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New York City Panel on Climate Change 2019 Report Chapter 3: Sea Level Rise

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Introduction

The New York City Panel on Climate Change (NPCC, 2015) sea level rise projections provide the current scientific basis for New York City scientific decision making and planning, as reflected in, for example, the City's Climate Resiliency Design Guidelines. However, since the IPCC (2013) and NPCC (2015) reports, recent observations show mounting glacier and ice sheet losses leading to rising sea levels. Furthermore, new developments in modeling interactions between oceans, atmosphere, and ice sheets suggest the possibility of a significantly higher global mean sea level rise (GMSLR) by 2100 than previously anticipated, particularly under elevated greenhouse gas emission scenarios.

Because of the potentially serious adverse consequences of soaring sea levels to people and infrastructure in low-lying neighborhoods of New York City, we introduce a new high-impact sea level rise scenario, Antarctic Rapid Ice Melt (ARIM), which includes the possibility of Antarctic Ice Sheet destabilization. An earlier "Rapid Ice Melt Scenario" (NPCC, 2010) assumed a late 21st century rate of high-end sea level rise of ∼0.39–0.47 in. per decade, based on paleo-sea level data after the last Ice Age. ARIM represents a new, physically plausible upper-end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from improved modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections.

We briefly summarize key processes that control sea level rise on global to local scales, observed trends, and risks the city faces due to current and ongoing sea level rise. We also briefly recap the NPCC (2015) sea level rise projections for comparison with ARIM. To set the stage for ARIM, we review recent trends in land ice losses (Section 3.5) that reinforce the need to consider such an upper-end scenario. A more detailed discussion of these trends and technical details of the ARIM scenario are provided in Appendix 3.A.

3.1. Key processes

Multiple physical processes govern sea level rise on global to local scales. These include: (1) ocean density changes (involving temperature and salinity); (2) changes in ocean currents and circulation patterns; (3) ice mass losses from glaciers, ice caps, and ice sheets; (4) redistribution of ocean water in response to changes in the Earth's gravitation, rotation, and deformation caused by current ice mass losses (collectively referred to as "fingerprints"); (5) past ice mass losses (i.e., glacial isostatic adjustments, GIA[a]); (6) other vertical land movements

[a]Glacial isostatic adjustment (GIA) refers to Earth's lithospheric responses to the addition or removal of ice masses, which affect land elevation (either subsidence or uplift).

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caused by ongoing tectonic activity, sediment compaction due to loading, and subsurface extraction of water, oil, gas; and (7) changes in land water storage, for example, in dams or from groundwater mining. Thermal expansion along with losses of ice from mountain glaciers and small ice caps have historically been the major contributors to observed mean global sea level rise, but in recent decades, shrinking ice sheets have played a growing role and dominate in the higher scenarios for future GMSLR (Slangen *et al.*, 2017, 2016; Kopp *et al.*, 2014; Church *et al.*, 2013, IPCC AR5).

These processes interact in ways that differ from place to place, such that for any given locality the sum of the components for local sea level rise may deviate significantly from the global mean. New York City lies in a region that experiences higher than average sea level rise due to enhanced thermal expansion, mounting ice losses from the Antarctic Ice Sheet, and GIA.

An additional possible factor is changes in ocean circulation. A major oceanic circulation system, the Atlantic Meridional Overturning Circulation (AMOC), could slow down due to decreased North Atlantic salinity resulting from Greenland ice losses, increased precipitation and northern river freshwater inflow, and sea ice attrition. The resulting heat build-up due to a weakened North Atlantic circulation would increase thermal expansion and redistribute water mass shoreward especially in the mid-Atlantic region, including New York City (Krasting *et al.*, 2016; Yin and Goddard, 2013; Yin *et al.*, 2010; 2009).

While a regional sea level acceleration "hotspot" has been observed in tide gauge records along the Atlantic coast from Cape Cod to Cape Hatteras (including New York City) since the early 1990s (Sallenger *et al.*, 2012; Boon, 2012), it is more likely that this hotspot reflects high interannual to multidecadal ocean variability than a shift in ocean circulation (Kopp, 2013; Valle-Levinson *et al.*, 2017). Attribution of the hotspot to a weaker Gulf Stream and slowdown of the AMOC (Rahmstorf *et al.*, 2015; Yin and Goddard, 2013) has not yet been substantiated (Böning *et al.*, 2016; Watson *et al.*, 2016) and is thus premature. However, this process could become important in the future (e.g., Section 3.4.2).

In addition—perhaps counterintuitively, given the great distance between Antarctica and New York City—ice losses from Antarctica are amplified along the mid-Atlantic coast by the gravitational responses to this change. As the mass of the ice sheet shrinks, its gravitational attraction weakens, and water congregates farther from it. This, as well as continued GIA-related land subsidence, leads to a higher than average local sea level rise. On the other hand, gravitational effects from more nearby ice losses on Greenland and northern hemisphere glaciers mean that these ice losses raise local sea levels less than the global average. The net effect of all these processes drives New York City sea level rise above the global average (e.g., Carson *et al.*, 2016; Slangen *et al.*, 2014; Kopp *et al.*, 2014.; Horton *et al.*, 2015a).

3.2 Observations and trends in sea level

Sea level rise represents one of the most momentous consequences of climate change, potentially affecting hundreds of millions of people worldwide. In recent decades, melting ice sheets and glaciers account for over half of the total observed current rise (Dieng *et al.*, 2017; Rietbroek *et al.*, 2016), a fraction likely to increase with continued global warming (see Sections 3.4.1, 3.5, and 3.6). This section briefly reviews current global and local/regional trends in sea level rise, to provide context for future sea level changes, discussed in later sections.

3.2.1 Global mean sea level rise. Tide gauge-based reconstructions of GMSLR between 1900 and 1990 range between 0.04 and 0.08 in./year (1 and 2 mm/year) (Dangendorf *et al.*, 2017; Jevrejeva *et al.*, 2017; 2014; Hay *et al.*, 2015; Church *et al.*, 2013; Church and White, 2011). Between 1993 and 2017, satellite altimetry shows an average GMSLR of around 0.12 in./year (3 mm/year),[b] after accounting for satellite instrumental drift that affected the earlier TOPEX/Poseidon mission between 1993 and 1998 (Watson *et al.*, 2015; Dieng *et al.*, 2017;

More inclusively, GIA refers not only to still ongoing viscous responses to ice removal following the last ice age, but also to elastic responses to recent ice melting.

[b]Most recent updated trends: 3.1 ± 0.4 mm/year; seasonal trends removed (http://sealevel.colorado.edu (posted 2/23/18; accessed 5/18/18); and 3.32 ± 0.5 mm/year, GIA-corrected (https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html posted 3/26/18; accessed 5/18/18).

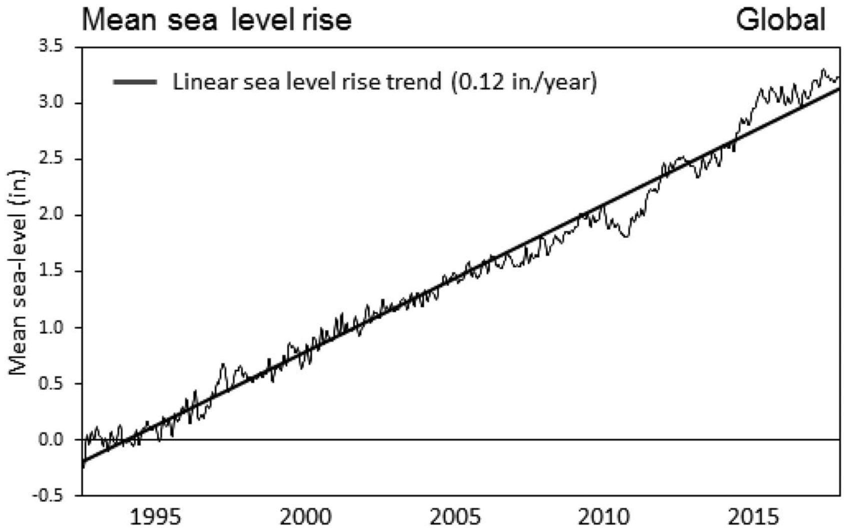

Figure 3.1. Global mean sea level rise during the satellite era, 1993–2018 (AVISO, France; posted March 26, 2018).

Beckley *et al.*, 2017). After further accounting for the effects of the 1991 Mt. Pinatubo volcanic eruption and of strong El Niño–Southern Oscillation events, these revised estimates show clear acceleration of the sea level record, attributable to accelerated ice sheet mass loss (Chen *et al.*, 2017; Dieng *et al.*, 2017; Nerem *et al.*, 2018; Fig. 3.1). Glaciers, ice caps, and ice sheets combined have raised ocean levels by 0.01 in./year (0.31 mm/year) between 1992 and 1996, increasing to 0.07 in./year (1.85 mm/year) between 2012 and 2016 (Bamber *et al.*, 2018).

Furthermore, GMSLR since the late-19th century has greatly exceeded the range of variability seen over the last three millennia (Kopp *et al.*, 2016; Gehrels and Woodworth, 2013). These results imply two stages of global mean sea level acceleration: the first between late 19th and early 20th century to around 1990, which may in part reflect natural climate cycles, and the second from the 1990s to the present. Since 1970, anthropogenic factors may account for over 70% of the rise (Slangen *et al.*, 2016).

3.2.2 Local and regional sea level rise. The local or relative[c] sea level rise in New York City has averaged 0.11 in./year from 1850 to 2017 as measured by The Battery tide gauge, nearly double the 1900–1990 mean global rate (Fig. 3.2; NOAA, 2017). Local GIA-related subsidence, which accounts for roughly half of the observed relative sea level rise (Engelhart *et al.*, 2011; Engelhart and Horton, 2012), is a key reason why New York City's rate of sea level rise is so high. As elsewhere, the historic New York City trend has increased markedly relative to the previous millennium (Kemp *et al.*, 2017).

3.2.3. Observed sea level rise since NPCC 2015. Sea level rise has been tracked over time by the NPCC using data from both tide gauges and satellite altimetry. (For more information on tide gauges, see the NOAA Tides & Currents[d] website; for satellite altimetry, see NASA Jason[e] and AVISO/CNEs[f] websites). New observations from these sources are included in updated analyses of sea level rise trends in each NPCC report and are included in reference to any new projected values.

NPCC 2019 extends the observed record for sea level rise from NPCC 2015. In addition, NPCC 2019 analyzed how the trends in recent sea level rise compare in general to the projected changes in sea level from NPCC 2015 into the 2020s timeslice, which encompasses the time period from 2020 to 2029.

[c]Relative sea level rise is that measured locally by instruments such as tide gauges. It can differ considerably from global mean sea level rise for any combination of the reasons given in Section 3.1.

[d]https://tidesandcurrents.noaa.gov/
[e]https://sealevel.nasa.gov/missions/jason-3
[f]https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html

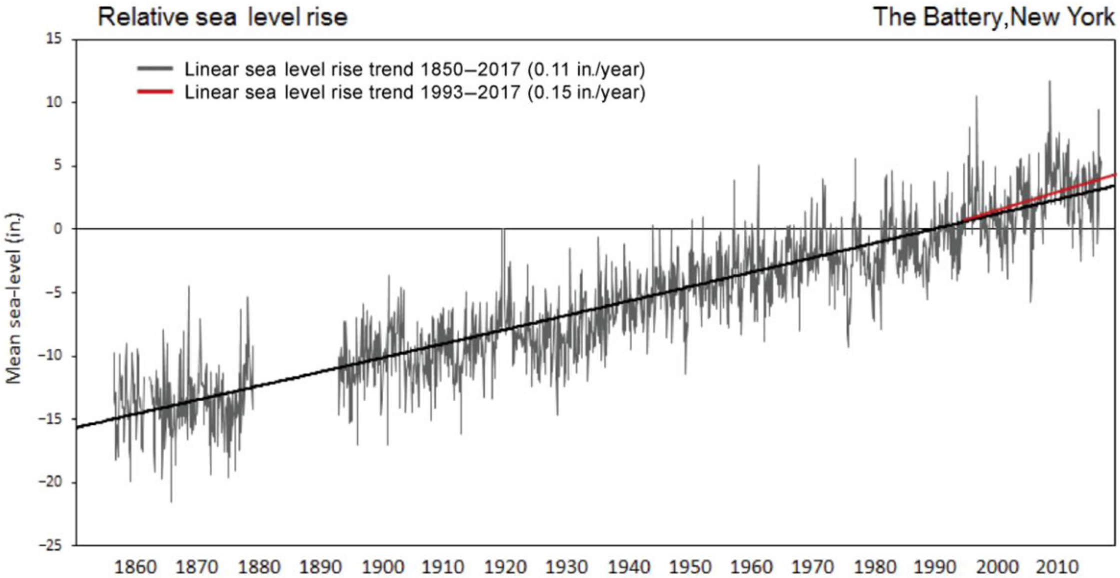

Figure 3.2. Historic sea level rise 1850–2017 in New York City at The Battery (NOAA, 2017). Black trend line shows an increasing trend from 1850 to 2017, while the red trend line shows a slightly higher trend from 1993 to 2017, which may reflect the apparent recent acceleration seen in the global sea level rise record.

Figure 3.3 shows the observed trend in sea level rise at The Battery in New York City from 1900 through 2017 compared to the NPCC 2015 projections. While NPCC3 cannot yet compare analytically projected to observed values from NPCC 2015 through 2017–2018 since we have not yet entered the onset of the 2020s time slice, nevertheless, the most recent observed trends show that sea level at The Battery has continued its upward rise since the previous NPCC report. A more comprehensive, comparative

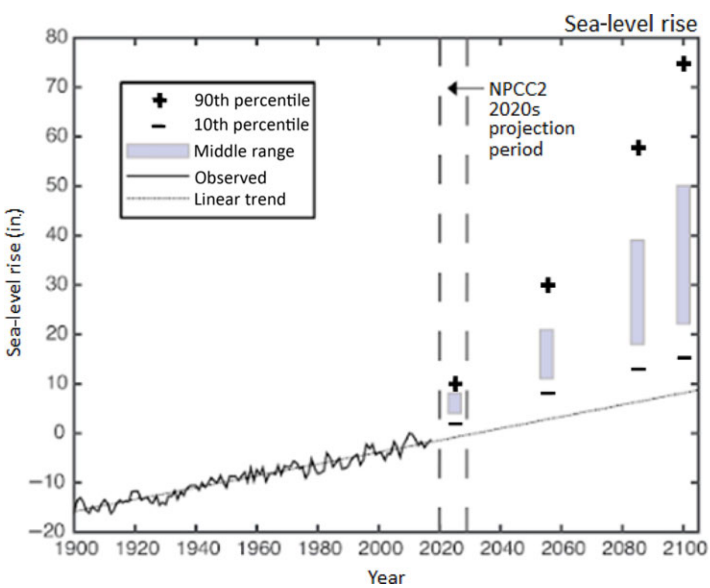

Figure 3.3. Observed sea level rise at The Battery in New York City from 1900 through 2017 compared with projected changes in sea level rise from the NPCC 2015 Report in the 2020s.

analysis will be part of the next NPCC report when a greater overlap will exist between the observed trend time period and projected values from NPCC 2015. However, such comparisons should be viewed with caution because of the role of natural variability in the short term.

3.3 Current risks: role of sea level rise

New York City is part of a metropolitan region (population 23.7 million[g]) that covers three adjacent states—Connecticut, New York, and New Jersey. Long-term sea level rise, as well as episodic coastal flooding, poses a high risk to the population, housing, and many essential New York City infrastructure facilities that line the 520 miles (837 km) of the city's waterfront. These include three major international airports, shipping infrastructure, segments of commuter and intercity bus and rail transit systems, many subway, tunnel, and bridge entrances, nearly all city wastewater treatment plants (WWTPs), oil tanks and refineries, most power plants, and telecommunication networks.

The combined effects of New York City sea level rise (18 in., 45.7 cm between 1856 and 2017; Fig. 3.2, NOAA, 2017) and changes in storm climate variability (Orton *et al.*, 2016; Lin *et al.*, 2016; Reed *et al.*, 2015; Talke *et al.*, 2014; and Wahl *et al.*, 2017) have increased the impact of coastal flood hazards (see also, Chapter 5: Mapping Climate Risk). Due to historic growth patterns and high-density shoreline development, a significant population resides within areas exposed to coastal hazards. The above-average water levels during strong hurricanes or hybrid storms, such as Sandy (Oct., 2012), Donna (Sept., 1960), Irene (Aug., 2011), and the unnamed 1788 and 1821 hurricanes, as well as "nor'easters" (e.g., Dec, 1992) resulted in substantial coastal flooding (Section 3.2.1).

The location of property and key infrastructure near the shore or within the FEMA 1%-annual-chance floodplain places them at increased risk to ongoing and future sea level rise, in the absence of protective structures, such as levees, or other adaptation strategies. For example, storm surges occurring on top of higher sea level can damage wastewater treatment facilities, causing combined sewer overflows and pollution of waterways (NYC Hazard Mitigation Plan 2014). Acutely aware of this hazard, especially following Hurricane Sandy, the New York City Department of Environmental Protection has taken steps to increase resiliency and minimize potential damages. Buildings damaged by severe coastal erosion, prolonged saltwater exposure, and/or tidal flooding in low-lying areas require costly retro-fitting or even eventual relocation. In addition to high coastal storm floods and heavy rain, rising sea level is currently causing sewer surcharge and flooding streets farther away from the coast. The probability of blocked outfalls caused by poor drainage and additional backflow increases with elevated coastal storm surge superimposed on rising sea levels.

[g]U.S. Census, 2017. U.S. Census Bureau Metropolitan Population Estimates July 1, 2016—Release Date: March 23, 2017.

3.3.1 Increasing coastal flooding. Historical sea level rise in New York City (Fig. 3.2) has intensified the effects of coastal storm floods (Talke *et al.*, 2014). In the lowest lying neighborhoods, flooding now occurs at times of high astronomical tides (tidal flooding), even in the absence of active storms. The frequency of such so-called "nuisance flooding" at The Battery has more than doubled since the 1950s (Sweet and Park, 2014; Strauss *et al.*, 2016). Sea level rise alone will increase the severity and occurrence of New York City coastal storm-driven flooding, irrespective of changes in storm characteristics (Buchanan *et al.*, 2017; Lin *et al.*, 2016; Orton *et al.*, 2016; Reed *et al.*, 2015; Talke *et al.*, 2014; Kemp and Horton, 2013). Further discussion on historic, current, and future flood risks is given in Chapter 4: Coastal Flooding.

3.3.2 Land inundation. The Mississippi Delta and Chesapeake Bay are examples of areas already experiencing permanent land inundation due to high rates of relative sea level rise from land subsidence superimposed on global sea level rise. The Chesapeake Bay area has the highest rates of relative sea level rise on the East Coast, due to GIA and groundwater withdrawal (Eggleston and Pope, 2013), which has led to the shrinkage or loss of several small islands (Gornitz, 2013). The high relative sea level rise has led to increased tidal flooding in places such as Norfolk, Virginia (see also discussion of tidal flooding in Chapter 4).

Although New York City is not at immediate risk of extensive land inundation, the regions currently experiencing inundation provide a preview of potential permanent land loss due to sea level rise facing some New York City neighborhoods under the ARIM scenario in the later years of the 21st century (see Chapter 5, Fig. 5.1). The first areas that could be affected include low-lying city neighborhoods that will experience frequent tidal flooding and, in a few cases, permanent inundation by the 2050s and especially the 2080s (e.g., compare Fig. 5.1 with Figs. 5.2 and 4.4). (Note: Because the ARIM scenario shown in these figures is based on data with high associated uncertainties, it should be regarded as suggestive of areas that might become inundated and should therefore not be used for planning purposes. See further discussion and disclaimer in Chapter 4: Coastal Flooding, and Chapter 5: Mapping Climate Risk).

3.3.3 Effects on salt marshes and natural wave attenuation. Studies show that intertidal salt marshes and particularly their substrate play an important role in attenuating storm waves as they break on shore (Marsooli *et al.*, 2017), although they may not lessen high storm water levels, or reduce flooding if deep shipping channels are present (Orton *et al.*, 2015).

Many New York City salt marshes, including in Jamaica Bay, have receded historically and have become increasingly ponded, with enlarging tidal inlets and pools (Hartig *et al.*, 2002). In addition to historic sea level rise, other stressors have led to attrition of local salt marshes, such as channelization, shoreline development and armoring with engineered structures, excess nitrogen nutrient loading from nearby sewage treatment plants, and inadequate sediment supply (e.g., Hartig *et al.*, 2002). As a result, salt marshes at the shoreline edge are converting to tidal mudflats. The National Park Service, in conjunction with the U.S. Army Corps of Engineers, is engaged in restoration efforts at several Jamaica Bay salt marshes (e.g., Elders Point Marsh, Yellow Bar Hassock, and Rulers Bar).

Rising sea levels lead to longer periods of salt marsh submergence during high tides. Salt marsh vegetation zones can gradually shift landward, but may not find space, due to urban development (i.e., "coastal squeeze") or too steep a rise in inland topography. Wetlands will drown in place wherever rates of accretion cannot keep pace with sea level rise, and/or if sediment supplies are insufficient. However, as noted above, sea level rise is just one of many environmental factors that contribute to New York City saltmarsh losses.

3.3.4 Effects of saltwater intrusion on New York City. Sea level rise, in addition to climate change, can alter the flow of saltwater and propagation of tide and storm surge up streams, in estuaries such as the Hudson River, and into coastal lagoons. The mean location of the salt front pushes upstream as a result. Hydroclimate also influences the position of the saltwater front in the Hudson River. A decrease in precipitation reduces streamflow, which allows the salt front to migrate further upstream (and vice-versa); higher temperatures increase evaporation and decrease freshwater runoff, also forcing an upstream migration of the salt front (Buonaiuto *et al.*, 2011).

Salt front migration up the Hudson River (and the Delaware River Basin; Chapter 2, Climate Science) during severe droughts and/or higher sea levels could adversely impact the emergency New York City drinking water supply from the Hudson River at the Chelsea Pumping Station.

Sea level rise will also increase the salinity of brackish water in the estuary and lagoons, also affecting inflow of seawater to sewers and WWTPs located along the saltwater-dominated coastline and thereby lessen infiltration efficiency. In addition, higher water levels will reduce the capacity of WWTP effluents to drain by gravity and pumping (see also Chapter 4, Coastal Flooding). Although less urgent today, salinization accompanying sea level rise may become a major issue for drainage systems and warrants further investigation. Structures not designed for exposure to repetitive and lengthening saltwater exposure would also face more frequent and higher repair or replacement costs (Solecki *et al.*, 2015).

3.3.5 Increased beach erosion. Sea level rise, in conjunction with higher waves and/or water levels during intense storms, such as Hurricane Sandy in 2012, is likely to exacerbate ongoing coastal erosion, particularly of exposed, ocean-facing shorelines. This can disrupt sediment transport and undermine natural landforms, like beaches and salt marshes offering protective features, with associated land loss and environmental degradation. In urban areas, coastal erosion and flooding can severely damage structures, and if unchecked, can undermine foundations, ultimately leading to building collapse, as shown during Hurricane Sandy for the New Jersey and New York regions (Hatzikyriakou *et al.*, 2016; Hatzikyriakou and Lin, 2018).

An integrated approach for managing high erosion risks includes upgrading major structural protections, such as seawalls, revetments, bulkheads, groins, etc., as well as implementing beach nourishment and living shorelines. Continual erosion of the city's sandy beaches requires periodic nourishment with sand dredged from offshore (New York City, 2014). Potential coastal restoration projects by the U.S. Army Corps of Engineers are in review for Coney Island and the Rockaways (USACE, 2016a, 2016b). Coastal erosion risks can also be mitigated by the limitation of high-density development in high-erosion hazard zones.

Three current "erosion hotspot" neighborhoods (south shore of Staten Island, Coney Island, and Rockaway Peninsula) have been designated Coastal Erosion Hazard Areas (CEHA), for which new construction or land use change requires special permits from the New York State Department of Environmental Conservation (NYC, 2014).

3.4 Future sea level rise

As atmospheric greenhouse gases continue to accumulate, and temperatures climb, sea level is expected to rise in the future at accelerating rates. Climate scientists look ahead by using computer-generated coupled global atmospheric-oceanographic models that are based on known laws of physics that govern our climate. Section 3.4.1 briefly reviews the sea level rise projections of the Intergovernmental Panel on Climate Change (IPCC, 2013), and several newer reports that suggest a higher future global sea level than that in the IPCC report. The sea level rise projections for New York City developed by NPCC (2015), which are reaffirmed for use as the basis of New York City resiliency planning, are described in Section 3.4.2.

3.4.1 Global mean sea level rise projections.

The IPCC AR5 (Church *et al.*, 2013) projects future climate changes for a set of four representative concentration pathway (RCP) scenarios, which represent different trajectories of greenhouse gas emissions, aerosols, and land use/land cover (Moss *et al.*, 2010). They range from a high greenhouse gas emission "business-as-usual" scenario (RCP8.5) to one involving strong mitigation efforts (RCP2.6). Driven by the RCPs, a suite of coupled atmospheric and oceanographic global climate models (AOGCMs) numerically simulate physical interactions between the atmosphere, ocean, continents, and sea ice, in order to project future trends in climate variables including temperature, precipitation, and sea level rise. AOGCMs directly compute changes in ocean density (temperature and salinity) and circulation patterns. Temperature and precipitation projections from AOGCMs are used to drive separate numerical models to estimate surface mass balance[h] of glaciers and ice sheets. Models that include both dynamic ice flow and surface mass balance driven by climate projections (i.e., temperature, precipitation) estimate future changes in discharge of ice past the grounding line[i] and calving rates of icebergs. The individual components are then summed to obtain global sea level.

An alternative approach to projecting GMSLR, the semiempirical approach, makes projections of future sea level rise based on the assumption that the statistical relationship that existed between past temperatures and rates of sea level change will continue into the future. Thus, the future trajectory of sea level rise remains closely linked to that of increasing global temperature (e.g., Moore *et al.*, 2013; Rahmstorf *et al.*, 2012, Rahmstorf, S., 2007; Kopp *et al.*, 2016). However, this assumption may no longer hold if processes that were minor contributors to past sea level change, such as ice sheet dynamics, become major contributors in the future.

IPCC (2013) projects a "likely"[j] GMSLR by 2100 of 0.9–2.0 ft for RCP2.6, 1.2–2.3 ft for RCP4.5, and 1.7–3.2 ft for RCP8.5 relative to a 1986–2005 baseline, and notes the potential for collapse of marine-based parts of the Antarctic Ice Sheet to contribute another several tenths of a meter (Church *et al.*, 2013), IPCC, 2013, Chapter 13, Table 13.5). An earlier assessment (Pfeffer *et al.*, 2008) suggested that 6.6 ft was a physically plausible upper bound to GMSLR, a level adopted by the Third National Climate Assessment for its highest sea level rise scenario

[h]Surface mass balance (glacier, ice sheet) is the net balance between snow accumulation and losses due to surface melting and runoff.

[i]Dynamic ice flow refers to the discharge of ice flowing past the grounding line, which defines the boundary between a land-based glacier and attached floating ice.

[j]The "likely" range of sea level rise represents a probability of approximately two-thirds (Church *et al.*, 2013).

(Parris *et al.*, 2012). However, this upper bound was subsequently criticized (Miller *et al.*, 2013) for failing to fully represent uncertainty regarding Antarctica (Bamber and Aspinall, 2013), thermal expansion (Sriver *et al.*, 2012), and land water storage (IPCC, 2013).

Since IPCC (2013), new observations from the Greenland and Antarctic Ice Sheets (e.g., Rignot *et al.*, 2014), progress in ice sheet–ice shelf–ocean modeling (e.g., Joughin *et al.*, 2014), and expert assessments (Horton *et al.*, 2014; Bamber and Aspinall, 2013) have reaffirmed the physical plausibility of sea level rise well in excess of the IPCC (2013) "likely" range (Jevrejeva *et al.*, 2014; Kopp *et al.*, 2014; Slangen *et al.*, 2017). Newly recognized mechanisms for ice-shelf instability further emphasize the plausibility of high-end outcomes, especially beyond 2100 in high-emission futures (Pollard *et al.*, 2015; DeConto and Pollard, 2016; Kopp *et al.*, 2017; Le Bars *et al.*, 2017; Wong *et al.*, 2017; see also, Section 3.4.2).

Based on these findings, the Fourth National Climate Assessment recommended a suite of GMSLR scenarios for the period 2000–2100 that range between a "low" scenario of 1.0 ft to a physically plausible "extreme" scenario of 8.2 ft by 2100 (Sweet *et al.*, 2017). Sweet *et al.* (2017) additionally describe methods for adapting these projections to regional scales, as illustrated for New York City in in Section 3.4.2. and Appendix 3.A.

Although many future global sea level rise projections end in 2100, the longevity of atmospheric CO_2 commits us to higher temperatures and sea level long after reduction of stabilization of greenhouse gas emissions. Ending further emissions by mid-century would allow some of the anthropogenic CO_2 and temperature to slowly diminish after several decades, with gradual dissipation of the balance. It would take centuries to millennia to reach a new equilibrium state. In the interim, sea level will continue to rise well beyond 2100, because of the continued climate warming and slow heat penetration into the deep ocean (Clark *et al.*, 2016; Mengel *et al.*, 2016; Golledge *et al.*, 2015).

3.4.2 Current New York City sea level rise projections. In its second report, the NPCC (2015) developed a multicomponent methodology for projecting future sea level rise for New York City (Horton *et al.*, 2015a). Components include oceanographic changes (thermal expansion, dynamic ocean height), ice mass losses with associated gravitational and glacial isostatic adjustments, and anthropogenic land water storage change, for an ensemble of 24 CMIP global climate models and two climate change scenarios (RCP4.5, RCP8.5), as well as literature review and expert judgment. Sea level rise, relative to the 2000–2004 base period, was calculated for the 10th, 25th, 75th, and 90th percentiles from a model-based distribution and estimated ranges from the literature.

Table 3.1. New York City sea level rise projections[a] for the 2020s, 2050s, and 2100, relative to 2000–2004, (NPCC, 2015)

Sea level rise baseline (2000–2004)	Low estimate (10th percentile)	Middle range (25th–75th percentile)	High estimate (90th percentile)
2020s	+2 in.	+4–8 in.	+10 in.
2050s	+8 in.	+11–21 in.	+30 in.
2080s	+13 in.	+18–39 in.	+58 in.
2100	+15 in.	+22–50 in.	+75 in.

[a]Based on 24 GCMs and two representative concentration pathways, RCP 4.5 and 8.5. Shown are the low-estimate (10th percentile), middle range (25th–75th percentile), and high-estimate (90th percentile).

NPCC (2015) assumed that all uncertainties were perfectly correlated so that, for example, the 90th percentile projection combined the 90th percentile values for each of the different terms. While this could lead to overly high estimates, NPCC (2015) offered some leeway in case the individual component projections—consistent with most sea level rise projections in recent decades—would later be found to underestimate the extreme tail of the distribution.

NPCC (2015) projects a mid-range (25th–75th percentile) sea level rise of 11–21 in. (0.28–0.53 m) at The Battery by the 2050s and 18–39 in. (0.46–0.99 m) by the 2080s, relative to a 2000–2004 baseline. High-end estimates (90th percentile) reach 30 in. (0.76 m) by the 2050s, 58 in. (1.47 m) by the 2080s, and 75 in. (1.91 m) by 2100 (Table 3.1). Appendix 3.B illustrates how recent observed trends in sea level rise from 1900 to 2017 compare to these projected changes from NPCC (2015).

The results of a similar study by Kopp *et al.* (2014), which did not assume perfect correlation of uncertainties, and applied a hybrid approach to ice sheets that blended NPCC (Horton *et al.*, 2015a) and IPCC methodologies, are shown in Appendix

Table 3.A.1. Results from a more recent study (Kopp *et al.*, 2017), incorporating Antarctic ice-sheet projections from DeConto and Pollard (2016), and projections based on these studies, are also shown in Appendix Table 3.A.1. Appendix Table 3.A.2 places these projections in the context of the local sea level rise scenarios developed by Sweet *et al.* (2017) for the Fourth National Climate Assessment (see Appendix 3.A for more details).

As mentioned in Section 3.1, sea level rise in New York City is expected to exceed global mean values (NPCC, 2015; Carson *et al.*, 2016; Kopp *et al.*, 2014; Love *et al.*, 2016). This arises primarily because of GIA-related subsidence, far-field effects of Antarctic ice loss, and above-average ocean dynamic height due to projected slowdown of the AMOC with continued ocean freshening and Greenland ice losses (Yin and Goddard, 2013; Yin *et al.*, 2010; 2009). Enhanced warming in the western Atlantic relative to the Pacific Ocean may also elevate steric sea level rise along the East Coast, particularly for high carbon emission scenarios (Krasting *et al.*, 2016). Although gravitational effects associated with proximity to Greenland and northern hemisphere glaciers will partially reduce sea level rise, the combined effect of all contributing factors will result in higher than average sea level rise for New York City (Sweet *et al.*, 2017; Love *et al.*, 2016).

It should be re-emphasized that the NPCC (2015) sea level rise projections represent the current scientific foundation for New York City decision making and planning. However, recent observed trends in land ice mass losses and advances in ice–ocean–atmosphere interactions raise the possibility of higher future sea levels than previously assumed (Section 3.5). Furthermore, NPCC (2015) sea level rise estimates lie within the 10–90% probability range. They do not provide sea level rise values with a lower than 10% probability of occurrence by 2100 (i.e., the very large sea level increases that lie in the upper 10% tail of the sea level rise probability distribution).

Nevertheless, consideration of such high-end sea level rise outcomes is of great importance for effective long-term decision making. Focusing on the central range may lead to underestimation of the future risks, especially in the light of science that suggests that high-end scenarios may become more probable under high-emissions scenarios than thought a few years ago.

A new upper-end, low-probability sea level rise scenario, introduced in Section 3.6, is designed to address the concerns of stakeholders interested in long-term planning, who may need to examine credible scenarios at the extreme upper tail of the distribution. The ARIM scenario provides one physically plausible, low-probability scenario (i.e., one with significantly less than 10% likelihood of occurrence by 2100) for considering the consequences of very unlikely, yet high-impact outcomes. For example, many public or private sector decision makers may need to examine future risks to the city over much longer time periods, for example, infrastructure lifespans, than those which generally interest many New Yorker City homeowners—namely, risks that play out over longer timescales than those of an average 30-year home mortgage.

Furthermore, sea level rise scenarios with a less than 10% chance of occurring by 2100 may become much more likely after 2100, especially if greenhouse gas emissions are not eventually reduced (see Sections 3.6 and 3.7). However, stakeholders using ARIM should also bear in mind that scientific understanding of processes affecting sea level rise will evolve over time, especially for such low-probability, high-impact eventualities.

3.5 Recent land ice losses and implications for future sea level rise

Recent observations of land ice mass losses and advances in ice sheet–ocean–atmosphere modeling suggest the physical possibility of higher sea levels by 2100 than previously assumed (reviewed in Sweet *et al.*, 2017; Slangen *et al.*, 2017, and briefly in this section), particularly under high-emission futures (Kopp *et al.*, 2017). Although it is premature to assign a probability to such extreme outcomes, in view of the potential for widespread infrastructure and societal impacts from a high-impact sea level rise in major coastal urban centers, such as New York City (e.g., Hauer *et al.*, 2016), we follow the example of the Fourth National Climate Assessment in proposing a new upper-end sea level rise scenario that includes the possibility of Antarctic Ice Sheet destabilization (Section 3.6).

Therefore, as a supplement to the current NPCC (2015) sea level rise projections (Table 3.1), the new scenario provides a physically plausible upper-end, low-probability alternate scenario for late 21st century New York City sea level rise. The ARIM scenario follows the same logic as used by the Fourth National Climate Assessment, namely, it is based on a number of lines of evidence (including, but not limited to, Deconto and Pollard, 2016) that 8.2 ft GMSL rise represents a physically plausible upper-end projection for 2100. It presents a scenario for sea level rise over space and time that is consistent with 8.2 ft (Sweet *et al.*, 2017). It resembles that of Kopp *et al.* (2017), which makes a set of assumptions similar to that of NPCC (2015) except with respect to ice sheets.

In the new scenario, the NPCC (2015) estimate of the Antarctic contribution is replaced by one taking an approach to ice sheet dynamics that incorporates findings from more recent studies. Values for the other components contain minor updates which have minimal impact in the current context (see discussion in Section 3.6). To justify the reason for this high impact, uncertain probability future, a brief summary of recent changes in land ice masses, with emphasis on the Antarctic Ice Sheet, is presented below. Additional information is furnished in Appendix 3.B.

3.5.1 Changes in land ice masses.

Glaciers. The observed rapid worldwide recession of mountain glaciers, especially in recent decades, demonstrates a high sensitivity to the recent global warming trend and probable response to continued future climate change. Glacier retreat has increased substantially since the 2000s, equivalent to a sea level rise of 0.02–0.03 in./year—around a fifth of the current global sea level trend (Marzeion *et al.*, 2017). By 2100, glaciers could contribute between 4 and 8 in. to sea level rise relative to the 2000s (Appendix Table 3.B.1).

Greenland Ice Sheet. Since the 2000s, Greenland contributed between 0.02 and 0.04 in./year to global sea level rise, of which 40% comes from surface melting and runoff; the balance comes from calving and responses to thinning of ice tongues/shelves (Appendix Table 3.B.2; Bamber *et al.*, 2018; Tedesco *et al.*, 2017; Forsberg *et al.*, 2017; van den Broecke *et al.*, 2016; Kjeldsen *et al.*, 2015). Greenland's growing contribution to sea level rise stems from sensitivity to both atmospheric and ocean warming (Appendix 3.B).

By 2100, Greenland is projected to add between 4 and 6.7 in. to sea level rise, from both surface melting and ice discharge, across the four IPCC RCP scenarios (Fürst *et al.*, 2015). Higher sea level is possible because parts of the Greenland Ice Sheet, like Antarctica, are also potentially vulnerable to a marine ice sheet instability (MISI) (Fig. 3.5) along several deeply buried subglacial valleys with possible marine outlets (Morligham *et al.*, 2014). Some of these lie, in part, on reverse slopes[k] that extend far inland. Furthermore, a temperature rise of only 1.8–7.2 degrees Fahrenheit could initiate irreversible melting of the Greenland Ice Sheet (Church *et al.*, 2013; Robinson *et al.*, 2012).

Antarctic Ice Sheet. Recent evidence has shown that Antarctica is increasingly contributing to global sea level changes, illustrating a need to better understand how this could amplify future sea level rise projections (Fig. 3.4). Since 2012, ice losses from Antarctica have tripled, increasing sea levels by 0.12 in. in that time frame (Shepherd *et al.*, 2018).

Appendix Table 3.B.3 shows that Antarctic ice losses exceed gains and that loss rates have been generally increasing since the 1990s (IMBIE TEAM, 2018). Furthermore, concerns are growing over the future stability of the West Antarctic Ice Sheet (WAIS). Melting of all marine-based WAIS ice[l] would elevate global-mean sea level by up to about 10 ft (Bamber *et al.*, 2009). Much of WAIS is grounded (i.e., rests on bedrock) below sea level and lies on reverse slopes. The MISI hypothesis proposes that an ice stream or glacier grounded on a reverse slope is inherently unstable, because it will accelerate across the grounding line, stretch, thin, and discharge more ice until the bed slope levels out (Fig. 3.5). Grounding lines of a number of WAIS glaciers have retreated in recent decades and attached ice shelves have thinned. While it remains unclear that an ongoing MISI process (Joughin *et al.*, 2014; Rignot *et al.*, 2014) could produce catastrophic collapse this century, 21st century warming could trigger such a reaction over several centuries or longer. Parts of East Antarctica are also potentially vulnerable to ocean warming (Appendix 3.B).

DeConto and Pollard (2016) presented an ice sheet/ice-shelf model which includes MISI, hydrofracturing, and ice-cliff collapse instabilities (MICI). These processes could accelerate ice mass

[k]One that tilts toward the center of the ice sheet.

[l]Where the base of the ice sheet rests on bedrock below sea level.

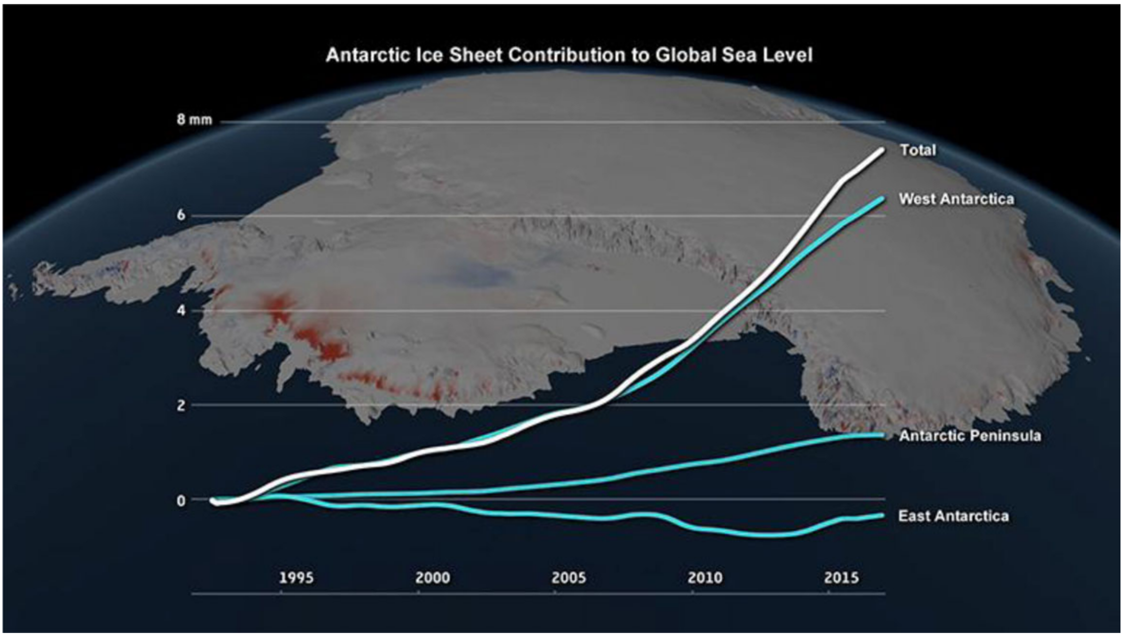

Figure 3.4. Cumulative Antarctic Ice Sheet mass change and contribution to sea level rise 1990–2017. *Source*: Shepherd *et al.*, 2018 and NASA Planetary Visions, 2018.

losses as explained further in Appendix 3.B (see also, Pollard *et al.*, 2015).

In simulations assuming continued high greenhouse gas emission rates, these mechanisms could initiate ice-shelf break-up starting after mid-century (DeConto and Pollard, 2016). By century's end, in their model, Antarctica alone could contribute a median of 2.3 ft of sea level rise, with 5th–95th

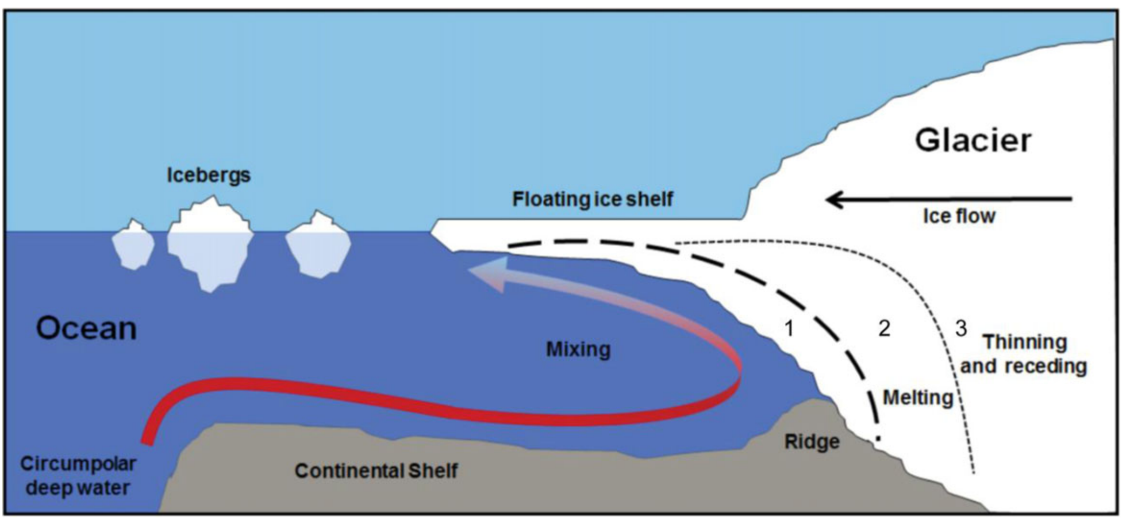

Figure 3.5. Marine ice sheet instability (MISI) on Antarctica: (1) ice stream or glacier is grounded on a bedrock ridge on the continental shelf; (2) warm circumpolar deep water flows into cavity beneath the ice shelf and melts the base of the glacier at the grounding line; (3) the grounding line continues to retreat beyond the ridge further downslope, causing the ice shelf to thin and the glacier to accelerate forward (Modified from Bethan Davies, AntarcticGlaciers.org).

percentile range of 0.7–5.2 ft. Such high rates would result in collapse of the WAIS and some parts of the East Antarctica Ice Sheet within a few hundred years, potentially contributing over 49 ft to global mean-sea level rise by 2500.

Inasmuch as the DeConto and Pollard (2016) model limits the maximum ice-cliff retreat rate, even higher rates than they project could be theoretically possible. While including several generally not previously modeled processes which could play an important future role in Antarctic ice mass losses, especially in higher emissions scenarios, the DeConto and Pollard (2016) paper represents just one study and remains to be confirmed by further observations or modeling.

By comparison, another study, which did not include hydrofracturing and ice-cliff collapse, found instead Antarctica would contribute, at most (95th percentile), around 1 ft by 2100 and 2.4 ft by 2200 (Ritz *et al.*, 2015) but for a moderate rather than high emission scenario.

The divergence among different models underscores the deep uncertainty surrounding high-end sea level rise projections for late in this century and beyond 2100. Given the potential consequences of the high-end projections, this divergence emphasizes the importance of considering extreme outcomes, even though the scientific community has not yet come to agreement on how probable they are.

3.6 Development of ARIM—a new upper-end sea level rise scenario for New York City

The NPCC (2015) sea level projections form the scientific basis for climate change adaptation guidelines in New York City at this time, and are plausible distributions that explicitly take into account multiple factors. New research developments illustrate the desirability of considering updating the New York City sea level rise projections in future NPCC assessments. Recent ice sheet trends and improved understanding of ice sheet–ocean–atmosphere interactions raise the prospects of higher sea levels than previously assumed (Sweet *et al.*, 2017; Slangen *et al.*, 2017). The sum of all ice mass losses (Appendix 3.B, Tables 3.B.1–3) constitutes half or more of total sea level rise in recent decades, a proportion likely to increase throughout this century (Nerem *et al.*, 2018; Dieng *et al.*, 2017; Rietbroek *et al.*, 2016). Gaining an improved understanding of potential upper limits to GMSLR by 2100 is therefore an important scientific objective to aid in critical and long-lived infrastructure decisions.

As discussed by Sweet *et al.* (2017), an increasing body of evidence—including observational evidence of marine ice-shelf instability in parts of the Antarctic Peninsula, further indications of potential MISI on the WAIS, consideration of previously omitted ice sheet dynamic processes, and revised estimates of "maximum physically plausible" sea level rise—argues that 8.2 ft represents an unknown-probability, yet physically plausible "extreme" GMSLR projection for the 21st century (see also, Hansen *et al.*, 2016).

This suggests that using a single probability distribution to represent such extreme outcomes inadequately expresses the current incomplete state of the science for Antarctic ice melt (see Kopp *et al.*, 2017, for further discussion). One workaround is to employ multiple probability distributions; but such an approach can be challenging for the users of projections. Accordingly, rather than producing an entire supplemental distribution, we instead provide a new, alternate upper-end, low-probability scenario, herein referred to as the ARIM scenario.

The ARIM scenario offers an alternate plausible upper-end sea level rise projection for 21st century rise for New York City, based on recent advances in understanding of ice sheet behavior, particularly that of Antarctica, in order to prepare for possible high-impact situations. For the ARIM scenario, there are multiple plausible alternative distributions that exhibit limited convergence (Horton *et al.*, 2018).

Following Sweet *et al.* (2017), we generate this upper-end scenario by filtering a set of probabilistic projections to isolate a subset consistent with 98.4 ± 5.9 in. (250 ± 15 cm) (i.e., between 92.5 and 104 in. (235 and 265 cm) of GMSLR between 2000 and 2100). Whereas Sweet *et al.* (2017) filtered the probabilistic projections of Kopp *et al.* (2014), we instead use a set of projections from Kopp *et al.* (2017) that employs the Kopp *et al.* (2014) sea level rise projection framework, but substitutes the Antarctic ice-sheet projections of DeConto and Pollard (2016). As described above (Section 3.5), the DeConto and Pollard (2016) model simulates the MISI, hydrofracturing, and ice-cliff fracturing

Table 3.2. New York City sea level rise projections, including the new Antarctic Rapid Ice Melt (ARIM) scenario, relative to 2000–2004 (in feet)

	NPCC2 2015 sea level rise projections[a] Projections of record for planning			NPCC3 ARIM scenario[b] Growing awareness of long-term risk
Baseline (2000–2004) 0"	Low estimate (10th percentile)	Middle range (25–75th percentile)	High estimate (90th percentile)	ARIM scenario[a]
2020s	0.17 ft	0.33–0.67 ft	0.83 ft	–
2050s	0.67 ft	0.92–1.75 ft	2.5 ft	–
2080s	1.08 ft	1.50–3.25 ft	4.83 ft	6.75 ft
2100	1.25 ft	1.83–4.17 ft	6.25 ft	9.5 ft

[a]The 10th, 25th–75th, and 90th percentile projections are taken from NPCC2 (2015); the six sea level rise components upon which they are based include global and local factors (see Section 3.4.2 and NPCC (2015)). Use of NPCC2 sea level rise projections is confirmed for decision making at this time. The ARIM scenario is based on DeConto and Pollard (2016), Kopp *et al.* (2014; 2017) and informed expert judgments with regard to maximum plausible ice loss rates from Antarctica (see above and Sweet *et al.*, 2017). See this section and Appendix 3.B for full ARIM scenario and explanation.

[b]ARIM represents a new, physically plausible upper-end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from recent modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections. In the 2020s and 2050s, the ARIM scenario does not lie outside the pre-existing NPCC 2015 range and therefore NPCC 2015 results apply to these two earlier time slices. The ARIM scenario contains uncertainties stemming from incomplete knowledge of ice-sheet processes and atmosphere, ocean, and ice–sheet interactions.

instabilities. The other components are projected as in Kopp *et al.* (2014).

For each of the RCP 2.6, 4.5, and 8.5 emission scenarios, the projections include (1) global-climate-model-driven projections of global mean thermal expansion, regional dynamic sea level, and glacier mass changes; (2) Greenland Ice Sheet projections based on structured expert judgment (SEJ) and the IPCC's AR5 assessment; (3) global mean land-water-storage changes based on the historical relationships between population, groundwater withdrawal, and dam construction; (4) a geophysical model of the gravitational, rotational, and deformational "static-equilibrium" ("fingerprint") effects of mass redistribution from the polar ice sheets and 18 glacial regions; and (5) geologically driven relative sea level change (at The Battery, due exclusively to GIA) based on analysis of tide-gauge observations.

To make ARIM projections consistent with the 2000–2004 baseline in NPCC (2015), instead of the 1991–2009 baseline used by Kopp *et al.* (2014) and Sweet *et al.* (2017), 0.8 in. (2 cm) was added to the projections. This amount corresponds to the observed difference between the two period averages in the New York City Battery tide gauge record.

The ARIM scenario can be thought of as a modification of Sweet *et al.* (2017), in which the physical basis of the relationship between late 21st-century global mean sea level and relative sea level over time comes from Kopp *et al.* (2017), rather than Kopp *et al.* (2014).

In the 2020s and 2050s, the ARIM scenario does not lie outside the pre-existing NPCC (2015) 10th–90th percentile scenario range (Table 3.2). This is because the ARIM scenario is constructed to be consistent with a 98.4 in. (250 cm) GMSL rise over the 21st century. To generate such an extreme outcome requires a substantial destabilization of marine-based parts of the Antarctic Ice Sheet, but physical modeling results (DeConto and Pollard, 2016; Kopp *et al.*, 2017; Le Bars *et al.*, 2017; Wong *et al.*, 2017) indicate that this destabilization is highly unlikely to emerge until the second half of the century, and only then under high emission scenarios. Relative sea level trends that lie within the mid-range of projections over the next few decades would therefore not exclude more possibly extreme outcomes later in the century.

Furthermore, sea level rise will not slow or reverse quickly even following deep emission reductions. Almost all scenarios suggest that sea level will continue to rise for centuries. Although ARIM ends at

2100, it provides insights into the large sea level rises that may occur beyond 2100.

Inclusion of nonlinear acceleration of ice-mass loss is an advance from Sweet *et al.* (2017), who filtered projections (Kopp *et al.*, 2014) that assumed a simple linear acceleration of Antarctic mass losses over the century and therefore showed a strong correlation between early- and late-century sea level rise. The possibility of nonlinear accelerations causes the ARIM projections consistent with 98.4 in. (2.5 m) of GMSL rise to be somewhat lower than the "Extreme" projections of Sweet *et al.* (2017), particularly earlier in the century (Appendix Table 3.A.3).

Differences between the ARIM Scenario and NPCC (2015) for the 2020s and 2050s arise from slightly different treatments of the non-ice sheet components, in addition to differences in treatment of ice sheets. Many stakeholders focus on the 2050s because that is, for their particular purposes, a rational near-term to medium-term planning horizon. This is before the ARIM scenario diverges significantly from NPCC (2015) projections and before the consequences of the differing greenhouse gas concentration pathways (RCPs) become significant (see the Appendix 3.B for fuller treatment of the ARIM scenario).

Although it is not currently possible to make a strong statement about the probability of the ARIM scenario, we have high confidence that it is more likely under high-end emission scenarios (e.g., RCP 8.5) and is implausible under the lowest emission scenarios (e.g., RCP2.6). Averting the ARIM scenario is thus another benefit that will accrue from greenhouse gas mitigation efforts. To summarize, the sea level rise scenarios presented in NPCC (2015) are still appropriate for New York City and are currently used in resiliency planning, especially for the 2020s and 2050s.

Because the ARIM scenario is in part based on a new, still preliminary and controversial model, a probability assignment would not be very meaningful. Stakeholders can obtain some indication of the potential range of outcomes for the 2080s and 2100 by keeping both ARIM and NPCC (2015) projections in mind.

One important consequence of an upper-end sea level rise scenario, such as ARIM, is not only the increased frequency of coastal flooding, but also the progressive expansion of the floodplain over time with sea level rise for both 100-year floods and monthly tidal flooding (although obviously to difference extents and frequencies) (e.g., Figs. 5.2 and 5.3). Another consequence, absent additional defensive measures, is the potential inundation due to the elevated sea level of low-lying neighborhoods by the end of the century that had previously experienced frequent tidal flooding. For example, a comparison of Figure 5.2 with Figure 4.4 (tidal flooding) suggests that many of the locations that could undergo monthly tidal flooding by the 2050s and 2080s in areas surrounding Jamaica Bay and Coney Island under the 90th percentile sea level rise projection (NPCC, 2015), shown in light and dark green, respectively, (Fig. 4.4), might face permanent sea level rise by 2100 under the ARIM sea level rise scenario, with current shoreline elevations (see Fig. 5.1 in Chapter 5: Mapping Climate Risk).

In addition to the Jamaica Bay and Coney Island areas, other potentially affected areas include portions of Staten Island, edges of the lower Manhattan waterfront, Red Hook, along the Gowanus Canal in Brooklyn, along Newton Creek in Brooklyn and Queens, and Pelham Bay in the Bronx.

3.6.1 Expert elicitation on the Antarctic contribution. Two separate workshops[m] were held on SEJ of ice sheets, a form of expert elicitation, in part as a supplement to the development of the ARIM scenario. SEJ elicits and combines individual expert judgments into outcome probability distributions, in this case, on various aspects of future contributions of the Antarctic and Greenland ice sheets to sea level rise (e.g., Bamber and Aspinall 2013). The performance of each expert on a set of calibration questions regarding uncertainties for ice sheet variables with known values is used to weight their judgments on the unknown quantities regarding future ice sheet behavior.

This approach has been used in the estimation of variables related to nuclear reactor safety, volcanology, ecology, and aeronautics/aerospace applications. Based on past experience, performance-weighting generally yields predictions with improved statistical accuracy as compared

[m]Elicitations conducted with support from Resources for the Future, Rutgers University, Princeton University, European Research Council grant number 684188, and the NYC Office of Recovery and Resiliency (ORR).

to individual predictions, and smaller associated uncertainties as compared to unweighted estimates (Oppenheimer *et al.*, 2016).

Twenty-two ice sheet experts assembled at two separate workshops, one in Washington, D.C. in January 2018, composed of North Americans, and the other, in London in February 2018, of Europeans. Experts were asked to estimate accumulation, runoff, and discharge for the Greenland, West Antarctic, and East Antarctic ice sheets under two warming scenarios.

The low scenario reached 2.7°F (1.5 °C) in the 2050s and 3.6°F (2.0 °C) in 2100, stabilizing thereafter; the high scenario reached 3.6°F (2.0 °C) in 2050 and 9.0°F (5 °C) in 2100, stabilizing thereafter. Each expert evaluated 5%, 50%, and 95% probability values for these contributory processes and quantified the dependence between these processes. North American and European experts were asked identical questions.

Estimates from the two groups were then combined to produce performance weighted (i.e., calibrated) and unweighted distributions. The experts' performance-weighted estimates for the Antarctic contribution to GMSLR between 2000 and 2100 was a median of 0.7 ft (21 cm) (5th–95th percentile range of –0.4 to 4.3 ft (–11 to 132 cm)) under the high scenario and 0.3 ft (9 cm) (–0.3 to 1.7 ft (–8 to 53 cm)) under the low scenario.

These estimates were combined with the projections for non-ice sheet components developed using the Kopp *et al.* (2014) framework to examine their implications for total GMSLR. In particular, they combined the low scenario estimate projections with a 3.6°F scenario developed by Rasmussen *et al.* (2018) and the high scenario estimate with RCP8.5.

Localizing these GMSL projections for New York City indicates that the judgment of this group of experts in early 2018 aligns reasonably well with the NPCC2 projections at the 50th, 75th, and 90th percentiles, and that the ARIM scenario has about a 3% chance of being realized by 2100 in a high-emissions future, but close to zero probability a low-emissions future.

3.7. Conclusions and recommendations

3.7.1 Findings. Consistent with other studies (e.g., Carson *et al.*, 2016; Kopp *et al.*, 2014; Tebaldi *et al.*, 2012; Sweet *et al.*, 2017, Horton *et al.*, 2011), projected sea level rise from NPCC (2015) and the new ARIM scenario suggest that sea level trends for New York City will likely exceed the global average. This arises because of processes that will affect the region's sea level change, such as enhanced thermal expansion, dynamic oceanographic changes, mounting ice losses from glaciers and ice sheets and their associated "fingerprints," as well as ongoing glacial isostatic adjustments. This would pose mounting hazards to substantial segments of the region's coastal population, infrastructure, and other built and natural assets in low-lying areas.

Sea level rise alone stands to increase the frequency and intensity of coastal flooding over time, as shown in Chapter 4. New York City sea level rise is expected to accelerate as the century progresses and could reach almost 9.5 ft. by 2100 in the new ARIM scenario, although this large estimate has a deeply uncertain probability and appears implausible under low-emission futures.

Recent increasing ice mass losses in Greenland and Antarctica, advances in modeling ice sheet–ocean–atmosphere interactions, as well as a potential for marine ice-shelf instability in West Antarctica, raise the prospects of higher sea levels than previously assumed. A growing awareness therefore exists for the need to consider high impact, low probability scenarios in coastal risk management, particularly when planning for long-lived infrastructure development (e.g., Wahl *et al.*, 2017; Sweet *et al.*, 2017). This new perspective also informs the need to supplement the NPCC (2015) sea level rise projections with an alternative, extreme scenario.

The ARIM scenario is constructed following an approach used for the Fourth National Climate Assessment and adopts the magnitude of the "extreme" GMSLR scenario developed for it (Sweet *et al.*, 2017). Its construction leverages the probabilistic projections of Kopp *et al.* (2014, 2017) and the Antarctic ice-sheet projections of DeConto and Pollard (2016), which includes improved models of ice dynamic processes.

Because the scenario uses information from the physical model of Deconto and Pollard (2016), it takes into account the possibility that considerably different and potentially destabilizing processes of Antarctic Ice Sheet mass loss will gain in importance in the second half of this century than those occurring in the first half, which differ little from previous results. Therefore, the ARIM projections, presented for the 2080s and 2100 in Table 3.2, are most applicable in late 21st century, at higher-end emission scenarios, such as RCP 8.5.

The implications of substantial economic and societal consequences to major coastal urban centers, such as New York City (e.g., Hauer *et al.*, 2016, Xian *et al.*, 2018), underscore the need to consider the possibility of such revised upper-end scenarios in coastal risk management. Therefore, the next NPCC report should continue to monitor new findings and update the latest trends in sea level rise from the various contributing components, especially those from the major ice sheets. In particular, the panel should periodically reassess the processes that could potentially destabilize the WAIS. Development of the next-generation sea level rise scenarios, including the latest CMIP climate model results, would form an important part of future research.

3.7.2 Beyond 2100. Because of the longevity of atmospheric CO_2, temperatures and sea level will continue to rise even after stabilization or reduction in greenhouse gas emissions. With total cessation of further anthropogenic CO_2 emissions by mid-century, CO_2 and atmospheric temperatures would slowly begin to decrease after several decades. But most of the CO_2 would still remain in the atmosphere and take centuries to millennia to slowly dissipate. This, and slow heat penetration into the deep ocean, would cause sea level to continue rising well beyond 2100 due to thermal expansion alone (Clark *et al.*, 2016; Mengel *et al.*, 2016; Golledge *et al.*, 2015).

Furthermore, during this extended period of sustained warmth, the losses of ice on Greenland and Antarctica will continue and could become quite substantial. Clark *et al.* warn that the Greenland Ice Sheet could be totally deglaciated within 2500–6000 years at higher emission scenarios (Greenland stores the equivalent of ∼23 ft, ∼7 m of GMSLR). Even greater losses are potentially possible if contributions from the WAIS are added. For both the NPCC 2015 projections and the ARIM scenario, much higher sea levels can be expected beyond 2100 than those projected for 2100.

3.7.3 Recommendations. NPCC3 therefore makes the following recommendations for research to address sea level rise in the New York metropolitan region:

- The NPCC should continue to monitor and periodically update trends in sea level rise, trends in glacier and ice sheet mass losses, and processes leading to destabilization of the WAIS.
- Further research into sea level change for the next several centuries, to 2200 and 2300, should be explored, in light of the sea level rise commitment on longer timescales.
- The consequences of long-term sea level rise scenarios on coastal flooding, including those stemming from low-probability, high-end scenarios, should also be examined.

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Appendix 3.A. NPCC3 sea level rise methods and projections

Introduction

Appendix 3.A presents the results of a study by Kopp *et al.* (2014) compared with those of the NPCC (2015) 10th-90th percentile range, as shown in Appendix Table 3.A.1.[a] Results of a study by Kopp *et al.* (2014) are similar to NPCC (2015), but do not assume perfect correlation of uncertainties. Appendix Table 3.A.1 also shows sea level rise projections from a more recent study (Kopp *et al.*, 2017), incorporating Antarctic ice-sheet projections from DeConto and Pollard (2016). Appendix Table 3.A.2 places these projections in the context of the local sea level rise scenarios developed by Sweet *et al.* (2017) for the Fourth National Climate Assessment.

As discussed in Section 3.6, the extreme scenario of Sweet *et al.* (2017) was developed using the same method as the ARIM scenario, except that in Sweet *et al.*, the underlying projections filtered were those from Kopp *et al.* (2014) rather than those of Kopp *et al.* (2017) that also incorporated data from DeConto and Pollard (2016) ice models (Appendix Table 3.A.2). Appendix Table 3.A.3 compares the filtered sea level rise projections for ARIM with those from Sweet *et al.* (2017). In addition to the median local projections consistent with 2.5 m of GMSL rise by 2100, Appendix Table 3.A.3 also

Table 3.A.1. Probabilistic New York City sea level rise projections (Kopp *et al.*, 2014, 2017) compared to the NPCC (2015) projections (10th–90th percentile range), m relative to 2000–2004 baseline

	NPCC (2015)	Kopp *et al.* (2014)			Kopp *et al.* (2017), DP 16		
	10th–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

Table 3.A.2. Fourth National Climate Assessment sea level rise projections for New York City (Sweet *et al.*, 2017), m relative to 2000–2004 baseline

	Low	Intermediate-low	Intermediate	Intermediate-high	High	Extreme
2020s	0.15	0.18	0.26	0.34	0.42	0.42
2050s	0.30	0.37	0.60	0.84	1.10	1.27
2080s	0.44	0.55	1.07	1.55	2.14	2.60
2100	0.48	0.63	1.32	1.99	2.81	3.44

[a]Data from Kopp et al. (2014) have been recalculated to conform to time slices and baseline period used in NPCC (2015), to facilitate comparison between the studies. See Appendix IIB (NPCC, 2015) and Kopp et al. (2014) for additional technical details describing similarities and differences in assumptions, methodology, and data sources.

Table 3.A.3. **Filtered sea level rise projections used to generate the ARIM scenario and the extreme scenario of Sweet *et al.* (2017), m relative to 2000–2004 baseline**

	ARIM (10th–90th %)		Sweet *et al.* (2017) (17th–83rd %)	
	Median	Range	Median	Range
2020s	0.20	0.10–0.29	0.42	0.23–0.46
2050s	0.74	0.58–0.89	1.27	0.85–1.34
2080s	2.07	1.79–2.31	2.60	1.94–2.71
2100	2.90	2.56–3.19	3.4	2.64–3.58

shows the 10th-90th percentile range of the filtered projections (for ARIM)[o] and the 17th–83rd percentile range for Sweet *et al.* (2017); Sweet *et al.* (2017) labeled the latter as the "low" and "high" variants, respectively. As shown in this paper, the assumption by Sweet *et al.* (2017) of linear changes in ice-sheet mass loss rates makes their extreme scenario exhibit unrealistically high projections in the 2020s and 2050s, whereas during this time period, the ARIM scenario values lie below those of the NPCC's (2015) 90th percentile projections. By the 2080s, however, the median ARIM projection lies within the range of the extreme scenario, as defined by Sweet *et al.* (2017); By 2100, the median ARIM projection lags the median of the extreme scenario, as defined by Sweet *et al.* (2017) by only about one decade.

Appendix 3.B. Cryosphere trends

Appendix 3.B summarizes recent observations that show mounting glacier and ice sheet losses contributing to sea level rise. In addition to observations, progress in modeling ocean–atmosphere–ice sheet interactions raises the possibility of a significantly higher global mean sea level rise by 2100 than previously projected, particularly for elevated greenhouse gas emission scenarios. These new developments, as well as serious socioeconomic impacts of rising sea levels in large urban centers, such as New York City, indicate the need to consider updated high-end scenarios in long-term coastal risk management decisions. The new Antarctic Rapid Ice Melt Scenario (ARIM), which includes the possibility of Antarctic Ice Sheet destabilization, represents a physically plausible upper-end, low probability late 21st century sea level rise scenario for New York City. Not meant to replace NPCC (2015), which still forms the scientific basis for the city's climate change adaptation efforts, ARIM instead offers an alternate plausible extreme late 21st century sea level rise scenario, based on recent progress in modeling ice sheet processes, particularly for Antarctica.

The following section summarizes recent increasing trends in ice mass losses from glacier and ice sheets that have added to sea level rise in recent decades, with emphasis on Antarctica, as well as several processes that may potentially lead to destabilization of the West Antarctic Ice Sheet (WAIS). These new findings reinforce the need for an extreme scenario, such as ARIM.

Changes in glaciers and ice caps

Glaciers, ice caps, and ice sheets are large masses of ice formed by compaction and recrystallization of snow that gradually flow downslope under the pull of gravity. Mountain glaciers respond relatively fast to climate variability, making them particularly important barometers of local to regional climate change. Rising air temperatures have led to increased surface melting and runoff on mountain glaciers and the Greenland Ice Sheet. Warmer ocean water entering fjords of Greenland, Arctic, and Alaskan glaciers penetrates beneath floating ice tongues and melts them from below. A similar process has also begun to affect many Antarctic ice shelves. As ice tongues or shelves thin, they weaken and break off large pieces of ice. The glaciers feeding the ice shelves begin to accelerate, stretch, and thin, increasing the discharge rate across the grounding line and calving of icebergs, ultimately contributing to sea level rise.

Mountain glaciers respond relatively fast to even minor climate fluctuations. Therefore, their observed rapid worldwide recession, especially in recent decades, demonstrates a high sensitivity to the recent global warming trend and probable response to continued future climate change. Glaciers hold enough ice to elevate the world's oceans by 0.35–0.41 m (1.3 ft), if all melted and the water spread out uniformly (Grinsted, 2013; IPCC, 2013). Glacier retreat has increased substantially since ∼2000, equivalent to a sea level rise of

[o]Those that that are consistent with 2.5 m of global mean sea level rise (i.e., that lie between 235 and 265 cm).

Table 3.B.1. Future sea level rise due to glaciers and small ice caps, m, 2010–2100, after Slangen *et al.* (2017)[a]

Sea level rise	RCP 2.6	RCP 4.5	RCP 8.5	Reference
	0.09 ± 0.3	0.12 ± 0.03	0.18 ± 0.03	Huss and Hock, 2015
	0.12 ± 0.03	0.13 ± 0.03	0.18 ± 0.04	Marzeion *et al*, 2012, updated
		0.16 ± 0.04	0.22 ± 0.4	Radić *et al.*, 2014, updated
		0.15 ± 0.04	0.21 ± 0.04	Slangen and van de Wal (2011), updated

[a]Includes peripheral glaciers. The last three sources listed in this table have been updated by Slangen *et al.* (2017).

0.4–0.8 mm/year—around a fifth of the current global sea level trend (Marzeion *et al.*, 2017; Bamber *et al.*, 2018). The range of estimates results from differences in instrumentation, data sources, averaging techniques, and uncertainties in extrapolating from limited spatial coverage. Nevertheless, while individual glaciers may show net growth, most glaciers have consistently retreated over the past century, and particularly within the two last decades.

Glacier ice mass losses exceeded the contributions of Greenland and Antarctica combined between 1993 and 2010 (IPCC, 2013, Table 13.1), although the ice sheets' share has grown significantly since then (e.g., Nerem *et al.*, 2018; Dieng *et al.*, 2017; Rietbroek *et al.*, 2016; Bamber *et al.*, 2018). Glacier contributions to sea level rise will continue to increase for the next several decades at least, but will decline in the long run, as the total glacier ice mass, if all melted, would raise global-mean sea level by less than half a meter (Grinsted, 2013). By 2100, glaciers could contribute between 0.1 and 0.2 m to sea level rise (Table 3.B.1).

Greenland Ice Sheet

The sensitivity of Greenland's marine-terminating, or tidewater glaciers, to both atmospheric and ocean warming accounts for their growing contribution to sea level rise. Greenland sea level rise, 2000–2100, including surface melting and ice discharge, is projected to range between 0.01 and 0.17 m, across the

Table 3.B.2. Recent observed Greenland Ice Sheet contributions to sea level rise, mm/year

Greenland Ice Sheet	Method(s)	Reference
	1980s–present	
–0.09 ± 0.23 (1992–1996)	Multiple	Bamber *et al.* (2018)
0.33 ± 0.08 (1993–2010)	Multiple	IPCC (2013)
0.39 ± 0.14 (1992–2011)	Multiple	Shepherd *et al.* (2012)
0.20 ± 0.11 (1983–2003)	Geodesy; laser altimetry	Kjeldsen *et al.* (2015)
0.47 ± 0.23 (1991–2015)	GRACE; mass budget model	van den Broeke *et al.* (2016)
	Post–2000	
0.63 ± 0.17 (2005–2010)	Multiple	IPCC (2013)
0.58 ± 0.10 (2000–2011)	Multiple	Shepherd *et al.* (2012)
0.68 ± 0.05 (2003–2009)	Laser altimetry	Csatho *et al.* (2014)
0.68 ± 0.08 (2000–2012)	Landsat 7 Enhanced Thematic Mapper+ and Terra ASTER	Enderlin *et al.* (2014)
0.42 ± 0.09 (2000–2005)	Landsat 7 Enhanced Thematic Mapper+ and Terra ASTER	Enderlin *et al.* (2014)
0.73 ± 0.05 (2005–2009)	Landsat 7 Enhanced Thematic Mapper+ and Terra ASTER	Enderlin *et al.* (2014)
1.04 ± 0.14 (2009–2012)	Landsat 7 Enhanced Thematic Mapper+ and Terra ASTER	Enderlin *et al.* (2014)
0.77 ± 0.16 (2003–2013)	GRACE gravimetry	Velicogna *et al.* (2014)
0.40 ± 0.04 (2003–2009)	Laser altimetry	Helm *et al.* (2014)
1.03 ± 0.07 (2011–2014)	Radar altimetry	Helm *et al.* (2014)
0.51 ± 0.05 (2003–2010)	Geodesy; laser altimetry	Kjeldsen *et al.* (2015)
0.65 ± 0.24 (2000–2011)	GRACE; mass budget model	van den Broeke *et al.* (2016)
0.72 ± 0.07 (2002–2015)	GRACE gravimetry	Forsberg *et al.* (2017)
0.74 ± 0.07 (2003–2017)	GRACE gravimetry	Tedesco *et al.* (2017)
0.69 ± 0.04 (2012–2016)	Multiple	Bamber *et al.* (2018)

Table 3.B.3. Recent observed Antarctic Ice Sheet contributions to sea level rise, mm/year

Antarctic Ice Sheet	Method(s)	Reference
0.20 ± 0.15 (1992–2011)	Multiple	Shepherd *et al.*, 2012
0.22 ± 0.10 (2005–2010)	Multiple	Shepherd *et al.*, 2012
0.27 (0.37–0.16) 1993–2010	Multiple	IPCC, 2013
0.41 (0.61–0.20) 2005–2010	Multiple	IPCC, 2013
0.31 ± 0.06 (2003–2012)	GRACE; GPS	Sasgen *et al.*, 2013
0.44 ± 0.13 (2010–2013)	Radar altimetry	McMillan *et al.*, 2014
0.18 ± 0.12 (2003–2013)		Velicogna *et al.*, 2014
0.25 ± 0.03 (2003–2014)	GRACE gravimetry	Harig and Simons, 2015
–0.31 ± 0.17 (1992–2001)	Radar, laser altimetry	Zwally *et al.*, 2015
–0.23 ± 0.07 (2003–2008)	Radar, laser altimetry	Zwally *et al.*, 2015
0.30 ± 0.15 (1992–2017)	Multiple	IMBIE Team, 2018
0.20 ± 0.15 (2002–2007)	Multiple	IMBIE Team, 2018
0.60 ± 0.12 (2012–2017)	Multiple	IMBIE Team, 2018
0.53 ± 0.07 (2012–2016)	Multiple	Bamber *et al.*, 2018

four IPCC RCP scenarios (Fürst *et al.*, 2015). Surface melting is expected to dominate future ice losses, because ice discharge will diminish once tidewater glaciers retreat upslope.

Greenland Ice Sheet mass loss rates have more than doubled over the past quarter century (Bamber *et al.*, 2018; Khan *et al.*, 2015). Ice losses, however, vary considerably, both spatially and temporally. Since ∼2000, Greenland contributed between 0.4 and 1.0 mm/year to sea level rise, of which over half comes from calving and basal melting of ice tongues/shelves (discharge); the balance comes from surface melting and runoff (Table 3.B.2, and recent references therein). Mass gains in Greenland's interior are offset by greater peripheral losses that have spread northeastward and northwestward since 2003 (Kjeldsen, *et al.*, 2015; Khan *et al*, 2014). Lowering of Greenland Ice Sheet surface albedo (surface reflectivity) due to expansion of summer meltwater pool area, along with airborne soot, dust, and exposed bare soil, amplifies surface melting in a positive feedback loop (Tedesco *et al.*, 2016).

Greenland's tidewater glaciers are highly sensitive to both atmospheric and ocean warming. Erosion of subglacial ice by warmer ocean water thins the ice tongues and initiates grounding line retreat, with consequent increased ice mass losses. Projected Greenland sea level rise, 2000–2100, including surface melting and ice discharge, is expected to range between 0.01 and 0.17 m, across the four RCP scenarios (Fürst *et al.*, 2015). Surface melting is expected to dominate future ice losses, because ice discharge will diminish once tidewater glaciers retreat upslope.

Parts of the Greenland Ice Sheet could potentially undergo a marine ice sheet instability (MISI) (see Antarctic Ice Sheet, below), because of several deeply buried subglacial valleys with potential marine outlets (Morligham *et al.*, 2014). The Northeast Greenland ice stream (NEGIS) drainage system, parts of which lie on a reverse slope,[p] extends deep into the heart of Greenland. The once-stable Zachariae ice stream, a branch of NEGIS, began to retreat in the early 2000s (Khan *et al.*, 2014). Several other glaciers, including fast-retreating Jakobshavn Isbrae, Helheim, and Kangerdlugssuaq glaciers, also lie on reverse slopes.

Antarctic Ice Sheet

Antarctic ice losses have been increasing since the 1990s and now mostly exceed gains (Appendix Table 3.B.3; IMBIE Team, 2018; Bamber *et al.*, 2018). However, future climate changes could potentially lead to destabilization of the WAIS. Melting of all marine-based WAIS ice[q] would raise global-mean sea level by up to about 3 m (Bamber *et al.*, 2009). Much of WAIS is "grounded" (i.e., rests on bedrock) below sea level and lies on reverse slopes, which makes it vulnerable to a MISI (Fig. 3.5). Fast-flowing glaciers in the Amundsen Sea sector, such as Pine Island, Thwaites, Smith, Kohler, Pope, and Haynes Glaciers, drain a third of the WAIS. Their grounding lines have retreated within the last few decades and abutting ice shelves have thinned. Grounding

[p]One that tilts toward the center of the ice sheet.
[q]Where the base of the ice sheet rests on bedrock below sea level.

lines of Pine Island and Thwaites Glaciers approach sections with reverse slope. Although an ongoing MISI process (Joughin *et al.*, 2014; Rignot *et al.*, 2014) may not cause catastrophic collapse this century, projected 21st century warming could trigger such a reaction over the next several centuries or longer. Parts of East Antarctica are also potentially vulnerable to ocean warming, for example, Totten Glacier (with a volume equivalent to around 3.5–3.9 m of sea level rise, if all melted, Rintoul *et al.*, 2016; Li *et al.*, 2015) and the Wilkes Basin (which holds a comparable volume of potentially unstable ice; Greenbaum *et al.*, 2015; Mengel and Levermann, 2014).

DeConto and Pollard (2016) presented an ice sheet/ice-shelf model which includes MISI, hydrofracturing, and ice-cliff collapse instabilities (MICI), which could accelerate ice mass losses (Pollard *et al.*, 2015). Hydrofracturing begins with downward propagation of small surface cracks under meltwater pressure and further expansion upon freezing. The enlarging crevasses weaken ice until it eventually splits. Additionally, stresses on thick ice cliffs and unbuttressed (unsupported) ice shelves induce grounding line fractures. While intact ice shelves slow the advance of ice steams at the grounding line, heavily fractured ice shelves are more subject to rapid disintegration. This in turn causes glaciers and ice streams to accelerate across the grounding line and discharge more ice.

At continued high greenhouse gas emission rates, these mechanisms could initiate ice-shelf break-up starting after mid-century and add up to 1.6 m (5.2 ft) to sea level rise for Antarctica alone by 2100 (DeConto and Pollard, 2016). Such high rates would result in collapse of the WAIS and some parts of the East Antarctica Ice Sheet within a few hundred years, potentially contributing over 15 m (49 ft) to global mean sea level rise by 2500. Inasmuch as this model limits the maximum ice-cliff retreat rate, even higher rates could be theoretically possible. Although DeConto and Pollard (2016) include several generally not previously modeled processes, which could become more important in Antarctic ice mass losses, especially in higher emissions scenarios, their paper represents just one study that remains to be confirmed by further observations or modeling.