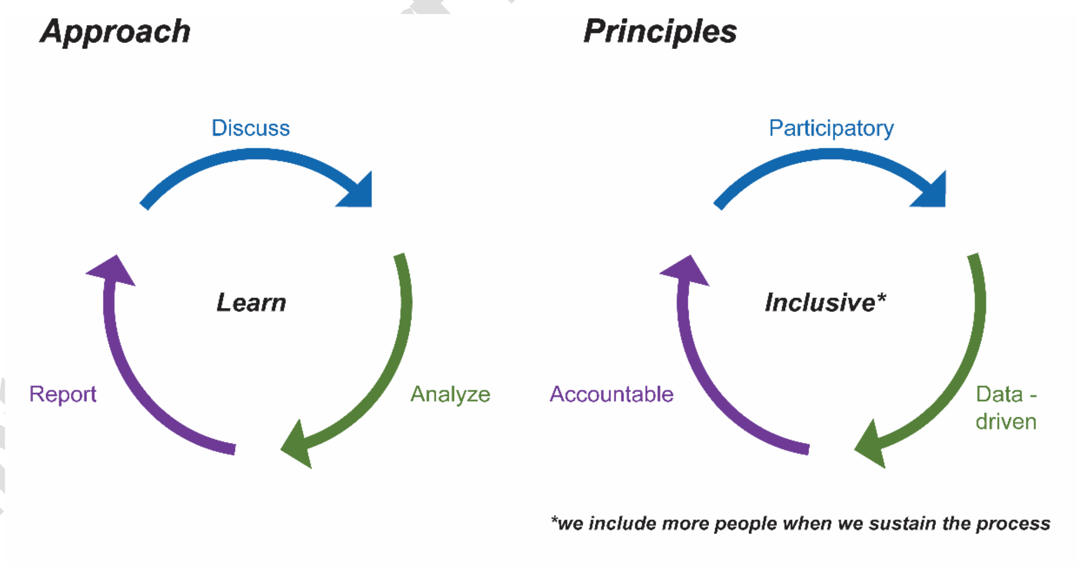


Figure 3. Schematic depicting the sustained assessment process and principles of the Climate Knowledge Exchange (CKE) initiative that inform NPCC4 activities. It involves four key components that occur sequentially: 1) group discussion, 2) surveys, 3) focus area identification and refinement, and 4) reporting (City of New York, 2021).

[6] The Mayor's Office of Climate and Environmental Justice (MOCEJ) piloted the CKE as an engagement process focused on identifying what City staff, nonprofit and community-based organizations, and scientists consider to be the biggest knowledge gaps impeding a just climate response in NYC. In the first year of the CKE, MOCEJ engaged over 170 people from 27 non-governmental organizations and 21 city agencies in 25 small discussion groups.

The goal of this report is to provide guidance and up to date climate risk information for the City of New York as it continues to develop equitable and flexible adaptation pathways[7] to cope with anthropogenic climate change (Amorim-Maia et al., 2022; C. Rosenzweig & Solecki, 2014). In addition to projections of record for sea level rise presented here, the fourth NPCC (i.e. NPCC4) is also planning to produce a more detailed assessment report that includes projections of record for temperature and precipitation as well as chapters focused on climate science, equity, futures and transitions, energy and energy insecurity, flooding, and health (Balk et al., 2024; Foster et al., 2024; Matte et al., 2024; Ortiz et al., 2024; B. Rosenzweig et al., 2024; Yoon et al., 2024). Each of these chapters will be guided by recognition of (and attention to) the interactions between the ongoing climate and racial justice crises, as well as consideration of the impacts of the COVID-19 pandemic on NYC (Bock et al., 2021; Johnson et al., 2021; Kruczkiewicz et al., 2021; Kyrkjebo et al., 2021; Marcotullio & Solecki, 2021; Richardson et al., 2020).

3 Climate Change Impacts on New York City

Located on the coast in an area subject to extreme coastal floods, heavy rainfall and intense summer heat waves, NYC faces many challenges in coming decades due to climate change and its interactions with social vulnerabilities and exposure inequities (Bock et al., 2021). For example, it is well documented that the “urban heat island effect” disproportionately impacts communities of color (i.e. non-White, low-income communities) in the U.S. (Benz & Burney, 2021; Hamstead et al., 2018; Hsu et al., 2021; Jackson et al., 2022; Johnson, 2022; McDonald et al., 2021; United States Environmental Protection Agency, 2021). A study of 108 urban areas in the United States underscores that the hottest urban areas tend to be inhabited by, “resource-limited residents and communities of color," (Hoffman et al., 2020). Nearly half of all heat-related deaths are among New Yorkers living in neighborhoods with high or very high poverty levels. Black New Yorkers are more than twice as likely to die from heat stress than White residents of NYC (City of New York Department of Health and Mental Hygiene, 2022a).

Over multi-centennial and longer timeframes, GMSLR could reach several meters above present-day levels[8], depending on the degree of warming resulting from current to near future emission levels (Fox-Kemper et al., 2021). One analysis suggests that a 2.7°F (1.5°C) warming could lead to 2.9 m global SLR, placing 7.6 % (3.2–11%) of today’s population living on land below the new high tide line (Strauss et al., 2021). The corresponding percentage for a 3.6°F (2°C) warming and 4.7 m global SLR would be 10% (7.4–12%). Based on these warming levels, sea level rise, and present population patterns, NYC is projected to be one of the most impacted cities, along with other populous coastal cities like Shanghai, Hanoi, Dhaka, Kolkata (Calcutta), Mumbai, Tokyo, and Jakarta. Sea level rise and associated coastal flooding is also likely to disproportionately affect low income and non-White communities posing another climate related environmental justice challenge for NYC (Herreros-Cantis et al., 2020).

[7] Adaptation pathways are sequences of linked (portfolios of) actions that can be implemented as conditions change (Haasnoot et al., 2019). Flexible adaptation pathways are sequences of “adaptation strategies that policymakers, stakeholders, and experts develop and implement that evolve as knowledge of climate change progresses” (C. Rosenzweig & Solecki, 2019).

[8] 'Present-day levels' denotes multi-century sea level projections based on cumulative emissions through 2020 only, assuming no further net emissions.

BOX 1: Hurricane Ida

Ida was a deadly Category 4 Atlantic hurricane that originally made landfall in Port Fourchon, southeastern Louisiana on August 29, 2021 before transforming into an extratropical low that caused record-breaking rainfall and deadly inland flooding in New York on September 1, 2021 (Beven et al., 2021). With reported sustained winds of 150 mph, it is the fifth strongest hurricane to make landfall in the United States (Masters and Henson, 2021). Ida developed from a combination of multiple low-latitude weather systems, starting with a tropical wave emerging from the coast of Africa on August 14, 2021 (Beven et al., 2021).

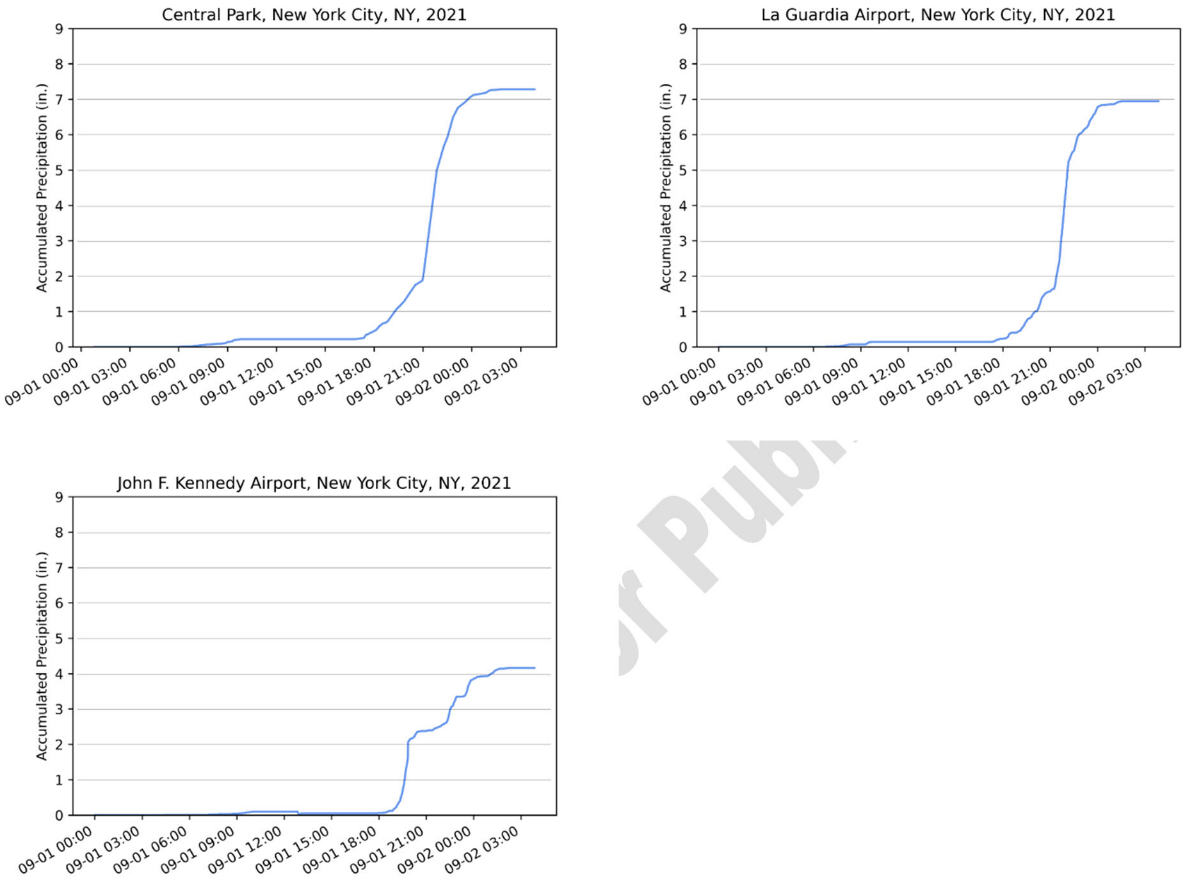


Figure 4. Observed accumulated precipitation at New York City Automated Surface Observing System (ASOS) weather stations during the Ida-remnants cloudburst (1-2 September 2021). Source:(ASOS data accessed through Iowa Environmental Mesonet, 2023a)

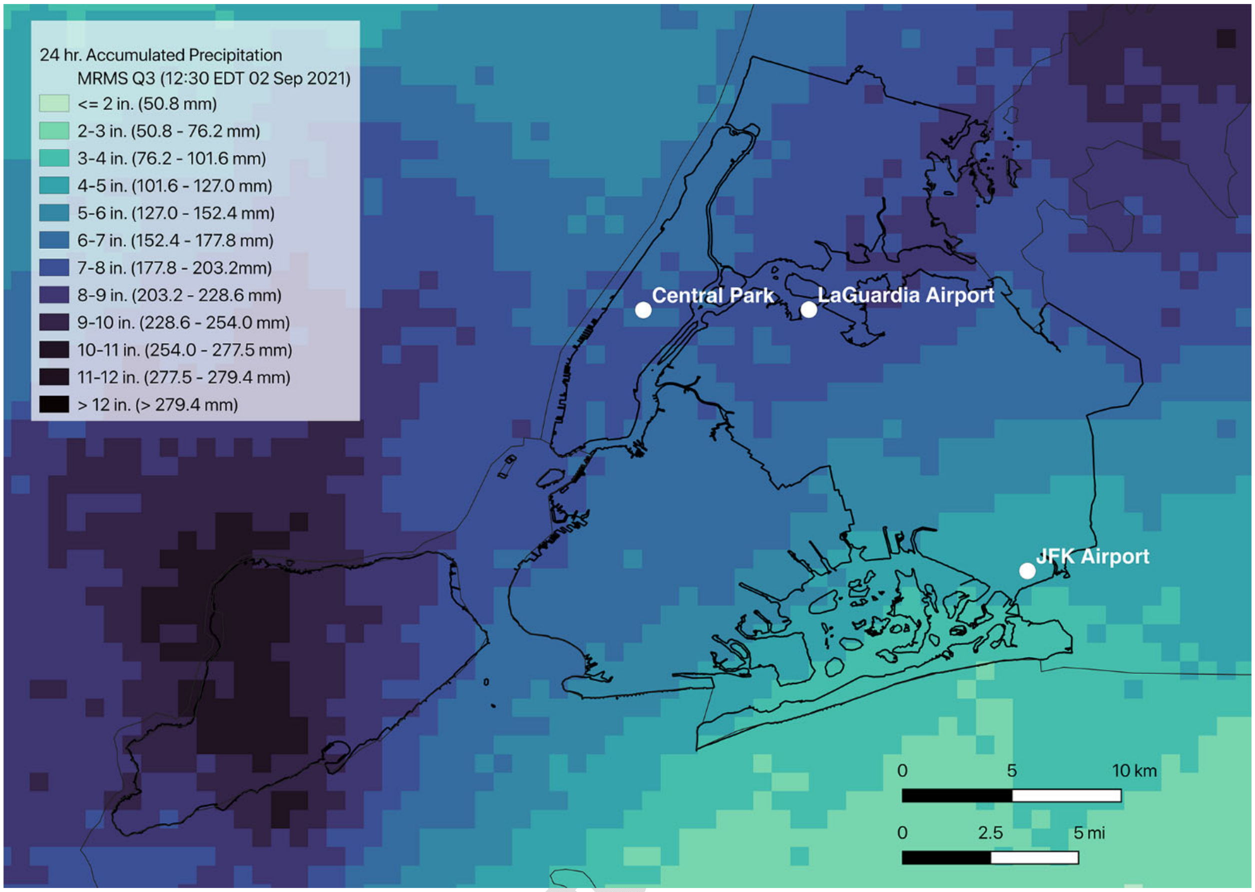


Figure 5: Radar-estimated 24-hour accumulated precipitation between 1 September 2021 (04:00 EDT) and 2 September 2021 (04:00 EDT). The locations of the New York City ASOS weather stations are also shown on this map. Source Multiradar Multisensor Q3 Precipitation Estimate. (Accessed through the Iowa Environmental Mesonet, 2023b).

There has not yet been sufficient research conducted to determine the extent to which the precipitation intensity and duration of the Ida-remnants cloudburst were influenced by anthropogenic climate change, although Frei et al. (2015) and Melillo et al. (2014) found that the Northeast U.S. has experienced an increase in heavy precipitation since the late 1950s. Future projections of North Atlantic (e.g. Emanuel, 2021) and specifically New York State tropical cyclone (TC) activity (e.g. Lee et al., 2022; Marsooli et al., 2019) project TC intensification and more major hurricanes. However, research on tropical cyclones show the past century has exhibited a trend toward decreasing frequency in most ocean basins and a roughly unchanged frequency in the North Atlantic (Chand et al., 2022). Recent work has shown upward trends in rapid intensification of hurricanes in the Atlantic Ocean from 1982-2009 due to anthropogenic climate change (Bhatia et al., 2019). One attribution study found that climate change may play a role increasing the risk of storms with Ida's characteristics, although other signals like the Atlantic Multidecadal Oscillation (AMO) also play a role in the formation of tropical cyclones (Faranda et al., 2022).

4 Sea Level Rise and Storm Surge

Sea level rise and coastal flooding pose growing challenges to protect the large population and major economic assets along NYC's waterfront, due to the city's proximity to the Atlantic Ocean and exposure to severe coastal storms, such as historic severe hurricanes (e.g., in 1821 and 1960) and nor'easters (extra-tropical cyclones; e.g., 1992). Notably, Hurricane Sandy (a hybrid hurricane/extra-tropical cyclone as it propagated into our offshore waters,) generated the highest water levels in at least 300 years (P. M. Orton et al., 2016), as well as extensive flooding, major power outages, transportation disruptions (that were particularly for detrimental for Asian and Latinx residents), 44 fatalities (with almost half of those who died due to Hurricane Sandy were over 65), and an estimated $19 billion in damages in NYC in 2012 (Chavkin, 2013; Faber, 2015).

Projected sea level rise for NYC and other vulnerable coastal locations will exacerbate the destructive hazards posed by storm surges. The increasing frequency of coastal flooding in the United States, for example, is to a large extent caused by rising sea level (e.g., Sweet et al., 2022). Current global and local NYC (NYC) sea level rise trends are briefly reviewed in Sections 4.1 and 4.1.1.

Tide gauges for the past century have measured hourly (or more frequent) variations in coastal ocean water levels. Coupled with earlier sea level measurements of varying frequencies, these provide detailed information on historic mean global sea level change. However, tide gauge observations contain significant temporal data gaps, are unevenly geographically distributed, and only sample coastal locations. Since 1992, radar and laser satellite altimetry observations supplement these measurements with near global ocean coverage at high spatial resolution and also map changes in land ice elevation and ice motion. In addition, since 2002, the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On gravity missions have measured gravity changes caused by increasing ice sheet mass losses, in agreement with satellite altimetry and standard glaciological observations (e.g., The IMBIE Team, 2018, 2020; Zemp et al., 2019). Near-global coverage of Argo ocean-profiling floats since 2006 has also yielded accurate estimates of ocean thermal expansion down to 2000 m depth. The combined analysis of these different observational methods has considerably improved the assessment of global SLR and has helped close the previously existing gap in in our understanding of the relative magnitude of processes leading to SLR (Fox-Kemper et al., 2021; Frederikse et al., 2020; Oppenheimer et al., 2021).

4.1 Global Sea Level Rise

The observed rate of global mean sea level rise (GMSLR) has increased from 1.7 [1.3 to 2.2] mm/yr from 1901 to 2018, up to 3.7 [3.2 to 4.2] mm/yr from 2006 to 2018 (Fox-Kemper et al., 2021, tbl. 9.5). Since the 1970s, thermal expansion and glaciers have been the two main GMSLR contributors with increasing inputs from ice mass losses on the Greenland and Antarctic Ice Sheets (Fox-Kemper et al., 2021). Between 2006 and 2018, the sum of all individual sea level rise components is 3.6 [2.9 to 4.4] mm/yr. Over this most recent period, glaciers and ice sheets combined are now the dominant contributors to GMSLR. The IPCC (2021) finds that human influence is “very likely” the main driver of these increases since at least 1970 (Fox-Kemper et al., 2021). In the future, the cryosphere contributions will dominate, especially in higher GMSLR scenarios (Aschwanden et al., 2019; Edwards et al., 2021; Fox-Kemper et al., 2021, tbl. 9.8; Hock et al., 2019; Quiquet & Dumas, 2021b, 2021a).

Satellite observations (The IMBIE Team, 2018, 2020) and projections in the Fifth IPCC Assessment (AR5) between 2007–2017 show that GMSLR tracks closest to the AR5 upper range of all emission pathways because of increasing ice sheet mass losses (Slater et al., 2020, 2021). Ice mass losses on the Greenland Ice Sheet have been rapidly accelerating since the 1990s (Mouginot et al., 2019; The IMBIE Team, 2020). Ice mass losses between 2000 and 2019 from the Greenland Ice Sheet have created a climate imbalance that commits the equivalent of 274 ± 68 mm to future GMSLR (Box et al., 2022), although at indefinite time scales of up to millennia. In the West Antarctic, a recent study of Thwaites Glacier reveals past periods of rapid ice retreat, which could recur in the near future, once the glacier passes a critical pinning point (Graham et al., 2022). Thwaites Glacier faces potential Marine Ice Sheet Instability (MISI) (see 4.1.1) that, once initiated, could extend the retreat deep inland, given the subglacial topography. These recent cryosphere findings underscore the potential for heightened flood risks associated with sea level rise faced by vulnerable coastal cities and emphasize the importance of improving our understanding of ice sheet processes, initiating significant CO_2 emission reductions, and strengthening our adaptation measures.

4.1.1 Regional Sea Level Rise

Spatial and temporal differences in sea level rise arise due to spatial variability in thermal expansion, changes in ocean circulation, geophysical responses to recent land ice mass losses, other vertical land motions (VLM; e.g., glacial isostatic adjustment [GIA], neotectonics, subsurface fluid withdrawal), and land water storage. Because of the spatial and temporal variability associated with these processes, the sum of sea level rise components at any specific locality may deviate significantly from the global mean (e.g., Garner et al., 2021; Sweet et al., 2022). These regional to local sea level differences become significant in urban planning and efforts to enhance coastal resilience.

Coastal locations in the NYC region continue to experience higher rates of relative, or local, sea level rise (RSLR) as compared to the global mean, a trend that is generally expected to continue into the future as well. This occurs because of glacial isostatic adjustment (GIA)-related subsidence, enhanced thermal expansion, and increasing land ice mass losses. Changes in ocean circulation, such as the Atlantic Meridional Overturning Circulation (AMOC) may also play an increasing role in the future. A slower North Atlantic circulation and weakened spiral oceanic currents would lead to a heat build-up and increased thermal expansion, which in turn would redistribute ocean water mass shoreward especially in the mid-Atlantic region, including NYC (Krasting et al., 2016; Yin & Goddard, 2013).

Sea levels for NYC since 1856 are shown in Figure 6 along with sea level rise driven by VLM and rising sea levels alone. These show that the total sea level rise has resulted from similar contributions of continual (linear) land subsidence (VLM) and accelerating sea level rise. Studies of RSLR impacts at NYC often cite the long-term linear rate of ~3 mm/y (~0.12 in/yr) from this entire period that is available from NOAA (2023), but Figure 6 helps demonstrate that NYC's RSLR is accelerating, as is GMSLR. An estimate of the recent RSLR rate is obtained from taking the 8-year running average at September 2018 minus the 8-year running average at 1990, which gives a rate of 4.6 mm/y (0.18 in/yr).

A key uncertainty in future sea level rise is the behavior of the ice sheets, and in particular, the Antarctic Ice Sheet, which holds the equivalent of 58.3 m (191.2 ft) of global SLR if all its ice melted. Therefore, NPCC3 (Gornitz et al., 2019) also considered one high end, low probability scenario—the Antarctic Rapid Ice Melt (ARIM) scenario, which includes potential instability of the West Antarctic Ice Sheet (WAIS). Much of the WAIS lies on land below sea level, on reverse slopes that tilt toward the continental interior. This is an inherently unstable topographic configuration which could lead to Marine Ice Sheet Instability (MISI), a potential process in which an ice stream or glacier on a reverse slope near the grounding line accelerates, discharging more and more ice, until the bed slope flattens or rises landward (e.g., Fig. 2 in Gornitz et al., 2019; see also Milillo et al., 2022).

Another posited process is the Marine Ice Cliff Instability (MICI) that depends on structural weakness of a high ice cliff (>100 m (~328 ft) exposure above sea level) after thinning and removal of a buttressing ice shelf. The longitudinal stresses on the exposed cliff face would lead to collapse. Additionally, in a warmer climate, meltwater that accumulates on top of an ice cliff during the summer season would propagate down crevasses and cut through the ice like a knife until reaching the bottom in a process known as hydrofracturing. As large ice masses split off, ice cliff retreat speeds up (e.g., Fig. 2 in DeConto & Pollard, 2016).

In the ARIM scenario, which considers the possibility of these instabilities by the end of this century, sea level rise could reach 2.1 m by the 2080s and 2.9 m by 2100 (Gornitz et al., 2019, Figure 2; 2020). Expert elicitation of future sea level rise, localized for NYC suggests that the ARIM scenario would have an estimated ~3% chance of occurring by 2100 at high emissions, but near zero probability under low emissions (Bamber et al., 2019; Gornitz et al., 2019), In a re-evaluation of their 2016 paper, Pollard et al. (2021) use improved model physics and revised atmospheric forcing to find a substantially lower RCP8.5 median contribution to global mean sea level (GMSL) by 2100 than in their earlier paper which delays the onset of increased surface melt. Nonetheless, by 2025, the median contribution to GMSL for Antarctica reaches 1 m and rates exceed 6 cm/yr by 2150. By 2300, Antarctica will contribute 9.6 m (31.5 ft.) of GMSLR under RCP8.5 (DeConto et al., 2021), due to sustained emissions increases that extend past 2100.

Conflicting assessments evaluate the future stability of the WAIS. On the one hand, negative feedbacks such as glacial rebound and a weaker gravitational attraction may mitigate the full extent of MISI (e.g., Barletta et al., 2018; Gomez et al., 2015). MICI may be delayed by a slow retreat of ice shelves (Clerc et al., 2019), and limitations of the rapidity (or effectiveness) of hydrofracturing (Robel & Banwell, 2019), as there is no solid evidence for an observed MICI in the modern era, nor in the geological past (Edwards et al., 2019). On the other hand, several regions of higher vulnerability to MISI appear on a recent topographic survey beneath the margins of the WAIS. In particular, the Thwaites Glacier, which once it passes beyond two ridges would become "unstoppable" (Morlighem et al., 2020). Several other potentially vulnerable regions on the East Antarctic Ice Sheet were also identified in that study. Lhermitte et al. (2020) detect highly fractured and crevassed areas on marginal shear zones near and at the grounding lines of the Thwaites and Pine glaciers. Damaged areas are rapidly expanding and contribute to the structural weakening of these glaciers, both of which lie on MISI-prone retrograde slopes. Three other WAIS glaciers near the Thwaites and Pine glaciers are also rapidly retreating in the last decade (Milillo et al., 2022). These recent observations raise renewed concerns over the long-term stability of the WAIS with continued climate warming.

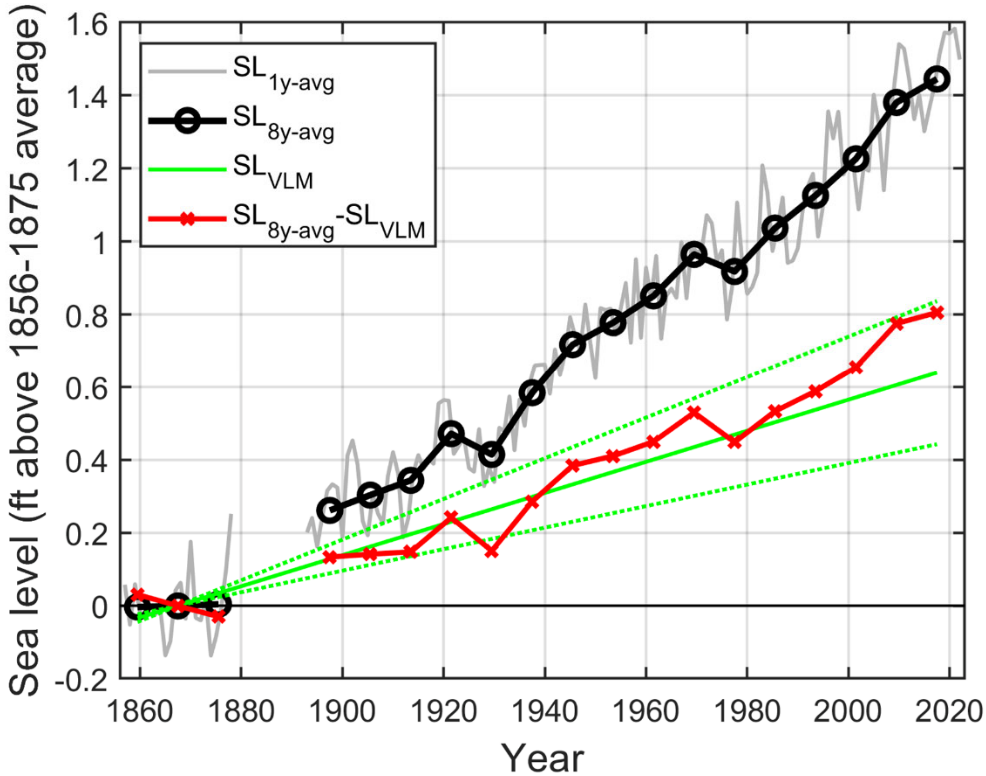


Figure 6: New York Harbor sea level from 1856 to 2022 with 1-year (gray) and 8-year (black) averaging, and as partitioned into change due to vertical land motion only (VLM; green) and rising sea levels only (red). A VLM estimate of -1.5 mm/year (+/- 0.2 mm 95% confidence) for the Battery tide gauge is utilized (Garner et al., 2021).

4.2 Sea Level Rise Projections

"Based on climate analyses, regional and global trends, and a review of scientific literature", NPCC confirms which climate projections of sea level rise (i.e. projections of record) are most appropriate for use in resiliency planning for the city and region (C. Rosenzweig & Solecki, 2019). The NASA Sea Level Projection Tool was utilized to download the sea level projection data from the IPCC 6th Assessment Report (AR6) as it is publicly available and provides easy access to the consensus projections found in the report. Table 1 shows that sea level is projected to rise along the New York State coastline and in the tidal Hudson by 7 to 11 inches (177.8-279.4 mm) by the 2030s, 14 to 19 inches (355.6-482.6 mm) by the 2050s, and 25 to 39 inches (635-990.6 mm) by the 2080s (all relative to a 1995-2014 baseline period). The high-end estimate (i.e. the 90th percentile) for sea level rise by the 2080s is 45 inches (1145 mm). By 2100, sea levels are projected to rise by as much as 65 inches (1651 mm) (See Appendix C.4 for methodological details).

Under the ARIM scenario presented in 2019 by NPCC3, accelerated loss of land-based ice could lead to sea level rise of up to 81 inches (2057.4 mm) by the 2080s and 114 inches (2895.5 mm) by 2100 under a plausible 'worst-case' scenario that cannot entirely be ruled out.

Given the risk tolerance of NYC stakeholders and their commitment to equitable adaptation, it is important for decision-makers to account for a broad range of sea level rise outcomes, including low-probability, high consequence scenarios (instead of planning based on one potential future). To this end, NPCC2 and NPCC4 instead provide a full range of projections. Here we utilize the newly available SSP5-8.5-*low confidence* SLR scenario (along with SSP2-4.5-*medium confidence* and SSP2-4.5-*medium confidence* scenarios) to quantitatively account for the potential impact of deeply uncertain ice sheet processes in a manner that was not possible when the ARIM scenario was developed (as the SSP5-8.5-*low confidence* scenario was not available for NPCC3). This work represents an advancement by NPCC in terms of developing SLR projections for urban risk management as we use three scenarios here (instead of only using two scenarios and not explicitly accounting for the risk associated with MISI and MICI) (Rising et al., 2022). This report also references the aforementioned higher-end ARIM scenario projection developed in 2019 for NYC by NPCC3 as we deem this to still represent a plausible low probability, high consequence outcome that is still useful in a variety of long-term decision contexts (Gorddard et al., 2016), where consequences would be particularly catastrophic.

Table 1: Projections for sea level rise in New York City for 2030 to 2150. Equal weights were assigned to each of the three scenarios utilized.

	10th Percentile	25th Percentile	75th Percentile	90th Percentile
2030s	6 in.	7 in.	11 in.	13 in.
2050s	12 in.	14 in.	19 in.	23 in.
2080s	21 in.	25 in.	39 in.	45 in.
2100	25 in.	30 in.	50 in.	65 in.
2150	38 in.	47 in.	89 in.	177 in.

An assumption applied in creating NPCC coastal flood maps has been and continues to be that future storm surges will change primarily due to sea level rise. However, it is increasingly understood that climate induced changes to tropical cyclones will impact storm surges as well. Specifically, there is consensus that atmospheric warming will likely intensify tropical cyclones in the future (Emanuel, 2005; Knutson et al., 2020). Cyclogenesis, storm frequency, and storm tracks are also likely to shift (Chand et al., 2022; Lee et al., 2020; Sobel et al., 2021). Any of these changes could directly impact storm surges in the NYC metropolitan region.

Projections of storm surges are often developed using statistical and/or deterministic downscaling approaches, which model tropical cyclones from global climate model data to simulate storms of a future climate. The simulated tropical cyclones are then coupled to numerical hydrodynamic models to assess the resulting storm surges (e.g., Camelo et al., 2020; Lin et al., 2012, 2012; Mayo & Lin, 2022). Recent studies of NYC predict large increases in extreme storm surge levels and inundation by the end of the 21st century due to sea level rise and additional increases due to the changing climatology of tropical cyclones (Camelo et al., 2020; Marsooli et al., 2019). However, there is considerable uncertainty and spatial variability in the supporting data, and projections of end of century storm surge risk remains an active research area.

5 Inland and Coastal Flooding

In the U.S., extreme flood events and their impacts have become more frequent and intense over the past several decades. The National Oceanic and Atmospheric Administration (NOAA) reports that the U.S. annual average of flood related deaths has increased over the past 10 years (National Weather Service, 2021). NOAA has estimated $60 billion of losses from Hurricane Ida in Louisiana, New York and New Jersey (National Oceanic and Atmospheric Administration, 2021). Global reinsurance provider Swiss Re estimated the devastation from Ida, including flooding damage in New York, at nearly $32 billion, equals nearly 30 percent of the $105 billion of total global insured losses caused by natural disasters in 2021, the fourth highest losses since 1970 (Swiss Re, 2021).

Although Hurricane Ida was not associated with a significant coastal storm surge event in the NYC area, flash floods due to heavy rainfall as the tropical storm passed overhead caused the deaths of 18 New Yorkers statewide, with 13 of those in NYC (Hanchey et al., 2021; New York City Government, 2021). Frei et al., (2015) show increases in extreme precipitation in the Northeastern U.S. during the period from 1935 to 2012, with more events occurring in the latter half of the period (since the 1970s) compared to the first few decades since 1935. Further, Howarth et al. (2019) report that extreme precipitation in the Northeast U.S. showed an increasing trend between 1979 and 2014, attributed to both an increase in the frequency and intensity of extreme events.

The exact number of residents occupying basement and cellar apartments in NYC is unknown and difficult to estimate, as many of these units are illegal and have not been permitted or registered. However, it should be noted that legal subgrade residences are often just as dangerous during floods as illegal, unregistered units. The requirements associated with permitting a basement residence address lighting and fire hazard, but not flooding. Based on comparisons of census data, records of construction and certificates of occupancy, it is estimated that

300,000+ New Yorkers may live in basement and cellar apartments across the city (Neuwirth, 2008, p. 2). A disproportionate number of these basement and cellar apartment residents may be low-income, immigrants, non-White, and/or working-class New Yorkers.

The NYC Comptroller submitted written recommendations on August 15, 2022 to NYC Emergency Management and New York State Division of Homeland Security and Emergency Services highlighting the equity gaps in current emergency response systems as well as short- and long-term relief and rehabilitation initiatives, including long-term case management (in the 10 citywide designated official languages) and post-disaster housing management for residents unable to return to their homes (Lander & City of New York Office of the Comptroller, 2022).

5.1 Inland and Coastal Flooding Projections

Sea level rise (SLR) is causing increases in coastal flooding during storm surge events (e.g., Buchanan et al., 2017; Kopp et al., 2014; Tebaldi et al., 2012) and more frequent high-tide flooding (e.g., Sweet et al., 2021, 2022). NPCC[9] has created extreme event flood maps since 2010 based on superimposing sea level rise on top of the FEMA 100- and 500-year flood elevations and using static (also known as bathtub) modeling to map the increasing flood area. NPCC3 provided new maps showing the advancement of monthly tidal flooding with sea level rise (P. Orton et al., 2019; Patrick et al., 2019), which can be complementary to the city's existing mapping of daily tidal flooding with sea level rise (e.g. City Planning flood mapper) because they better capture the onset of tidal flooding that can occur decades earlier than daily tidal flooding (P. Orton et al., 2019).

FEMA has a project underway to update the 100- and 500-year flood zones, and the city's Future Flood Risk Mapping (FFRM) project will use these results to update the future flood maps. However, the FEMA project's delays have led to delays for the FFRM and its outputs. Also, NPCC has never created maps of rainfall-driven (pluvial or fluvial) flooding, in part because urban pluvial flood modeling is in relative infancy compared with coastal or fluvial flood modeling (B. R. Rosenzweig et al., 2021). However, NYC recently completed its first ever citywide extreme rainfall driven flood projections which it released as part of the first NYC Stormwater Resiliency Plan in May 2021 (City of New York Mayor's Office of Resiliency, 2021). Three stormwater flooding scenarios have so far been made publicly available. The moderate scenario corresponds to a 1-hour, 10-year storm (approximately 2 inches) and 2.5 feet of sea level rise above a 2000 baseline, based on NPCC3 projections for 2050 and the more extreme scenario corresponds to a 1-hour, 100-year storm (approximately 3.5 inches) and 4.8 feet of sea level rise (NPCC's 90th percentile estimate for 2080; Gornitz et al., 2019). Though NPCC has not previously studied probabilities or mapped compound flooding, current research to assess vulnerability, impacts and adaptations (funded by NYC's Department of Citywide Administrative Services) is quantifying the potential for surge and rainfall to occur simultaneously, compounding flood depths or area . We expect that the results of these analyses will be available to inform future NPCC assessment reports.

6 Temperature and Precipitation

6.1 Observed Annual Temperature Trends

This report extends temperature trends reported in previous NPCC reports to the year 2021 using data from the Central Park weather station (Table 2). Annual mean temperatures for this report's baseline period (1981-2010) were approximately 55.1°F at Central Park and 55.8°F at LaGuardia Airport, marking an increase of close to 0.6°F from the 2015 NPCC report's baseline (1971-2000) at both stations (Menne et al., 2012, 2018; National Centers for Environmental Information, 2023). Multi-decade trends vary across time. For example, temperatures between 1941-1970 decreased at a pace of -0.3°F per decade at Central Park and -0.7°F per decade at LaGuardia, while the most recent 30-year period (1991-2020) exhibited warming of 0.5°F and 0.6°F per decade for Central Park and LaGuardia, respectively. Longer term trends, however, indicate overall warming, with temperatures increasing at a rate of 0.38°F per decade and 0.52°F per decade at Central Park at LaGuardia, respectively (Figure 7). Long term trends between the two stations are not directly comparable, as the Central Park (1900-2021) record is several decades longer than that of LaGuardia (1942-2021). However, when considering trends over their overlapping temporal coverage, between 1942-2021, results are virtually unchanged. There are spatial variations in temperature and temperature change trends across NYC. For instance, temperature records from the weather station at LaGuardia are consistently warmer than Central Park by close to 1.6°F, with the difference between them growing larger over time.

[9] There are no revisions to previously developed flood maps, nor new flood mapping/analysis, in this NPCC report.

Table 2: Mean temperature and precipitation accumulation in New York City using the baseline period from 1981 to 2010 and based on data from the Central Park weather station (National Centers for Environmental Information, 2023).

Time Period	Mean Temperature	Mean Precipitation
Annual	55.2°F	49.9 in.
January	32.8°F	3.7 in.
February	35.5°F	3.1 in.
March	42.7°F	4.4 in.
April	53.3°F	4.5 in.
May	62.6°F	4.2 in.
June	71.7°F	4.4 in.
July	76.7°F	4.6 in.
August	75.5°F	4.4 in.
September	68.2°F	4.3 in.
October	57.2°F	4.4 in.
November	47.9°F	4.0 in.
December	37.8°F	4.0 in.
Winter	35.4°F	10.7 in.
Spring	52.9°F	13.0 in.
Summer	74.6°F	13.5 in.
Fall	57.8°F	12.7 in.

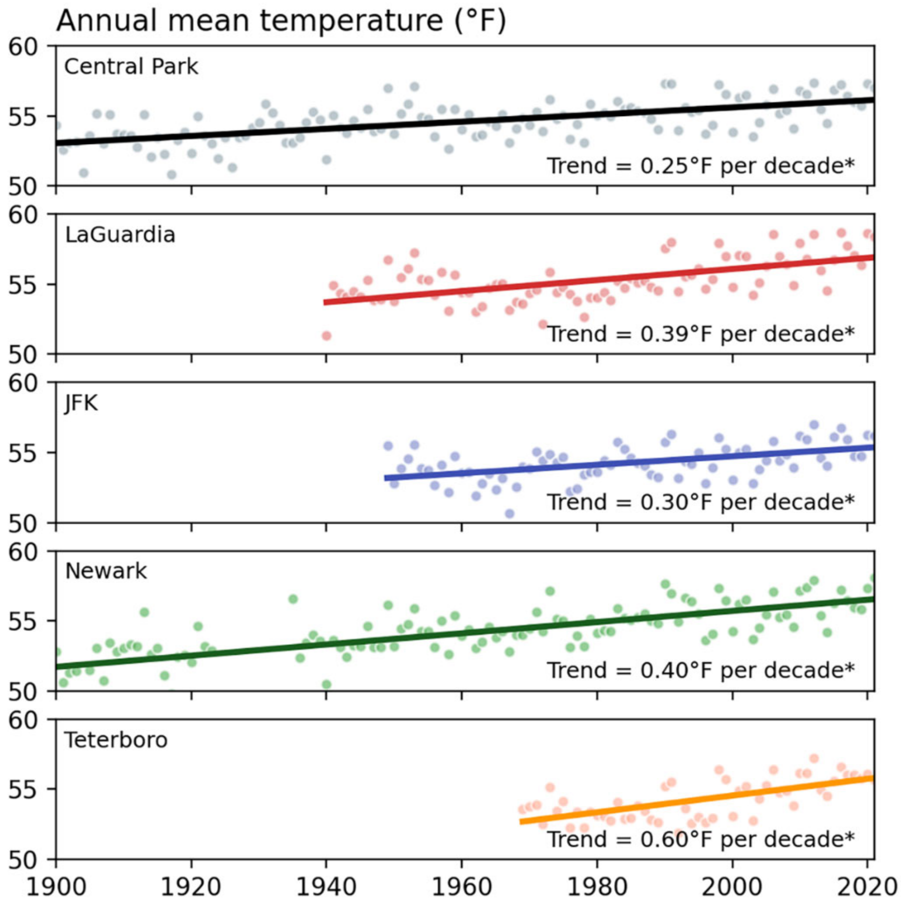


*Figure 7: Observed annual temperature trend in NYC and surrounding areas. Data are from the Global Historical Climatology Network-Monthly (GHCN-M) Version 4 (Menne et al., 2018). *Yearly trend is statistically significant.*

6.2 Observed Extreme Heat Events

Extreme temperatures impact NYC in a variety of ways. Hot days can lead to increased deaths and hospitalizations due to heat stroke and exacerbated existing conditions (City of New York Department of Health and Mental Hygiene, 2022a). Although trends in the incidence of temperature extremes are often not statistically significant, records show that the most recent 30-year period experienced the highest number of days above 90°F (17 days per year), the temperature threshold used by the National Weather Service to declare a heat wave, compared to the first 30 years in the record at Central Park (11 days per year), shown in Figure 8.

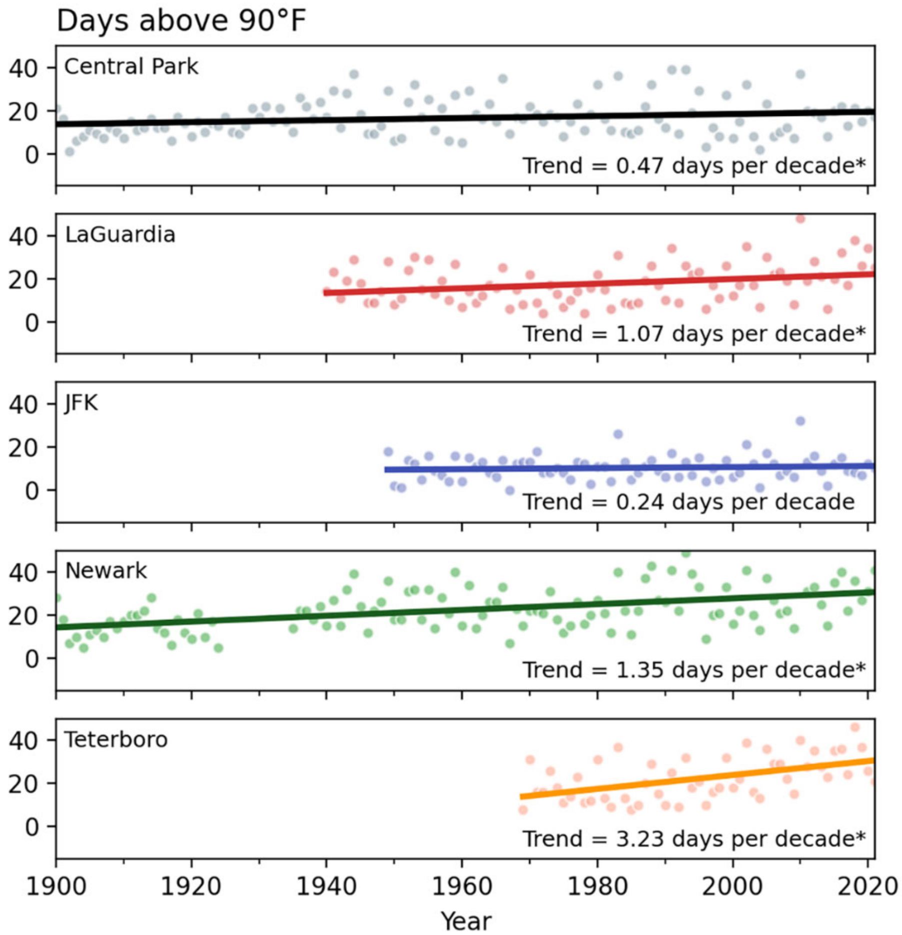


*Figure 8: Number of days with temperatures above 90°F in NYC and surrounding areas from 1900 to 2021. Data are from the Global Historical Climatology Network-Daily (GHCN-D) Version 4 (Menne et al., 2018). *Yearly trend is statistically significant.*

Within the last decade the number of summer (June- August) days over 90°F has increased (Figure 9). Temperature increases between JFK and Central Park are marginal, most likely due to the buffers of the Atlantic Ocean and park vegetation at the two sites, respectively. Over 20% of the summer days over the past decade at LGA have a daily maximum temperature greater than 90°F. This is 8% more than the previous five decades. The hottest month is July where over 33% of mid-July dates over that past decade experience extreme heat.

Similar to the daytime temperature, nighttime temperatures at LGA have increased by a wider margin than Central Park and JFK. Nearly 26% of the summer days at LGA have a daily minimum temperature greater than 75°F (i.e. the inflection point on heat mortality (City of New York Department of Health and Mental Hygiene, 2021) over the past decade (Figure 10). More than 40% of July observations are greater than 75°F. Elevated nighttime temperatures pose the greatest risk to human health as they do not allow time for the body to recover from high daytime temperature, creating extended exposure to high temperatures.

Extreme heat poses a major risk to the public health of NYC residents (See Appendix A). The heat vulnerability index (HVI) (Figure 11) is an epidemiological study (City of New York Department of Health and Mental Hygiene, 2022b) which characterizes the relative risk of heat related mortality during a heat wave event. HVI scores range from 1 (low risk) to 5 (high risk) and include both environmental (i.e. surface temperature, NDVI) and social (i.e. air conditioning access, percent of Black residents, percent poverty) indicators. The spatial distribution of the HVI varies unequally across NYC neighborhoods. NYC agencies have used the HVI to develop neighborhood scale climate adaptation and mitigation programs that are equitably distributed across the city. Two examples include the Cool Neighborhoods

NYC initiative (City of New York Mayor's Office of Resiliency, 2017) and Green Roof Tax Abatement program (City of New York Department of Finance, 2023).

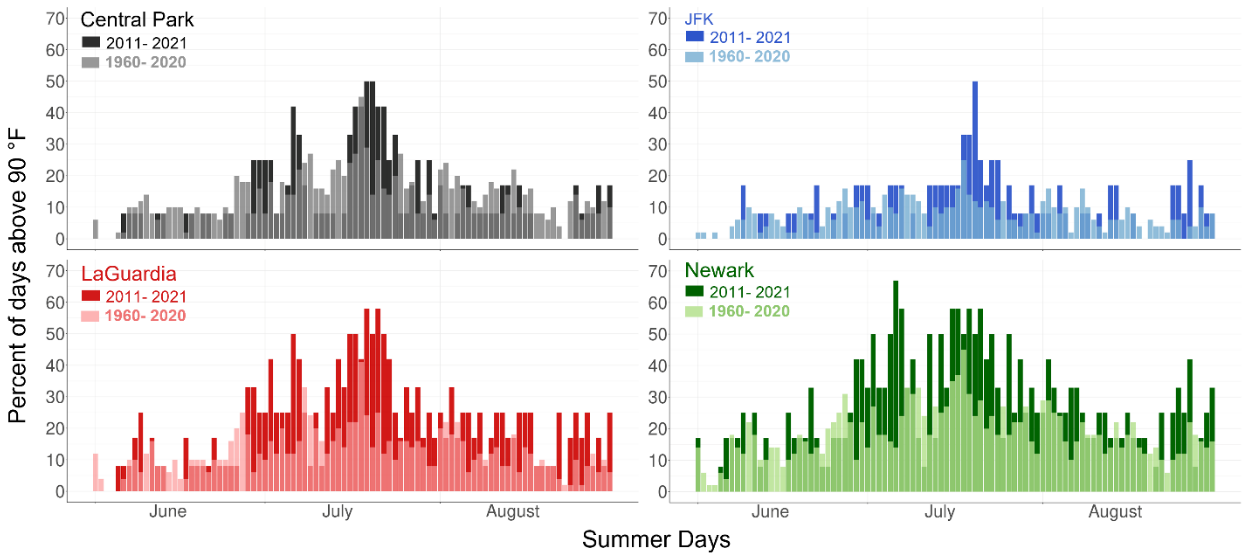


Figure 9: Percentage of days at or above daily maximum air temperature of 90°F on each summer date for years 1960-2010 and 2011-2021 at Central Park, LaGuardia, JFK and Newark airports. Data smoothed with a 7-day moving average. Data Source: NOAA National Centers for Environmental Information - Climate Data Online (www.ncei.noaa.gov/cdo-web/)

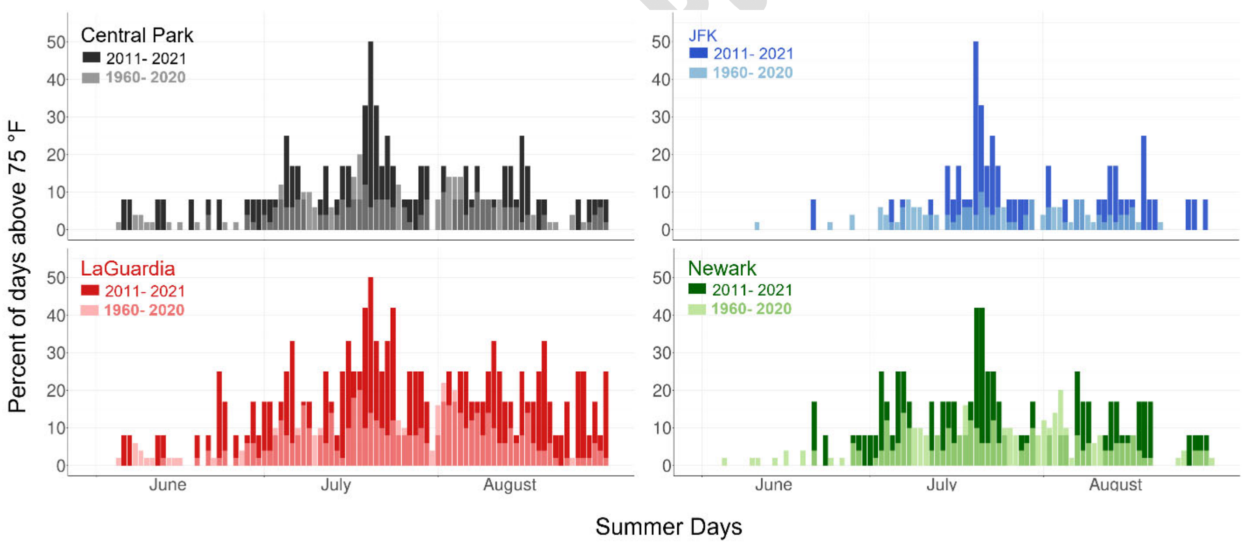


Figure 10: Percentage of days at or above daily minimum air temperature of 75°F on each summer date for years 1960-2010 and 2011-2021 at Central Park, LaGuardia, JFK and Newark airports. Data smoothed with a 7-day moving average. Data Source: NOAA National Centers for Environmental Information - Climate Data Online (www.ncei.noaa.gov/cdo-web/)

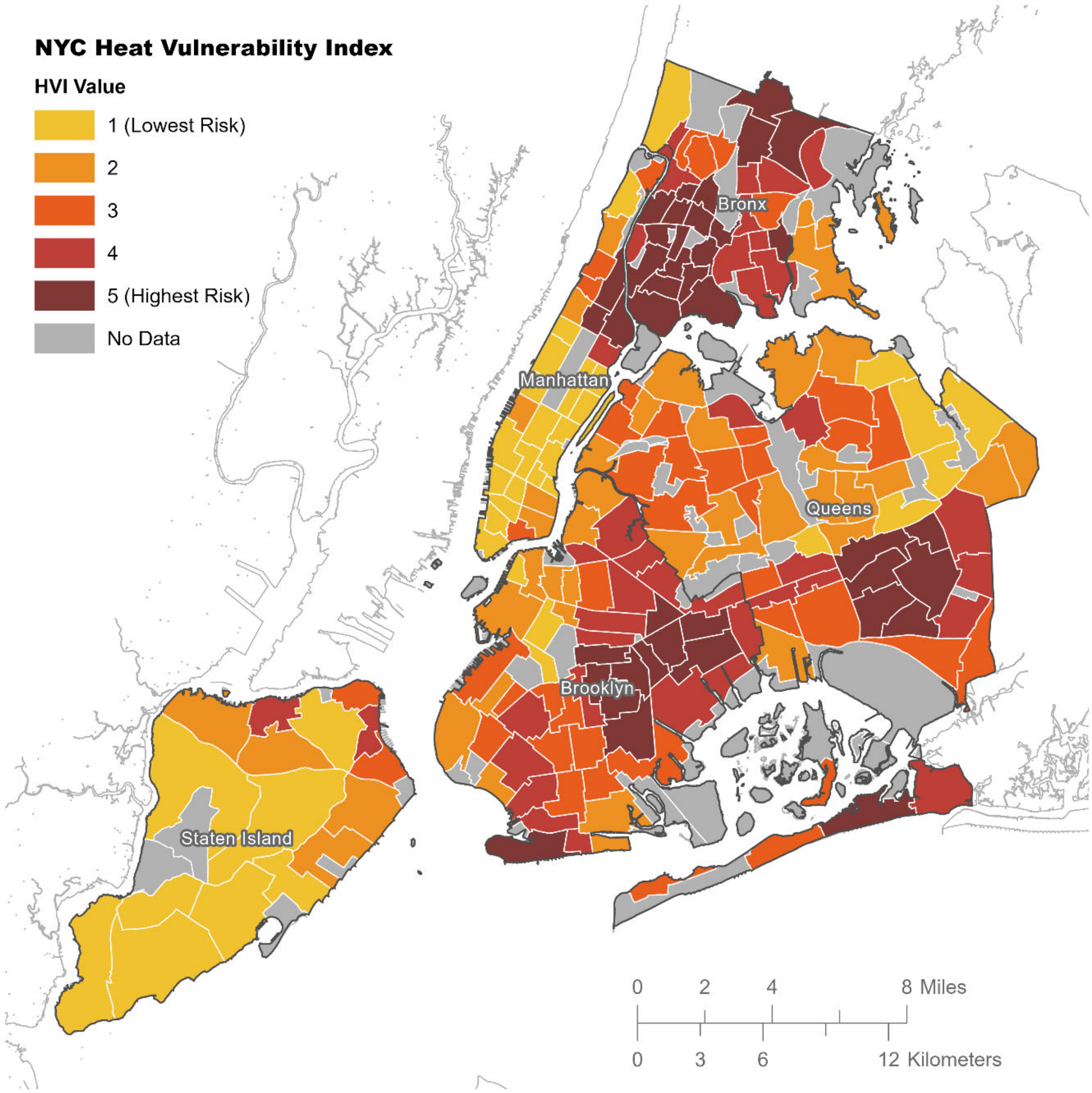


Figure 11: NYC Heat Vulnerability Index. Data Source: (City of New York Department of Health and Mental Hygiene, 2023).

6.3 Observed Extreme Cold Weather Events

Meanwhile, the number of days with minimum temperatures below freezing has been steadily declining since 1900, with the records showing a statistically significant trend of approximately 2 and 3 fewer days per decade at the Central Park and LaGuardia Airport weather stations, respectively (Figure 12). On average, the number of days below freezing at Central Park during the 1900-1929 period was 87, with the most recent 30 years experiencing less than 70 days.

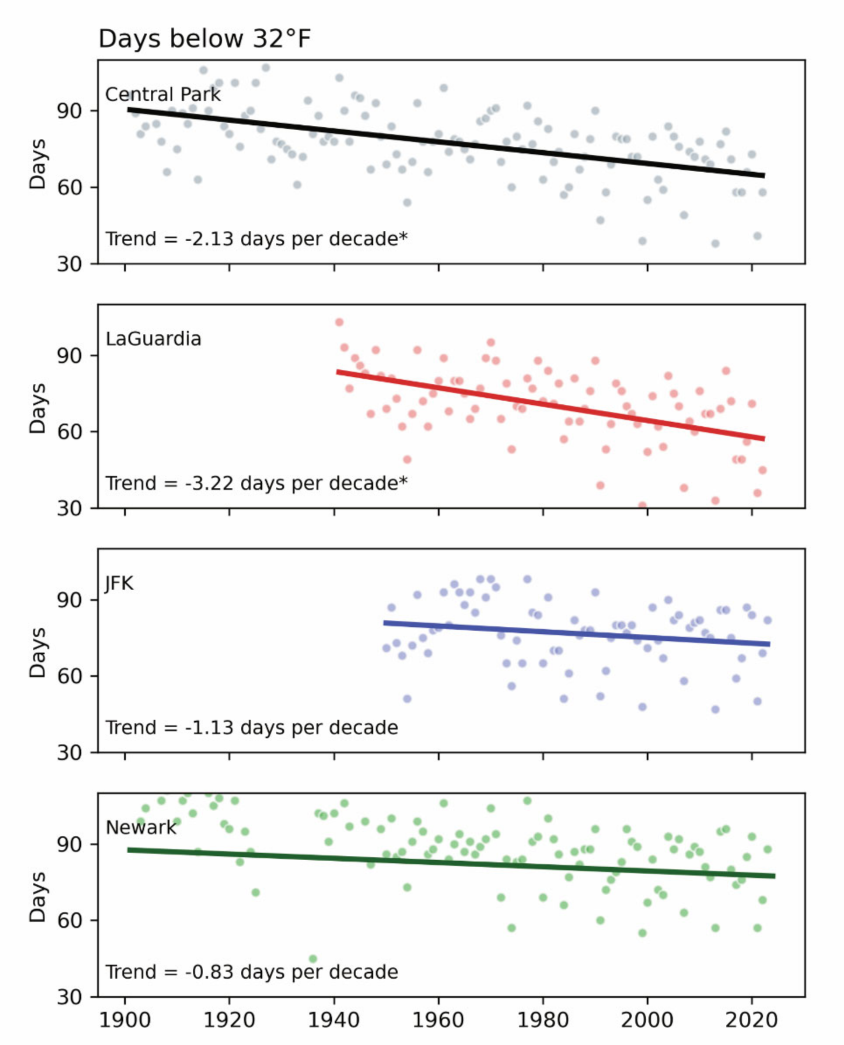


*Figure 12: Number of days with temperatures below freezing (32 degrees F) in NYC and surrounding area from 1900 to 2021. Data are from the Global Historical Climatology Network-Daily (GHCN-D) Version 4 (Menne et al., 2018). *Yearly trend is statistically significant.*

6.4 Temperature and Precipitation Projections

"Based on climate analyses, regional and global trends, and a review of scientific literature", NPCC confirms which climate projections of temperature and precipitation (i.e. projections of record) are most appropriate for use in resiliency planning for the city and region (C. Rosenzweig & Solecki, 2019). As shown in Table 3, average annual precipitation is projected to increase by approximately 2 to 7 percent by the 2030s, 4 to 11 percent by the 2050s and 7 to 17 percent by the 2080s (See Appendix C.1 for methodological details). In general, the projected changes in precipitation associated with increasing GHGs in the global climate models (GCMs) are small relative to year-to-year variability. Although seasonal projections are less certain than annual results, the greatest increases in precipitation are projected to occur during the winter months. In the summer and fall seasons, smaller increases are generally projected. Across all seasons, some GCMs project reductions in mean precipitation, with the greatest decreases projected for the summer and fall seasons.

As shown in Table 3, average annual temperatures are projected to increase across NYC by 2.7 to 3.9 F by the 2030s, 4.0 to 6.0 F by the 2050s, and 5.6 to 9.8 F by the 2080s. The projected changes are similar for both SSPs until approximately the 2040s, when they begin to deviate and SSP5-8.5 has greater warming for the remainder of the century. The climate models suggest that each season will experience a comparable amount of warming relative to the 1981 to 2010 baseline period.

Higher temperatures are extremely likely for the New York metropolitan region in the coming decades. Compared to changes in surface temperature, changes in air temperature may be considered more relevant for human living conditions (Winckler et al., 2019). However, it should be noted that Avashia et al., (2021) recently found that “the microclimate in a city as represented by land surface temperatures is a better indicator for estimating relative risk of temperature related mortality as compared to air temperature”. All model simulations project continued temperature increases for NYC through the end of this century. Nearly all GCM simulations indicate small increases in precipitation. Natural precipitation variability is large; thus, precipitation projections are less certain than temperature projections.

Table 3: Projections for average annual temperature and precipitation accumulation for 2030 to 2100. Projections are based on 35 GCMs and 2 SSPs; shown are the low-estimate (10th percentile), middle range (25th to 75th percentile), and the high-estimate (90th percentile) from left to right. Equal weights were assigned to each GCM and to each of the two selected SSPs.

Decadal Period	Mean Annual Temperature*	Mean Annual Precipitation*
2030s	+2°F (+2.7°F to +3.9°F) +4.7°F	+0% (+2% to +7%) +10%
2040s	+2.8°F (+3.3°F to +5°F) +5.9°F	+0% (+3% to +9%) +13%
2050s	+3°F (+4°F to +6°F) +7.1°F	+0% (+4% to +11%) +14%
2060s	+3.6°F (+4.7°F to +7.1°F) +8.6°F	+0% (+5% to +13%) +16%
2070s	+4.2°F (+5.1°F to +8.4°F) +10.2°F	+0% (+6% to +14%) +19%
2080s	+4.8°F (+5.6°F to +9.8°F) +11.6°F	+2% (+7% to +17%) +22%
2100	+5.1°F (+6.1°F to +10.7°F) +13.5°F	-1% (+5% to +21%) +30%

** Several of the 35 GCMs utilized for temperature and precipitation projections are associated with the “hot model” problem identified by Hausfather et al., (2022); See Section 6.4.2.*

6.4.1 Extreme Weather Event Projections

Although the increase in total annual precipitation is projected to be relatively small, models project somewhat larger increases (i.e. larger positive percentage changes) in the frequency of extreme precipitation events (defined as events with more than 1, 2, or 4 inches of precipitation at daily timescales).

The total number of hot days in NYC is expected to increase as this century progresses. The frequency and duration of heat waves, defined as three or more consecutive days with maximum temperatures at or above 90°F, are also expected to increase. In contrast, extreme cold events, defined as the number of days per year with minimum temperature at or below 32°F, are expected to decrease.

The projections for extreme heat and extreme precipitation events are summarized in Table 4 (See Appendix B for additional climate risk information associated with extreme precipitation). Projections of daily temperature (maximum and minimum) and precipitation were computed using a method known as quantile mapping (See Appendix C.2). The projections are based on 16 GCMs and 2 emission scenarios (i.e. SSP2-4.5 and SSP5-8.5). Baseline data are for the 1981 to 2010 base period and are from the NOAA National Climatic Data Center (NCDC) (Arguez et al., 2012). Shown are the low-estimate (10th percentile), middle range (25th to 75th percentile), and high-estimate (90th percentile) 30-year mean values from model-based outcomes. Decimal places are shown for values less than 1, although this does not indicate higher precision or certainty. Heat waves are defined as three or more consecutive days with maximum temperatures at or above 90 °F.

Table 4: Projections for extreme heat and extreme precipitation events in NYC for 2030 to 2100. Baseline data are for 1981 to 2010.

2030s	Baseline	10th Percentile	25th Percentile	75th Percentile	90th Percentile
Days at or above 90°F	17	27	27	46	54
Days at or above 95°F	4	8	8	17	27
Days at or below 32°F	70	34	39	52	58
Days at or above 1 inch precipitation	14	14	14	16	17
Days at or above 2 inches precipitation	3	3	3	4	5
Days at or above 4 inches precipitation	0.2	0.2	0.3	0.4	0.4
Number of heat waves	2	3	3	6	7
Avg. length of heat waves (days)	4	5	5	5	6
2050s					
Days at or above 90°F	17	32	38	62	69
Days at or above 95°F	4	10	14	32	35
Days at or below 32°F	70	17	31	48	52
Days at or above 1 inch precipitation	14	14	15	17	17
Days at or above 2 inches precipitation	3	3	4	5	5
Days at or above 4 inches precipitation	0.2	0.2	0.3	0.4	0.4
Number of heat waves	2	4	5	8	9
Avg. length of heat waves (days)	4	5	5	6	6
2080s					
Days at or above 90°F	17	46	46	85	108
Days at or above 95°F	4	17	17	54	73
Days at or below 32°F	70	3	9	39	48
Days at or above 1 inch precipitation	14	14	15	17	18
Days at or above 2 inches precipitation	3	4	4	6	6
Days at or above 4 inches precipitation	0.2	0.3	0.4	0.6	0.7
Number of heat waves	2	6	6	9	10
Avg. length of heat waves (days)	4	5	5	8	10

6.4.2 Indoor temperatures and climate change

Indoor temperatures in non-air-conditioned spaces are often hazardous. In NYC, the majority of direct heat-attributed and heat-exacerbated deaths start inside insufficiently cooled homes (City of New York Department of Health and Mental Hygiene, 2022a). Studies evaluating linkages between observed outdoor and indoor temperatures often find weak correlations (Nguyen et al., 2014; Vant-Hull et al., 2018; Waugh et al., 2021) due to non-linear energetic interactions between building envelopes and the atmosphere as well as prevalence and usage of air conditioning. One of the leading sources of these non-linear interactions, heat stored in building materials, can significantly impact indoor temperatures by holding on to heat and slowing down cooling compared to outdoor air.

Understanding the impact of NYC's changing climate on indoor temperatures requires observations and modeling of indoor conditions and the processes that contribute to its spatiotemporal variability. Monitoring campaigns of indoor thermal comfort in NYC have found significant differences between not only indoor and outdoor temperatures, but also between dwellings with different characteristics like presence of indoor cooling, type of air conditioning, and even proximity to the roof (Quinn et al., 2017; Vant-Hull et al., 2018). Meanwhile, Hrisko et al (2021) found significant spatiotemporal variability of heat storage in NYC using highly temporally-resolved satellite imagery.

Advances in urban-scale climate models have begun to quantify how changing climate may impact indoor conditions. A case-study using the an urbanized Weather Research and Forecasting Model (WRF) in NYC found that absent air conditioning, large portions of the city could experience more than double the amount of hours with heat index levels categorized by the National Weather Service as *Very Hot* (heat index > 40.6°C) by end of century under a high emissions scenario, with currently warm locations like the South Bronx expected to see close to 90% of total summer hours past that threshold (Ortiz et al., 2022).

6.5 Comparative study of CMIP6 models

Several studies including the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6) have identified global climate models (GCMs) associated with the Coupled Model Intercomparison Project Phase 6 (CMIP6) that project rises in temperature by the end of the century that might be larger than that supported by other evidence (e.g., Ribes et al., 2021). To constrain the model sensitivity and warm bias, Hausfather et al. (2022) recommends using the Transient Climate Response (TCR) of the GCMs as a filtering category. The IPCC 'very likely' range for TCR of 1.2 to 2.4 degrees C. (IPCC, AR6-WG1, TS) filters GCMs to 24 models out of 30 available[10] models.

To assess this further, we compare projections from two storylines to provide stakeholders with comprehensive risk information. The two storylines include a) ensemble projections for scenarios SSP2-4.5 and SSP5-8.5 from 30 GCMs and b) ensemble projections for scenarios SSP2-4.5 and SSP5-8.5 from a subset of 24 models based on the TCR 'very likely' range.

Projections for both the storylines are calculated from NASA Earth Exchange (NEX) Global Daily Downscaled Projections (GDDP) dataset for 2 scenarios, SSP2-4.5 and SSP5-8.5 as shown in (Figure 13)(Thrasher et al., 2022). Baseline data are for the 1981 to 2010 base period. This dataset includes 35 global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) for the period from 2015 to 2100, and historical experiments for the period 1950-2014 (Eyring et al., 2016). The Bias-Correction Spatial Disaggregation (BCSD) method was used to generate the NEX-GDDP dataset. This is a statistical downscaling algorithm specifically developed to address the limitations of global GCM output, like coarse resolution that does not capture local climate patterns or local biases. The NEX dataset utilized Global Meteorological Forcing Dataset (GMFD) for Land Surface Modeling historical data to bias-correct GCM outputs. After spatial disaggregation, the spatial resolution of the interpolated NEX output data is 0.25 x 0.25 degrees. All projections calculated in this section are averaged over 3 grids of resolution 0.25 x 0.25 degrees covering NYC.

[10] 35 models total in NASA NEX-GDDP dataset, but only 30 were selected for use when this analysis was conducted; CESM2-WACCM, both GFDL models, and HadGEM3-GC31-MM had missing scenarios, while IITM-ESM had a missing year in all files.

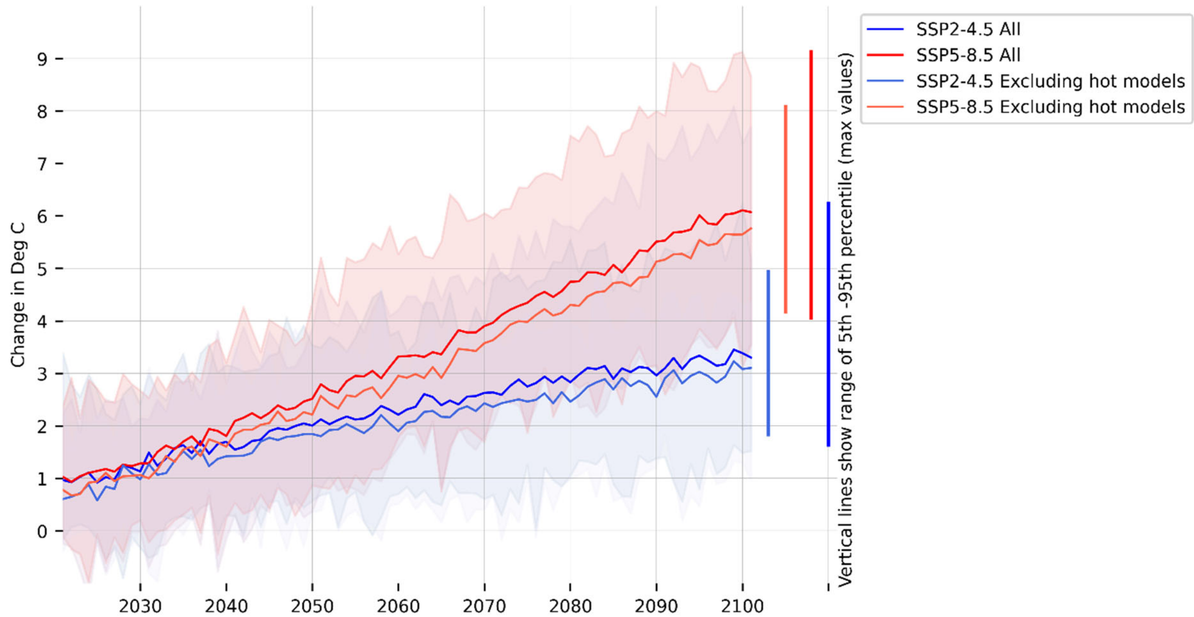


Figure 13: Change in average annual temperature in NYC, calculated from NASA NEX-GDDP for scenarios SSP2-4.5 and SSP5-8.5 to highlight difference in projections after excluding hot models using Transient Climate Response (TCR) range of 1.2°C to 2.4°C deemed 'very likely' in IPCC AR6.

The unweighted average of these models plots a graph closer to the global warming projected by the IPCC. Results of this analysis show a relatively small difference of about 0.48 degrees C in temperature projections by the 2090s for SSP2-4.5 scenario and about 0.54 degrees C by the 2090s for the SSP5-8.5 scenario (Table 5). Further investigation focused on precipitation and extreme event metrics is necessary to fully understand the potential benefits of using TCR as a GCM filtering category.

Table 5: Temperature change in NYC (degrees C) as low-estimate (10th percentile), middle range (25th to 75th percentile), and high-estimate (90th percentile) computed as 30-year mean values centered over desired decades from model-based outcomes.

Decades	Intermediate Emissions (SSP2-4.5)	Intermediate Emissions (SSP2-4.5) - Excluding 'hot models'
	Baseline 1981 - 2010	
	10th (25th to 75th percentile) 90th	10th (25th to 75th percentile) 90th
2020s	+0.37 (+0.56 to +1.07) +1.66	+0.34 (+0.53 to +0.82) +1.22
2030s	+0.75 (+0.98 to +1.47) +2.18	+0.74 (+0.84 to +1.34) +1.57
2040s	+0.88 (+1.31 to +1.90) +2.51	+0.77 (+1.19 to +1.76) +1.99
2050s	+1.07 (+1.55 to +2.27) +3.02	+0.97 (+1.51 to +2.22) +2.28
2060s	+1.18 (+1.72 to +2.69) +3.36	+1.02 (+1.64 to +2.58) +2.76
2070s	+1.47 (+1.97 to +2.93) +3.66	+1.33 (+1.93 to +2.69) +3.21
2080s	+1.64 (+2.24 to +3.17) +3.86	+1.48 (+2.19 to +2.77) +3.45
2090s	+1.76 (+2.39 to +3.26) +3.98	+1.56 (+2.32 to +2.89) +3.50

Decades	High Emissions (SSP5-8.5)	High Emissions (SSP5-8.5) - Excluding 'hot models'
	Baseline 1981 - 2010	
	10th (25th to 75th percentile) 90th	10th (25th to 75th percentile) 90th
2020s	+0.34 (+0.57 to +1.26) +1.73	+0.19 (+0.50 to +1.03) +1.46
2030s	+0.73 (+1.07 to +1.88) +2.46	+0.68 (+1.03 to +1.66) +2.17
2040s	+1.31 (+1.61 to +2.55) +3.15	+1.29 (+1.51 to +2.24) +2.66
2050s	+1.87 (+2.10 to +3.18) +3.96	+1.85 (+2.01 to +2.85) +3.25
2060s	+2.23 (+2.76 to +4.04) +4.56	+2.30 (+2.72 to 3.43) +4.02
2070s	+2.84 (+3.49 to +4.93) +5.43	+2.89 (+3.41 to +4.10) +5.04
2080s	+3.30 (+4.18 to +5.60) +6.40	+3.33 (+4.06 to +4.83) +5.86
2090s	+3.66 (+4.45 to +5.91) +6.90	+3.65 (+4.36 to +5.28) +6.27

6.5.1 Drought

Droughts (i.e. temporal water availability shortages) pose unique challenges for NYC in that they can "evolve rapidly within a month or slowly over a season, and span months to decades without a clear beginning or end" (Sugg et al., 2020). While the impacts of droughts on water security, agriculture, and energy systems are fairly well understood, "little is known about the effect of drought on all-cause mortality, especially in higher income countries such as the United States" (Lynch et al., 2020). It is important to note that institutional constraints leading to (mis)management (Calverley & Walther, 2022; Closas, 2020) of water resources can also lead to drought vulnerability and result in environmental and societal costs (Brüntrup & Tsegai, 2017; Salvador et al., 2020). Salvador et al. (2020) summarized the direct and indirect links between climate, droughts, human health, and environmental and socioeconomic problems. Similarly, Bell et al. (2018) also provide context related to the health impacts of droughts, which disparately impact the marginalized population. More recently, Salvador et al. (2022) analyzed the short-term effects of different drought severity levels on circulatory and respiratory mortality in 13 urban areas in Brazil and found substantial gender differences with females and children most vulnerable and affected. Although the studies mentioned above do not pertain specifically to NYC, it is important to note that future droughts could impact marginalized communities in the city most and exacerbate heatwaves while simultaneously decreasing air quality (Naimark et al., 2021).

This section focuses on synthesizing drought declaration markers for New York State and NYC, and the role of demand projections in quantifying future drought risk for the area. The NPCC3 assessment report focused on drought indices developed for the city's major reservoir system using paleoclimate data (González et al., 2019) and found at least eight incidences of historical drought lasting five consecutive years or longer in the region since 1750 by examining this historical record. The drought of record in the New York metropolitan region continues to be the one that occurred in the early to mid-1960s (Namias, 1966). It is a potential marker for NYC drought and water shortages. Utilities are particularly concerned with the threat of the recurrence of the 1960s drought and the uncertainty for an even larger drought. Current and proposed reservoir operating rules governing water management for the region depend mainly on performance testing under the 1960s drought of record (Devineni et al., 2013; Kolesar & Serio, 2011; Ravindranath et al., 2016).

The State Drought Index, which compares streamflows, precipitation, reservoir storage levels, and groundwater levels to climatological normals, is used for evaluating droughts in New York. The Drought Management Task Force of New York uses the State Drought Index along with water use, duration of the dry period, and season to assess drought in different parts of the state. Other standard drought indices, such as the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Evapotranspiration Index (SPEI), are also monitored. Current drought conditions at the State level can be obtained from New York State Department of Environmental Conservation at https://www.dec.ny.gov/lands/5017.html.

Drought in the Catskill region is an essential marker as the Catskills (and nearby Delaware regions) have the primary water supply reservoirs for NYC. The city bases its assessment of drought conditions on the probability of these reservoirs being full by June every year. The current reservoir levels and drought conditions for NYC can be monitored NYC Water Supply System at https://www.nyc.gov/site/dep/water/reservoir-levels.page. Increasing water supply needs have stressed these water systems that must additionally meet several purposes, such as ecological habitat protection, recreation, hydropower, and flood control. Recent scenario modeling for the Northeast suggests similar or slightly decreased summer precipitation and droughts that are more frequent but perhaps similar to historical conditions in magnitude (Hayhoe et al., 2007, 2008). Decreased summer precipitation will result in reservoirs being drawn down, which may increase the frequency of short-duration droughts (C. Rosenzweig et al., 2011). Since the 1960s drought of the record, several smaller droughts (e.g. in the 1990s and 2000s) have had measurable impacts (Pederson et al., 2013). Research on streamflow reconstructions for the upper Delaware River Basin using tree rings revealed a moderate probability of recurrence of droughts with similar characteristics to the 1960s drought of record (Devineni et al., 2013). Recently, observations of a lack of snowpack and more frequent summer low flow periods have led to questions on the long-term sustainability of current reservoir operating policies. These issues expose an unappreciated climatic and institutional vulnerability to droughts that needs attention.

Water use for various sectors (e.g., public water supply, industrial use, mining, thermoelectric, irrigation, etc.) also plays a significant role in understanding droughts in the New York area. However, the nature of drought risk for New York has not been articulated beyond an analysis of the potential imbalance between estimates of average annual supply and evaporative demand. For sector-specific droughts, one needs to go beyond using a purely supply-based index since the frequency, severity, and duration of deficits are not adequately indicated, especially in a comparative setting across markedly different demand patterns in the same climatic regime. For providing sector-based drought information, one must think of droughts as a manifestation of the non-linear interaction between supply and demand since the risks faced by water users vary over time and by sector of use. Historic and projected water use data for the Delaware River Basin area (the major watershed for New York) for eight major sectors is available from Thompson and Pindar (2021) See Figure 14. Their summary of the key findings from water use data states that the peak water withdrawal from the Basin already occurred in 2005-2006. Further, irrigation water use and the public water supply as well as industrial and thermoelectric water use is projected to stay constant at current consumption (or decrease further) between 2020 and 2060. A more comprehensive drought risk assessment for water utility operations could be better informed if appropriate stress indices were developed for drought conditions relative to current and projected demands and their likelihood assessed through future climate scenarios.

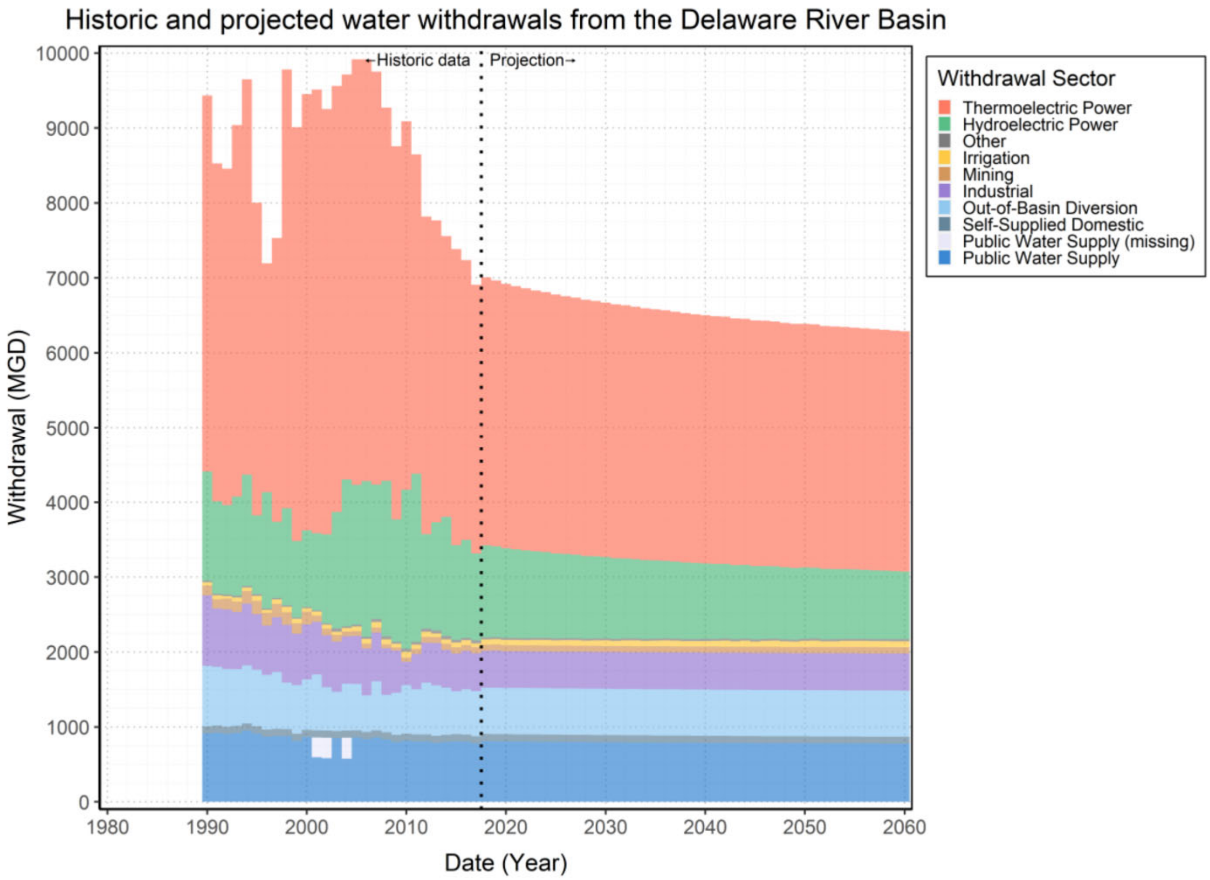


Figure 14: Historic and projected water withdrawals from the Delaware River Basin (Thompson & Pindar, 2021).

Integrating water demand projections with climate projections is necessary to better prepare for future drought conditions. Sector-specific drought early warning predictions and monitoring tools can help NYC better prepare for and operate through extreme drought periods. Recent works on demand-sensitive drought indicator development (Devineni et al., 2015; Etienne et al., 2016; Ravindranath & Devineni, 2020) that consider regional water demands for specific purposes (e.g., municipal use, other sectoral use such as irrigation, and ecological releases) and their temporal distribution over the year can be leveraged to develop spatially explicit demand-driven drought indices for water users. Following this approach, water managers at utilities and relevant agencies could utilize their temporal water demand pattern (e.g., daily scheduled releases and diversions) to generate a customized index.

7 Conclusions and Recommendations

The compound effect of "inland precipitation (pluvial flooding), high wind speeds, storm surge and waves, played an important role in exacerbating the impacts" of Hurricane Sandy in 2012 (Zscheischler et al., 2018). Following the initial convening of NPCC and Hurricane Sandy, the city channeled major investments into climate resilience. These efforts include both completed projects (e.g. Reconstructed Rockaway Boardwalk, wetland restorations in Sawmill Creek and Sunset Cove Park) and ongoing efforts, including coastal protections as well as programs to increase social resilience, strengthen small businesses, and harden critical infrastructure. This NPCC report contributes to the Panel's mandate to advise the City of New York on climate change and provide timely climate risk information that can inform equitable and flexible adaptation pathways.

NYCNPCC4 confirms new sea level rise projections of record for use by NYC in this report and presents a new methodology related to climate extremes. Future work by the Panel should compare the extreme temperature and precipitation projections presented in this report with a subset of models to fully determine the potential impact and relevance of the "hot model" problem (Hausfather et al., 2022). NPCC4 expects to establish new projections of record for precipitation and temperature in 2024 based on this comparison and additional analysis. Nevertheless, the temperature and precipitation projections presented in this report may be useful for NYC stakeholders in the interim as they rely on the newest generation of global climate models.

NPCC5 should assess the value of presenting climate projections that are based on global warming levels rather than only presenting projections based on time. For example, instead of assessing changes in extreme rainfall in the 2050s, the Panel could report changes at global warming levels of 1.5, 2, and 3 °C. In addition, NPCC5 should develop an approach for regularly updating drought projections using climate observations and models for climate risk assessment at different timescales as more research is needed on the frequency, duration, and magnitude of future droughts as well as the potential for future drought conditions to exacerbate heatwaves in NYC and decrease air quality. Further, NPCC5 should utilize ongoing research (funded by NYC's Department of Citywide Administrative Services) to assess the potential for surge, tide and stormwater merging to cause flooding.

7.1 Additional Recommendations for Research and Future Work

More research is needed on compound extreme events (e.g. tropical cyclone-blackout-heatwave events) as well as processes that could lead to destabilization of ice sheets, such as MISI and MICI.

More research is needed on the meteorological factors that contributed to Ida's extreme rainfall characteristics in the NYC metropolitan region. Researchers should aim to improve sub-hourly extreme precipitation projections that consider urban meteorological effects and identify neighborhoods most likely to experience flooding.

Additional research is needed to better understand the impact of land use change, population growth and urban development on storm surge impacts as well as the most appropriate intervention measures such as flood protection systems (both built and nature-based). The methods tested by NPCC3 utilizing GCM and RCM ensembles and scenarios should be utilized and expanded by NPCC5 for the identification of climate change "hotspots" of vulnerability at finer spatial scales within the city and across the region. Using expanded observations, bias correction, and RCMs, these methods can provide quantitative analyses associated with heat extremes, heavy downpours, and droughts. Indoor heat exposure is the most common cause of both heat-related and heat-exacerbated deaths in NYC. However, there is limited research quantifying the physical linkages between climate and weather temporal variability, characteristics of the built environment, and indoor temperatures. In order to better understand indoor temperature change and address its impacts, there is a need for (1) operational monitoring of indoor temperatures in order to map the spatial distribution of indoor hazardous heat, (2) research to quantify the climate and infrastructure drivers of indoor temperature, and (3) better communication and warning systems when hazardous indoor conditions can be expected.

8 Competing Interests

The authors declare no competing interests.

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The assessment does not represent the policy position of any agencies whose staff are co-authors.

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Appendix A. Heat Exposure Inequity in NYC

Extreme heat is a recurring climate hazard increasing in frequency and intensity with anthropogenic climate change. Extreme heat negatively impacts people's health, ranging from triggering temporary acute conditions to exacerbating existing illnesses and causing death. In the United States, more people die each year from heat than from all other weather-related hazards combined11, illustrating the significant morbidity and mortality burden extreme heat carries. In NYC, there are on average 370 heat-related deaths12 each year, with people of color (i.e. non-White people) and low-income communities at disproportionately higher risk. This risk is further compounded by air pollution as well as inadequate access to thermally safe housing, cooling areas or green spaces (Raven et al., 2022). Notably, the historical practice of redlining has implications for climate risk exposure experienced in the present day (Bock et al., 2021).

The term "redlining" refers to the four-category rating system created by the Home Owners' Loan Corporation (HOLC) in the 1930s that color coded and rated neighborhoods as follows:

A — "Best" (Green)
B — "Still Desirable" (Blue)
C — "Definitely Declining" (Yellow)
D — "Hazardous" (Red)

This rating system informed the distribution of subsidized loans for people in specific neighborhoods by conducting residential security map surveys. While the rating system was determined by multiple factors, it was significantly influenced by the social construct of race, with "D" graded (red) neighborhoods often being communities that were predominantly composed of non-White residents (Hoffman et al., 2020).

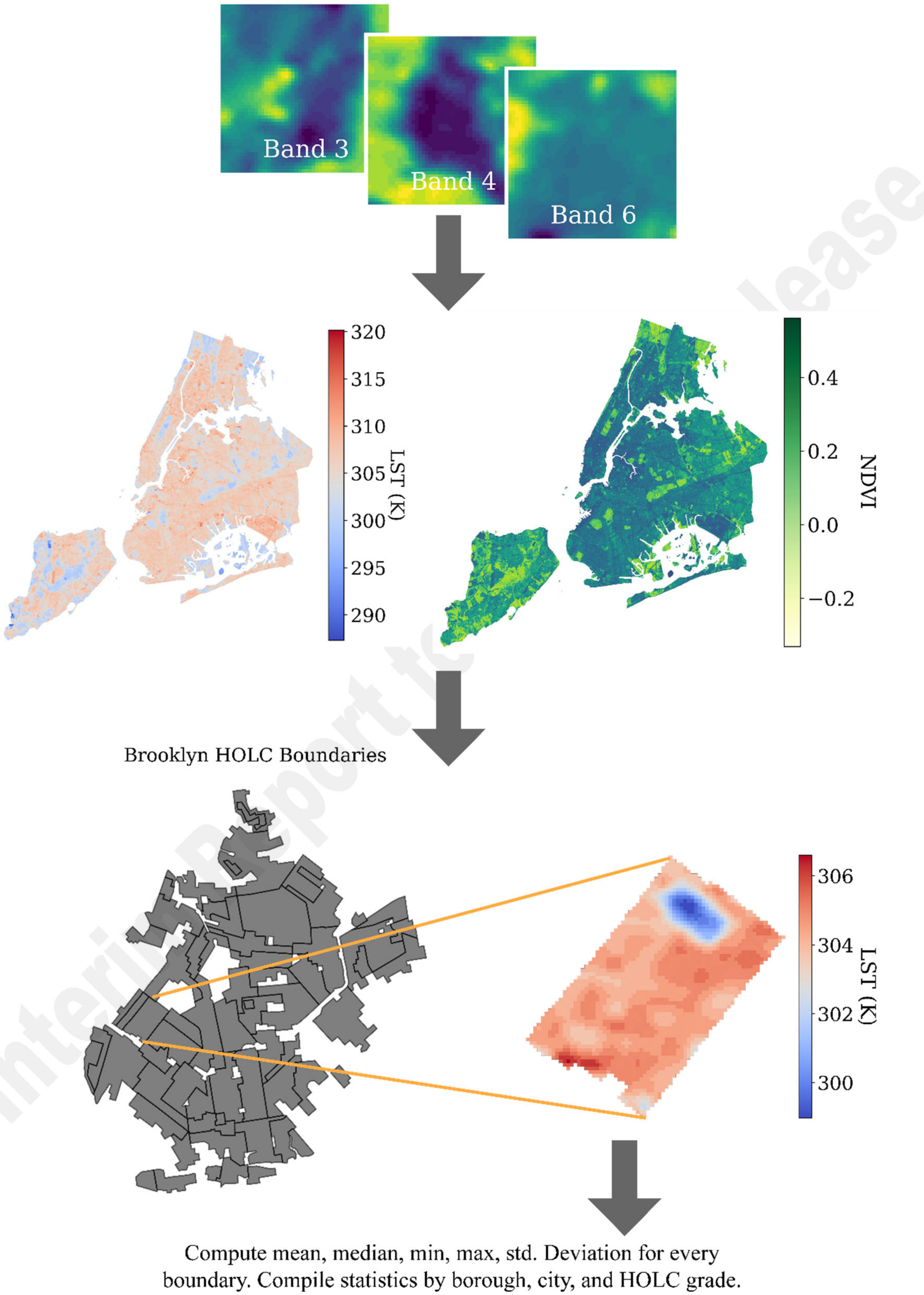
Research conducted through the Climate Change Research Initiative (CCRI13) evaluated the risk of exposure to elevated land surface temperatures (LSTs) and the amount of vegetation cover across the four HOLC categories in NYC. Using Earth observations from satellite imagery, LSTs and vegetation cover estimates were derived for each HOLC for each summer (June, July, August) from 1984 to 2022.

To calculate LST and vegetation cover, using an index known as the Normalized Difference Vegetation Index (NDVI), data from Landsat 5 and Landsat 8 was used (See Appendix Figure A-1. Both satellites measure data according to spectral bands that can be used to estimate LST and NDVI. NASA satellite imagery from Landsat 5 is used for scenes from 1990-2011 and Landsat 8 imagery is used for scenes from 2013 to 2022. Additionally, scenes were filtered for those images that had less than 10% cloud cover resulting in a total of 114 scenes collected for this study.

[11] EPA Climate Change Indicators: Heat-Related Deaths at https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths

[12] New York City 2022 Heat-Related Mortality Report at https://www1.nyc.gov/site/doh/about/press/pr2022/heat-related-mortality-report.page

[13] NASA 2021-2022 Climate Change Research Initiative via Amel Derras-Chouk at https://github.com/aderras/nyc-lst-ndvi



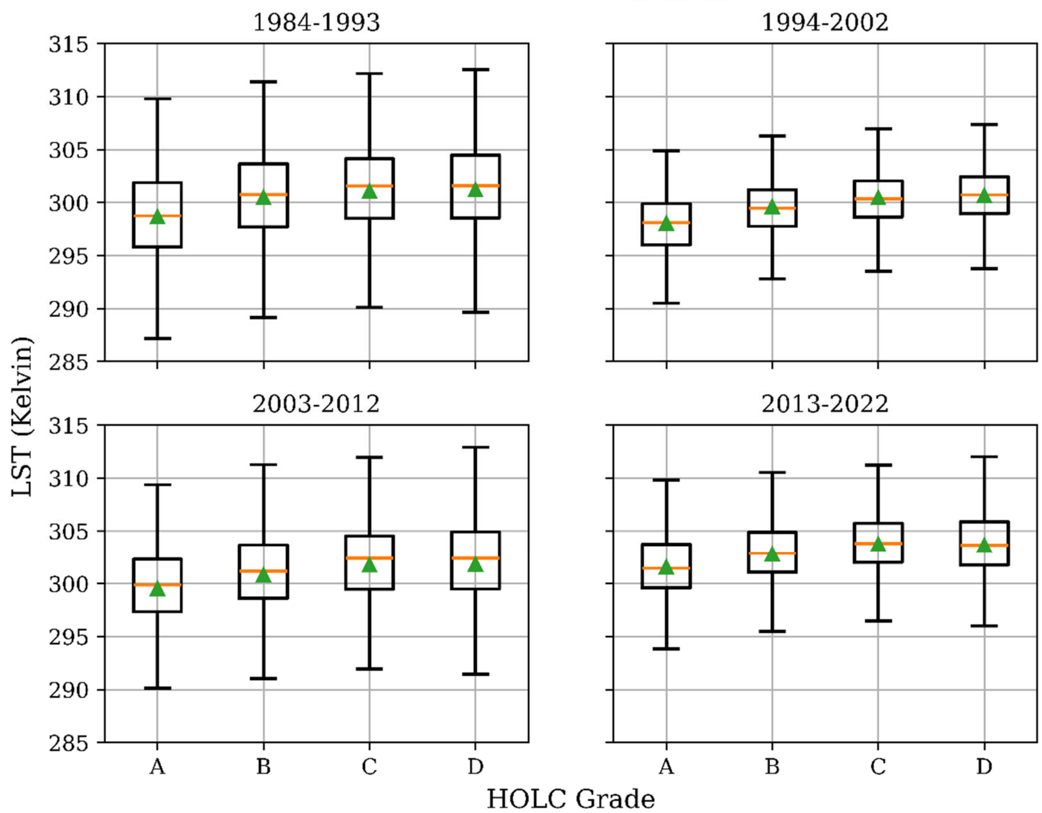
Appendix Figure A-1: Schematic depicting the workflow for computing land surface temperature (LST) and the normalized difference vegetation index (NDVI) with Landsat 5 imagery. An analogous workflow is used for Landsat 8.

Each Landsat scene was clipped to the NYC boundary before performing calculations and the data was organized into 10-year periods to study changes in LST and NDVI by decade. The mean, median, maximum, and minimum pixel values were calculated for each decadal period and the statistical significance across grades and decadal time scales were evaluated. The decadal periods considered and the number of scenes within each decadal period are summarized in Table A.1.

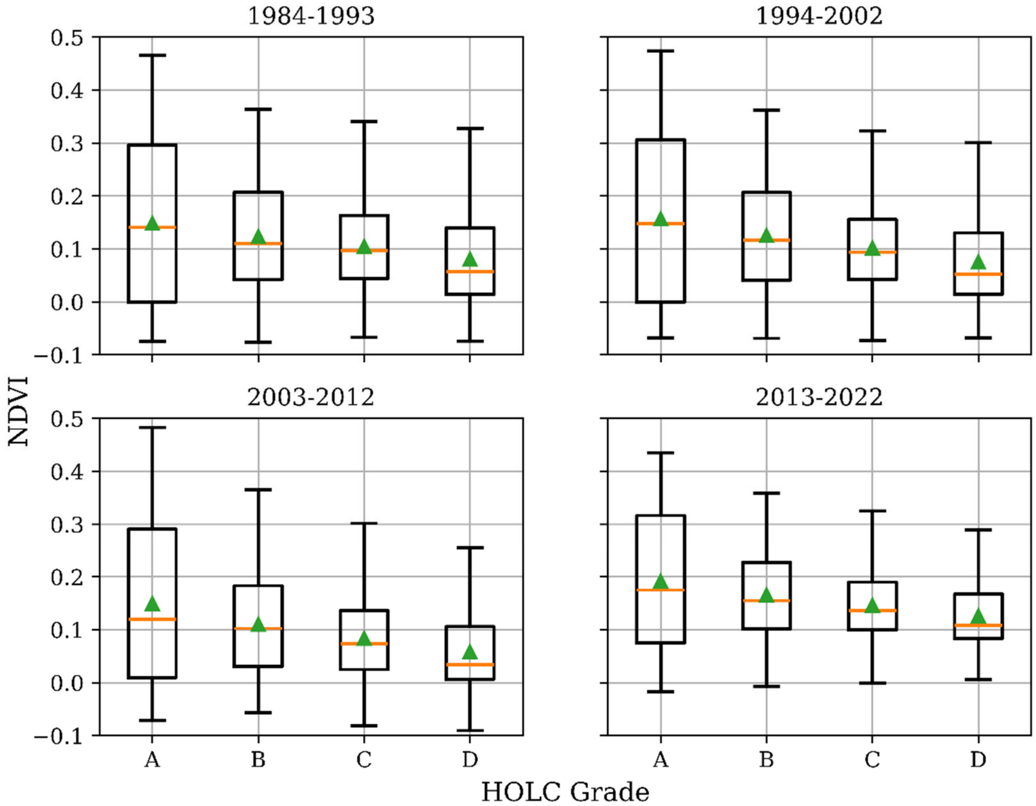
Table A.1. Year ranges considered and number of Landsat scenes within each range.

Year Range	# Scenes
1984 - 1993	26
1994 - 2002	26
2003 - 2012	33
2013 - 2022	21

Results show that areas that were redlined, classified with a “D” grade (hazardous), experienced higher LSTs than the areas classified with an “A” grade (best) across each decade. Additionally, the formerly redlined areas classified with a “D” grade were also found to have lower NDVI values than the “A” grade areas throughout the city. Lower NDVI values suggest that there is lower vegetation density; this aligns with the LST trends observed. The results for LSTs are shown in Figure A.2. and the results for NDVI are shown in Figure A.3.



Appendix Figure A-2: Box-and-whisker plots of median land surface temperature (LST) across HOLC grades for different year ranges. The orange line is the median of the medians, and the green triangle is the mean of the medians. NASA satellite imagery from Landsat 5 is used for scenes from 1990-2012 and Landsat 8 imagery is used for scenes from 2013 to 2022.



Appendix Figure A-3: Box-and-whisker plots of median NDVI across year ranges for different HOLC grades. The orange line is the median of the medians, and the green triangle is the mean of the medians. NASA satellite imagery from Landsat 5 is used for scenes from 1990-2012 and Landsat 8 imagery is used for scenes from 2013 to 2022.

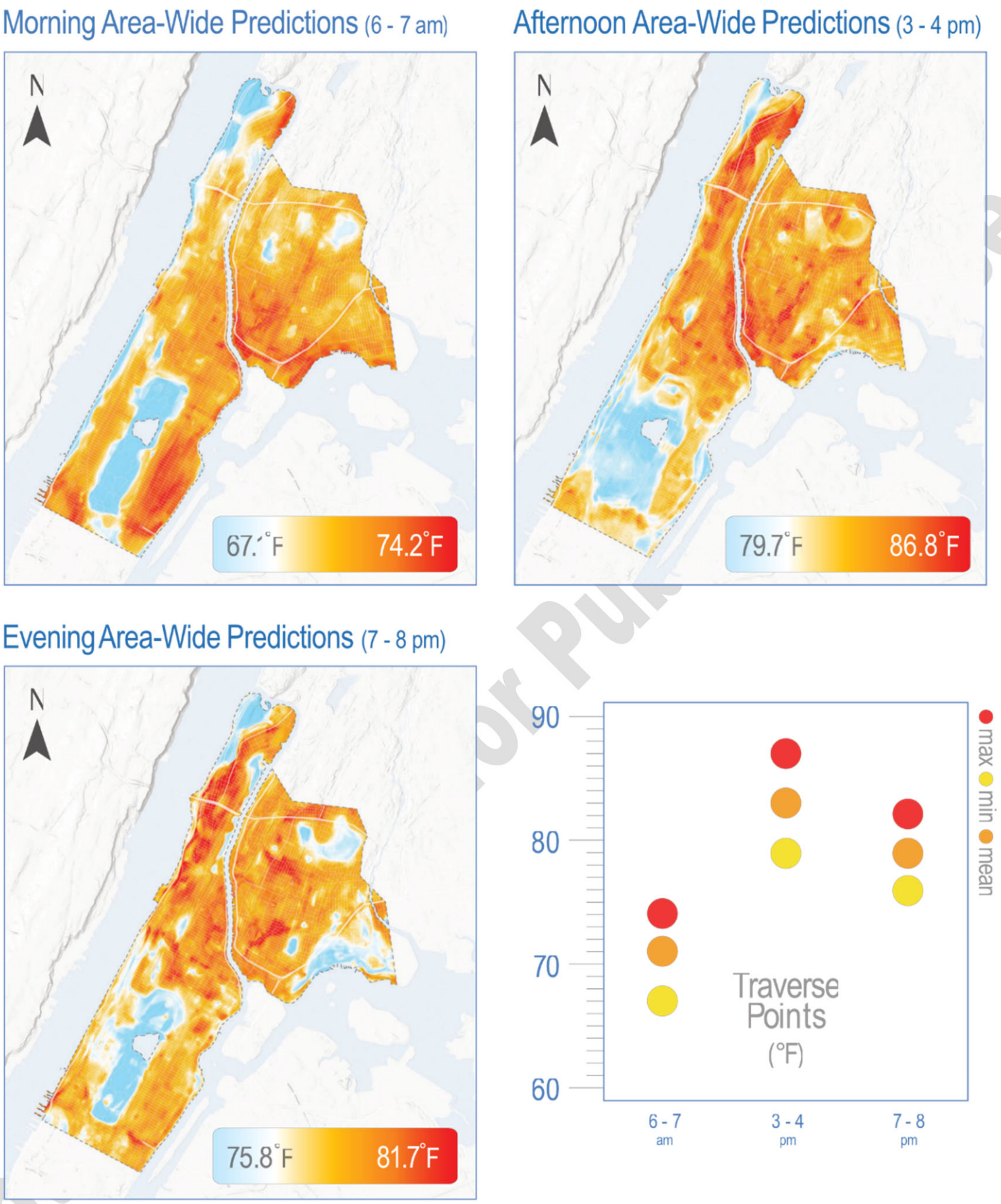
With the tenets of environmental justice and community based participatory research at its core, Columbia University researchers collaborated with South Bronx Unite to lead an urban heat island (UHI) mapping campaign on July 24, 2021[14]. Additionally, researchers wanted to empower a group of community members from the South Bronx and Upper Manhattan, areas disproportionately impacted by heat, to become community scientists.

With remuneration from Columbia University, community scientists and volunteers collected data traversing along 10 different routes, collecting over 40,000 data points using heat sensors from NOAA's partner CAPA Strategies, three times through the day[15] (CAPA Strategies, 2021). Predictive models developed from the data collected demonstrate that areas marginalized along the axes of race and class, such as the South Bronx[16]were up to 8° F (4.5° C) hotter than areas in more affluent Upper West Side and Upper East Side communities, just a few miles away (See Appendix Figure A-4). Notably, the Mott Haven-Port Morris section of the Bronx has been nicknamed "Asthma Alley" by some as it is surrounded by heavy-traffic highways and polluting industry, which also bring compounding hazards such as air pollution (Braneon et al., 2021; Hwa Jung et al., 2022; Lane et al., 2022; Naimark et al., 2021). Overall, the results confirm what residents of these areas and researchers indicate they have known for years – that people of color and low-income residents are disproportionately exposed to urban heat and its compounding consequences. This data collection campaign mirrors similar efforts performed by Voelkel et al. (2018) in Portland, Oregon, who helped devise the first iterations of the methodology employed in NYC.

[14] The resulting storymap with accounts of lived experiences can be found at heatstorynyc.org

[15] Data Dive: Heat Mapping New York City and Environmental Justice at https://news.climate.columbia.edu/2022/04/08/heat-mapping-new-york-city-environmental-justice/

[16] The City at https://as-she-rises.simplecast.com/episodes/the-city-A_7XROTV



Appendix Figure A-4: Map[17] displaying modeled air temperature at three different times of day on 7/24/21 (CAPA Strategies, 2021).

[17] CAPA/NIHHIS. (2022, August 2). Heat Watch Bronx & Manhattan (2021). Retrieved from osf.io/j6eqr

Appendix B. Tail Risk of Extreme Precipitation in NYC

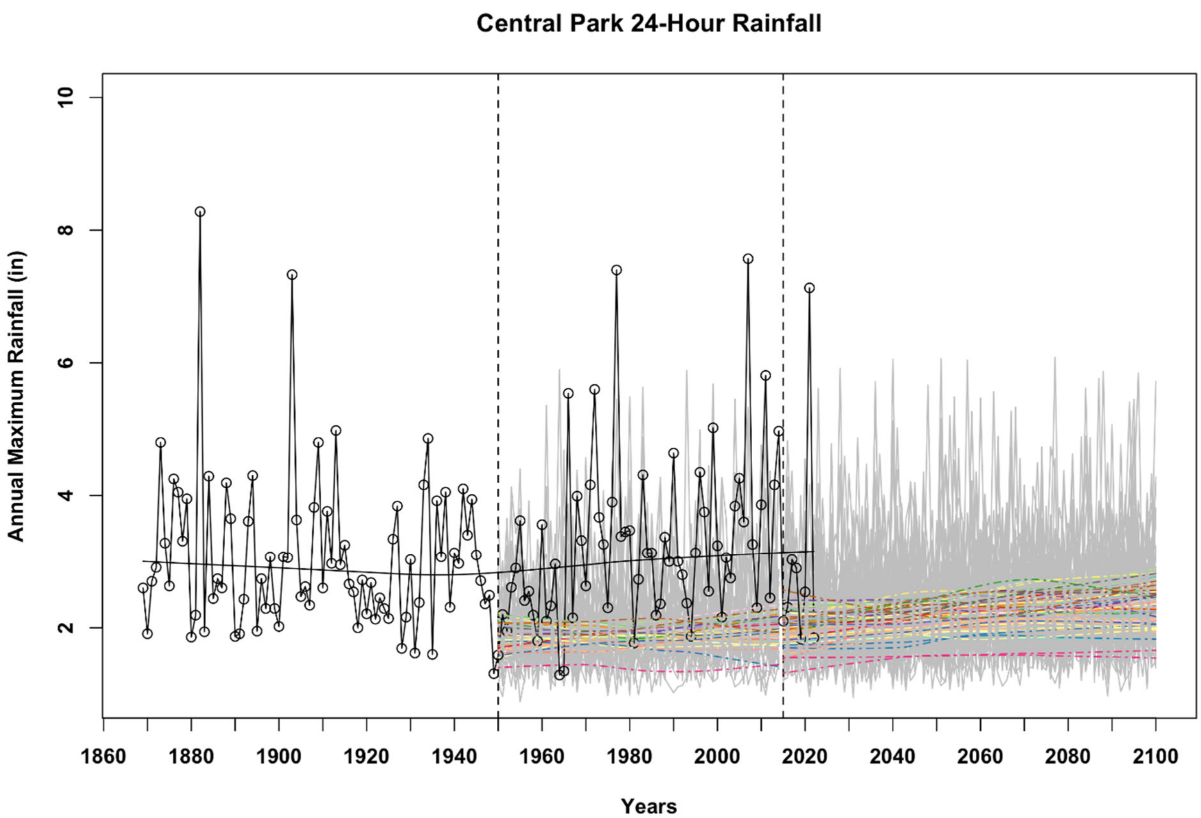
This section focuses on climate projections for extreme precipitation, how they compare with observed extreme precipitation data, and the projected changes in the tail risk of extreme precipitation for NYC.

A total of 32 global climate models associated with the sixth phase of the Coupled Model Intercomparison Project (CMIP6) are available from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) (Thrasher et al., 2022) and used to understand future precipitation patterns for NYC. The models have a spatial resolution of 0.25^{o} by 0.25^{o}, and the data from the grid overlapping the National Weather Service's Central Park weather station is selected as representative for climate projections in NYC.

Mean daily precipitation rates in kg m^{-2} s^{-1} are converted to inches/day. The model data (daily) are available as historical experiment (1950-2014) and projected scenarios (2015-2100) in the two Shared Socioeconomic Pathways (SSPs) utilized: SSP2-4.5 and SSP5-8.5. Daily precipitation data from the Central Park Weather Station is available from 1869-present (National Centers for Environmental Information, 2023). The precipitation data from the models are compared to observed precipitation data from the Central Park weather station.

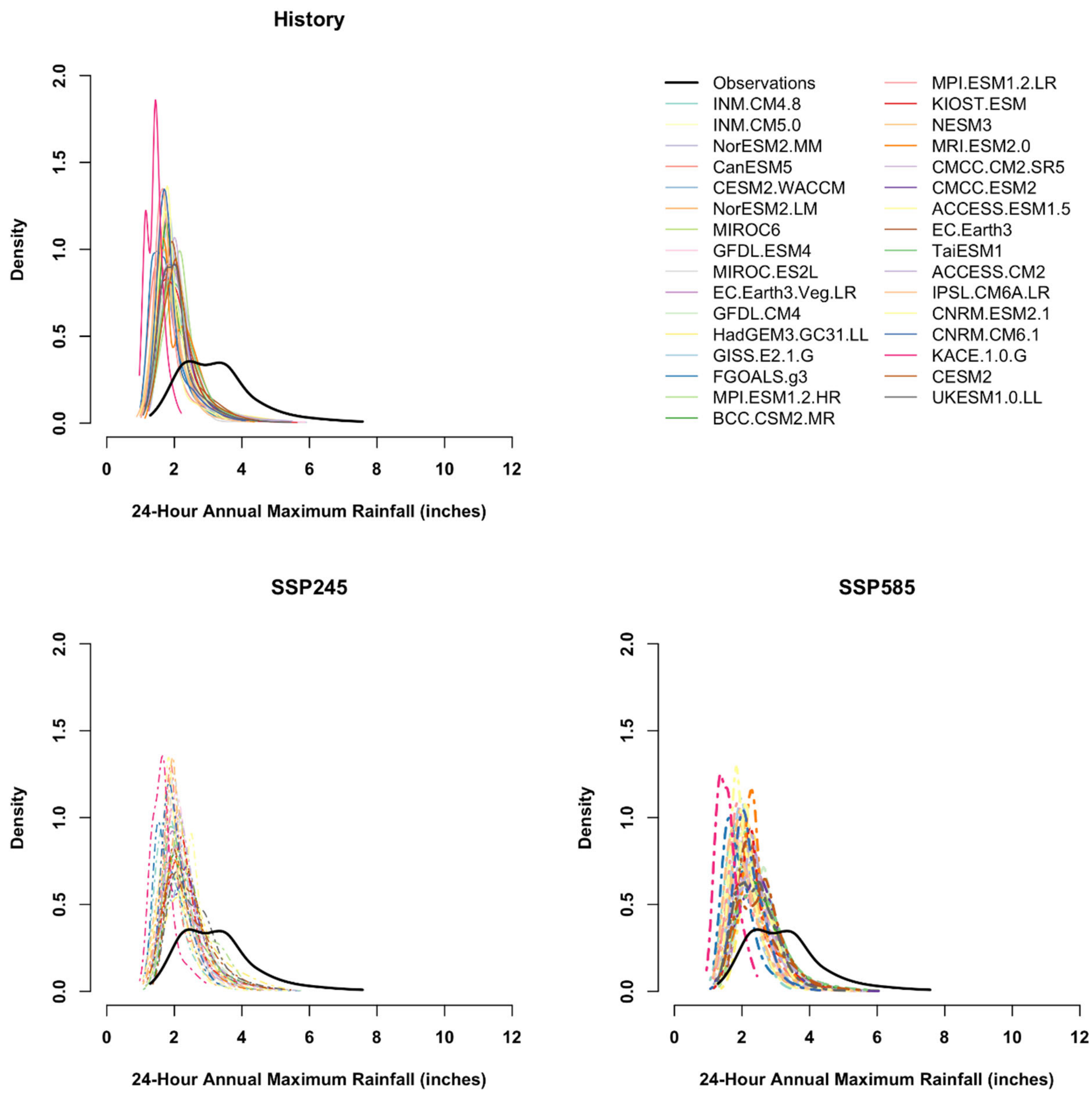
The annual maximum event (i.e., the highest magnitude precipitation in a calendar year) is used as a criterion for extreme precipitation to be consistent with block maxima extreme value analysis (Cooley et al., 2019).

Appendix Figure B-1 presents the time series of the annual maximum precipitation estimated from the observed data (1869-2022) and the two emissions scenarios (SSP2-4.5 and SSP5-8.5) driving the 32 models utilized. The weather station-recorded annual maximum events are shown as a circle-marked line from 1869 to 2022. A smooth black line (based on lowess smoother, Locally Weighted Scatterplot Smoothing (Loader, 1999) is also shown to depict the long-term trend. The model data are presented as grey lines from 1950 to 2100 (with 1950-2014 representing the historical experiment and 2015-2100 representing the projections) with a smooth dashed line depicting the long-term trend. While the models project an upward trend of extreme precipitation in the future, they exhibit a bias in reproducing the observed distribution of extreme precipitation. The models seem to be systematically underestimating the overall distribution, especially the tails.



Appendix Figure B-1: Time series of observed and projected annual maximum precipitation for NYC.

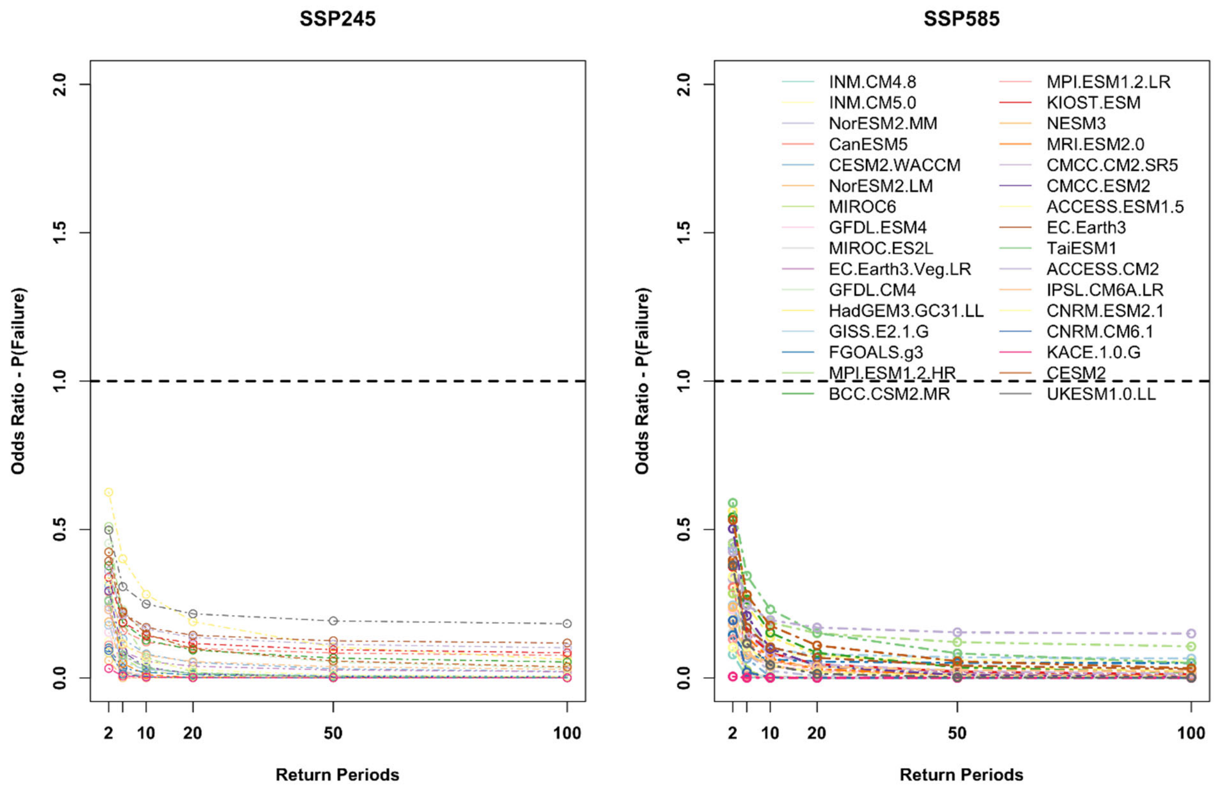
To verify this further, a comparison was made between the probability distribution function of the models and the observed annual maximum precipitation. Appendix Figure B-2 compares the probability distributions (estimated using a local polynomial density estimator (Loader, 1999) of the observed annual maximum precipitation with models' historical experiment (1950-2014) and the two projected scenarios (SSP2-4.5 and SSP2-8.5). Significant biases are revealed across all quantiles, but especially in the tails of the distribution, which will have implications when assessing the reliability of current stormwater designs and upgrading them for future precipitation conditions.



Appendix Figure B-2: Probability distributions of observed and projected annual maximum precipitation for NYC.

A failure odds ratio between the model and observation data is computed to adequately quantify the nature of the bias across the upper quantiles. For a specific quantile that corresponds to a T-year return period event, the failure odds ratio is computed as the ratio of the probability that the model-projected extreme precipitation exceeds the T-year return period event to the probability of the T-year event. As an example, for a 100-year return period event, the failure odds ratio is computed as the ratio of the probability that the model-projected extreme precipitation exceeds the 100-year event. Since the 100-year return period event is expected to be exceeded 1% of the time on average, if the model-projected extreme precipitation exceeds this (design) event by more than 1%, then the failure odds ratio will exceed 1 (or alternatively it is less than 1). In other words, if the failure odds ratio is greater than 1, the future risk of exceeding the T-year return period event is greater than that current risk (1/T % failure). If the failure odds ratio is less than 1, the future risk of exceeding the T-year return period event is less than that current risk (1/T % failure).

Figure B.3 presents the bias estimated by the failure odds ratio for return periods ranging from 2 years to 100 years (2-yr, 5-yr, 10-yr, 20-yr, 50-yr, and 100-yr). SSP2-4.5 driven model projections' tail risk comparison is shown on the left in Figure B.3, and the SSP2-8.5 model driven projections' tail risk comparison is shown on the right in Figure B.3. Consistent with Figures B.1 and B.2, all models across the two SSPs and return periods project a risk that is much lower than the current risk (1/T %).



Appendix Figure B-3: Failure odds ratio presenting the changes in the projected tail risk.

It is widely acknowledged that the CMIP gridded products exhibit biases when compared to any single station observations and more so in extreme values. Moreover, using the CMIP6 GCM data for engineering or design studies must be cautiously done with collaborative discussions with climate experts and practicing engineers. The current analysis can be expanded to include model comparisons with several weather stations in the greater NYC region and by verifying other metrics of extreme precipitation, such as precipitation events (extreme precipitation days) greater than certain thresholds (e.g., 1 inch, 2 inches, and 4 inches or various higher percentile precipitation events such as 95 or 99th percentile daily rainfall).

Appendix C. Methods of Climate Projections

NPCC4 utilizes a range of climate model-based outcomes for temperature and precipitation from global climate model (GCM) simulations based on two shared socioeconomic pathways (SSPs). Temperature and precipitation projections for the NYC metropolitan region were derived from an ensemble of 35 GCM simulations across a range of emission scenarios. The scenarios represent a range of plausible future global socioeconomic and emissions pathways. Further, the GCM simulations represent a broad range of what we consider plausible climate outcomes, including the high consequence outcomes that are critical for risk management.

For some variables, climate models do not provide results, the model results are too uncertain, or there is not a long-enough history of observations to justify quantitative model-based projections. For these variables, a qualitative projection of the likely direction of change is provided on the basis of expert judgment. Both the quantitative and qualitative approaches parallel methods used in the IPCC AR6 report.

C.1 Mean Temperature and Precipitation

Projections for mean annual temperature and mean annual precipitation were computed using 35 GCMs and two SSPs. The combination of the 35 GCMs and two scenarios produces a 70-member matrix of outputs for temperature and precipitation for a given time period. The results constitute a climate model–based range of outcomes, which can be used in risk-based decision-making. Equal weights were assigned to each GCM and to each of the two selected SSPs.

Mean annual temperature and precipitation projections are calculated using the delta method, consistent with prior NPCC reports. The delta method is a type of bias-correction whereby the difference between each model's future and baseline simulation is used, rather than “raw” model outputs. The delta method is a long-established technique for developing local climate-change projections (see prior NPCC reports[18] and references therein).

C.2 Extreme Temperature and Precipitation

For projections of extreme events, daily data from local weather stations and GCM[19] outputs are utilized. Projections of daily temperature (maximum and minimum) and precipitation were computed using a method known as quantile mapping. Quantile mapping adjusts model values by mapping percentiles of the model’s distribution onto percentiles of the observations (Cannon et al., 2015; Thrasher et al., 2012; Zhao et al., 2017). When applying a quantile mapping-based bias correction to daily temperature extremes and daily precipitation, the approach uses a base period where both daily observations and daily GCM-simulated values are available. The quantile mapping was performed by defining the percentiles based on the entire twelve-month calendar year.

The quantile mapping approach in this report uses one-percentile bins, in order to strike a balance between 1) capturing rich information about how baseline bias and projected change can differ across the distribution of a variable and 2) including a sufficient number of days per bin (over 100 days across the 30-year period) to minimize the role of random variability associated with small sample sizes.

For each 30-year time period, model, SSP, and station, the bias correction and downscaling approach was conducted such that each observed day between 1981 and 2010 was assigned a temperature percentile. The same procedure was applied separately to the GCM data in the base period and in a future period. For example, if May 25, 1995, was ranked in the 61st percentile of days for temperature in the observations, the warming experienced in the GCM at the 61st percentile of temperatures in the two time periods (e.g., 4.0°F) was applied to the observed day. The resulting dataset can be thought of as a synthetic time series, based on the sequence of weather experienced at the station historically, but modified by the amount of warming projected by each GCM in the temperature percentile associated with each day. This approach yields results that conform closely to the sequences of weather experienced over the observational period, but could underestimate the risk of sequences of events, such a long-duration heat wave, if the observational record underestimates the true historical variability, or if climate change modifies the sequences of hot days. The synthetic time series were then used to calculate the metrics of extreme temperatures and precipitation.

[18] NYC MOCEJ New York City Panel on Climate Change at https://climate.cityofnewyork.us/initiatives/nyc-panel-on-climate-change-npcc/

[19] A total of 16 models had daily data available for both SSPs at the time of analysis.

C.3 Climate Projection Timeslices

GCMs are valuable tools for projections of the likely range of change over multidecadal time periods. These projections are expressed relative to a baseline period of 1981 to 2010 for temperature and precipitation while the baseline period is 1995 to 2014 for sea level rise. This base period has been revised since the NPCC3 report to become more consistent with U.S. climate normals.

Projections are provided for 30-year timeslices with the time periods centered on a given decade. Thirty-year timeslices are used to provide an indication of the climate normals for those decades. By averaging over this period, much of the random year-to- year variability — or noise — is canceled out, while the long-term influence of increasing greenhouse gasses — or signal — remains.

Projections are provided for each decade from the 2030s through the 2080s following the priorities of municipal stakeholders. For certain basic quantitative projections (e.g., annual temperature and annual precipitation) the projections are extended to 2100 using an alternate method developed for the 2015 NPCC assessment report (see Horton, Bader, et al., 2015 for methodological details) based on a hybrid of timeslices and trend extrapolation of trends from earlier in the 21st century.

C.4 Sea Level Rise Methods

Historic GMSLR data comes from tide gauges, which however contain significant temporal data gaps, uneven geographic distribution, and only sample coastal locations. Since 1992, tide gauge observations have been supplemented by radar and laser satellite altimetry with near global ocean coverage. In addition, since 2002, Grace Recovery and Climate Experiment (GRACE) and GRACE Follow-On Satellites have measured gravity losses due to ice sheet mass losses, while near-global coverage of Argo ocean-profiling floats since 2006 provide data on ocean thermal expansion down to 2000 meters depth.

Since the last NPCC update of the full set of sea level rise projections in 2015, there have been advances in sea level rise understanding and projection methodologies, including new approaches to capture the possibility of rapid ice melt from land-based ice sheets (Bamber et al., 2019; Fox-Kemper et al., 2021; Gornitz et al., 2019). Several recent studies confirm the plausibility of high-end sea level rise scenarios (e.g., Slangen et al., 2017) and offer techniques to adapt projections to the regional/local scale (Fox-Kemper et al., 2021; Kopp et al., 2017; Sweet et al., 2017). Coastal locations in NYC continue to experience faster rates of sea level rise when compared to the global average, a trend that is generally expected in the future as well (Ezer, 2015).

There is growing evidence that supports the plausibility of higher-end sea level rise projections, primarily based on observations of land-based ice loss and advances in climate modeling. Probabilistic sea level rise associated with high emissions scenarios, such as those presented in Kopp et al. (2017), may represent possible future outcomes. These projections are similar to those presented in the most recent National Climate Assessment (Sweet et al., 2017). These two studies, along with several others, informed the development of an Antarctic Rapid Ice Melt (ARIM) Scenario as part of the 2019 New York City Panel on Climate Change Report (Gornitz et al., 2019). The ARIM scenario represents one example of a high impact, low probability future event. The scenario incorporates the latest science, as of 2019, on changes in land-based ice, including glaciers, the Greenland Ice Sheet, and the Antarctic Ice Sheet.

Projections for NPCC4 include updated projections based on those developed for the IPCC 6th Assessment report; data associated with the projections can be found via the NASA Sea Level Projection Tool at https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool. These projections are based on the CMIP6 models and SSP framework, and also incorporate advances in process understanding, improved and lengthened observational records, and ice sheet modeling. Three scenarios used by the IPCC, SSP2-4.5-*medium confidence*, SSP5-8.5-*medium confidence*, and SSP5-8.5-*low confidence* are selected for use here as they span a broad range of plausible outcomes. IPCC expresses a level of confidence using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., medium confidence. The IPCC provides, for each scenario, a full set of percentiles in 1 percent increments, for tide gauges (e.g., the Battery). Because this data is available for years at the start of each decade (e.g., 2050), we interpolated the values to the middle year (e.g., 2055) of the decade, in order to align with the decadal time periods (e.g., the 2050s) previously used for NPCC sea level rise projections. Ten-year sea-level rise timeslices, rather than the 30-year timeslices used for other climate variables, are adequate given the small interannual variability of sea level rise relative to its accelerating trend. After adjusting to the midpoint of each decade, the individual one percentile distributions of samples for each of the 3 scenarios from the IPCC are combined. This results in a 'distribution' of 297 values (3 scenarios x 99 quantiles) for each station. The percentile values are taken across this 'model-based distribution', to form the updated sea level rise projections.

The updated projections for sea level rise use the same six components as were used in the prior NPCC2 products. These components are: ocean dynamics; thermal expansion; vertical land motion; loss of land-based ice; gravitational, rotational, and deformational effects; and land-water storage.