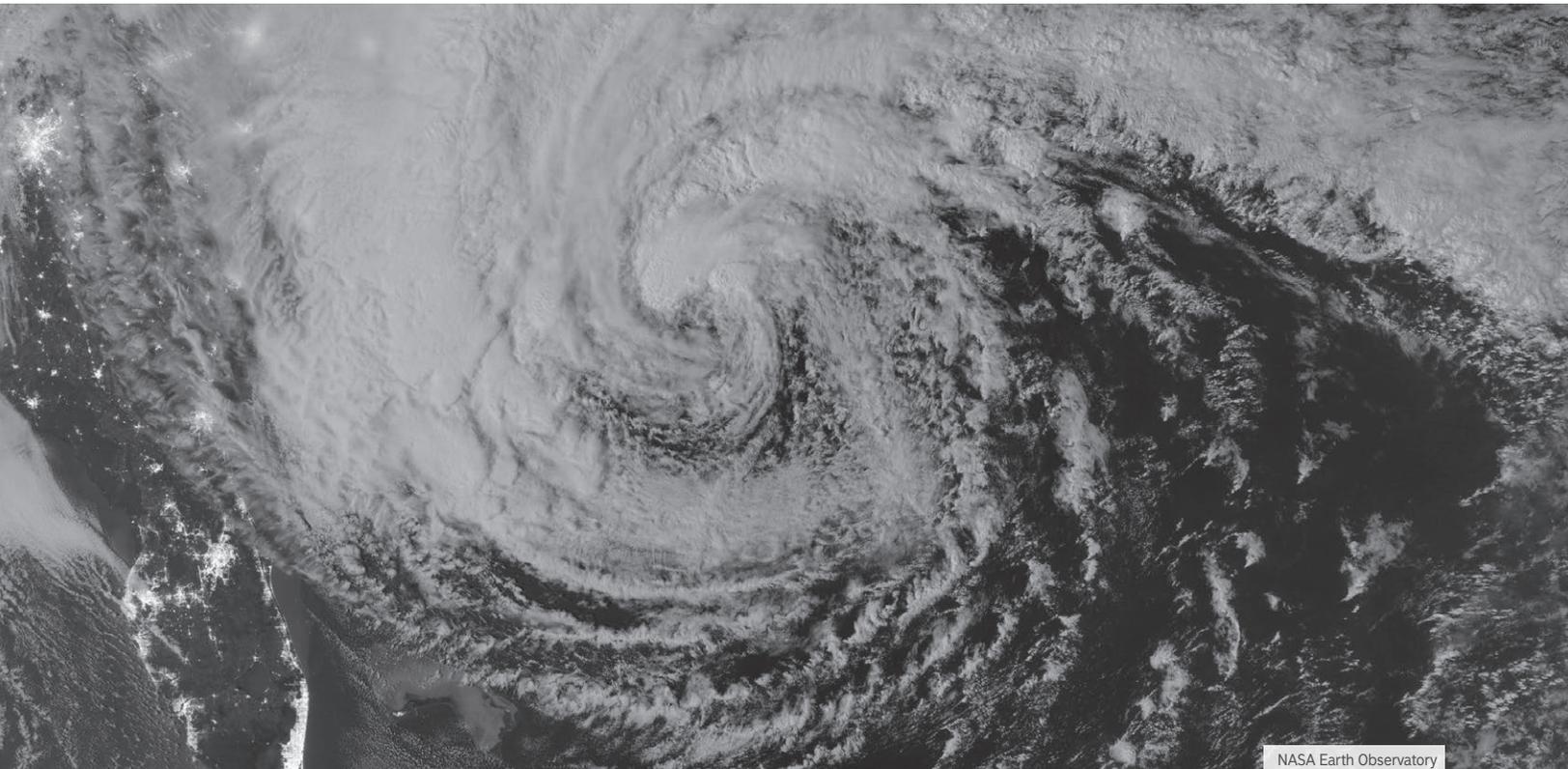


# Urban Transit Systems and Conditions of Enhanced Climate Variability

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Metropolitan public transit sectors will be impacted in a variety of ways by climate change, principally from rising temperatures, rising sea levels, higher storm surges, changing precipitation patterns and extreme events such as floods and droughts.<sup>1</sup> This paper documents state-of-the-art understanding of current and future climate risk for urban transit systems. Increasing climate variability is driving urban transit systems to be more flexible and adaptive in response. Transit systems are designed and managed to operate within an expected range of environmental conditions. Climate change is associated with gradual and punctuated shifts in this environmental baseline of cities. Urban transit systems are already experiencing the effects of climate change, and greater impacts are expected with the onset of an increasingly dynamic climate.

According to global climate modeling scenarios, cities can expect directional shifts in average annual climate-related conditions such as higher average annual temperature and more rapid sea level rise, as well as more frequent and intense extreme weather events. Observed climate data from the early 20th century to the present illustrate a shift in the frequency and magnitude of extreme events, particularly heavy precipitation events and heat waves. Worst-case scenarios for future climate

change include instances where multiple extreme events occur at the same time – for example, a large coastal storm with tidal surge and flooding coincident with an extreme heat event.

Climate change will increase the exposure and vulnerability of urban transit systems to hazards. Climate-related shifts represent significant challenges as well as potential opportunities for these systems and their managers. In this paper, the new challenges and opportunities brought by climate change are discussed within the context of climate impacts, vulnerabilities and the potential for enhanced resiliency across a set of cities: London, Los Angeles, Madrid, New York, Santiago, Tokyo and Vienna. This paper brings forward general observations and statements drawn from detailed city case studies as well as from other cities experiencing changes in climate.

The paper also examines how urban transit system managers have begun to recognize and respond to the challenge of climate change. In many cases, response has come after a severe disruption and devastating loss caused by an extreme event. In other situations, managers have been more proactive. Central to all discussions is how to finance the necessary adaptations and promote the resiliency that climate change requires, and how to integrate capital investing and management into the everyday operations of transit systems. This analysis also discusses how

<sup>1</sup> Rosenzweig et al.

local, national, and international organizations and networks such as The C40 Cities Climate Leadership Group and the International Association for Public Transport can play a critical role in helping transit managers better understand, and act on, current and future climate risks. In this paper, the terms “resilience” and “preparedness” refer to different qualities of response capacity to extreme to extreme events while “adaptation” is used to describe a broader effort to respond to a diversity of climate change challenges, including gradual shifts in baseline conditions as well as extreme events.

## Key Climate Risk Impacts on Urban Transit Systems

Climate change will bring a range of impacts for urban transit systems – both acute and gradual. In the short term, the most likely impacts will be acute – more frequent extreme weather events and increased climate variability. Over the longer term, other threats such as sea level rise will compound the potential for more frequent intense coastal storms. Cascading system impacts and associated vulnerabilities, together with transit service disruption, could result in wider-scale, secondary social and economic costs.

Urban climate change impacts will result from the following four broad categories:

1. Increased frequency of extreme precipitation events
2. Increased frequency of extreme heat days and heat waves
3. Sea level rise and coastal storm surge events
4. Increased frequency of extreme wind events

Drought also could affect urban transit systems but not to the degree seen in the other categories. Table 1 provides a listing of climate risks within each of the four categories.

Major investments in transit infrastructure and emergency plans will be necessary to adapt to climate change, and will have to be site-specific. For example, whether infrastructure is at ground level, underground or elevated changes the impact of flooding.<sup>2</sup> Flooding can come from a variety of sources, including storm surge in coastal communities, riverine and lake flooding in inland areas, and street level flooding from intense precipitation events. Infrastructure in low-lying areas in the floodplain and areas below ground such as tunnels, vent shafts, and ramps are clearly at risk. To recover from flooding, transportation managers will require the use of numerous, large-scale pumps, debris removal and the repair or replacement of key infrastructure, such as motors, relays, resistors and transformers.

**Table 1. Climate Risks and Hazards That Will Affect Transit Systems.**

Climate Hazard	Impact
<b>1. Increased frequency of extreme precipitation events</b>	Inland and street level flooding
	Landslides
	Heavy snowfall
<b>2. Increased frequency of extreme heat days and heat waves</b>	Threats to customer and worker health safety
	Overhead electric equipment - excessive heating
	Stretched overhead catenary wires
	Overheated vehicles and failed air conditioning systems
	Blackouts - e.g., from power failures during peak load demand
<b>3. Sea level rise / coastal storm surge</b>	Inundation
	Wave action and scour
	Salt water corrosion
<b>4. Increased frequency of extreme wind events</b>	Blackouts and large scale power loss
	Loss of equipment - e.g. localized loss of power and overhead wiring
	c. Obstructions - e.g., downed trees

Source: Adapted from FTA 2011.

Besides sea level rise and storm surge vulnerability, steel rail and overhead electrical wires in transportation systems are particularly vulnerable to excessive heat. Overheating can deform transit equipment, causing steel rail lines to buckle and throwing them out of alignment, which can cause train derailments.<sup>3</sup> Additionally, heat can reduce the expected life of train wheels and vehicle tires. Roadways made of concrete under extreme heat conditions can buckle and asphalt roads can melt. Downed power and telecommunication systems can create additional risks in the transportation network via power shortages or by limiting communication, particularly during extreme events and emergencies. Passengers also may experience more heat-related illnesses due to higher temperatures and more frequent heat waves. Transit managers need to assess the capacity of their systems to respond to worst-case scenarios, including situations where multiple hazards occur at the same time – e.g., an extreme flooding event during a heat wave.

Transit managers will also need to ensure high standards of safety, maintain infrastructure in a state of good repair, and provide service to transit-dependent populations equitably—all while minimizing costs and responding to new and changing climate risks.

<sup>2</sup> Prasad et al.

<sup>3</sup> Mehrotra et al.

# Dynamic Climate Risk

This section reviews the most recent global climate change scenarios and predictions for climate impacts for the 21st century as prepared by the International Panel on Climate Change,<sup>4</sup> and then examines examples of climate conditions specifically for the case study cities.

## Temperature and Precipitation Change

Observed global temperatures show an increase of approximately 1 degree Celsius since late 19th century, with more rapid warming during the latter part of the data record. While projections continue to show wide variation in the range of possible future conditions, there is greater understanding regarding the factors behind the variation and the level of uncertainty in the model results.

Projections of future climate show a possibility of greater change in the 21st century. Current projection estimates indicate that global temperatures will increase 2 degrees Celsius in the mean annual temperature by the mid 21st century and 3.7 degrees Celsius by the end of the century. Model results for future precipitation patterns are more variable, but most of the findings illustrate higher amounts of precipitation and greater hydrologic variability.

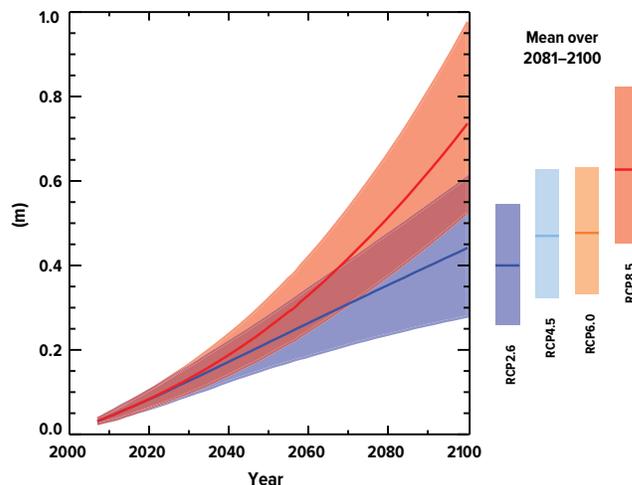
## Projected Sea level rise

Climate warming will result in sea level rise. Sea level rise is caused by the thermal expansion of the upper layers of the world's oceans and seas and from the melting of glaciers and ice sheets. Large continental scale ice sheets such as the Greenland ice sheet are melting more rapidly than expected. Global mean sea level rise for 2081–2100 relative to 1986–2005 will likely be in the ranges of 0.26 to 0.55 meters (10 inches to 21.66 inches) for a low global greenhouse emission scenario, and from 0.45 to 0.82 meters (17.72 inches to 32.28 inches) for a high emissions scenario (see Figure 1). The range of possible future sea level rise is defined by the variation in the scenarios and the level of uncertainty in the models. It should be noted that local rates of sea level rise can vary widely based on rates of erosion, groundwater withdrawal and other local factors. In the case of New York City, the projected rate is roughly double these numbers, with a high estimate of just under 2 meters (78.73 inches) of sea level rise by 2100.<sup>5</sup>

<sup>4</sup> The IPCC Working Group I Report (IPCC Fifth Assessment Report 2013, known as AR5), provides updated information on the observed global climate trends. This state-of-the-art report is the latest in the series produced by the science-based Intergovernmental Panel on Climate Change under the auspices of the World Meteorological Organization and the United Nations. The IPCC assessment reports have been released since 1990. With each iteration, the amount of observed data and model sophistication have increased as have the strength of the argument that the world's climate is warming and that human action is at least partially responsible.

<sup>5</sup> NPCC

Figure 1: Projected global mean sea level rise.



Source: IPCC AR5 2013.

## Extreme Weather and Climate Event Frequency

Changes in many extreme weather and climate events have been observed since about 1950. It is very likely that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale. It is likely that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. In most areas, the number of heavy precipitation events annually has increased. The frequency or intensity of heavy precipitation events has likely increased in North America and Europe. In other continents, confidence in changes in heavy precipitation events is at most medium. There is low confidence in observed trends in small-scale severe weather phenomena such as hail and thunderstorms because of historical data alterations (e.g., new sampling regimes, changes in sensors) and inadequacies in monitoring systems.

It is expected that climate change will influence the frequency and severity of weather and climate events defined as extreme. This potential extreme event frequency change can take several different complex trajectories, as highlighted by the following graphic presentation (Figure 2).<sup>6</sup>

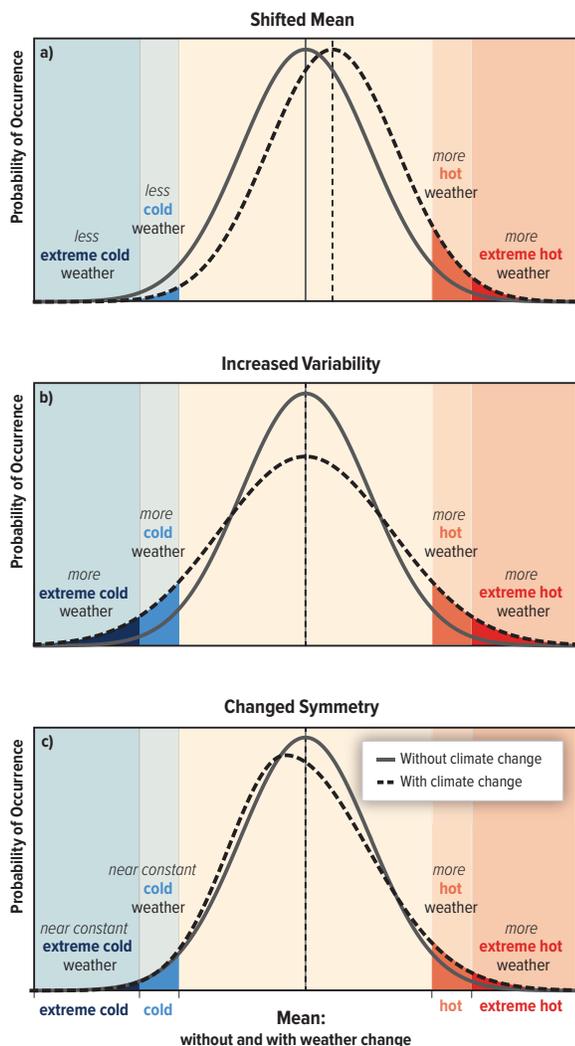
Changes in extremes include a simple shift in the mean resulting in, for example, fewer extreme cold days and more extreme hot days (Figure 2a). Another scenario illustrates a condition of increased variability with a greater number of extreme events at both tails of the distribution (Figure 2b). Another possibility includes a change in overall symmetry in the distribution of extreme events (Figure 2c). Translating these projected shifts to specific cities and their transit systems indicates there will be more frequent extreme heat days. For example, in New York City, the number of days with temperatures greater than 32.2 degrees Celsius (90 F) will rise from a baseline of 18 days during the period 1971-2000 to as many as 57 days in the 2050s.<sup>7</sup> In Vienna, by 2040 every fourth day in the summer will

<sup>6</sup> IPCC

<sup>7</sup> NPCC CRI2014

be an excessive heat day, and the number of heat days in the urban core of Vienna will increase from 5.1 days per year (1961-1990) to 17.7 days per year during the period 2010-2039.

**Figure 2: Change in distribution of weather and climate extremes.**



Source: IPCC SREX 2011.

Extreme event frequency can be best understood by examining the past, current, and future conditions of heat stress. It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase. It is very likely that heat waves will occur with a higher frequency and duration. Occasional cold winter extremes will continue to occur. This is an average value; in some areas rapid urban development and land use change will create or exacerbate urban heat island conditions, resulting in substantially greater temperature increases. Urban heat islands result from intense urban development that causes warmer temperatures in cities as opposed to outlying areas. The urban heat island phenomena are particularly observed at night.<sup>8</sup>

<sup>8</sup> Observed global temperature data has been partially corrected for the urban island effect. It is unlikely that any uncorrected urban heat-island effects and land use change effects have raised the estimated centennial globally averaged land surface air temperature trends by more than 10 percent of the reported trend.

Globally, there is medium confidence that the length and frequency of warm spells, including heat waves, has increased since the middle of the 20th century, mostly owing to lack of data or studies in Africa and South America. However, it is likely that heat wave frequency has increased over this period in large parts of Europe, Asia and Australia.

**Figure 3: Tokyo "guerrilla rain storm" during the summer of 2013 caused by the city's heat-island effect.**



Source: Japan Times, Jake Adelstein, July 13, 2013.

## Extreme Rainfall Events

Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions are very likely to become more intense and more frequent by the end of this century as global mean surface temperature increases. Even so, there is high confidence that, as the climate warms, extreme precipitation rates (e.g., on daily time scales) will increase faster than the time average. Changes in local extremes on daily and sub-daily time scales are expected to increase by roughly 5 to 10 percent per degree Celsius of warming (medium confidence).<sup>9</sup> As previously stated here, in North America and Europe there have been likely increases in either the frequency or intensity of heavy precipitation.

## Extreme Wind Events

Wind extremes seem to be declining in mid-latitudes and increasing in high latitudes.<sup>10</sup> However, confidence in trends in extreme winds is low, due to quality and consistency issues with analyzed data.

<sup>9</sup> Global mean sea level has risen by 0.19 [0.17 to 0.21] meter, estimated from a linear trend over the period 1901–2010, based on tide gauge records and additionally from satellite data since 1993. It is very likely that the mean rate of sea level rise was 1.7 [1.5 to 1.9] mm yr<sup>-1</sup> between 1901 and 2010. Between 1993 and 2010, the rate was very likely higher at 3.2 [2.8 to 3.6] mm yr<sup>-1</sup>; similarly high rates likely occurred between 1920 and 1950. The rate of GMSL rise has likely increased since the early 1900s, with estimates ranging from 0.000 [–0.002 to 0.002] to 0.013 [–0.007 to 0.019] mm yr<sup>-2</sup>. It is very likely that the rate of GMSL rise during the 21st century will exceed the rate observed during 1971–2010 for all Representative Concentration Pathway scenarios (four possible climate futures described in IPCC AR5) due to increases in ocean warming and loss of mass from glaciers and ice sheets. Projections of sea level rise in IPCC AR5 are larger than in the Fourth Assessment Report (IPCC AR4), primarily because of improved modeling of land-ice contributions (see Figure 4). For the period 2081–2100, compared to 1986–2005, GMSL rise is likely (medium confidence) to be in the 5 to 95 percent range of projections from process based models, which give 0.26 to 0.55 meter for RCP2.6, 0.32 to 0.63 meter for RCP4.5, 0.33 to 0.63 meter for RCP6.0, and 0.45 to 0.82 meter for RCP8.5. For RCP8.5, the rise by 2100 is 0.52 to 0.98 meter with a rate during 2081–2100 of 8 to 16 millimeter per year<sup>-1</sup>.

<sup>10</sup> IPCC AR5

## Extreme Storm Events - Hurricanes, Typhoons (Cyclonic Storms)

Scientists are almost certain that the frequency and intensity of storms in the North Atlantic have increased since the 1970s, although the reasons for this increase are debated. Climate model projections indicate that it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rainfall rates. There is lower confidence in region-specific projections of frequency and intensity. However, due to improvements in model resolution and downscaling techniques, it is more likely than not that the frequency of the most intense storms will increase substantially in some basins under projected 21st century warming.

## Droughts

Drying in the Mediterranean, southwestern U.S. and southern African regions is consistent with projected changes in global wind circulation patterns. Confidence is low for a global-scale observed trend in drought or dryness (lack of rainfall) since the middle of the 20th century, owing to lack of direct observations, methodological uncertainties and geographical inconsistencies in the trends.<sup>11</sup>

## Climate Trends and Projections in Case Cities

The weather and climate of any local area is highly particular to that site. Any given city experiences some climate variability and, at times, extremes that need to be managed for within the organization and operation of local urban systems. For the case study cities for which data were available, all experienced warming over the period of 1901-2012. The most warming was observed in Tokyo (1.3 degrees Celsius), with slightly lower amounts in London (1.2 degrees Celsius), Madrid (1.2 degrees Celsius), New York City (1.2 degrees Celsius) and Vienna (1.2 degrees Celsius). Los Angeles experienced the lowest amount of warming (0.8 degrees Celsius).<sup>12</sup>

Transit managers in these cities already recognize the new risks posed by climate change. This is especially true for flooding and heat stress events. All of the cities have experienced extreme events in the recent past that significantly disrupted the transit system. The case study cities are observing climate change now and will experience further change and accelerated change in the future. Table 2 presents some regional projections of temperature change and precipitation change.<sup>13</sup>

**Table 2: Regional Projections of Temperature and Precipitation Change with Reference to Case Study Cities (Min-Max)**

Region	City	Temperature			Precipitation		
		2035	2065	2100	2035	2065	2100
Eastern North America	New York	0.4 - 1.9°C	1.0 - 3.5°C	1.0 - 4.2°C	-4 to +9%	-1 to +14%	-2 to +14%
		0.3 - 1.9°C	0.9 - 3.4°C	1.1 - 4.3°C	-4 to +6%	-3 to +14%	-4 to +11%
North-ern Europe	Vienna & London	1.0 - 2.7°C	-0.5 - +3.8°C	-2.3 - +4.5°C	-2 to +12%	-5 to +17%	+1 to +24%
		0.4 - 1.3°C	1.0 - 2.4°C	1.2 - 3.0°C	-8 to +6%	-14 to +6%	-17 to +9%
Central America	Mexico City	0.4 - 1.2°C	0.6 - 1.7°C	0.3 - 2.0°C	-7 to +5%	-8 to +5%	-8 to +6%
		0.3 - 2.0°C	0.7 - 3.1°C	0.6 - 4.0°C	-12 to +3%	-14 to +3%	-19 to +4%
South-ern Europe	Madrid	0.3 - 1.7°C	0.9 - 3.0°C	0.7 - 3.9°C	-3 to +7%	1 to +18%	-1 to +21%

\*For precipitation and temperature, (-) values correspond to a decrease in precipitation or temperature and (+) values correspond to an increase in precipitation or temperature. Source: IPCC AR5 2013.

The case study cities have available to them detailed climate change assessments that provide finer spatial and temporal resolution data regarding possible future climate change. Several of the cities conducted extensive surveys of climate trends and projections that were used by transit managers, while others developed data on an ad hoc basis connected with national or global efforts to understand future climate dynamics.

Some of the most extensive work has been completed by London and New York. For London, defined administratively by the Greater London Authority, the primary source for climate information has been the national government's data sets on climate conditions and climate change. The U.K. Climate Impacts Programme was established in 1997 and generated climate scenarios in 1998, 2002 and 2009.<sup>14</sup> Using the UKCIP's 2002 national climate scenarios, the London Climate Change Partnership produced regional scenarios and a report on London's climate risks, *London's Warming*.<sup>15</sup> The City of New York, through its Office of the Mayor, created the New York City Panel on Climate Change in 2008. The NPCC provides comprehensive data on climate trends and future climate projections, including quantitative and qualitative information on the likelihood of extreme events. Similar science-policy working committees have been developed in many of the case study cities. In Vienna, for example, the local scientific community has worked closely with city administrators, including transit officials, via the Master Plan and Klimaschutzprogramm to bring cutting-edge climate science into planning processes.

<sup>11</sup> This does not mean that drought is unlikely to occur in the future. Based on updated studies, conclusions regarding global increasing trends in drought since the 1970s were probably overstated. However, this masks important regional changes: the frequency and intensity of drought have likely increased in the Mediterranean and likely decreased in central North America since 1950.

<sup>12</sup> Similar data were not available for Santiago or Mexico City.

<sup>13</sup> Derived from IPCC AR5

<sup>14</sup> The UKCIP was established with the aim of providing a framework for an integrated national assessment of climate change impacts, and subsequently to help organizations assess how they might be affected by climate change, so they can prepare.

<sup>15</sup> UKCIP

In most cases, the data developed for local contexts is of a finer spatial resolution than what is available at a national or continental spatial scale, but rarely do the data or model result in conflict in direction. For example, within New York City the projected rate of sea level rise developed by the NPCC is up to double the rate defined for North America within the IPCC efforts. This difference results from the fact that regional and local scale-modeling can incorporate a variety of site-specific factors that influence the rate of sea level rise. Several international efforts, including the Urban Climate Change Research Network and the Durban Adaptation Charter, have worked to develop fine-scale climate change data through collaborations between local scientists and local stakeholders.

## Effects of Climate Variability and Dynamism on Urban Transit Systems

The cumulative effect of climate change, including system-level cascade effects, will vary significantly from city to city. While all transit systems experience climate risk, the intensity and extent of the effects are influenced by the level of risk (a measure of exposure and frequency of events) and the vulnerability and resiliency of the system.

Some cities have experienced frequent disruptive events while others have not. Within the case study cities, London, New York, Tokyo, and Vienna have experienced frequent disruptive events that have sharpened their focus on climate change. Other cities that historically have not experienced as many events or such defining events have still been affected by a broad variety of climate stresses, such as Santiago, Madrid and Los Angeles.<sup>16</sup> Both sets of cities illustrate how urban transit systems respond to climate risks.<sup>17</sup>

The connection between climate experience, current risks and potential future risk is well illustrated in Madrid, where a relatively resilient urban transit system has experienced significant climate events, and where future climate change is likely to impact various sectors. According to Madrid's sustainability plan, *Ayuntamiento de Madrid* (2008), it is anticipated that Madrid temperatures will increase significantly 4 – 7 degrees Celsius in the summer and 2 – 4 degrees Celsius in the winter by 2100 (relative to the period of 1960-1990). Precipitation is generally expected to decrease, particularly during the spring and summer months, which tend to be historically dry.

With respect to extreme events, more frequent heatwaves and flooding events in areas close to the Manzanares River, which traverses Madrid and is close to residential housing, are likely. Intensification of the urban heat island effect is also likely. UHI

<sup>16</sup> Los Angeles, Santiago and Tokyo have a long history of earthquake risk and hazards that enhance their awareness of the potential for large scale system disruptions.

<sup>17</sup> It should be noted that London, New York, Tokyo and Vienna, given their temperate region locations, already have dynamic seasonal shifts in climate, temperature and precipitation. Los Angeles, Madrid and Santiago are located in Mediterranean climate regions associated with less violent climate shifts except for flash flooding in mountainous terrain and summer heat stress.

over Madrid has raised surface temperatures by 5 – 6 degrees Celsius for some portions of the city.<sup>18</sup> Severe droughts are highly likely to occur in the future, as the city is in a Mediterranean climate zone that is projected to become increasingly drier over time and experience more extensive droughts.<sup>19</sup> For many portions of Spain, including Madrid, a drought during 2005 caused a 36 percent decrease in national hydroelectric power production.<sup>20</sup> Development patterns are also leading to increasing flood risks. A lack of available land to build on has led to some river channels being encroached on by the outer limits of Madrid.<sup>21</sup> Where the Manzanares River flows past Madrid, there is also likely to be a heightened risk for flooding. Flooding in this part of Madrid could negatively impact public drinking water resources and damage housing units.<sup>22</sup>

Figure 4: A semi-flooded Plaza Mayor in Madrid after a 2008 storm.



Source: Luis Roderero-Merino (flickr)

Although Madrid's climate is changing, Madrid's transit system may not be very vulnerable to damages with respect to climate change when compared with other cities such as New York and London due to their lower elevations and location along major waterways.<sup>23</sup> Despite this and the fact that Madrid has been increasing the energy efficiency level of its transportation fleets (metro and bus), there are still many climate risks that may be exacerbated by climate change. High temperatures can lead to problems with pavement durability, and roadways that buckle can cause car accidents, among other problems. Higher winter temperatures lessen the demand for snow clearing, but at the same time increase the need for de-icing when rain falls on cold road surfaces. Increased temperatures can lead to ruts or cracks in non-structural features, which could be of concern for older buildings in the city. Heavier storms around Madrid are likely to lead to the destabilization of slopes upon which infrastructure may be situated – including road-and-rail-based transport. Flash floods can cause erosion of slopes, and roadway or railway washouts around the city.

<sup>18</sup> Salamanca et al.

<sup>19</sup> Moreno

<sup>20</sup> DG Environment

<sup>21</sup> Ayuntamiento de Madrid

<sup>22</sup> Moreno

<sup>23</sup> Ayuntamiento de Madrid; Doll et al.

Figure 5: Vienna streets after a 2013 flood.



Source: Variegator (flickr)

Around the world, transit system operations, management and policy will have to cope with the effects of climate change. For operations, the central questions regard disruption or delay of service as well as cascading failures that could significantly interrupt services for an extended period – weeks and months. In the case of New York's MTA, Tropical Storm Irene in 2011<sup>24</sup> caused the washout of a commuter rail line that took three months to repair and re-open. In the management context, transit managers will need to use forward-looking information such as climate change projections instead of historical information to make decisions. Vienna has already learned this lesson: Vienna's transit managers had to adjust and enhance their flood control policies after their system experienced frequent flooding from more severe storms, exceeding statistical expectations. For transit planners and decision-makers, the best policies and plans will be flexible and adaptable over time. Transit managers will have to recognize that with climate change their current policies might be insufficient.

## Key Effects on Case Study Cities

All the transit systems in the case study cities recognize the importance of climate risks and have completed assessments of the potential impacts of enhanced climate variability and change. The key climate impacts included flooding and inundation and a variety of other extreme events, particularly heat stress. Several of the individuals interviewed recognized that recent weather and climate patterns illustrated greater variability. In many cities, extreme events and/or unusual seasonal patterns such as the intense flooding of the New York subways, flooding and warm winter temperatures in Vienna and extremely snowy winters in Tokyo alerted the interviewees to the need to investigate climate dynamics and systems operation. Increased temperatures were especially significant for transit systems that were pressing up against limits to effective system operation. For cities such as Vienna, where air conditioning was not traditionally put into public transit, warmer summers over the past two decades have led to the integration of cooling equipment in the system's

<sup>24</sup> Events like Tropical Storm Irene, which followed a two month period of unusually heavy rains, are consistent with climate change predictions.

trams. In Los Angeles, passengers waiting for transit service or maintenance personnel working on equipment are already overheating. These conditions present a spectrum of significant adaptation challenges for cities, including how to respond to the cost and funding demands associated with the retrofitting of the existing systems to meet these emerging climate change requirements.

The interviewees recognized a variety of key immediate and long-term effects of climate variability and change:

- Immediate impacts included loss of revenue from train cancellations and expenses to restore damaged assets.
- Longer-term impacts were associated with increased capital expenditures for replacing and updating infrastructure, as well as increased expenses to train system operators on emergency response and new adaptive management practices.
- Several transit managers also noted the possible increase of emergency response services, including evacuation and sheltering.

In general, the case study city transit managers are largely focused on the effects of extreme events and climate variability that could disrupt or influence their systems in the short-term. This is largely because of the traditional 10-20 year planning horizon and a general lack of confidence in long-term climate projections. In most cases, the municipal transit systems had not yet performed the formal assessment of key climate risk impacts in the second half of this century. Where work of this type was done, the results indicate a potential for accelerated climate change. In the case of New York, the rate of sea level rise could increase five times above the 20th century rate of 2.5 cm (1 inch) per decade by mid-century; and increase to almost 10 times above by the year 2100.

All the cities maintain systems that collect information on climate risk in their transit system service shed, as well as data on service delivery during highly disruptive events. However, not all cities are able to collect high-quality and extensive data – typically, only the larger and wealthier cities do. Creating an integrated indicator and monitoring system which can build off of the existing weather and climate data-gathering equipment and protocols would assist in the development of climate resiliency and adaptation strategies. This is an activity that could be funded through current expenditures for such data gathering and could be expanded through forward-planned budgeting within the transit agencies.

In many cities, extreme weather events become focused moments for the transit system operators and managers to reassess risk and identify opportunities for coordinated resiliency and adaptation planning and response. The relative role of extreme events setting off a policy response is particularly evident in the case of New York (see Appendix B). While New York City includes agencies and organizations with extensive resources and has been presented as an outlier given its size and complexity, the New York City transit system has been confronted by several massive, system-wide shutdowns in recent years, including major weather events in 2007, 2011 and 2012, the Northeast Blackout in 2003, and the attacks on September 11, 2001. These extreme events have provided the impetus for advanced planning for

natural and man-made risks. Hazards and disasters research shows that especially after multiple harmful or disabling events, organizations and individuals will take action. Given that, it can be assumed that as other cities experience extreme climate events actions will follow. Clear evidence for similar advanced action in response to recent histories of extreme events also can be seen in Tokyo and Vienna.

## Climate Adaptation and Urban Transit Systems

Transit systems have long had to manage the impacts of climate under the auspices of variety disaster risk reduction, hazard mitigation, and emergency response strategies. In many ways, climate change represents an extension or augmentation of known risks such as more flooding or more frequent intense heat events. In other cases, climate change will manifest itself as new risks or hazards or events historically seen as highly unusual or “freakish,” such as historically unprecedented long heatwaves or extended periods of precipitation.

In response to these threats, urban transit systems are now witnessing a blending of these earlier approaches with modern climate change adaptation strategies. A range of basic approaches to respond to climate risk has been defined for the urban transportation sector.<sup>25</sup> Most of these approaches focus on “technological fixes.” Historically, infrastructure has been protected from floods by building or strengthening levees, elevating equipment or improving drainage or pumping capacity. The transit systems in all of the case study cities have adopted flood hazard mitigation strategies; Tokyo is particularly illustrative. East Japan Railway Company, Tokyo Metro, Toei Subway and to a lesser extent the other 22 railway operators in Tokyo,<sup>26</sup> in concert with the local and national governments, have built and put into practice a wide variety of large, medium and small-scale infrastructure devices, including extensive levees and station specific water barriers to protect the systems from flooding and a range of other hazards.

Significant changes in the climate risk protection within cities and their transit systems have emerged in recent years. These focus on three general areas of advancement: 1) instrumentation, sensing, and smart systems; 2) integration of ecosystem services; and, 3) resiliency practice. Advanced instrumentation and sensing capacity, including the development of microsensors, now allow transit systems to monitor the shifts in risk and hazard conditions and alert managers to potential immediate threats. Most transit systems now accept flood detention strategies and passive cooling as part of risk and hazard mitigation.

The integration of resiliency into urban system operation has been equally important. Broadly defined as the capacity to “bounce back” after a shock or stress, resiliency practice has

been expressed in a variety of ways, which for transit could include temporarily moving rolling stock in advance of storms to protected locations and diversifying transport modal choices.

It is critical that climate adaptation considerations be incorporated into transit plans, construction and management even while retrofitting existing transportation assets. Several factors have been associated with adaptation efforts in urban transit systems that could reduce their overall level of exposure and vulnerability and enhance their resiliency to climate change. The two key factors seen as most critical in the literature and by transit managers were access to resources (e.g., human, institutional and financial) and the capacity to put them into use.

Several additional factors were also identified in the research literature and include:

1. Flexibility, broad cross-disciplinary involvement and buy-in
2. Embedding climate change into work streams rather than developing a special system
3. Prioritizing “no-regrets” strategies to understand the consequences of inaction and meeting multiple goals
4. Planning for and executing effective communication with customers
5. Top level engagement with a central point of coordination
6. Coordination with other infrastructure and service providers within the system’s service-shed

Type of ownership (private, public or quasi-public) is not consistently associated with conditions of higher or lower response capacity. In case study cities, conditions of ownership and related structural conditions and constraints, including funding sources, revenue streams and executive decision-making, vary widely based on whether the transit organization is public or private. Despite these variations, in all cases close and interdependent relationships between private and public sectors are maintained.

### City Case Study-Related Adaptation Strategies

All the case study transit agencies have recognized the importance of assessing the potential impacts of increased climate variability and change, yet only a few have dedicated climate adaptation planning and assessment processes and have also committed extensive resources to climate adaptation. Conversely, much greater attention has been focused on climate mitigation, greenhouse mitigation and energy savings that could result from urban transit use and system expansion. In general, urban transit is presented as a critical component of the case study cities’ attempts to define and meet greenhouse gas emission goals. This is especially true for Madrid, Santiago and Tokyo. With respect to climate adaptation, the London, Los Angeles and New York systems have been able to focus the greatest amount of resources on these issues. A similar level of variation exists with respect to the conditions of climate governance and decision-making framework for climate adaptation strategies.

<sup>25</sup> Revi

<sup>26</sup> The Toei Subway is the other major metro operator, but is owned and directly operated by the Tokyo municipal government. In total there are 25 different railway operators in the Tokyo metropolitan area.

The Greater London Authority has created an extensive policy infrastructure to bring climate science information into a decision-making process and to define steps to enhance the resilience of its transit system to climate change. In most other places, the governance of climate risk takes place within the existing codes and regulations used to maintain the operation of the transit systems. Transit agencies are sensitive to the possibility of emergent climate change. Several agencies, but not all, say they have actively tried to draw attention to the ever-present signals of increased climate dynamics (e.g., more frequent weather-related delays, etc.).

In many cities, opportunities exist for day-to-day operators and upper level managers to discuss weather and climate related risks. All city transit systems maintain basic metrics of weather and climate related risks, but most have not yet developed metrics to assess the value or contribution of climate resiliency and adaptation strategies. One exception is the Los Angeles Metro, which has developed a set of metrics focused on sustainability and resiliency – including several climate change and adaptation measures.

Networks and international organizations have been quite valuable for transit organizations in understanding climate risk and developing and implementing adaptation strategies. Meaningful cooperation between cities was often cited; for example, New York's MTA has worked extensively with Tokyo and London as well as other cities on both flooding and heat mitigation measures. Networks include transit-focused and climate focused organizations such as The C40 Cities Climate Leadership Group. The prevailing approach has been to incorporate increased climate dynamism into everyday operations and life-cycle capital redevelopment. This integration and enhanced flexibility or adaptive management structure is seen as the most robust response to climate change impacts and effects.

## Concluding Thoughts

It is clear that urban transit systems have been affected by climate change and that a wide variety of potential and emerging impacts have been identified. The costs and disruptions associated with recent climate events have been documented and studied. Every agency interviewed for this analysis has experienced increased climate variability, though many of them do not formally recognize this as part of a long-term trend and broader-scale climate change. It was stated that within many agencies a significant proportion of employees remain skeptical regarding the reality of long-term climate change, and in general the term “climate change” is not widely used in planning, management and operation.

## Opportunities for Transit Agencies to Improve Resiliency and Adaptation Strategies

Several clear opportunities exist to enhance transit system response capacity, resiliency and adaptation in the face of climate risk. Many of these opportunities are illustrated by the city transit systems presented in this paper.

To build the response capacity of the transit systems, it is critical to increase the level of connection between the different constituencies with interests in urban transit systems operation and upper-level strategic management. Additionally, creating more and broader links between managers and operators could enhance the level of information and resource flow needed to implement effective climate resiliency strategies. Just as the connections between transit system representatives via national or international partnerships/networks have promoted local capacity, greater communication between the operational and managerial elements within transit agencies can also promote response capacity. Some of the case study cities have already informally begun integrating operational and managerial decision making around climate resiliency, which could eventually lead to more formal links over time.

Other possible actions to advance resiliency and adaptation include:

1. Create climate change science panels that produce updated and on-demand climate data and modeling results for transit officials and utilize the expertise of the local science community and local transit community.
2. Develop and implement robust indicator and monitoring systems that include among other sources of data the “local knowledge” of day-to-day operators.
3. Use extreme events as learning opportunities to review all aspects of the transit system's operation and management, including an assessment of every individual's responsibility during a system crisis.

## Challenges to Implementing Climate Resiliency and Adaptation Strategies

A significant challenge for promoting resiliency and adaptation rests with the complex nature of cities and their extended metropolitan regions, including the administration of urban transit systems and other critical infrastructure. Within any large metropolitan region there may be several separate entities responsible for different components of the region's public transit infrastructure – each entity with its own revenue stream and set of stakeholders. In addition, the operation of any one transit service is dependent on a variety of other urban systems such as energy supply, road and highway maintenance and communications. Coordination across these different organizations and associated constituencies is inherently difficult. In such a highly fragmented system, the capacity to develop and

implement integrative adaptation plans can be limited. Even in the case of New York City, quite advanced in climate adaptation, the post-Hurricane Sandy resiliency and adaptation planning did not include comprehensive and detailed strategies because the city's transit system is operated by the State of New York – a distinct governmental entity which was to receive separate post-disaster federal aid.

Another significant challenge for urban transit system operations is defining climate action plans that include a diversity of strategies instead of ones that only focus on a single approach to adaptation. The research literature and empirical evidence illustrates that physical intervention, including hard risk and hazard mitigation infrastructure (e.g., walls and levees) by themselves have limited capacity for reducing vulnerability and improving resiliency. An integrated approach including hard and soft (ecosystem services) intervention on a variety of scales, coupled with management and policy reform are currently seen as leading to the most meaningful and robust adaptation approaches.

A crucial element in this integrated approach – or really any adaptation strategy – will be identifying funds to support these efforts. In general, transit authorities have limited ability to raise significant funds for large scale interventions and typically must do so with significant support from state or national government. Integrating adaptation planning and implementation into regular capital expenditure upgrades while also promoting resiliency actions (e.g., removing assets in harm's way before a disaster), is seen as the most cost effective and financially realistic approach. This is especially true in our current era of increasing fiscal stress and lack of alternative revenue streams.

The potential connections between climate change mitigation and adaptation are especially important in the context of urban transit systems. Urban transit provides clear advantages for promoting greenhouse gas emission reduction strategies and goals. Although the numbers vary widely, transportation can be responsible for 20-50 percent or more of the greenhouse gas emissions of developed cities. The case study cities all highlight the benefits of urban transit systems as an effective low carbon mechanism for mobility. In Madrid, a recent survey found that road transportation was responsible for 46.9 percent of the greenhouse gas emissions, while other forms of transit contributed 5.8 percent.<sup>27</sup> In New York City, automobiles emitted 20.6 percent of greenhouse gas and transit only 2.6 percent, with most of balance originating from buildings.<sup>28</sup> The capacity to take further advantage of urban transit greenhouse gas emissions reductions benefits by increasing ridership are hampered by the significant investments required to expand infrastructure at a time when the existing infrastructure is increasingly at risk from increased climate dynamics and extreme events.<sup>29</sup>

As demands for climate mitigation and adaptation increase, it will be beneficial to identify cross connections between these two streams. Yet, while there are potential synergies, there are also conflicts. For example, some adaptation approaches might encourage air conditioning in response to increasing heat stress, which then could result in increasing greenhouse gas emissions.

A central long-term synergy might arise in future low carbon scenarios in which cities could accrue financial benefits from transit-related greenhouse gas emission reduction via a carbon fee system. These benefits could be used to both expand the service to encourage more ridership and greenhouse gas reduction, as well as promote more rapid expansion of the adaptation strategies. This approach is well exemplified by the KLiP climate planning strategy that is now being implemented in Vienna. This effort is consciously attempting to incentivize the expansion of public transit and reduce auto use.

## Final Thoughts, Longer-Term Reorientation

One of the greatest challenges is how “resiliency” is defined by these transit systems. In most cases, the term illustrates an engineering and safety perspective to enable a system to “bounce back” after a disaster. While this definition is logical and laudable, the challenge will be to embrace the broader and longer-term aspects of resiliency which, given the projections for future climate change, could require more profound adaptation of systems whose operation will become increasingly fragile in the face of ever more dramatic climate shifts.

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<sup>27</sup> Madrid

<sup>28</sup> NYC

<sup>29</sup> The costs of service expansion and extreme event damage vary widely from city to city and are based on the structure of the existing systems, opportunities for expansion (including settlement patterns), and the level and character of climate risk and hazard.

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## Appendix A: Climate Change Projections – Additional Details

Figure 2 illustrates the distribution of global temperature change, with higher amounts in more northerly and southerly latitudes as well as some areas of average number temperature increases. It is difficult to define global trends for specific weather and climate measures, but it is very likely that during the period of record, the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale between 1951 and 2010. A recent decrease of the warming rate increase has been the subject of intense scientific debate but has not altered the overall profile of a dramatically warming planet.

Global surface temperature change for the end of the 21st century is likely to exceed 1.5 degrees Celsius relative to 1850 to 1900 for all Representative Concentration Pathways scenarios except one. The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 will likely be in the range of 0.3 degree Celsius to 0.7 degree Celsius (medium

confidence). This assessment is based on multiple lines of evidence and assumes there will be no major volcanic eruptions or secular changes in total solar irradiance. Relative to natural internal variability, near-term increases in seasonal mean and annual mean temperatures are expected to be larger in the tropics and subtropics than in mid-latitudes (high confidence).

The globally averaged combined land and ocean surface temperature data, as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] degree Celsius, over the period 1880–2012, when multiple independently produced datasets exist, and about 0.72 degree Celsius [0.49°C to 0.89°C] over the period 1951–2012. The total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78 [0.72 to 0.85] degree Celsius and the total increase between the average of the 1850–1900 period and the reference period for projections, 1986–2005, is 0.61 [0.55 to 0.67] degree Celsius, based on the single longest dataset available. The trends for 15-year periods starting in 1995, 1996, and 1997 are 0.13 [0.02 to 0.24], 0.14 [0.03 to 0.24] and 0.07 [–0.02 to 0.18], respectively.

Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to likely be in the ranges derived from the concentration-driven CMIP5 model simulations, that is, 0.3 degree Celsius to 1.7 degree Celsius (RCP2.6), 1.1 degrees Celsius to 2.6 degrees Celsius (RCP4.5), 1.4 degrees Celsius to 3.1 degrees Celsius (RCP6.0), 2.6 degrees Celsius to 4.8 degrees Celsius (RCP8.5). Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform.

Global precipitation trends are complex and more difficult to document. The best current understanding is that, averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (medium confidence before and high confidence after 1951). For other latitudes, area-averaged long-term positive or negative trends have low confidence.

The high latitudes are likely to experience an increase in annual mean precipitation by the end of this century under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase by the end of this century under the RCP8.5 scenario. Note that these projections encompass large regions, so caution should be used when connecting these values to specific cities or metropolitan regions (e.g., the values that encompass Los Angeles seem a bit unlikely at this point).

Global mean sea level has risen by 0.19 [0.17 to 0.21] meter, estimated from a linear trend over the period 1901–2010, based on tide gauge records and (since 1993) satellite data. It is very likely that the mean rate of sea level rise was 1.7 [1.5 to 1.9] mm/yr–1 between 1901 and 2010. Between 1993 and 2010, the rate was very likely higher at 3.2 [2.8 to 3.6] mm/yr–1; similarly high rates likely occurred between 1920 and 1950. The rate of GMSL rise has likely increased since the early 1900s, with estimates ranging from 0.000 [–0.002 to 0.002] to 0.013 [–0.007 to 0.019] mm/yr–2. It is very likely that the rate of GMSL rise during the

21st century will exceed the rate observed during 1971–2010 for all RCP scenarios due to increases in ocean warming and loss of mass from glaciers and ice sheets.

Projections of sea level rise in the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (see Figure 4) are larger than in the Fourth Assessment Report, primarily because of improved modeling of land-ice contributions. For the period 2081–2100, compared to 1986–2005, global mean sea level rise is likely (medium confidence) to be in the 5 to 95 percent range of projections from process based models, which give 0.26 to 0.55 meter for RCP2.6, 0.32 to 0.63 meter for RCP4.5, 0.33 to 0.63 meter for RCP6.0, and 0.45 to 0.82 meter for RCP8.5. For RCP8.5, the rise by 2100 is 0.52 to 0.98 meter with a rate during 2081–2100 of 8 to 16 mm/yr–1.

## Appendix B: City of New York Case Study

The connections between hazard mitigation, climate change adaptation, and the evolution of adaptation and resiliency strategies are well illustrated by the climate change action in New York City, where the Metropolitan Transit Authority runs the city's subways and most of the buses.

Climate change adaptation opportunities and challenges for New York already were being considered in the spring of 2007 when the city released its first comprehensive sustainability plan, PlaNYC. This plan called for the creation of a climate change adaptation taskforce, the development of adaptation plans, and the need to consider highly vulnerability communities in the city. The discourse of adaptation planning and action, however, changed later that year. On August 8, 2007, a severe and largely unpredicted thunderstorm swept through the city, resulting in major and in some areas prolonged service disruptions of the MTA transit system. The flash flooding rendered almost the entire subway system inoperable, causing significant economic losses that day because employees and customers could not get into the city's central business districts. Suddenly the prospect of climate change impacts seemed more immediate and relevant. The event became a policy window for the initiation of climate change adaptation policy in New York City, and marks a transition in the city's climate action.

In the immediate aftermath of the 2007 storm, the New York State Governor directed the MTA to conduct an assessment of the system's vulnerability to future storms. Specific recommendations for improving the MTA's operations, communications, engineering and regional interagency issues were put forth, including the creation of an Emergency Response Center and Inter/Intra-Agency Flooding Task Force. These adaptation measures, developed in response to crisis, increased the capacity of the MTA in the face of future storm events.

Several years later, two other storms presented additional opportunities and policy windows to catalyze new and larger scale climate action. Hurricane Irene struck the metropolitan region in late August 2011. Local officials and other stakeholders

broadly described it as another focusing event for putting extreme event resiliency planning proposals into practice. Hurricane Irene resulted in extensive flooding in distant suburban and exurban areas north and west of the city, and resulted in only slight storm surge flooding in the city itself. It caused approximately \$65 million of damage for the MTA and, most important, the loss of a section of commuter train to rain-induced railway bed washout.<sup>30</sup> Fourteen months after Irene, Hurricane Sandy hit the metropolitan region, causing catastrophic damage, the most significant of which came from record storm surge and coastal flooding. In the aftermath of Hurricane Sandy, former Mayor Bloomberg created the Special Initiative for Rebuilding and Resilience (SIRR) and reconvened the New York City Climate Change Adaptation Taskforce.

Hurricane Sandy dealt New York's transit system a massive blow, resulting in approximately \$4.75 billion of damage.<sup>31</sup> As projected in earlier assessment reports, almost all of the major subway tunnels flooded because of the record storm surge. Other disruptions were present in the above-ground components of the system. Sandy made landfall on a Monday evening, and the majority of systems were shut down for the remainder of the workweek (see Figure 6). The recovery process included pumping storm surge out of the tunnels and checking all the equipment. Loss and damage were significantly less than they could have been because the entire transit system was closed well in advance of the storm's full impact, and mobile assets such as subway cars and buses were relocated to higher elevation sites away from storm surge zones.

The SIRR focused on assessing the damage from Sandy, understanding how future climate change might influence the level of coastal risk, and promoting resiliency efforts in neighborhoods most at risk of current and future flooding. The SIRR released its report in June 2013, and the NPCC released its climate projection updates at the same time. Similar to the two previous PlaNYC documents, the SIRR report highlighted dozens of new initiatives and actions designed to reduce vulnerabilities, aid in rebuilding, and institutionalize resiliency practice. The SIRR only focused indirectly on the Metropolitan Transit Authority infrastructure and systems because of how the federal recovery money was to be allocated. Funding would be provided to the City of New York and the State of New York, as well as other states. SIRR was directed at wholly city-owned/housed infrastructure, of which the MTA is not included. In the months that followed Hurricane Sandy, the MTA created its own climate change taskforce to address the broader management, planning and operational issues associated with climate risk and resiliency.

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<sup>30</sup> MTA 2012

<sup>31</sup> MTA 2013

