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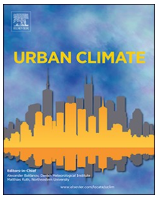

Enhancing New York City's resilience to sea level rise and increased coastal flooding

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ABSTRACT

Accelerating Greenland and Antarctic Ice Sheet ice mass losses and potential West Antarctic Ice Sheet instability may lead to higher than previously anticipated future sea levels. The New York City Panel on Climate Change Antarctic Rapid Ice Melt (ARIM) upper-end, low probability sea level rise (SLR) scenario, which incorporates recent ice loss trends, improved ice sheet-ocean-atmosphere modeling, and potential ice sheet destabilization, projects SLR of up to 2.1 m by the 2080s and up to 2.9 m by 2100, at high greenhouse gas emissions (NPCC, 2019). These results exceed previous high-end SLR projections (90th percentile) of 1.5 m by the 2080s and 1.9 m by 2100, relative to 2000–2004 (NPCC, 2015).

By 2100, the 1% annual chance (100-year) floodplain could cover 1/3 of the city's total area under ARIM; around 1/5 of the area could be flooded during monthly high tides. Some low-lying locations could become permanently inundated by late century. Will New York City coastal resiliency initiatives, guided, in part by NPCC findings, suffice for very high sea levels? Additional research is needed to determine technological, environmental, or economic limitations to coastal protection and to decide when and where strategic relocation may become necessary.

1. Introduction

Sea level rise (SLR) and coastal flooding will pose growing challenges to protect the large population and major economic assets along New York City's waterfront, due to the city's proximity to the Atlantic Ocean and exposure to severe coastal storms. The city has a lengthy history of coastal storm flooding from both severe hurricanes (e.g., in 1821 and 1960), as well as nor'easters (extra-tropical cyclones; e.g., 1992), and most recently, Hurricane Sandy, on October 29, 2012.[1] Sandy generated the highest water levels in at least 300 years (Orton et al., 2016; Talke et al., 2014). In addition to extensive flooding, major power outages, and transportation disruptions, the storm caused 43 fatalities and an estimated $19 billion in damages in New York City (SIRR, 2013). The storm's severity arose from a highly unusual merging of meteorological and tidal forces, amplified by ongoing sea level rise.

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[1] Technically, a hybrid tropical-extratropical cyclone upon landfall in New Jersey.

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Hurricane Sandy spurred a comprehensive city-wide future climate risk mitigation program (SIRR, 2013), drawing upon the scientific expertise of the New York City Panel on Climate Change (NPCC). This special advisory group of academic and private-sector experts provides New York City with up-to-date science information on future climate change-related risks and adaptation recommendations (NPCC, 2010, 2015, 2019). New York City is actively employing earlier NPCC (2015) results as the current scientific basis for New York City's ongoing and planned coastal resiliency programs.

However, many of these programs are directed toward upgrades to city building codes and other regulations to protect against current severe storms and near-term higher SLR (i.e., up to the 2050s). The real challenge will occur during the second half of this century and later when sea levels may soar, particularly at higher greenhouse gas emission levels. When strengthening coastal defenses in high population density areas with long-lived infrastructure, one needs to consider low probability, high-end scenarios, as well as more likely ones. Some of the issues the city will confront in the event of upper-bound SLR scenarios and associated flooding (described in Sections 4–6) will include establishing protection levels for planned coastal defense structures. Other important considerations include coastal protection costs, effective infrastructure life-times, and optimum timing of implementation. A major unknown, aside from the likelihood, timing, and amplitude of significant ice sheet mass losses, is the ability of these coastal resiliency provisions to withstand the resulting sea level changes.

Almost all major land ice reservoirs, including most glaciers and both polar ice sheets, show accelerating rates of mass loss. The observed rapid worldwide recession of glaciers added the equivalent of about 0.4 mm/yr to global-mean sea level between 1961 and 2006 (assuming all water spread uniformly across the ocean), increasing to about 0.9 mm/yr between 2006 and 2016 (Zemp et al., 2019). Greenland added ~0.1 mm/yr over the 1980s and 1990s, ~0.5 mm/yr over the 2000s, and ~ 0.8 mm/yr over 2010–2018 (IMBIE TEAM, 2019; Tedesco et al., 2019; Bamber et al., 2018; Mouginot et al., 2019; Forsberg et al., 2017). Antarctica added ~0.1 mm/yr over the 1980s and 1990s, ~0.5 mm/yr over the 2000s, and ~ 0.7 mm/yr over 2009–2017 (Rignot et al., 2019; Shepherd et al., 2018; IMBIE TEAM, 2018) and its share will likely expand in the future. These observations underscore the urgency of improving our understanding of how changes in ice sheet processes could amplify future sea level rise.

The increasing SLR contributions from land ice, as well as advances in ice sheet-ocean-atmosphere modeling (e.g., DeConto and Pollard, 2016; Sweet et al., 2017; Kopp et al., 2017; Le Bars et al., 2017; Wong et al., 2017), and expert elicitation (Bamber et al., 2019) suggest that the probability of high-end sea-level rise scenarios may have been previously underestimated, particularly under high carbon-emissions futures. For example, Bamber et al. (2019) estimate a combined ice sheet contribution to SLR by 2100 of 81 cm in the low (+2 °C) scenario at the 95th percentile. The corresponding SLR in the high scenario (+5 °C) is 178 cm. Soaring sea levels would pose serious adverse risks to people and built structures in low-elevation districts of New York City and in other coastal cities, worldwide. These findings reinforce the rationale for inclusion of an upper-end sea level rise scenario in long-term coastal risk management.

In designing and constructing long-lived infrastructure, buildings, transportation networks, and zoning districts, urban planners and decision-makers should probe not only the most likely impacts, but also rare events with a potential for highly destructive consequences. A long-term planning horizon is essential in building infrastructure such as seawalls, breakwaters, and storm surge barriers, with expected lifetimes of 30 to 100 years and longer (Hinkel et al., 2019). Furthermore, densely-populated coastal cities with valuable assets near the shoreline, such as New York City, have a low risk tolerance and need to protect vulnerable areas against unlikely, yet possibly extreme sea levels (Hinkel et al., 2019; IPCC, 2019, p. 4–109). With these considerations in mind, this paper reviews a high-impact sea level rise scenario, ARIM (Antarctic Rapid Ice Melt), which includes the possibility of Antarctic Ice Sheet destabilization (Section 4; NPCC, 2019). ARIM depicts an alternative physically credible upper-end, yet very low probability late 21st century SLR scenario, which could become more likely over longer time horizons.

Storm floods represent a major destructive natural hazard facing coastal settlements. The globally increasing frequency of coastal flooding is to a large extent caused by rising sea level (e.g., Marcos and Woodworth, 2017; Marcos et al., 2015). Current global and local New York City (NYC) sea level rise trends are briefly reviewed in Section 2. Sections 3–5 summarize key NPCC, 2015 and 2019 findings to see how these could impact vulnerable neighborhoods. Changes in the frequency and areal extent of flooding for the 100-year flood[2] and for monthly tidal flooding due to sea level rise are presented in Section 5. We compare two upper-end SLR scenarios: 1) the 90th percentile level (NPCC, 2015) and 2) ARIM. Section 6 examines current and proposed New York City resiliency efforts, which in part are guided by NPCC, 2015 sea level projections. In so far as these plans largely address anticipated mid-century sea level rise, the long-term viability of these efforts under an ARIM-type scenario, is not well established. Some of the implications of a high-end sea level rise are critically assessed in Section 7.

2. Current global and local sea level rise trends

The 1900 to 1990 global mean SLR averaged about 1.2–1.9 mm/yr (IPCC, 2019; Dangendorf et al., 2017; Jevrejeva et al., 2017; Hay et al., 2015; Church et al., 2013). This trend has jumped to over 3 mm/yr between 1993 and 2019 (AVISO, 2019; WCRP, 2018; Nerem et al., 2018; Dieng et al., 2017). This recent acceleration derives largely from recent land ice contributions, particularly ice sheets. This latter fraction will continue to grow and probably dominate in future higher-end global sea level rise scenarios (Bamber et al., 2019; WCRP, 2018; Kopp et al., 2017).

However, relative, or local, sea level rise often deviates from the global mean because of multiple physical processes. These include: (1) steric changes (changes in ocean temperature and/or salinity); (2) ocean circulation changes (dynamic sea level changes);

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[2] The flood with a likelihood of occurring, on average, once per century. Also known as the 1% annual chance flood.

(3) land ice mass losses (3) changes in gravitation, rotation, and crustal deformation (i.e., “fingerprints”) associated with diminishing land ice mass; (4) glacial isostatic adjustments (GIA); (5) other vertical land movements (e.g., neotectonism, sediment compaction and loading, subsurface fluid extraction); and (5) changes in land water storage (e.g., in reservoirs or groundwater overdrafts).

Relative sea level rise[3] in the New York City harbor has averaged 2.9 mm/yr between 1900 and 1990, increasing to 4.5 mm/yr between 1990 and 2019[4] (Fig. 1). Although the choice of 1990 as the start date for the apparent acceleration is uncertain, its timing is consistent with the observed global increase in sea level over the 1993-present satellite altimeter era and is regional in extent (Boon et al., 2018; Davis and Vinogradova, 2017). The local NYC sea level rise trend is generally higher than the corresponding global trend for both time periods. The higher sea level trend in New York City and environs is largely attributed to GIA-related subsidence, greater local dynamic sea height, and diminishing glacier and ice sheet mass. Ocean circulation changes may also play an increasing future role. The Atlantic Meridional Overturning Circulation (AMOC), an important branch of a major global oceanic circulation system, could weaken and decelerate in response to Greenland ice losses, reduced Arctic Ocean sea ice, increased precipitation, and freshwater river inflow lower North Atlantic salinity. A weakened North Atlantic circulation would lead to greater heat accumulation, increased thermal expansion and shoreward flow of water mass in the mid-Atlantic region, including New York City (Krasting et al., 2016; Yin and Goddard, 2013). Such a slowdown, yet to be confirmed, would enhance future regional SLR (Yin and Goddard, 2013).

Ice sheet mass losses also affect New York City sea level indirectly. Mass losses weaken the gravitational attraction between ice sheet and ocean, driving water away. Thus, the near field sea level falls and amplified far field sea level rises. New York City therefore experiences greater than global average sea level rise from distal Antarctic melt, while more proximal Greenland Ice Sheet mass losses from the Greenland Ice Sheet and northern hemisphere glaciers lead to below-global-average local sea level rise. Because of the GIA contribution and a potential larger Antarctic contribution, total New York City sea level rise may substantially exceed the global average, underscoring the city's heightened regional risk (e.g., Kopp et al., 2014, 2017; Carson et al., 2016; Krasting et al., 2016).

3. Previous research

3.1. The New York City anel on climate change (NPCC, 2015) report

Sea level rise projections for New York City employed a multi-component methodology that included global and local steric changes, land ice mass losses and accompanying gravitational/rotational/crustal deformation, GIA, and effects of global mean anthropogenic land water storage changes. Sea level rise was calculated for the 10th, 25th, 75th and 90th percentiles from a model-based distribution and estimated ranges from the literature for two climate change scenarios (RCP 4.5, RCP8.5[5]). Future thermal expansion and dynamic ocean changes were obtained from an ensemble of 24 CMIP global climate models. Glacier and ice sheet contributions to future sea level were estimated from literature review and expert judgment (e.g., Bamber and Aspinall, 2013). Uncertainties were assumed to be perfectly correlated, leading to a broader range of projections compared to sea-level rise projections that assumed weaker correlations among different components (e.g. Kopp et al., 2014). Additional methodological details can be found in Appendix II·B, NPCC, 2015.

NPCC (2015) projected a SLR of 0.28–0.53 m by the 2050s, 0.46–0.99 m by the 2080s, and 0.56 to 1.27 m by 2100 at the Battery (25th -75th percentile), relative to 2000–2004 (Horton et al., 2015). High estimates (90th percentile) reach 0.76 m by the 2050s, 1.47 m by the 2080s, and 1.91 m by 2100 (Table 1). New York City currently utilizes these projections in coastal resiliency planning.

The SLR estimates in Table 1 do not cover 2100 sea levels above the 90th percentile (nor below the 10th percentile). Nevertheless, the small chance of sea level rise exceeding the 90th percentile could raise serious concerns for those public or private sector decision-makers who need to assess infrastructure and construction standards over longer timespans. Even though quite unlikely by 2100, the catastrophic impacts of such an eventuality makes it advisable to take this possibility into account beforehand (e.g., Kulp and Strauss, 2019; Hinkel et al., 2019: Hauer et al., 2016, Xian et al., 2018). Furthermore, sea level rise will not cease in 2100, thus higher levels will eventually occur–earlier in high greenhouse gas emission scenarios than in lower ones. Such outcomes, important to city agencies such as the New York City Department of City Planning, are addressed in the recent upper-end sea level rise scenario (ARIM; Section 4). One should bear in mind, however, that our scientific understanding of sea level rise processes, particularly those involving future ice sheet behavior in low probability, high impact situations, continues to evolve over time. Therefore, city planners and decision-makers should regard ARIM as offering a preview of a very high-end scenario, yet still premature to be used for actual planning purposes. Before turning to Section 4, we briefly review several other recent related New York City-based sea level studies.

3.2. Related New York City-based sea level studies

Table 2 compares results of related studies. Kopp et al. (2014) employed a similar methodology as that of NPCC (2015) but included IPCC (2013) assessments of future ice-sheet changes. Furthermore, they did not assume perfect correlation of uncertainties

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[3] Relative (local) sea level rise is that measured locally by tide gauges and is the change in the height difference between the sea surface and the ocean floor.

[4] The SLR trend for the entire period, 1856 to 2019, is 2.87 ± 0.09 mm/yr (NOAA Tides&Currents). https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750 (accessed 2/20/2020).

[5] NPCC (2015) omitted RCP2.6 as an overly optimistic mitigation pathway, while RCP 6.0 was regarded as intermediate between RCP 4.5 and RCP 8.5. Furthermore, some model results show RCP 6.0 projections very close to those for RCP 4.5.

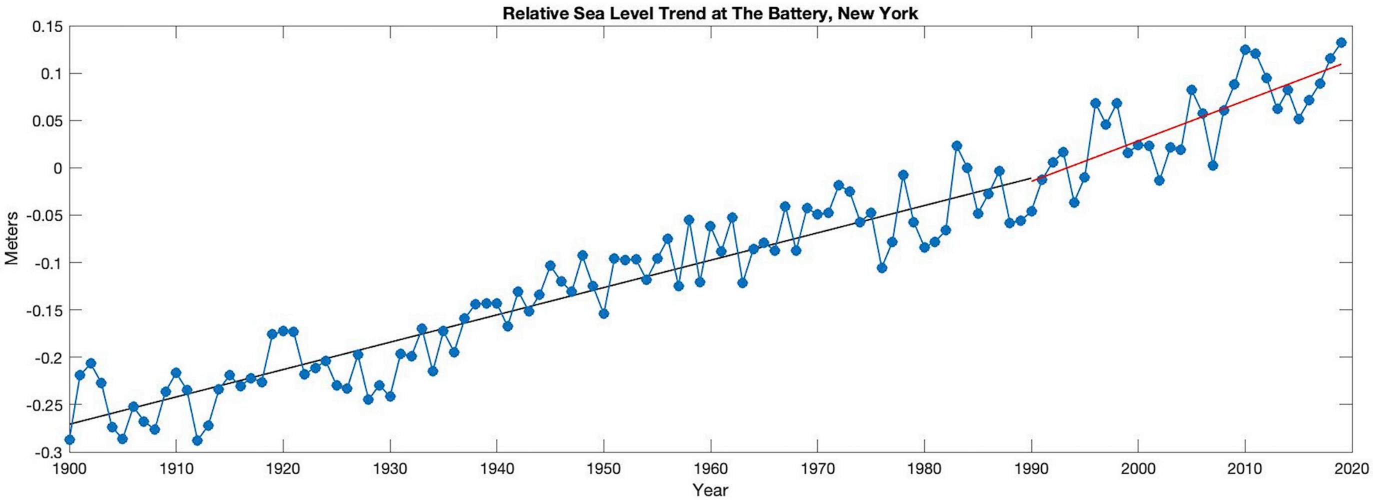

Fig. 1. The New York City sea level rise trend at the Battery between 1900 and 1990 is 2.9 mm/yr, increasing to 4.3 mm/yr between 1990 and 2019 (Permanent Service for Mean sea Level (PSMSL), 2012 https://www.psmsl.org/products/trends; NOAA Tide&Currents NOAA (National Ocean and Atmospheric Administration), 2020, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html. GIA-related land subsidence accounts for ~1.2 mm/yr (Englehart and Horton, 2012; Peltier 2012 databasein PSMSL, 2020). https://www.psmsl.org/train_and_info/geo_signals/gia/peltier/index.php.

Table 1

New York City sea level rise projections for the 2020s, 2050s, 2080s, and 2100, relative to 2000–2004, in meters (Horton et al., 2015).

Sea level rise baseline (2000–2004)	Low-estimate (10th percentile)	Middle range (25th to 75th percentile)	High-estimate (90th percentile)
2020s	+ 0.05 m	+ 0.10 to 0.20 m	+ 0.25 m
2050s	+ 0.20 m	+ 0.28 to 0.53 m	+ 0.76 m
2080s	+ 0.33 m	+ 0.46 to 0.99 m	+ 1.47 m
2100	+ 0.38 m	+ 0.56 to 1.27 m	+ 1.91 m

Table 2

Probabilistic New York City sea level rise projections from Kopp et al. (2014, 2017) adjusted for the 10th–90th percentile range, in meters, relative to the 2000–2004 baseline and time periods of Table 1.

	NPCC (2015)	Kopp et al. (2014)			Kopp et al. (2017), DP 16		
	10th to 90th percentile	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
2020s	0.05–0.25	0.11–0.26	0.12–0.25	0.09–0.29	0.08–0.27	0.09–0.26	0.06–0.29
2050s	0.20–0.76	0.22–0.58	0.25–0.60	0.26–0.66	0.19–0.62	0.25–0.66	0.30–0.75
2080s	0.33–1.47	0.28–0.89	0.35–0.99	0.44–1.19	0.30–0.96	0.51–1.30	0.80–1.87
2100	0.38–1.91	0.31–1.03	0.40–1.18	0.52–1.49	0.35–1.12	0.67–1.69	1.13–2.65

among the different components. Kopp et al. (2017) substituted into the Kopp et al. (2014) framework the Antarctic Ice Sheet projections from DeConto and Pollard (2016, [DP 16 in Table 2]), which assumes an Antarctic ice sheet highly sensitive to potential instabilities (described further in Section 4.1).

4. Antarctic rapid ice melt (ARIM): A new upper-end sea level rise scenario for New York City

4.1. Recent Antarctic ice sheet trends

As stated in the Introduction, increasing Antarctic ice mass losses since the 1990s and accumulating evidence for potential instability of the West Antarctic Ice Sheet (WAIS) raise the possibility of higher future sea levels than previously foreseen. Much of WAIS lies on land below sea level, on reverse slopes that tilt toward the continental interior. This topographic configuration is inherently unstable, according to the Marine Ice Sheet Instability (MISI) hypothesis. An ice stream or glacier retreating along a reverse slope near the grounding line[6] encounters thicker ice, accelerates, stretches, and discharges more ice, until the bed slope flattens or rises landward (e.g., Fig. 2). Grounding lines of many WAIS glaciers are retreating (Konrad et al., 2018; Christie et al., 2016); attached ice shelves have also thinned in recent decades (Sutterley et al., 2019; Reese et al., 2018).

Recent observations and dynamic simulations of retreat and ice melt on Thwaites Glacier—which accounts for close to one third of the recent mass loss from the Amundsen Sea Embayment of WAIS–lend further support to the MISI hypothesis (Milillo et al., 2019; Seroussi et al., 2017; Joughin et al., 2014; Rignot et al., 2014). In one model, projected warming could potentially initiate a WAIS destabilization later this century that would lead to a 3 m rise in sea level over centuries to several millennia (Feldmann and Levermann, 2015). Parts of Wilkes Land, East Antarctica could also be vulnerable to a future MISI process (Morlighem et al., 2020).

An additional mode of ice sheet instability could raise sea levels still higher (DeConto and Pollard (2016). The Marine Ice-Cliff Instability (MICI) arises from the interaction of two processes: (1) hydrofracturing, in which summer meltwater on ice shelves propagates down into small crevasses, which deepen and widen under pressure, ultimately breaking ice shelves apart; (2) gravitational instability of thick coastal ice cliffs that are not buttressed by ice shelves. Intact ice shelves restrain forward ice stream motion near the grounding line of the ice sheet. Heavily fractured ice shelves disintegrate more rapidly, which speeds up ice stream motion and ice discharge. These mechanisms could initiate ice shelf break-up after the 2050s at high greenhouse gas emission rates, potentially raising sea level by over a meter for Antarctica alone by 2100. Such rates, if sustained, could initiate collapse of the West Antarctic Ice Sheet (WAIS) and some parts of the East Antarctica Ice Sheet within several centuries, potentially raising global mean-sea level rise by over 15 m by 2500.

This single study complements other plausible arguments for a high-end sea-level rise, but should be viewed cautiously (e.g., Edwards et al., 2019; Bamber et al., 2018). MICI has not been observed in operation in the modern world, and Edwards et al. (2019) argue that it is not necessary to explain the paleo-observations that DeConto and Pollard (2016) use to calibrate their model.

Two important negative feedbacks may to some extent lessen the effects of a marine ice sheet instability. Firstly, a less massive ice load produces a near-instantaneous elastic isostatic rebound, leading to land uplift and regional sea level fall (Barletta et al., 2018; Gomez et al., 2015). The grounding line then advances seaward, inhibiting a MISI. Secondly, the reduced ice mass weakens the gravitational attraction between ice sheet and ocean, allowing water to flow away from the ice sheet, lowering proximal sea level. A sea level drop at the grounding line prevents warmer Circumpolar Deep Water (CDW) incursion at the base of ice shelves, impeding

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[6] The boundary between land-based ice and an attached floating ice shelf or tongue.

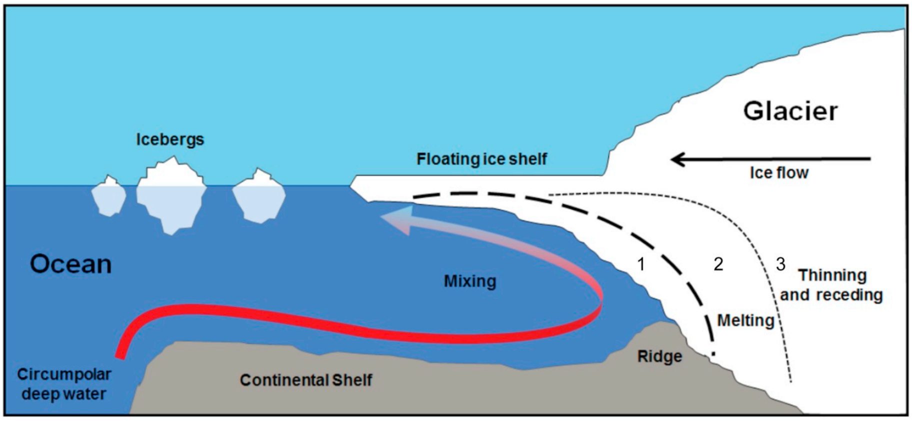

Fig. 2. The Marine Ice Sheet Instability: 1) Ice stream or glacier is grounded on a bedrock ridge on the continental shelf; 2) Warm Circumpolar Deep Water enters cavity beneath the ice shelf and melts the base of the glacier at the grounding line; 3) the grounding line recedes further downslope beyond the ridge, leading to ice shelf thinning and seaward acceleration of the glacier. (Modified from Davies, 2014).

basal melting and ice-shelf break-up. Moreover, glacial rebound flattens and even tilts the original reverse slope seaward. Computer models find that both feedbacks together significantly lower millennial time-scale Antarctic ice losses, as compared to models without these offsetting feedbacks (Gomez et al., 2015). These negative feedbacks may not be overly significant on the centennial time-scale. Claims of a late 21th century onset of marine ice cliff instabilities should therefore be treated warily at this time. Nevertheless, the sensitivity of sea-level projections to as-yet incompletely understood geophysical processes involving ice sheets illustrates why high-end possibilities should be examined, even although their likelihood remains highly uncertain.

4.2. The ARIM scenario: methodology and results

Increasing ice mass losses on the Greenland and Antarctic Ice Sheets, (e.g., Rignot et al., 2019; IMBIE TEAM 2019, 2018; Tedesco et al., 2019; Bamber et al., 2018; Mouginot et al., 2019; Forsberg et al., 2017; Sweet et al., 2017, expert assessments (Bamber et al., 2019; Horton et al., 2014; Bamber and Aspinall, 2013), and progress in ice sheet-ice shelf-ocean modeling (e.g., DeConto and Pollard, 2016) point to the possibility of sea level rise exceeding the IPCC (2013) “likely” range (Garner et al., 2018; Kopp et al., 2017). Newly recognized mechanisms for ice-shelf instability lend further support for high-end scenarios, especially after 2100 in high-emission scenarios (Kopp et al., 2017; Le Bars et al., 2017; Wong et al., 2017; DeConto and Pollard, 2016). This led the Fourth National Climate Assessment to recommend a set of global mean sea level rise scenarios spanning the period 2000 to 2100 that range from a “Low” 0.3 m scenario to an “Extreme” 2.5 m scenario by 2100 (Sweet et al., 2017).

The ARIM scenario adopts the magnitude of the “Extreme” global-mean sea level rise scenario and methodology as in Sweet et al. (2017). ARIM screens a subset of probabilistic projections from Kopp et al. (2017) that lies within 250 ± 15 cm global mean sea level rise by 2100 (as in Sweet et al.'s “Extreme” case). The Kopp et al. (2017) projections update those in Kopp et al. (2014) for Antarctica by substituting DeConto and Pollard's (2016) Antarctic Ice Sheet modeling, which includes ice sheet instabilities (i.e., MISI and MICI, Fig. 2), leaving all other sea level components from Kopp et al., 2014) unchanged. Because a linear acceleration was assumed, the earlier Kopp et al. (2014) projections yield a strong correlation between near-term and late-century high-end outcomes. The ARIM projections, on the other hand, allow for the possibility of nonlinear acceleration in ice mass loss (see Gornitz et al., 2019 for additional details).

ARIM projections for the 2020s and 2050s lie within the earlier NPCC (2015) 10th–90th percentile range (Table 3). By the 2080s, however, sea level under the ARIM scenario rises by 2.1 m, reaching 2.9 m by 2100 (Table 3). The Kopp et al. (2017) projections

Table 3
New York City sea-level rise projections, comparing the new Antarctic Rapid Ice Melt (ARIM) scenario (NPCC, 2019) to those from NPCC (2015), relative to 2000–2004.

Baseline (2000–2004) 0”	NPCC, 2015 Sea Level Rise Projections, m			ARIM Scenario, m
	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)	ARIM scenario[a]
2020s	0.05	0.10–0.20	0.25	–
2050s	0.20	0.28–0.53	0.76	–
2080s	0.33	0.46–0.99	1.47	2.06
2100	0.38	0.56–1.27	1.91	2.90

[a] In the 2020s and the 2050s, the ARIM scenario lies within the pre-existing NPCC (2015) range and therefore NPCC (2015) results can be used for these two earlier time slices.

consistent with ARIM are almost all associated with RCP 8.5.

An implication of the ARIM scenario is the possibility that mechanisms of ice mass loss on the Antarctic Ice Sheet could differ substantially after the 2050s from those currently in operation. Since these represent nonlinear processes, a mid-range relative sea level rise by mid-century would therefore not preclude much higher values toward the end of the 21st century. Furthermore, sharp emissions reductions would not quickly slow down or reverse any ensuing sea level rise. Almost all scenarios agree on continued sea level rise for centuries (see below). Although the chance of ARIM remains quite low by 2100, the likelihood of such a scenario increases further into the future (NPCC, 2019; Kopp et al., 2017). This provides an added incentive to include an upper-bound scenario, particularly in long-term planning.

Despite increasing ice mass losses and potential ice sheet instabilities, no consensus has yet emerged over the upper bound SLR nor of a best estimation method (Garner et al., 2018). The presently incomplete state of knowledge of important ice processes and their associated uncertainties makes it difficult to specify a probability distribution that can quantify the likelihood of the ARIM scenario and define an exact upper bound SLR (see also discussion in Hinkel et al., 2019). Rather, "upper bound" is used more loosely to represent an example of a credible very high-end SLR scenario. ARIM includes recent improvements in oceanic-ice sheet-atmospheric modeling and presents an alternate physically–plausible upper-bound, low-probability sea level rise scenario for late 21st century New York City. Despite the preliminary and somewhat speculative nature of this scenario, which needs further testing, we believe that its likelihood would increase toward the end of this century at high emission scenarios (e.g., RCP 8.5), while remaining quite unlikely under low emission scenarios (e.g., RCP 2.6). Expert judgment of global SLR (Bamber et al., 2019), localized for New York City, corresponds reasonably well to middle to high estimates for NPCC (2015); the ARIM scenario would have an estimated ~3% chance of occurring by 2100 at high emissions, but near zero probability under low emissions. ARIM gives city managers with a low risk tolerance and long planning horizons an opportunity to consider an unlikely but possible extreme late-21st century SLR, for which additional levels of coastal protection may be required.

Sea level will continue to rise well beyond 2100 because of the long lifespan of atmospheric CO_2. Even after termination of further anthropogenic CO_2 emissions by mid-century, while some atmospheric CO_2 diminishes within decades, the remainder will probably take millennia to slowly adjust to a new equilibrium level (Clark et al., 2016). This longevity of atmospheric CO_2 commits us to higher global temperatures and sea level rise long after greenhouse gas emission stabilization and reduction. Ice sheet mass losses would continue to increase during this extended warm period and could ultimately lead, at worst, to significant deglaciation of the Greenland Ice Sheet[7] within several millennia at high emissions scenarios (Clark et al., 2016). Potential West Antarctic Ice Sheet losses could add further to SLR. The likelihood of WAIS destabilization by mechanisms, such as MISI and MICI under high emissions, would grow in coming centuries.

The following section looks at the consequences of the ARIM scenario on increased frequency and extent of coastal flooding in New York City, with particular attention given to high-risk neighborhoods surrounding Jamaica Bay, Queens and Brooklyn.

5. Coastal flooding

Sea level rise is a major reason for the globally increasing severity of major storm surge flooding (Marcos and Woodworth, 2017; Marcos et al., 2015). It also leads to the rapid annual increase in minor "nuisance flooding" in low-elevation neighborhoods (e.g., Sweet et al., 2018, 2019; Strauss et al., 2016). Historically, coastal storms have flooded New York City's lowest-lying neighborhoods multiple times, as noted in the Introduction.

This section assesses coastal storm-driven extreme floods using Federal Emergency Management Agency (FEMA, 2013) baseline flood hazard data for the current 1% annual chance flood (popularly known as the "100-year" flood, or "1-in-100-year flood"), NPCC sea level rise scenarios, and corresponding maps of expanding flood risk zones. A new dynamic-model analysis compares monthly tidal flooding under the NPCC (2015) and Antarctic Rapid Ice Melt (ARIM; NPCC, 2019) sea level rise scenarios (Section 4).

5.1. Future coastal storm Flood risks; the 100-year flood

5.1.1. Methods

Coastal flooding is here defined both in terms of water level relative to the geodetic North American Vertical datum of 1988 (NAVD88) and with maps of flood extent. Future changes in coastal flood area, depth, and frequency are based on simple superposition of the 90th percentile sea level rise projections (Table 3) on a baseline of FEMA (2013) 100-yr flood water levels (the "static" approach). The static approach produced nearly identical results as dynamic flood modeling for this location and FEMA flood assessment (Orton et al., 2015a; Patrick et al., 2015). While FEMA baseline ignores possible changes to storm climatology, recent studies for New York City find that this factor is very small in comparison to sea level rise (e.g., Roberts et al., 2016; Marsooli et al., 2019) and furthermore, high model-to-model differences reflect high uncertainty (see review in Orton et al., 2019). This approach also neglects possible future anthropogenic or natural changes in coastal geomorphology, which are a challenge to predict. Studies of historical changes in flooding show that, despite sea level rise, coastal protection can reduce flood risk (Haigh et al., 2020). Estuary bathymetric changes such as landfill and dredging can also significantly increase or decrease flooding (Ralston et al., 2019; Orton et al., 2020).

Although a wide range of estimates exists for the 100-year storm flood level (see review in Orton et al., 2019), here we use the

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[7] The Greenland Ice Sheet holds the equivalent of ~7 m of global-mean sea-level rise.

Table 4

Future 100-year flood levels (1% annual chance), in m, relative to NAVD88) for the 10th–90th percentiles (NPCC, 2015) and ARIM sea level rise scenarios at the Battery, assuming static superposition and unchanged storm climatology (NPCC, 2019). (The baseline 100-year water level is 3.44 m, relative to NAVD88; FEMA, 2013).

100-Year Flood Levels, m	10th	25th	75th	90th	ARIM
2020s	3.50	3.54	3.66	3.69	–
2050s	3.66	3.72	3.96	4.21	–
2080s	3.78	3.90	4.42	4.91	5.49
2100	3.81	3.99	4.72	5.36	6.31

same FEMA baseline as in earlier NPCC studies to provide continuity with planning products created from those studies (e.g., NYC-DCP, 2016a, 2016b).

This study assumes unchanged future storm climatology and omits wave effects ("still water elevation"). The static approach also overlooks possible compound effects of SLR combined with changes in cyclonic storm track, intensity, or frequency (e.g., Garner et al., 2017; Lin et al., 2016), as well as interannual to interdecadal climate fluctuations, such as the North Atlantic Oscillation (NAO), which can also affect storm tracks and extreme water levels (e.g., Talke et al., 2014). While changes in storm frequency may have little impact, the intensity of tropical cyclones could increase in this region (e.g., Kossin et al., 2014), but this would be counter-balanced by the offshore shift in storm tracks (Garner et al., 2017). This implies that projected increases in storm surge heights would be largely due to SLR. A similar study finds instead that compound effects of sea level rise and storm climatology would enhance the frequency and magnitude of New York City's extreme flood levels (Lin et al., 2016).

Not considered in this study is the role of dredging for navigational channel deepening on storm tide height. Channel deepening in New York harbor has altered circulation patterns, which may have amplified tidal water levels and augmented storm flood heights (Ralston et al., 2019). The net effect of these additional factors acting together with sea level rise could enhance future coastal flooding impacts.

5.1.2. Results

Table 4 lists results for 100-year extreme water levels at the Battery for the same set of sea level rise projections and time intervals as in Table 3, assuming static superposition and unchanged storm climatology. For example, by the 2080s, the 100-year water level ranges from 3.78 to 4.91 m for the projected 10th to 90th percentile SLR and up to 5.49 m under ARIM. By 2100, corresponding water levels reach 3.81–5.36 m (10th -90th percentiles) and up to 6.31 m (ARIM).

Table 5 shows the reduction in the future 100-year flood (1% annual chance) return periods relative to the baseline 100-year flood, due to rising sea level. The 100-year flood return period (1% annual chance) would shorten to 71–28 years, on average (1.4%-3.6% annual chance) by the 2050s, and to 59–8 years (1.7%-12.5% annual chance) by the 2080s (10th -90th percentiles). By 2100, the 100-year flood return period would recur on average once in 54 to < 5 years (1.9% to > 20% annual chance). Under the more extreme, but considerably less likely ARIM scenario, by 2100 the 100-year flood event could recur possibly as often as every few days.

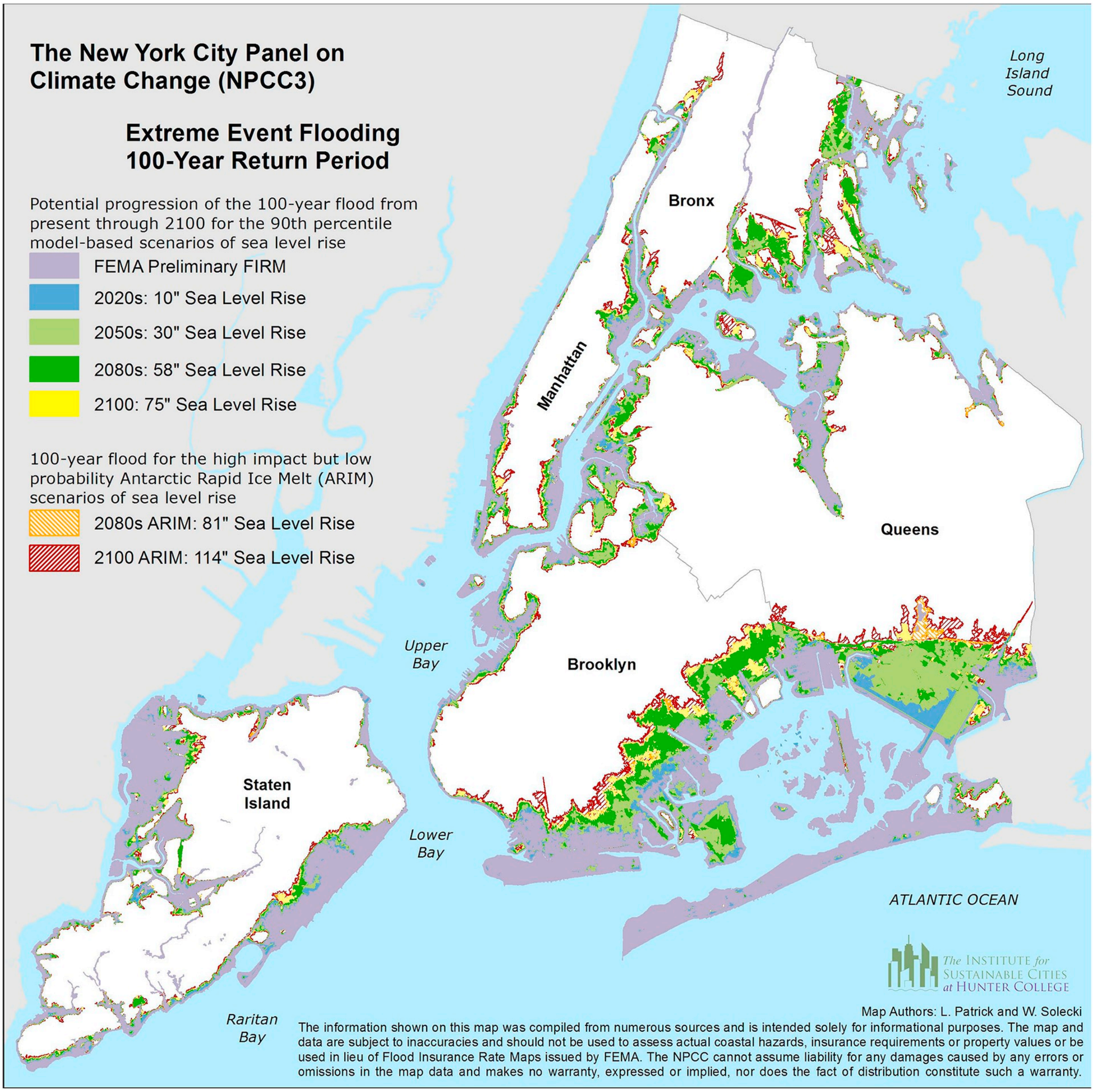
Fig. 3 maps the successive citywide expansion of the 100-year flood zone over time for the NPCC (2015) 90th percentile and ARIM sea level rise projections (Patrick et al., 2019). Hurricane Sandy flooded an area broadly corresponding to that of the FEMA (2013) 100-year flood zone indicated in purple (Orton et al., 2015a), which covers some of the lowest, most vulnerable areas of the city. Topographically higher areas farther inland enter the 100-year flood zone between the 2020s and 2080s under the 90th percentile SLR scenarios (shown in greens and yellow in Figure 3). However, the much higher projected ARIM 2080s and 2100 sea levels add a smaller area to the 100-year flood zone than that engulfed by 2020s-2100 90th percentile sea levels, because the new landward elevation change exceeds the projected vertical rise in sea level (Table 6; Patrick et al., 2019). Topography therefore spares a greater portion of the city from more severe future flood risks. Nevertheless, with a total land area of 784 km^2, by 2100 the 1% annual chance floodplain under ARIM could cover one third of the city; around 1/5 could be flooded during monthly high tides (U.S. Census, 2010; Table 6).

Fig. 4 enlarges the view of the evolution of the 100-year flood zone over time for the low elevation area surrounding Jamaica Bay,

Table 5

Future 100-year flood return periods (in years) for the same set of sea level rise scenarios and time intervals as in Table 4. (The FEMA, 2013 baseline flood exceedance curve data does not cover return periods under 5 years; hence " < 5" is indicated for the later time periods).

Time Period	10th	25th	75th	90th	ARIM
2020s	93	85	71	66	–
2050s	71	64	42	28	–
2080s	59	47	19	8	< 5
2100	54	40	11	< 5	~1 day



Map Authors: L. Patrick and W. Solecki

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Fig. 3. Expansion of the 100-year return period floodplain over time between the baseline period 2000–2004 and 2100, for New York City for the 90th percentile SLR (2020s = 0.25 m; 2050s = 0.76 m; 2080s = 1.47 m; 2100 = 1.91 m; NPCC, 2015) and ARIM SLR (2080s = 2.06 m; 2100 = 2.90 m; NPCC, 2019; Table 3). Results assume no future shoreline changes due to either coastal erosion or flood protection measures and may therefore over- or underestimate flood area. (Because of remaining uncertainties associated with ARIM (section 4), its inclusion here serves to raise risk awareness only, and should not be used for planning purposes at this time).

Table 6

Citywide changes in area over time above the baseline for the 100-yr flood (1% chance) and monthly tidal flood for the 10th–90th percentile and ARIM sea level rise scenarios.

Sea level rise scenario	Sea level rise, m	Area, 100-yr flood, km^2	Percent increase in area	Area, monthly tidal flood, km^2	Percent increase in area
2020s 90%	0.25	154.0	18	24.9	19.2
2050s 90%	0.76	185.2	22	40.0	60.3
2080s 90%	1.47	219.5	18	79.4	98.5
2100 90%	1.91	235.3	7	113.1	42.5
2080s ARIM	2.06	240.0	2	127.3	12.5
2100 ARIM	2.90	266.3	11	178.6	40.3

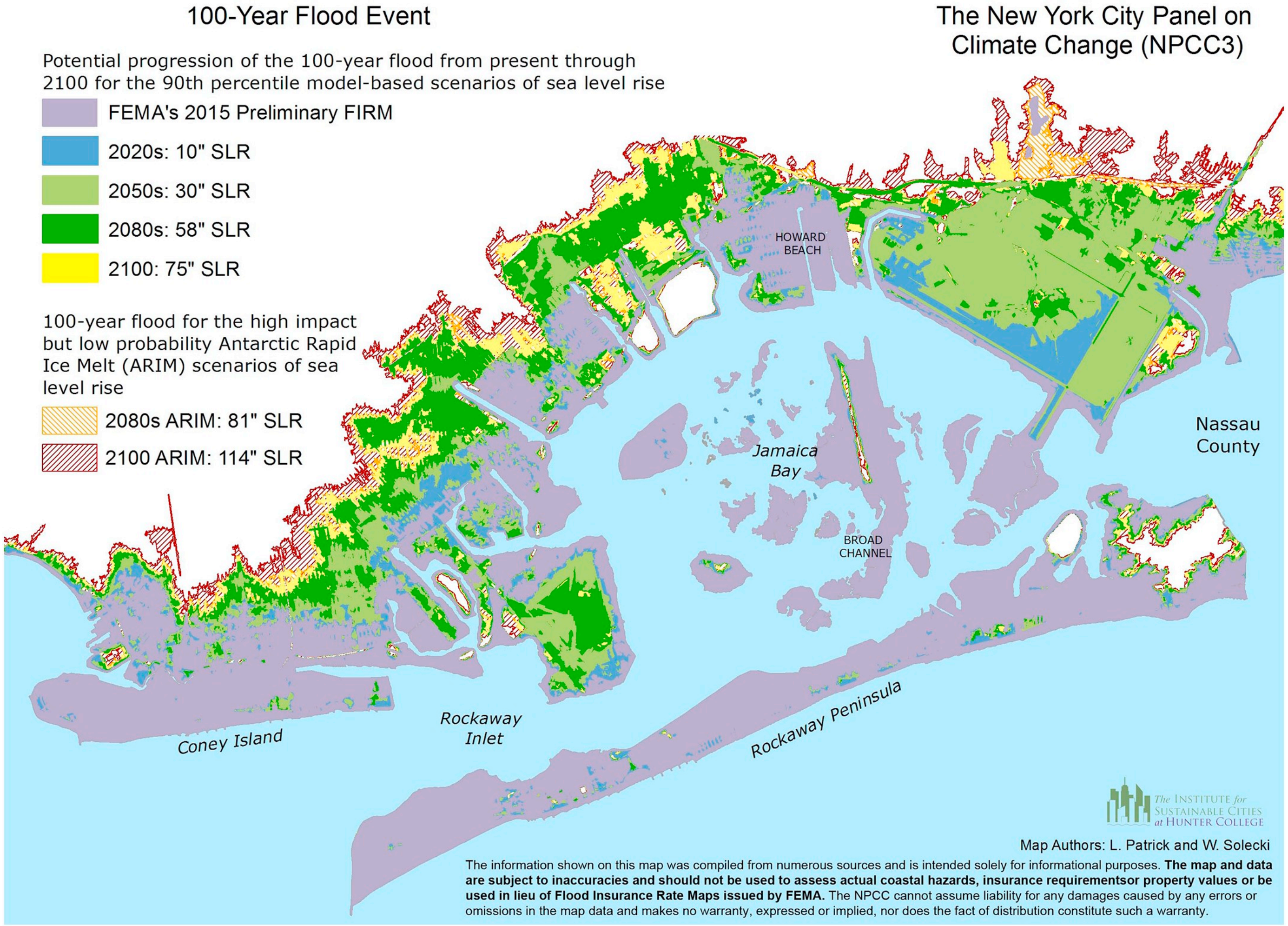

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Fig. 4. Expansion of the 100-year return period floodplain over time for Jamaica Bay, the Rockaways, and Coney Island for the 90th percentile SLR (2020s = 0.25 m; 2050s = 0.76 m; 2080s = 1.47 m; 2100 = 1.91 m; NPCC, 2015) and ARIM SLR (2080s = 2.06 m; 2100 = 2.90 m; NPCC, 2019; Table 3). Results assume no future shoreline changes due to either coastal erosion or flood protection measures and may therefore over- or underestimate flood area. (Because of remaining uncertainties associated with ARIM (section 4), its inclusion here serves to raise risk awareness only, and should not be used for planning purposes at this time).

the Rockaways, and Coney Island, for the same set of sea level rise scenarios and time intervals as in Fig. 3. A significant proportion of the city's total floodplain at risk to severe future storm flooding lies in this area. Implications of these growing risks to the communities are discussed in the following sections.

5.2. *Future monthly tidal flooding*

One of the earliest manifestations of sea level rise is the increasing incidence of clear weather "nuisance flooding", or of tidally related coastal flooding. The incidence of nuisance flooding has increased significantly in the United States between 1950 and 2015 (Sweet et al., 2018). The mounting frequency of such "minor" coastal floods that encroach onto streets, into basements, and low-lying infrastructure, could lead to escalating damages in the absence of protective measures. Frequent nuisance flooding already affects several low-lying New York neighborhoods surrounding Jamaica Bay and Rockaway Peninsula.

5.2.1. *Methods*

Dynamic model simulations, which explicitly calculate all physical forces acting on water and resulting water movement, were used in conjunction with sea level rise projections to investigate changes in future monthly tidal flooding over time. The NYHOPS forecasting system performed three-dimensional dynamic simulations of tides over a 35-day period starting in August 1, 2015, under tide and streamflow forcing (without wind). Additional methodological details can be found in Orton et al. (2019).

This study uses the Mean Monthly High Water (MMHW, the average of all monthly maximum astronomical tide levels) as a reference datum, instead of the more commonly used Mean Higher High Water (average of the higher of the two daily high tides, NOAA, 2000). In general, MMHW exceeds MHHW by 0.6–1.0 ft. (0.18–0.3 m) around New York City, and is therefore a more sensitive indicator than the latter of when tidal flooding would reach a given area of the city with SLR. Furthermore, high MHHW levels are exceeded far more frequently. Therefore, this tidal datum gives more useful insights into the potential impacts of sea level rise on neighborhood habitability and timing of when to implement coastal protection measures.

5.2.2. *Results*

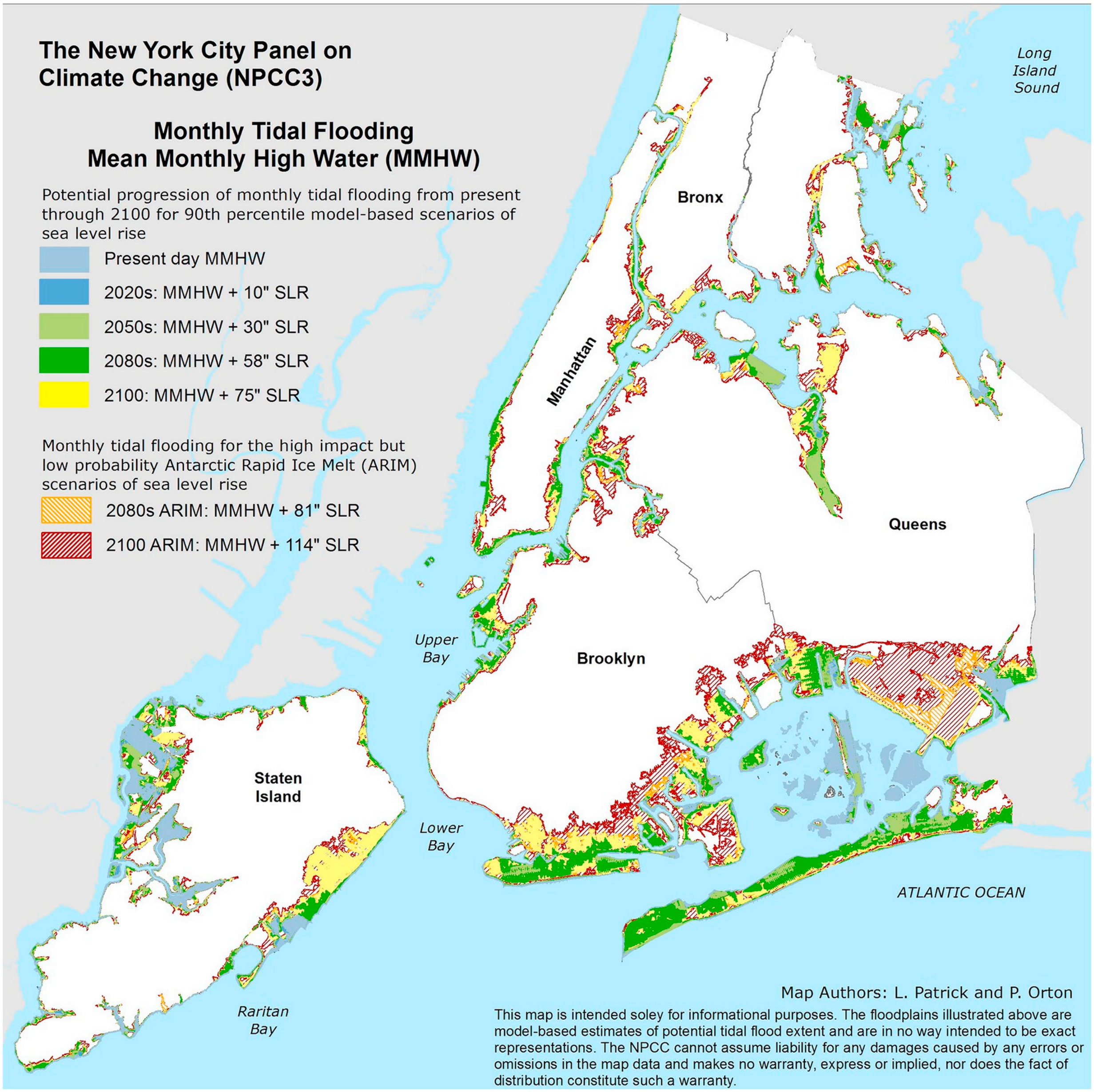
Citywide monthly tidal flooding for the same set of sea level rise projections and time periods as in Section 5.1 is shown in Fig. 5. Table 6 indicates increases in area subjected to monthly tidal flooding. By the 2050s, parts of south Brooklyn and Queens, eastern Staten Island, Flushing Meadow, Queens, and several other scattered shoreline locations around the city, could experience monthly tidal flooding. Fig. 6 illustrates an enlarged view of the progressive expansion of monthly tidal flooding around Jamaica Bay and Rockaway Peninsula over time at the 90th percentile NPCC, 2015 SLR. Large swaths of the south shore of Brooklyn and Queens would experience monthly tidal flooding, starting in the 2050s and becoming more extensive by 2100 (Fig. 6). By late 21st century, monthly tidal flooding under the ARIM SLR scenario would penetrate still farther inland, including much of John F. Kennedy Airport (Fig. 6, top right; Table 6). The lowest sections of neighborhoods around Jamaica Bay and Coney Island previously exposed to monthly tidal flooding under the 90th percentile SLR scenario could experience daily high tide flooding, even permanent inundation, under late 21st century ARIM SLR, potentially compromising habitability. Other low-elevation waterfront communities elsewhere around the city could face similar flooding hazards (Fig. 5).

6. New York City coastal resiliency measures

In 2011, former Mayor Michael R. Bloomberg initiated *Vision 2020: New York City Comprehensive Waterfront Plan*—an ambitious citywide initiative to increase public waterfront accessibility, support recreational and economic activity, restore natural habitat, extend parkland and greenways, improve water quality, and enhance climate resiliency (NYC DCP, 2011). The report called for promoting flood protection in vulnerable areas, integrating climate change projections into emergency preparedness efforts, and coordination with relevant city, state and federal agencies and stakeholders to mitigate future coastal hazards. A follow-up *Vision 2030: New York City Comprehensive Waterfront Plan* is scheduled for completion by the end of 2020 (NYC DCP, 2020, in prep.).

Shortly after Hurricane Sandy, Bloomberg (2013) proclaimed: "As New Yorkers, we cannot and will not abandon our waterfront. It's one of our greatest assets. We must protect it, not retreat from it." The storm's aftermath stimulated a massive climate risk mitigation program (SIRR, 2013; NYC 2014a,b; NYC DCP, 2016a,b; NYC DCP, 2017; NYC DCP, 2019; NYCEDC, 2019). Revised FEMA NFIP building codes for new or renovated buildings within the 1% annual floodplain with waves < 0.5 m, require elevation of utilities above base flood elevation (BFE, or 1% annual floodplain), or their flood-proofing. Lowest occupied floors must lie above BFE. Buildings in the BFE with ≥ 0.9 m waves must rest on pilings or have an open foundation. New York City codes furthermore specify an extra 0.6 m of freeboard protection above the 1% annual chance flood level for one and two-family houses; and an extra 0.30 m for most other buildings. Other enhanced structural flood-resiliency measures include: a) additional building flood-proofing, b) installation of raised air vent gratings over subways to prevent entry of water, c) elevation of track switches and electrical equipment, d) increased pumping capacity in underground rail and tunnel systems, and e) construction of new electric power substations beyond the flood zone (New York City, 2014a).

Other enhanced "hard" shoreline protections include raising levees, dikes, and construction of neighborhood-scale tidal barriers. These measures are tailored to specific neighborhood needs (e.g., NYCEDC/NYCORR, 2019; NYC DCP, 2017; NYC DCP, 2016a, 2016b). The New York City Department of City Planning interacts closely with the community to discuss flood risks and proposed resiliency actions (NYC DCP, 2016a, b; New York City Department of City Planning—Resilient Neighborhoods: Old Howard Beach, Hamilton Beach, and Broad Channel, 2017). In Broad Channel, a small, tightly-knit, but highly vulnerable community within Jamaica



Map Authors: L. Patrick and P. Orton

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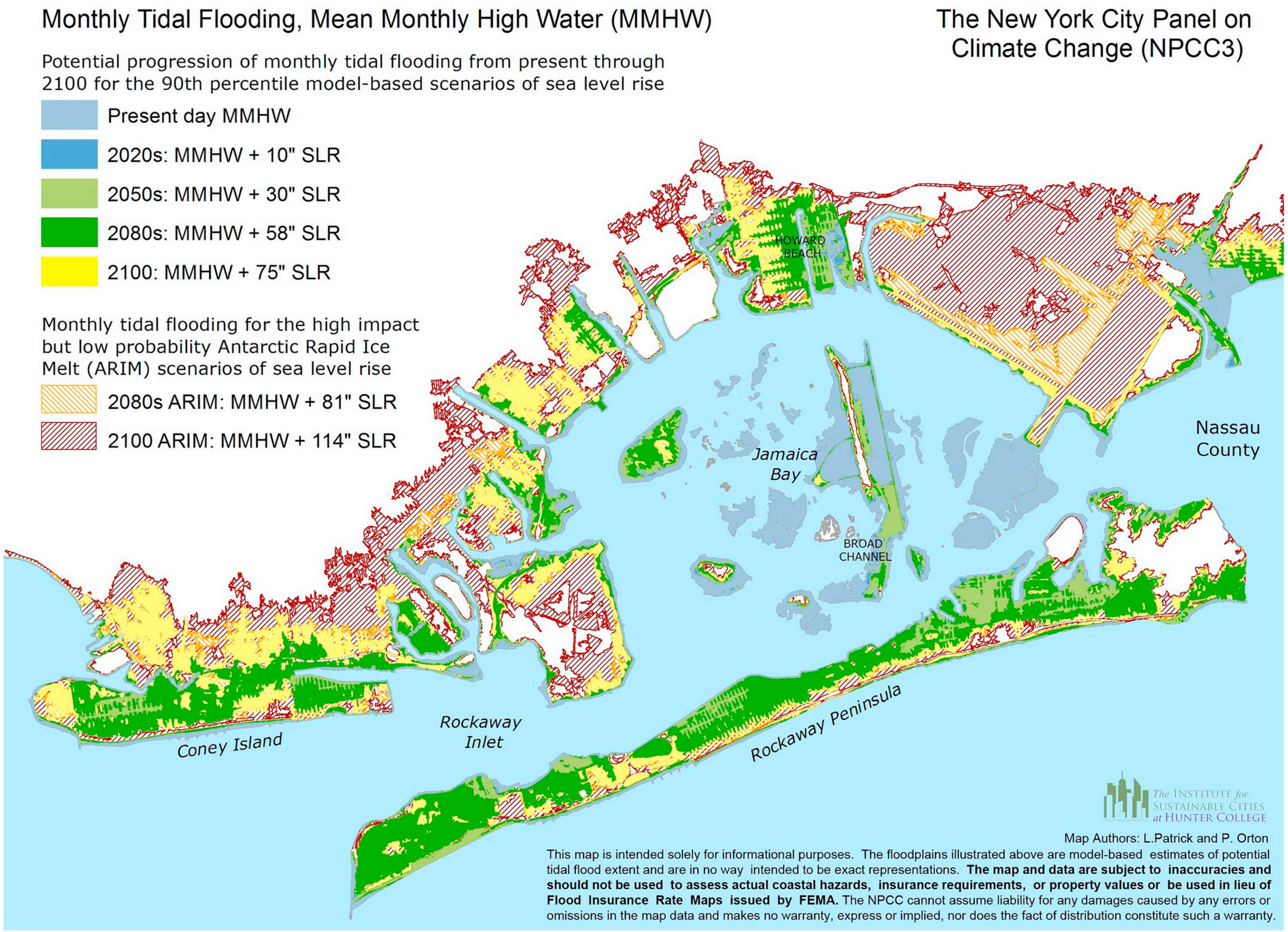
Fig. 5. Expansion of the area affected by monthly tidal flooding between the baseline period 2000–2004 and 2100 for New York City for the same SLR projections as in Fig. 3 (2020s = 0.25 m; 2050s = 0.76 m; 2080s = 1.47 m; 2100 = 1.91 m, 90th percentile SLR; NPCC, 2015) and (2080s = 2.06 m; 2100 = 2.90 m, ARIM SLR; Patrick et al., 2019; NPCC, 2019; Table 3). Results assume no future shoreline changes due to either coastal erosion or coastal flood protection and may therefore over- or underestimate flood area. Because of remaining uncertainties associated with ARIM, its inclusion here serves to raise awareness only and is not intended for planning purposes.

Bay (Figs. 4, 6), the city is raising bulkheads and strengthening seawalls, plans to elevate frequently flooded streets and street edges, encourages retrofitting of existing houses, and intends to reduce residential density by limiting new construction in this Special Coastal Risk District.

A "soft" coastal defense pathway involves replanting and restoration of salt marshes in nearby Jamaica Bay, Gateway National Recreation Area, in partnership with the New York City Department of Environmental Protection, New York City Department of Parks, and United States Army Corps of Engineers (USACE), which will help attenuate storm-driven waves (Marsooli et al., 2017; Orton et al., 2015b), preserve wildlife habitat, offer recreational benefits (boating, fishing, birding), and improve water pollution filtration (Fig. 7). Another nature-based approach entails creating a "Living Shorelines" like that along the shores of Brooklyn Bridge Park (Fig. 8). This waterfront park is lined by a mix of riprap, salt-tolerant vegetation, newly-planted salt marsh wetlands, and pilings that dampen wave action and help stabilize the shoreline (NYC 2014b). Abandoned piers, once used for shipping, now offer multi-



Monthly Tidal Flooding, Mean Monthly High Water (MMHW)

The New York City Panel on Climate Change (NPCC3)

Map Authors: L.Patrick and P. Orton

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Fig. 6. Expansion of the area affected by monthly tidal flooding for the Jamaica Bay and Coney Island areas of New York City. SLR projections are same as in Fig. 4 (2020s = 0.25 m; 2050s = 0.76 m; 2080s = 1.47 m; 2100 = 1.91 m, 90th percentile SLR; NPCC, 2015, and 2080s = 2.06 m; 2100 = 2.90 m, ARIM SLR, NPCC, 2019; Table 3). Results assume no future shoreline changes due to either coastal erosion or coastal flood protection and may therefore over- or underestimate flood area. Because of remaining uncertainties associated with ARIM, its inclusion here serves to raise awareness only and is not intended for planning purposes.

Fig. 7. Replanting of salt marsh grass, Jamaica Bay, New York. (Source: United States Army Corps of Engineers).

Fig. 8. Soft edge "living shoreline", Brooklyn Bridge Park, New York City. (Source: New York City Department of City Planning, 2013).

purpose uses for sports, entertainment, sunbathing, and picnicking.

Coastal defenses planned for Lower Manhattan, another highly vulnerable part of New York City which encompasses the highly-developed financial district, the South Street Seaport, and several historically important sites, include temporary deployable flood protection barriers (e.g., Tiger Dams), installation of permanent, retractable "flip-up" barriers, elevating the Battery esplanade seawall and installing a grassy berm in the existing park (NYCLMCR, 2019; NYC, 2019; NYCEDC/NYCORR, 2019). A project to extend the shoreline and build a berm for this district is still in its early stages. Other coastal protection projects are planned for vulnerable neighborhoods, including the East Shore of Staten Island, Red Hook, Brooklyn, and other at-risk areas. The city will also update existing zoning regulations and recommend enhanced flood-resistant building design options. Additional resiliency steps include coordination with local utilities to incorporate climate risks into systems planning and design, fortify energy and telecommunications assets, as well as reinforce transportation networks, wastewater treatment plants, and sewers against higher sea levels.

Tidal barriers, such as the Thames barrier in England (TE, 2019), or the Maeslant barrier in the Netherlands, have been proposed as a means of protecting New York City from much higher future sea levels. A set of three storm surge barriers located at narrow points were proposed to protect the financial district of lower Manhattan, adjacent areas of Brooklyn, Queens, and the Bronx, as well as Hoboken, Jersey City, and Newark, including Newark International Airport (Bowman et al., 2005). However, this plan would leave unprotected large portions of Staten Island, Brooklyn, and Queens, including JFK International Airport, as well as nearby communities on the Atlantic coast of Long Island and Long Island Sound, also exposed to higher waters. At present, the U.S. Army Corps of Engineers, states of New York and New Jersey, and New York City are partnering under the Harbor and Tributaries Focus Area Feasibility Study (HATS) to evaluate several alternative options to manage coastal storm risks, including storm surge barriers that cross the harbor and have retractable gates (United States Army Corps of Engineers (USACE), 2019). Such a massive undertaking would require comprehensive engineering and environmental impact evaluations as well as consideration of possible social and economic repercussions. Aside from major environmental and cost concerns, the inability of proposed surge barrier systems to protect the entire shoreline would raise serious equity issues and controversy, potentially pitting neighborhoods that would be protected against remaining exposed communities.

Other less controversial, creative future options, not actively pursued by the city at present, include floating neighborhoods. For example, low-lying waterfront communities could be accommodated on houseboats or barges, as in Rotterdam, the Netherlands; Seattle, Washington state; Sausalito, California; and Bangkok, Thailand. Floating houses that rise and fall with the tides, could be built, as in the Netherlands and Victoria, British Columbia. Regularly-flooded streets could be converted to canals, as in Venice, Italy or Amsterdam, the Netherlands, accessible by boat, rather than automobile or bus. As parts of the city become more aquatic, the importance of waterway transportation networks will grow. The venerable Staten Island Ferry, operated by NYC Department of Transportation, provides free daily rides between the Battery and Staten Island. Several private companies offer ferry transportation with multiple stops connecting the remaining four boroughs. For example, the New York Water Taxi route covers points between Midtown Manhattan 42nd Street and DUMBO in Brooklyn, with stops at Battery Park and New York Seaport in lower Manhattan. The NYC Ferry, operated by Hornblower, offers various routes with multiple stops along the East River, DUMBO, Red Hook, Bay Ridge in Brooklyn, and one stop in the Rockaways, Queens. Existing routes and service between various city shoreline locations should be maintained and expanded in the future to serve neighborhoods where frequent flooding disrupts normal surface transportation or subway service.

In the event of extreme SLR, such as ARIM by 2100 or later, it may prove extremely challenging to defend all 837 km of New York City's shoreline. Although the city has made considerable progress toward coastal resiliency improvements since the SIRR (2013) report, the pace of progress has been slow. By March 31, 2019, the city had spent only 54% of the $15 billion in combined Federal grants allocated for Sandy recovery and resiliency improvements, in part delayed by burdensome government bureaucracy (Stringer, 2019). An ambitious plan, announced in March of 2019, is the $10 billion Lower Manhattan Climate Resiliency Study, which would expand the shoreline into the East River (NYCLMCR, 2019). While it is essential to defend the city's financial center, estimated costs of the plan are staggering; the bulk of the funding sources have yet to be determined. A comprehensive citywide coastal resiliency plan (e.g., NYC DCP, 2019) will therefore need to prioritize neighborhood resiliency strategies based on multiple factors, including data on the latest climate science, vulnerability to frequent or severe flooding, infrastructure and land property values, at-risk population, and additional coastal protections required. A complete overview of the entire shoreline will enable the city to make well-informed decisions of how best to allocate available resources toward enhanced coastal resiliency.

Many of the above-mentioned New York City's resiliency actions address current or near-term coastal flood risks, which will only provide temporary solutions to a growing climate problem. Long-term coastal resiliency planning for high-risk, flood-prone areas must also embrace appropriate land-use zoning. Those areas should avoid or strictly limit new high-density development. For example, NYC Planning—Resilient Neighborhoods is already designating special high flood risk neighborhoods, such as Broad Channel and Hamilton Beach, where overall population growth will be limited, and new construction will be restricted to single or double family residences (NYC DCP, 2017). Vacant or under-developed property would instead be converted to "green infrastructure"—-expanded parkland or additional tree plantings to enhance water drainage; the land could also serve as flood buffer zones. For example, the Bluebelt program, originally implemented in Staten Island, is a connected series of streams, ponds, and wetlands that acts as a natural drainage corridor to handle runoff from heavy rainfall, coastal flooding. It also provides green space and enclaves for wildlife habitat (NYC DEP, 2013).

Strategic (or managed) relocation of the highest-risk areas, including sections surrounding Jamaica Bay, may eventually become unavoidable. Even under more moderate sea level rise, it could become extremely costly to defend portions of some neighborhoods against growing frequency of monthly (perhaps even daily) tidal flooding by mid- to late-century (e.g., Figs. 5, 6). One potential solution is expansion of a voluntary buyout program for the most vulnerable residential neighborhoods (Stringer, 2019). A successful program in New York City was New York State's post-Sandy *New York Rising Buyout Program*, which purchased 473 significantly damaged homes in three Staten Island neighborhoods at pre-storm, full market value, plus an additional 5% incentive bonus to relocate within NYC boundaries. New York City has designated $5 billion of a HUD CDBG-DR grant for a pilot "Resiliency Property Purchase Program", initiated in 2018, to buy private 40 properties at risk to repeated flooding, by spring 2021. As of March 31, 2019, none of the appropriated funds had been spent. Despite the slow start, NYC Comptroller Scott Stringer recommends expanding the buyout program and include areas at risk to flood waters not immediately adjacent to planned resiliency projects, obtaining funding from both city and federal sources. The vacated land would be restored to natural habitat and wetlands and serve as "green" or "blue infrastructure". While such a program may appear costly in the short-term, it would ultimately save the government money otherwise spent on repairing or rebuilding repeatedly flooded homes. It would also save homeowners the increasing costs of National Flood Insurance Program (NFIP) premiums.

7. Discussion and conclusions

New York City and environs can anticipate higher than global mean sea levels due to enhanced thermal expansion, dynamic ocean changes, mounting ice losses from distal ice sheets and associated "fingerprints", as well as ongoing glacial isostatic adjustment. The NPCC (2015) reports a sea level rise of nearly 1.5 m by the 2080s, and up to 1.9 m by 2100 in the 90th percentile estimate. The ARIM scenario, which includes recent cryosphere developments, projects a sea level rise of up to 2.1 m by the 2080s and up to 2.9 m by 2100 under high greenhouse gas emissions futures. These high sea levels contain deep uncertainties and would have less than a 3% chance of occurring by 2100 only under high-emissions pathways (Bamber et al., 2019). Furthermore, the importance of the marine ice cliff instability by 2100 needs further evaluation (e.g., Barletta et al., 2018; Edwards et al., 2019).

The higher and faster sea level rises, the more challenging and costly coastal defenses or barriers capable of resisting flooding will become. Nevertheless, a wealthy megalopolis of international commercial significance like New York City, with its financial resources, will most likely take all steps to insure its survival, as former Mayor Bloomberg promised. While many of the city's resiliency efforts (Section 6) respond to current or near-term climate risks, infrastructure with expected operating lifetimes greater than 50 years require long-term planning horizons that should include low probability, upper end scenarios such as ARIM. The likelihood of this very low probability outcome by 2100 would grow in coming centuries, inasmuch as the present business-as-usual CO_2 emissions pathway is committing us to long-term continued sea level rise, as discussed in Section 4.2. Substantial deglaciation of the Greenland Ice Sheet[8] could occur within several millennia under sustained high emissions scenarios (Clark et al., 2016). ARIM, although probably premature by 2100, therefore offers a foretaste of much higher possible future sea levels. The recent ARIM scenario (NPCC, 2019) is not yet used in planning because of ongoing resiliency programs already based on NPCC (2015) and ARIM's dependence, in part, on an untested and much-debated model.

Planned resiliency measures, such as those described earlier, would need to be substantially upgraded in the event of a high-end outcome, to protect long-lived infrastructure and important assets along the city's lengthy shoreline. Despite detailed city guidelines for improved flood-resiliency (e.g., NYC DCP, 2019; NYC DCP, 2016a, 2016b; New York City, 2014a, 2014b), numerous technical and regulatory hurdles will remain in retrofitting existing buildings within vulnerable, densely populated neighborhoods. For example, existing zoning regulations for structures within flood-prone portions of Howard Beach, Broad Channel, and Hamilton Beach in Jamaica Bay pose retrofitting challenges that are difficult to implement and that could alter neighborhood character. Proposed new changes recommend revised building heights and setbacks better suited for existing narrow lots, improved emergency access, future growth limits, and return of vacant city-owned property to natural habitat (NYC DCP, 2016a).

An important consequence of an upper-end SLR scenario is the progressive landward expansion of areas subjected to monthly tidal, to near-daily nuisance flooding, and ultimately, complete inundation. Under ARIM and unchanged storm climatology, some of the low-elevation New York City neighborhoods, particularly those surrounding Jamaica Bay and Rockaway Peninsula, could experience recurring daily to monthly flooding by the 2050s, and a few of the lowest neighborhoods could become permanently submerged by 2100.

Substantial numbers of the region's coastal population, infrastructure, and other built assets in adjacent Long Island and New Jersey are exposed to analogous escalating coastal hazards (Kopp et al., 2019). A recent NOAA study concludes that by 2100, three U.S. cities—New York City, Miami, and San Francisco—can expect daily high tide flooding under Intermediate (1 m) to Extreme (2.5 m) global mean SLR scenarios (Sweet et al., 2018). More vulnerable localities along the East Coast of the U.S. would undergo high tide flooding almost every other day under an "Intermediate Low" global sea level rise scenario (0.5 m).

Sea level rise will impact the world's cities to varying degrees. In the continental United States alone, Hauer et al. (2016) project a population of 13.1 million people at risk to inundation from 1.8 m global mean SLR by 2100 (a value close to Sweet et al.'s (2017) "High" scenario of 2.0 m by 2100). Using an improved coastal digital elevation model, Kulp and Strauss (2019) estimate that 220–520 million people would be exposed to permanent inundation by 2100 globally, at high emissions (RCP8.5; 5 to 95 percentiles) and potential Antarctic instability, while 380–630 million would face annual flooding. Growing awareness of the mounting risks has prompted many cities to undertake actions to advance coastal adaptation (e.g., Dawson et al., 2018).

A controversial implication of an ARIM-type scenario is that conventional coastal defense measures may be not be feasible for all locations. Strategic relocation of people living within the highest-risk neighborhoods in New York City, and in many other of the world's vulnerable coastal settlements–both large and small—may therefore eventually become necessary in very high-risk places. One study finds that for a 1.8 m SLR by 2100, Florida stands to lose over 2.5 million residents by emigration, mainly concentrated in the Miami-Fort Lauderdale-West Palm Beach area, whereas Texas would gain 1.5 million people (Hauer, 2017). Nine other states could see population losses. Relocation costs for large numbers of displaced populations at upper end sea level rise scenarios could become prohibitive. Limited data suggest current strategic relocation costs for small vulnerable population groups ranging from over $100,000 per person in the U.S. to under $10,000 per person in Fiji and the United Kingdom (Hino et al., 2017). A proposed relocation of only 40 households as a group, in the Mississippi Delta, Louisiana, could cost up to $48 million (IPCC, 2019, p. 4–101).

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[8] The Greenland Ice Sheet holds the equivalent of ~7 m of global-mean sea-level rise.

However, these figures should be regarded as very preliminary because of generalized assumptions, insufficient data, and small sample size.

An effective means of dealing with large future uncertainties is a flexible adaptation pathway strategy, as originally proposed for the TE 2100 Plan (2009) and recommended for New York City by the NPCC (2010, 2015, 2019) and Rosenzweig and Solecki, 2019This stepwise adjustable approach is well-suited for coastal adaptation projects with long expected lifetimes and deep uncertainties in sea level change. It has been successfully implemented in several other cities as well (e.g., IPCC, 2019, p. 4–111; Hallegatte, 2009).

However, the suite of proposed coastal resiliency actions discussed above could engender a false sense of security and encourage additional high-density development in high-risk areas. Overlooked is a real possibility that ultimate limits may exist to engineering or nature-based solutions to coastal protection and accommodation at very high sea levels. Therefore, further research should first aim toward development of more accurate sea level rise models to predict future timing and magnitude of ice sheet mass losses. Other research should be directed toward establishing the most useful indicators that define significant sea level rise thresholds and optimal timing of when to undertake critical adaptations. A need also exists to determine potential technological, social, and economic limitations to coastal adaptation strategies under extreme sea level rise scenarios. Addition research should also be undertaken to investigate changing attitudes and risk tolerance levels toward growing coastal hazard risks, when and where to initiate strategic relocation, and how to implement resettlement most equitably under a broad range of conditions. Finally, New York City should continue to play a leading role in future climate resiliency planning and adaptation, which stands as a model to cities around the world.

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Declaration of Competing Interest

None.

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