MTA Adaptations to Climate Change

A Categorical Imperative.

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Metropolitan Transportation Authority *Going your way*

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"Act only according to that maxim
by which you can at the same time will that it should become a universal law".
Immanuel Kant, 1724-1804

I: Introduction and Overview of Adaptation and Climate Risk Management

For organizations to survive, flourish and deliver public services, they must adapt to changing conditions and demands. Climate change is such a demand. Already it has impacted MTA facilities and operations, and will do more so during this century and beyond. *The climate-induced change of the physical environment necessitates that MTA find an effective way to adapt its infrastructure, operations, and policies.* This chapter provides a risk-based framework for adaptations to climate change. A risk-based, systematic approach to adaptation is important *now* because of the long lifetimes of urban infrastructure, long planning horizons, and the significant social, economic, and environmental risks faced by urban coastal areas already. New Orleans and hurricane *Katrina* are an extreme case in a special location far from the MTA service area, but they can serve as a wake-up call: lack of preventive action in the face of known threats can lead to unacceptable losses and outcomes. But not just such extreme events need attention. More frequent seemingly lesser events cause considerable disruptions and losses, as demonstrated by the modest storm of Aug 8, 2007 (MTA 2007). It severely disrupted much of the region's mass transit. In addition, MTA facilities face a long-term threat from rising sea levels and higher storm surges.

Adaptation measures fall into different categories, and may follow distinct timelines and decision paths: first, a general *adaptation policy* needs to be adopted to guide the MTA leadership and MTA agencies in their adaptation efforts. It should include the mandate to develop a set of general *performance standards* for its facilities and operations vis-à-vis climate change; the *implementation* of these policies will require, in turn, agency-wide *vulnerability assessments* of the MTA's physical assets and operations; an *engineering-based feasibility assessment of remediation options* with estimates of the economic, environmental, and social costs and benefits associated with the various risk reduction measures; MTA actions may require extensive *cooperation and integration* with other stakeholders, agencies, governments, communities and planning organizations.

These emerging adaptation plans will need to be fully integrated into the *fiscal planning* process, including preparation of long-range *capital spending plans.*

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[2] This draft was written by Klaus Jacob (Lamont-Doherty Earth Observatory), and Cynthia Rosenzweig, Radley Horton, David Major and Vivien Gornitz (Center for Climate Systems Research, Columbia University). The intent of this "white paper" is to be excerpted for, and referenced as a website/hyperlink by the Adaptation Chapter of the 2009 Final Report of the MTA Blue Ribbon Commission on Sustainability (BRCS). This version has not been reviewed by BRCS or MTA. It may contain factual errors and omissions, and may present views not necessarily shared by MTA or BRCS.

The planning process will need to develop solutions for *different time horizons*: a *short-term* horizon for the next decade or less; a *mid-range* horizon of several decades; and a *long-range* preview on the order of a century or even longer. Such long time horizons typically apply to long-lasting infrastructure (e.g. bridges, tunnels, rights-of-way). On these longer time scales some climate-change-related threats (e.g. sea level rise and related storm surge inundations) could become severe and may require much more broadly based (regional, multi-agency) land-use and urban planning solutions than the shorter time horizon's tasks demand. The *National Academies* (2008) have issued a report that outlines a framework for climate change adaptation specifically aimed at the transportation sector. It provides valuable information and generic guidance.

Some major regional adaptation measures (e.g. whether to consider *regional* storm barrier systems or not) constitute substantial policy issues that will require full coordination and joint actions with many levels of government and with stakeholders in the public and private sector, since larger and very fundamental social, economic and environmental issues related to land-use, urban planning and sustainability of entire communities and their livelihoods are at stake, if not those of the entire City *and* metropolitan region.

Climate risks to coastal urban areas largely stem from *temperature* rise, changes in *precipitation*, and *sea level rise* (SLR) and consequent higher storm surges. They manifest themselves by the *frequency, intensity and duration of extreme events* including heat waves, droughts, river and street flooding, and storm- and sea-level-rise-induced coastal flooding. Some of the MTA systems are more vulnerable than others: low-lying fixed structures such as below-sea-level road- or subway-tunnels, or near-sea-level railroad tracks, rail yards and shops are more prone to coastal and urban street flooding than bus routes that can be readily rerouted on short notice according to flood conditions.

In planning for adaptation, it is important to recognize that there is no "one size fits all" approach. For given expectations about climate change, different adaptations are appropriate for different types of facilities and their different life spans or criticalities. Rail yards, for example, may need hard protection against rising sea levels and storm surges, whereas other facilities, such as recreation areas, open space, and parking lots, can be allowed to flood temporarily at acceptable frequencies. A facility that will last for 20 years may not require significant adaptation now, whereas a substantial transportation facility with a lifetime of 100+ years and tied to a given right of way will require important adaptation elements with a well planned schedule. The timing of adaptations will differ according to rehabilitation and replacement cycles in addition to magnitude of risk exposure as, in general, adaptations to climate hazards are less expensive when undertaken as part of otherwise needed rehabilitation, replacement, or expansions.

The most challenging decisions may be those where MTA programs are tied to landuse-, community-, urban and regional planning that at some point in time may require the abandonment of land, real estate, or rights of way used for generations, or may need radical and expensive measures to raise or otherwise protect the infrastructure and/or communities from the risk of rising waters. As the last resort, options may include relocation and may require new rights-of-way at safer elevations.

This Adaptation Chapter expands on these general ideas as they apply to MTA facilities, operations, capital planning procedures, and related policies.

II: Steps in Adaptation Assessment

In order to effectively integrate climate change adaptation into MTA programs, it is helpful to follow some logical steps for analysis, planning and implementation. This section outlines these steps and elaborates some in more detail.

Identify MTA facilities and programs subject to climate risk

This step requires first a suitable inventory of MTA facilities and operations in relation to climate risk. The clearest need for such an inventory is for the physical infrastructure, although policy, management and institutional issues also need to be examined. Normally, infrastructure has not in the past been inventoried in ways that are suitable for climate risk management. Infrastructure is often not consistently identified by parameters (height above mean sea level and storm surge records, distance from shore, expected lifetime, rehabilitation cycle) relevant to climate change. Such an inventory is an essential starting point for the identification of MTA facilities and programs subject to climate risk. Special attention should be paid to the possibility of synergistic interaction between climate risks; for example, flooding of low-lying areas can be due to the combined effects of rainfall and storm surge.

Identify main climate change impacts to MTA facilities and programs

A substantial amount of work has been done on this step in the NYC Metro Area (Rosenzweig and Solecki, 2001; NYCDEP, 2008; MTA, 2007), and the main climate change impacts have been identified. The main climate changes posing risks to MTA facilities will be from: temperature rise (especially number of extreme hot days), changes in precipitation (frequency of intense precipitation), sea level rise, and coastal storm surge. The risks will be realized by changes in the frequency, intensity and duration of extreme events including heat waves, droughts, inland and coastal flooding, saltwater intrusion, and the effects of heat and humidity on people (customers and workforce), buildings and materials. Each of these risks needs to be related to the inventory of facilities and their operations. Not all risks will increase: the number of extreme snowstorms or cold spells may gradually reduce as the climate warms.

Apply future climate change scenarios by time slice

Climate scenarios for the NYC Metro region, applicable to the area in which MTA operates, have been increasingly refined and improved since the late 1990s (Rosenzweig and Solecki, 2001; MTA 2007; Rosenzweig et al. 2007a, 2007b; NYCDEP 2008).

Model-based climate projections for the region are derived from global climate model simulations forced with internationally agreed upon green house gas emissions scenarios (IPCC, 2000). Using a suite of models and emissions scenarios allows characterization of uncertainties and risks associated with climate change. The most up to date assessments, to be used with the PlaNYC study, include 16 global climate models (GCMs) and three emissions scenarios, providing 48 scenarios that characterize the distribution and range of climate projections. These scenarios provide a scientific base and input for developing climate protection levels for agencies such as MTA; the proposed scenarios are applied by time slice (2020s, 2050s, 2080s) and may be interpolated as appropriate for agency planning procedures and capital cycles. The authoritative document succinctly describing the basics of climate change science, and recent *global* trends and projections, is the IPCC AR4 Summary for Policymakers (IPCC, 2007a). The technical details are in the IPCC Synthesis Report (IPCC, 2007b). These consensus documents provide much of the scientific framework and will be generally used to develop *local* applications with one prominent exception: for sea-level rise projections subsequent new scientific evidence has been rapidly forthcoming and requires special consideration to be discussed below.

Characterize adaptation options

As noted above, there is a wide range of potential adaptations available for the management of risks from climate change in urban areas. Adaptations include *management and operations adaptations*, options for *infrastructure investment*s, and *policy change*. It should be noted that many adaptations fall into multiple categories. The process of developing adaptation strategies for transportation agencies has been reviewed with a national scope by the National Academies (2008); basic climate change facts and basic adaptation strategies for the NYC metro area are described in Rosenzweig and Solecki (2001); Hansler and Major (1999), Jacob et al. (2007), MTA (2007), and NYCDEP (2008). Regional information for the northeastern US and adaptation advice has also been provided by NECIA (2006, 2007).

Examples of *management and operations adaptations* likely to be undertaken by MTA include revised emergency procedures for rail operations and equipment safety during anticipated floods, and review of its insurance policies vis-à-vis climate change impacts and risks. *Infrastructure adaptations* may include improved drainage (MTA 2007) and flood barriers for rail yards and other infrastructure. *Policy adaptations* include working together in a more consistent fashion with other agencies and jurisdictions, such as agencies responsible for assets that affect runoff from heavy rains into MTA facilities. These and other adaptations are further discussed.

Conduct initial feasibility screening

In this step, after the risks from climate change to MTA facilities are quantified, planners and engineers review a range of options relating to specific facilities in order to choose those measures which appear to be feasible and sustainable in technical, financial and policy terms, and by timing. An example of an adaptation that might be screened out is flood protection work that is excessively expensive compared to alternatives such as raising facilities, relocation or operational changes. However, it is important in this step to be more, rather than less, inclusive in providing alternative options, as feasibility criteria can change within the time span of adaptation planning. This feasibility must include time-dependent decision pathways and must consider not only initial capital spending, but also maintenance and upgrading costs over much of the life cycle of the proposed solution. The solution(s) must be dynamically upgradeable to the varying demands imposed by accelerating climate change. What may seem for some time a highly cost effective solution, can at a later time or during the most extreme events contribute to rather catastrophic outcomes. Using again *Katrina* and New Orleans as an extreme example from elsewhere: the levees and pumping systems designed as protection for the city decades ago were not capable of dealing later on with an extreme (but anticipated) event in part because the new conditions, brought about by sea level rise and local delta subsidence not fully understood during the original design of these defenses, rendered them ineffective, partly amplified by lack of funds and political will to carry out overdue repairs and upgrades. The failure of the defenses under these circumstances turned into a weapon that hit the largely defenseless *and* unprepared city and caused unmitigated losses. An adaptation strategy based on *probabilistic risk assessment* for multiple time horizons is highly recommended to help find optimal and sustainable decision paths that meet the agreed-upon safety levels, yet at affordable and sustainable costs, and find public approval.

Link to capital replacement and rehabilitation cycles

A survey of capital replacement and rehabilitation cycles for MTA infrastructure should be made, to which the pre-screened adaptation alternatives can be linked in the evaluation processes that comprise the next step.

Evaluate options: benefit/cost analysis, environmental impacts

Potential climate change adaptations can be assessed by their relevance in terms of climate change time frame (immediate, medium, and long-term), the capital cycle, costs, and other impacts. Evaluation should take into account changes that occur over time (such as population growth and changes in per capita use of public transportation) irrespective of climate change. Potential adaptations are designed to manage the risks of climate change to infrastructure, providing an overall coping strategy (Ayers et al. 2003) for the agency. Evaluation is based on standard planning procedures (Goodman et al., 1984; Orth and Yoe, 1997; Yeo and Neumann, 1997), with the significant addition of climate change, agency planning lags, and an explicit link to agency capital cycles to provide for efficient incorporation of adaptations during rehabilitation and replacement. Among the important innovations in evaluation of adaptations for climate change is optimal scheduling—whether implementation at an early period (during rehabilitation, for example) is more efficient than postponement, with increased risks but increased savings in discounted capital outlay.

Develop implementation plans, including timeframes for implementation

This step is the culmination of the previous steps. Specific adaptation measures are selected, engineered, scheduled, and integrated into the MTA capital budgets to be finally implemented. This element of the risk management framework provides decision-makers with plans for proposed capital expenditures over different time horizons some of which may be much longer than the typical agency capital planning cycle. This will require some modifications in MTA planning and implementation procedures, since potentially highly dynamic environmental processes will affect the capital budget.

Monitor and reassess adaptation strategies according to unfolding of climate change and developments in climate science

For all adaptation work, it will be necessary to monitor parameters of climate change, to consider new projections, to re-evaluate adaptations by assessing their effectiveness, and to incorporate new insights into future work. An important element of this step is the use of indicators (Clean Air et al., 2005; Lemmen and Warren, 2005) that can be tracked to assess and monitor the need for, as well as the performance of, specified adaptations. Indicators can be direct climate model outputs, data derived from model outputs, or data series from other sources; developing an appropriate set of indicators must be an important element of MTA's climate adaptation work.

Climate Related Insurance Issues

One common risk management tool not relying on operational, engineering, or landuse options is to buy insurance for partial or full coverage of risks. The MTA has an ongoing centralized insurance program that covers for all its agencies (to various degrees) the physical assets, operational income losses from business interruptions, and ordinary liabilities. This innovative program is a mixture of self-insurance and coverage by outside insurers/reinsurers. MTA losses related to climate change, whether insured or not, can be expected to rise with time unless engineered and operational prevention measures keep them in check.

The MTA asset portfolio is concentrated in a single metropolitan region. For this reason, losses across the combined MTA assets are likely to be highly correlated (a single hurricane may affect all MTA agencies at the same time). Hence self-insurance may not remain effective for climate-related events. At the same time the price of covering the respective risks by outside insurers is likely to rise or may become unavailable as outside insurers tend to be quite aware of the increased risks from climate change. The MTA therefore may want to carefully balance its reliance on insurance vs. investing into measures that make its assets and income streams less vulnerable to, and more resilient against climate change hazards, and therefore minimize climate-induced losses in the first place. Insurers may take on a portion of the remaining risks more readily if the MTA sets high resilience and performance standards able to cope with most future climate conditions. Layering of insurance, with the lower-end losses covered by self-insurance or deductibles, and higher end losses covered by outside insurance or catastrophic bonds are options to be considered. Close cooperation between insured and insurers may find mutually acceptable optimum solutions; alternatively, new mutual or other insurance tools not limited to a single metropolitan region may have to be devised, possibly with federal facilitation, in which the MTA participates in a larger, geographically dispersed portfolio. This would allow sharing the risks with other agencies elsewhere to reduce the likelihood of correlated losses across the larger, dispersed portfolio.

III. Climate Change Scenarios and Challenges.

The primary challenges from climate change to the MTA facilities and operations stem largely from temperature, precipitation, and sea-level rise combined with coastal storm surges. Many of these climatic features were recently addressed in the August 8, 2007 storm report (MTA, 2007). Other sources for regionalized climate change projections are found in NYCDEP (2008), NECIA (2006, 2007), and the landmark study known as Metro-East Coast (MEC) climate change impact study (Rosenzweig and Solecki, 2001). Using a variety of climate models and multiple emission scenarios, all forecast climate parameters have a distribution rather than single values. This report does not reiterate the details of these climate forecasts, many of which were provided for *local* conditions by Columbia University's Center for Climate Systems Research and cooperating affiliates (see e.g. Rosenzweig and Solecki, 2001; MTA, 2007; NYCDEP, 2008). Instead we present here overall results illustrated by a few key examples. Readers with the need for more technical details should consult these reports, many of which are readily accessible via Internet links (see the Chapter's Reference Section).

Many of the forecasts are made for multiple time horizons: short-range (typically for the 2020's), mid-range (2050's), and longer-term (2080's or the end of this century). Sometimes qualitative comments for even longer time frames are mentioned where absolutely necessary, although climate information for such long time frames is so uncertain (partly because of the unknown future emission scenarios) that they have only conceptual or strategic value, rather than being useful for specific engineered solutions.

Selected key features of some of the climate forecasts for the region are:

- <u>Increased Annual Average Temperatures:</u> modeling yields temperatures rising over a wide range (for the 2080s, as an example) of 2 to 10ºF, with the majority of forecasts clustered around 4 and 7ºF (CCSR in MTA, 2007).

- <u>A Marked Increase in Hot Days:</u> for instance, by the end of the century, New York City can expect up to 38 days per year over 90ºF under a lower-emissions scenario, and up to 70 days per year under the higher-emissions scenario, up from about 17 such days per year at the end of past century **(Figure 1).** Moreover, before the 1990's New York City experienced on average one or two days per summer over 100ºF. This number could increase by the late century up to eight days under lower emissions and up to 28 days under higher emissions (NECIA, 2006).

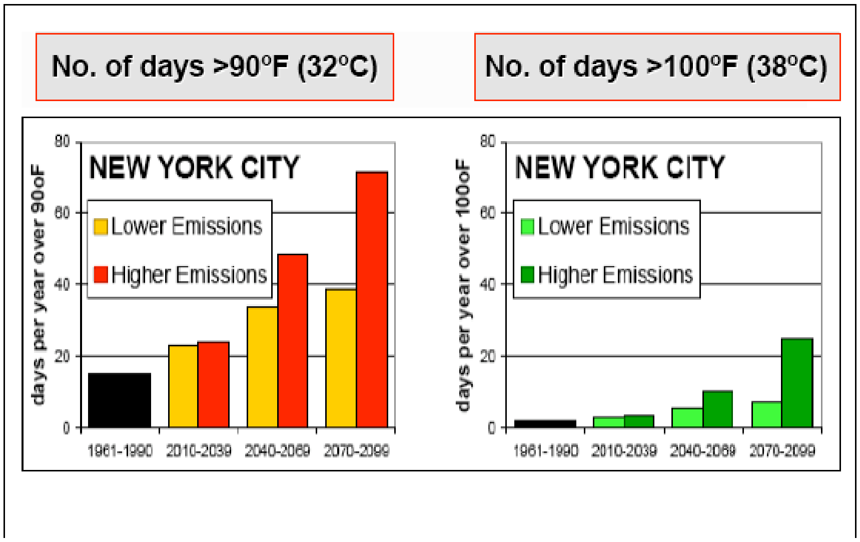

Figure 1. Forecast of number of days/year in New York City with temperatures exceeding 90ºF (left) and 100ºF (right) for different decadal periods, and for two green house gas emissions scenarios. The black bar represents observed occurrences prior to 1990. (Source: NECIA, 2006)

- Increased Annual Average Precipitation: No clear trend exists prior to the 2050s but a clearer pattern emerges from then on with 70% of the models producing projected precipitation increases of between 5 and 15% (CCSR in MTA, 2007)

- Seasonal Precipitation Patterns: Winter precipitation (in the form of both snow and rain falling in winter months) has been increasing over the past few decades, and is projected to continue increasing, with slightly larger changes under the higher-emission scenario than the lower- emission scenario. Little change is expected in summer rainfall, although projections are highly variable (NECIA, 2006)

- Extreme Precipitation and Storms: The frequency of heavy rainfall events is increasing across the Northeast. Under both low and high emission scenarios, rainfall is expected to become more intense. In addition, periods of heavy rainfall are expected to become more frequent. For instance, the number of days with rains exceeding 2 inches will increase by the end of this century by a factor of about 1.4 for the low emissions, and by a factor of about 1.8 for the high-emission scenario **(Figure 2).** Some East Coast winter storms (Nor'easters) are projected to shift from earlier to later in the winter season as temperatures rise, and more storms are expected to travel further up the coast and affect the Northeast (NECIA, 2006).

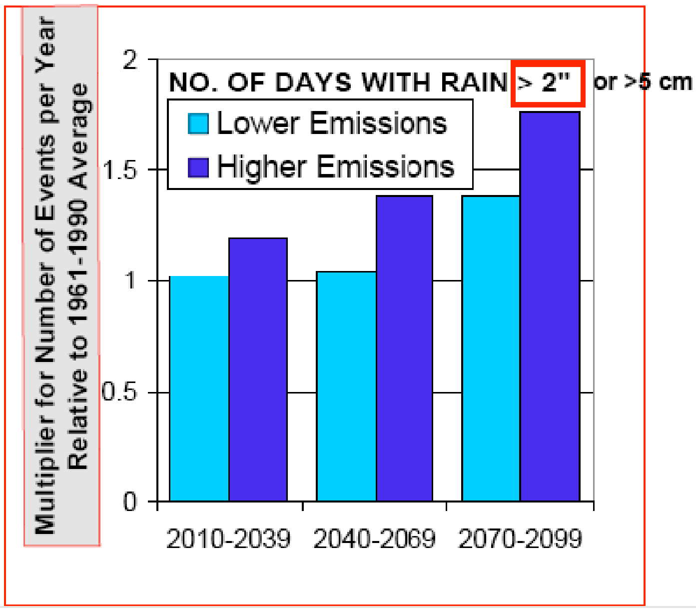

Figure 2. Multiplier for the forecast number of days per year with rains exceeding 2 inches/day, relative to the observed average during 1961 to 1990, for two emissions scenarios and for thee time periods (Source: NECIA, 2006).

Sea Level Rise (SLR) and Coastal Storm Surges.

The observed average rate of sea level rise during the last century for New York City (as measured at the Battery tide gauge), is 0.96 ft/century **(Figure 3).**

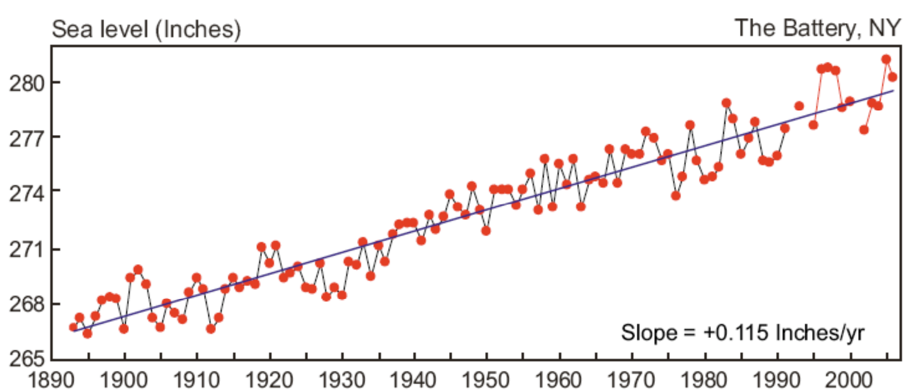

Figure 3. The observed averaged rate of local sea level rise for the past century in New York City measures approximately 1 ft/century (Source: CCSR, Columbia University).

Climate change is expected to increase this historically observed rate of local SLR. But by how much? And on what time scales? Because SLR, especially in combination with coastal storm surges, is such a critical climate variable for all land-based transportation near coasts, and because SLR is a challenging variable to project with a high degree of confidence, it deserves special attention. A range of factors operating over various time frames (from seasons to millennia) determine mean sea level in any given location. These factors include:

- Change in global mean sea level associated with expansion of ocean water as it warms;
- Change in global mean sea level associated with an increase in mass brought on by melting of land ice that makes its way to the oceans as water;
- Regional changes in ocean height caused by changes in winds and currents;
- Regional changes in coastal land elevation (i.e., subsidence or uplifting) due to geological factors; and
- Other factors including management of land-based water, e.g. depletion of aquifers not adequately recharged.

Of these factors, the geological changes in coastal land elevation occur essentially at a constant rate. At the other extreme, melting of land ice (largely in Greenland and West Antarctica) has the potential to accelerate rates of SLR dramatically over the course of the 21st century and beyond. The dynamic processes causing the recently observed accelerated collapse of some of the Earth's major land-based ice masses are currently not well understood but are being intensely studied. Given these uncertainties, a range of rates of SLR for the twenty-first century has been estimated. The Intergovernmental Panel on Climate Change (IPCC) emphasized elements that can be modeled more readily (e.g. ocean expansion), but it introduced only a small factor to represent ice melt over land (IPCC, 2007b). **Figure 4** shows the sea-level rise projections for the New York Metropolitan Region for the 21st century, based on this IPCC approach.

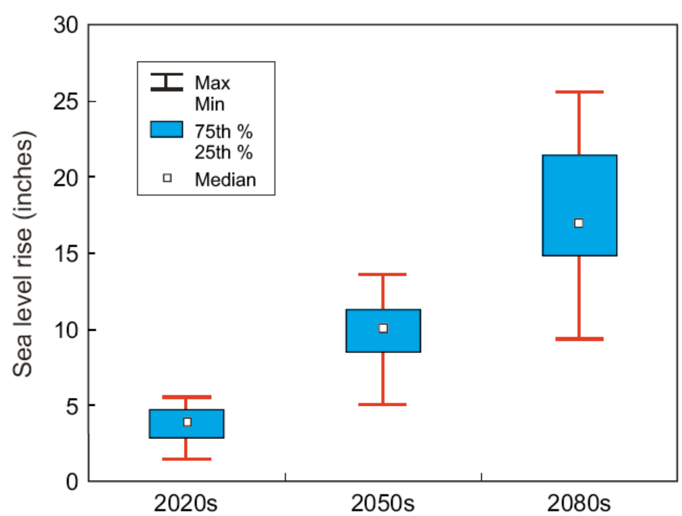

Figure 4. Range of *local* SLR forecasts for New York City based on *global* IPCC (2007) SLR models that do *not*, however, fully account for dynamically accelerating melt rates and partial collapse of land-based ice sheets in Greenland and West Antarctic. See text for explanation (Source: CCSR, Columbia University).

By including into the IPCC approach a large number of global climate models and greenhouse gas emission scenarios, a model-based *probability distribution* of SLR forecasts has been generated **(Figure 4).** This distribution does not include, however, the full range of possible scenarios for dynamically accelerating melt rates of land-based ice.

For this study, and because new evidence for the accelerated melting of land-based ice has emerged since release of the IPCC 2007 report, new estimates of SLR rates applicable to NYC are made that account for new pertinent information. Higher estimates of SLR emerge from considering the periods in the Earth's past when rapid temperature changes have been found to accompany fast rising sea level (meters per century). A review of pertinent research and policy issues can be found, for example, in Hansen (2007) and Horton et al. (2008). These alternative approaches allow the currently relatively stable relationship between temperature and sea level to vary quite rapidly as ice responds dynamically to increasing temperatures. Continental *ice melt rates* have indeed increased in recent years, but seem to have failed so far to noticeably increase *SLR rates*. The concern is, however, that if the rate of collapse of ice sheets continues to accelerate, sea level rise could become extreme later this century and beyond. *One or even two meters of total SLR by 2100* cannot be ruled out, and can be used as a rough precautionary estimate, not as outcome with high probability of occurrence, but rather for long-term *planning high-end scenarios* for protection, and for developing flexible adaptation and decision pathways for this region.

Link between Sea Level Rise and Storm Surge Inundation Risks

SLR is an ongoing process, whose impact on coastal regions becomes progressively greater with time. SLR progressively amplifies inundations associated with *coastal storms* (i.e. hurricanes and nor'easter winter storms). Coastal storm surges with modeled heights that can reach tens of feet under current climate conditions **(Figure 5)** have the potential to affect large portions of New York City and the surrounding metropolitan region in the entire MTA service area. Even under the current climate conditions, such storms pose one of the most severe risks to New York City and surroundings with total loss potentials measuring in the tens to hundreds of billions of dollars for the metro region (Jacob et al., 2007). The MTA would incur a substantial percentage of these losses. However the associated risks, and magnitude and nature of losses to the MTA have not yet been assessed or quantified.

Storm inundations can give us today a preview (albeit amplified, reversible and only for the storm's duration) of what SLR will produce ever more irreversibly during decades and centuries to come. The coastal inundation flood risks are increasing because future storm surges will be *superimposed* on the ever-rising sea levels.

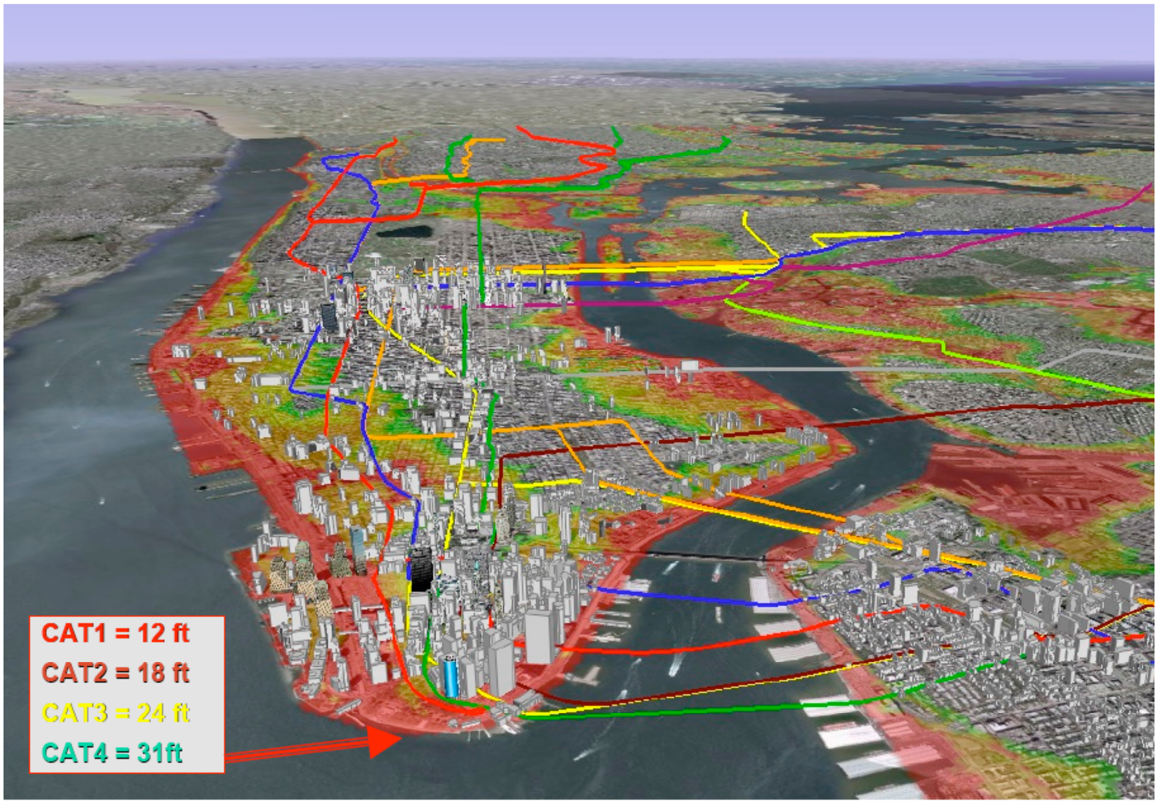

Figure 5. Bird's eye view of New York City with maximum reach of modeled storm surge inundations for hurricanes with Categories 1 (red), 2 (brown), 3 (yellow) and 4 (green), respectively, and for year 2000 sea levels. Predicted maximum model storm surge heights at the southern tip of Manhattan measure for the four storm categories: CAT 1 = 12 ft, CAT 2 = 18 ft, CAT 3 = 24 ft and CAT 4 = 31 ft. Many entrances and ventilation shafts and grates for the various MTA/NYCT subway lines (colored solid lines) that are at elevations at or below grade level in the inundated areas provide a pathway for the flood waters to enter the subway system with to date unassessed consequences. A number of other MTA facilities (not shown), including road tunnels and access ways to bridges, rail yards, shops and tracks, lie also in the outlined inundation zones. The reach of storm surge inundations will increase in accordance with future sea level rise. (Source: K. Jacob, Lamont-Doherty Earth Observatory of Columbia University).

Currently, a strong link between changes in *total number* of storms to climate change has not been proved; but there are some indications from recent research that the *strength* of storms may increase with warmer ocean surface temperature. Yet even without change in storm frequency or intensity, rising sea level alone means that if today's storm strengths were applied in the future, they will then cause greater coastal flooding damage, simply because mean ocean height is higher, i.e. coastal flooding increases in frequency and intensity just because of SLR alone. Probabilistic estimates show (Jacob et al., 2007) that by the end of this century the elevations now requiring a 100-year storm are likely to be reached by a weaker 10-year storm because its weaker surge is superimposed on a higher mean sea level. *This corresponds to a tenfold increase in the annual coastal flooding probability* (from about 1% to nearly 10% chance per year) at any given location or facility. Correspondingly, the 100-year coastal flood elevations will - more or less directly - rise by the amount of *local* sea-level rise.

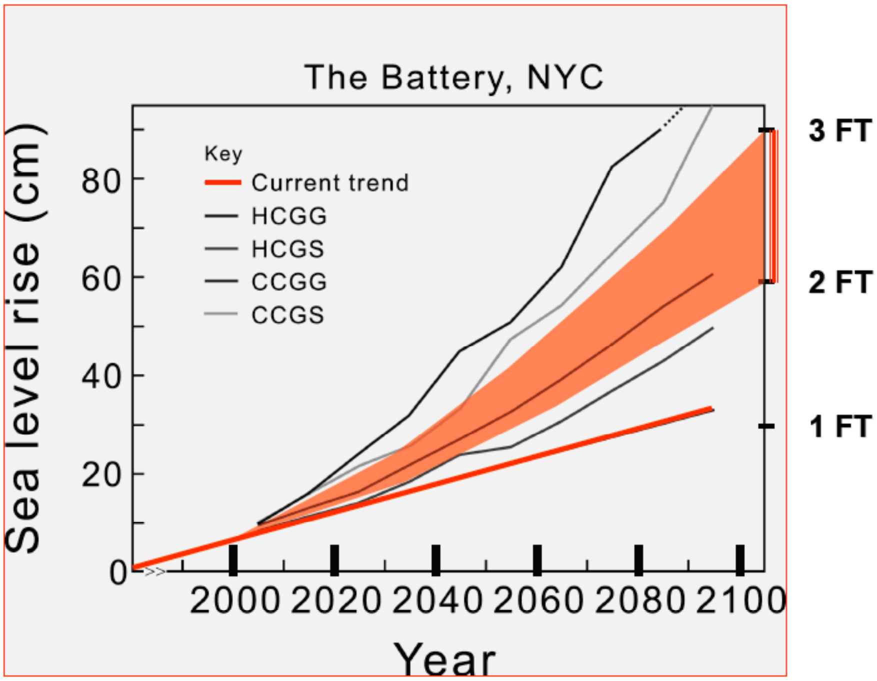

Figure 6. Range of projected *local* sea level rise for New York City as optional input for precautionary planning purposes. The *black and gray solid lines* represent projections for various atmospheric green house gas scenarios and climate models originally used in the MEC (2001) Report. The red solid line is the *observed* rate of SLR for the 20th century, extrapolated into the 21st century, merely for background information. A range of optional SLR planning scenarios during this century is shown as *orange band*. It implies as a *minimum* scenario 2 ft, and as *precautionary* target planning scenario 3 ft by the end of this century. Amounts of sea level rise *greater* than 3 ft per century are possible (see text), but their probability cannot be readily quantified at this time, and at the current state of science that is in very rapid flux. Therefore the planning projections will need periodic *updating* at intervals on the order of 5 to 10 years or less, especially when major science breakthroughs yield new and more reliable SLR information. Planners must note of course that sea level rise will *continue beyond this century*, and will likely do so at ever increasing rates for multiple centuries to come. (Source: Modified from Jacob et al, 2007).

A range of SLR scenarios should be used when precautionary planning and design purposes are discussed by the MTA with sister organizations. Such discussions should take advantage, and contribute to, the coordinating function to be offered by an adaptation task force created as part of PlaNYC (2007) under its climate adaptation goals. An example for a possible range of potential planning scenarios for such coordination efforts is shown in **Figure 6.** But it should be kept in mind that the design elevations chosen for a particular project may very well depend on a variety of considerations including its importance for the transportation system, expected life time or rehabilitation cycle, risk reducing capacity vs. cost to achieve benefits, and its flexibility to be adapted to future (but at this time uncertain) climate conditions.

Sea level rise and storm surges need to be considered together as a linked issue in future probabilistic risk assessments, and for the development of coastal adaptation and coping strategies.

This is an issue not to be confused with risks from often quite localized rainstorms that do *not* cause storm surges and coastal inundation, but rather tend to be destructive because of local high winds and heavy rains causing urban street flooding and impacting MTA facilities and operations. The wind- and rainstorm of August 8, 2007 is a vivid example of such localized storms not associated with a surge and coastal flooding, but instead with intense local winds and rainfall that tend to cause urban street flooding and disruption of MTA operations (MTA, 2007). Such local rainstorms are likely to also increase in frequency and intensity **(Figure 2),** and hence tend to increase the risks from climate change *in addition to increasing coastal flooding hazards*.

Multiple, time-dependent decision paths.

The need for time-dependent, staged yet flexible, risk- and cost/benefit-conscious, multiple decision pathways to manage adaptations to climate change has already

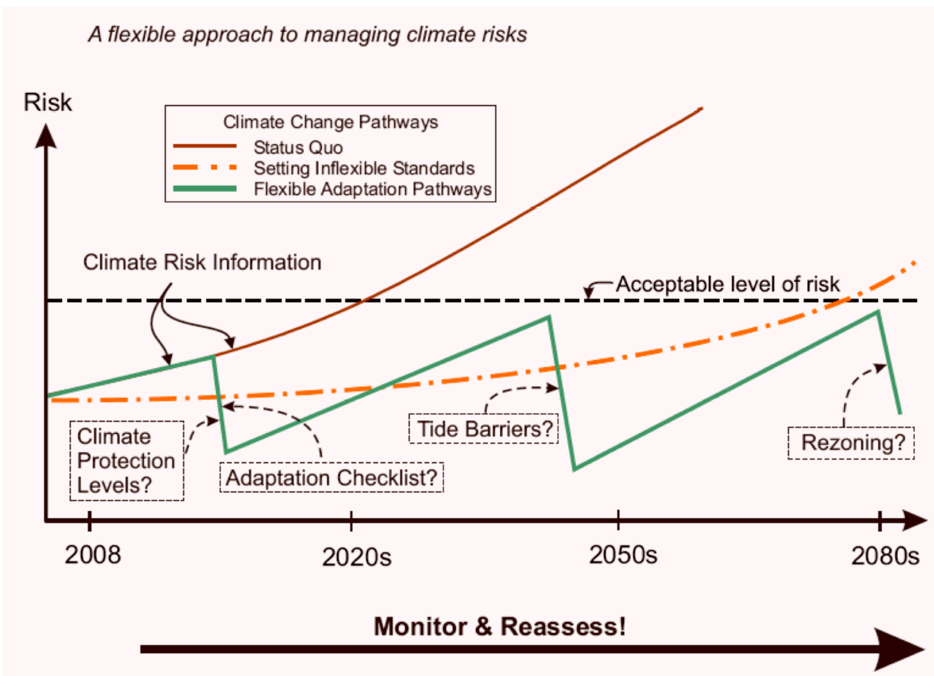

Figure 7. Generic illustration of flexibly staged, multiple decision paths for adaptation measures to manage rising risks related to climate change. Note that timing and actions are hypothetical examples only and do not imply recommendations for real actions. For details see text. (Source: CCSR of Columbia University)

been heavily emphasized throughout this Chapter. This is especially the case because many of the longer-term aspects of climate change are highly uncertain. But what does this approach actually mean? **Figure 7** illustrates in a generic way this approach, although the various timelines and sequences of depicted measures are only typical examples and do not mean to reflect necessarily the actual situation to be faced by MTA, nor the only adaptation steps to be undertaken, nor at the times indicated.

Actual adaptation pathways need to be mapped out by MTA in close coordination with many stakeholders and jurisdictions in the NYC metro region, based on risk assessment and feasibility-, engineering and financial studies that need to be performed at various degrees of detail commensurate with the importance of the issues at stake.

IV. Key Vulnerabilities of MTA Assets and Operations.

At this time a systematic assessment of the vulnerabilities to climate change of MTA's assets, operations and financial health does not exist. An initial survey of some of the most glaring vulnerabilities of selected MTA facilities and operations was provided in the aftermath of the August 8, 2007 storm (MTA 2007). Earlier broad regional, but not MTA-specific assessments were made by the MEC study (Rosenzweig and Solecki, 2001) and Jacob et al. (2007). The absence of a *systematic and quantitative assessment* of MTA's vulnerabilities to varying current and future climate conditions using proven engineering and risk management methods is a deficiency that needs to be rectified as soon as possible. This mandate applies to many other transportation organizations, owners of infrastructure and operators of many utilities and services, and the public and private sector at large, whether for the New York City metro region, or the nation as a whole. But MTA should assume leadership and set an example for achieving effective adaptation since its viability to serve the nation's largest and most populous urban region under changed climate conditions is central to the sustainable functioning and the economic and social heartbeat of the entire region.

The Commission sought, without investing in an extended and costly study, at least a cursory listing of the key vulnerabilities of MTA's facilities and operations. Input was provided on an *ad hoc* basis (without the normally required engineering rigor) by the various MTA operational agencies and affiliates, and from centralized management. The current and anticipated impacts for key climate parameters, and for the key operational units, insofar as they could be ascertained on this *ad hoc* basis, are summarized below. This summary obviously does not replace the need for future thorough engineering and management assessments of these issues. *Rather it strongly indicates that such vulnerability assessments must be a high-priority undertaking* as part of MTA's mission to adapt to, and manage the risks associated with climate change, and thus strive for true sustainability even under changed climate conditions.

We first list key vulnerabilities grouped by agency, then summarize them by type of climate hazards, and then revisit them in the context of the Commission's major Working Groups for their cross-cutting implications.

Vulnerabilities and Challenges by Agency:

<u>MTA New York City Transit (NYCT)</u>.
NYCT operates mass transit in New York City by rail and bus operations. With respect to climate change they have quite different vulnerabilities. Some are in common, but many of them quite different.

NYCT Subway and Staten Island Railway: NYCT operates some 228 route miles of 'subway' in Manhattan, the Bronx, Queens, and Brooklyn of which about 60% are below-grade in tunnels, about 30% mostly on elevated tracks; and 10% at grade. NYCT also operates the (entirely *at grade* but road-crossing-free) Staten Island Railway (SIR, 14 miles); it remains unconnected to the subway system, except by transfer via the Staten Island Ferry (operated by NYC), and via NYCT bus services from Brooklyn across the Verrazano-Narrows Bridge. The total replacement value of the NYCT tunnel-, elevated- and roadbed route structures (excluding stations) is on the order of $190 Billion (all values in 2006 dollars). The length of *rail tracks* along the 288 route miles is about 628 miles at a value of about $11 Billion. There are nearly 300 pump stations, nearly 200 fan plants, and more than 200 electric substations, with a combined asset value of about $22 Billion. There are nearly 280 underground stations ($11 B) and more than 200 Elevated Stations ($5 B) plus some 20 "mega structures" (e.g. Times Square, or Grand Central Terminal) that serve multiple subway lines and other interconnections. In addition there is the rolling stock worth nearly $11 Billion. Then there are rail yards and maintenance shops.

These assets are exposed and vulnerable to various degrees (that remain largely undocumented) to the following climate stressors with which they and their operations have to cope:

- Extreme hot/humid and cold days,
- Extreme precipitation in form of rain, snow and ice and as run-off from streets;
- In addition to water from street run-off and underground seepage, there is the risk from coastal storm surge inundation of subway tunnels and stations;
- Weather related (including heat wave induced) power failures can knock out power supply at some substations and route segments, or in the worst case, for the entire system;
- High winds and ice/snow condition can affect the elevated operations;
- During coastal storm surges (hurricanes or extreme nor'easter winter storms coinciding with high tides) the entire rolling stock has to be moved and parked at sufficiently high and safe elevations, but preferably in tunnels so as to avoid wind damage (precautionary operational plans for this exist, but are complicated in their timing by the fact that NYC's Office of Emergency Management's [OEM's] hurricane emergency evacuation procedures in coastal storm-surge-prone neighborhoods depends to a high degree on public transportation / mass transit in the hours proceeding the storm's arrival). Here are some of the lowest critical elevations (LCEs) of NYCT subway lines where operations will be jeopardized, should coastal flooding reach these elevations (measured in ft above the National Geodetic Vertical Datum of 1929 – NGVD'29 - ; see Jacob, 2000):

NYC Transit Auth. - Subways	Lowest Elevation
A & C Lines	7.0
M, N & R Lines	7.5
World Trade Center	8.1
1 & 9 Lines	9.1
2 & 3 Lines	9.1
4,5 & 6 Lines	9.9
E & F Lines	10.0
B & Q Lines	12.7

The most common weather related stresses experienced in the last few decades (see also MTA, 2007) have been: excessive water in some subway tunnels and stations often from street run-off via open ventilation grates and station entrances. This influx at excessive rates tends to overwhelm the installed pumping capacity at certain locations.

Temporary fixes are:

- Raising curbs at ventilation grates and subway entrances sufficiently high above grade and/or street level to reduce water influx;
- Increasing the fixed pumping station capacity;
- Sealing tunnel walls, ceilings and floors more efficiently to reduce seepage from ambient ground water. Ground water has been rising in many parts of the City during the last century; it will rise more with SLR, and could become also more saline in some areas causing accelerated corrosion.
- Providing mobile pumping capacity before and during extreme events, preferably as *precautionary stand-by measures* at the known most vulnerable locations.
- Preventive interaction and coordination with New York City Department of Environmental Protection to increase *storm sewer capacity*, and channel effectively the disposal of the pumped excess water from the tunnels during emergencies;
- Department of Sanitation for street cleaning *before* imminent storms to minimize clogging of storm sewers at the street level;
- Department of Highways to adjust some street grades and slopes to minimize excessive runoff, and/or encourage permeable surfacing of the most flood prone road ways and parking lots; and last but not least with the
- Department of Buildings to modify building codes and other regulations or provide incentives, all to minimize run-off from building roofs and other surfaces possibly including facades and parking facilities.

Subsets of preventive measures are already undertaken by the MTA, especially where actions do not require much interaction and coordination with one or more external agencies. Staff suggested that subway lines in areas not threatened by inundation and flooding could be prepared to operate as segmented flood-uninterruptible services, during storm emergencies, even if other segments are non functional; this is an option to be further explored.

Options for mid-to-longer-term solutions for reducing the climate related vulnerabilities of the NYCT subway systems may include:

- Investigating the feasibility and costs (and then implementing where possible) for entirely eliminating the "open access" of tunnels via street-level ventilation grates and subway entrances, at least in service areas with high flood potential (from local street flooding, and coastal storm surges);
- The aim would be to go to a partially "closed system", with all the consequences for air venting and temperature/humidity conditioning this would require;
- While solutions for closing the grates permanently in inundation prone areas may be technically possible, this would be unlikely to be the case *for subway entrances*. For these, options may have to be considered how (and where) to install effective floodgates or other devices (high-pressure inflatable plugs?) that would be closed *only shortly before and during* the times when expected or actual flood heights exceed the entrance curb elevations.
- Such measures would serve to at least greatly reduce, if not prevent, large amounts of water flooding the subway system, thereby reducing the time for pumping, repairs and restoring services.

More radical regional and *long-term* solutions should be explored for their feasibility and cost effectiveness to serve adaptation to climate change:

- Included into these fundamental adaptation options should be any *new and newly planned* subway structures and route expansions (e.g. all the potentially flood prone portions of the 2nd Avenue line; the #7-subway line extension to the Hudson Yards; the new Fulton Street Center, and Staten Ferry Island subway station).
- Such future long-term investments should be innovatively engineered and/or the uncompleted project phases modified to set the tone as to how MTA will envision making in the long run its *entire* subway system optimally resilient to the combined storm-surge and sea-level-rise risks.
- Close cooperation will be required with NYC, and with other MTA and non-MTA regional transportation agencies, especially where transfer connections exist or new ones are planned to facilities operated by these other agencies, e.g. at the World Trade Center transportation hub (PANYNJ PATH), the old and new ARC/Penn station (PANYNJ and NJTransit, Amtrak), and the East Side Access project beneath Grand Central Terminal.
- Some options may include in selected, inundation-prone areas the *routing above street and/or foreseeable inundation elevations*. This option still could be explored for the outstanding Downtown phases for the new 2nd Ave line.
- Seriously considering and evaluating the *'pros and cons'* (regarding potential catastrophic risks *a la 'Katrina'*, see earlier sections) of constructing three or four storm barriers at key entrances to the entire NY/NJ Harbor and Hudson/East River Estuary. Storm barrier solutions have been, or are being implemented in the Netherlands, London (UK), Venice (Italy), St. Petersburg (Russia) and other places; barrier options were proposed for feasibility consideration by a research

group from SUNY Stony Brook (Bowman et al., 2004, 2005, 2008; Colle et al., 2008; Hill, 2008; SUNYSB 2008); they may be attractive as an interims solution, but not as a sustainable solution since storm barriers become eventually ineffective against SLR. For a discussion of risks and benefits associated with barriers for NYC see, for instance, Jacob et al. (2007).

- No clear upper limits can be established for rates of sea level rise, and at what elevations sea level may begin to stabilize (depending on the global carbon output and ability to curb global warming). Therefore it is likely that storm barriers as currently conceptually proposed could serve the City only for a limited time (and even then could give rise to catastrophic failure a la New Orleans, for near and below sea-level assets). Therefore the MTA in conjunction with New York City, and regional and national planners may want to think *now*, at least conceptually, about the kind of a world New Yorkers would want to live in at such times of raised seas and receded shorelines; and may want to make investments today, and in the next few centuries, that at least admit that such a world is possible; planners must devise strategies how to ever more systematically avoid investments in infrastructure and landuse patterns that almost certainly will have to be abandoned at a later time. Such visionary long-term thinking may actually provide opportunities for urban renewal that otherwise would not be thought of at this time; and certainly future generations of New Yorkers would very much appreciate such foresight – if this generation can muster the courage to think the almost unthinkable. If a subway were to exist in such a *"new New York",* it cannot look anything like our open access system now, nor of course would the rest of new New-York look as it does today, especially along its water front and vis-à-vis its subterranean maze of infrastructure. An old saying states: *only when it gets dark can you see the stars very cl*early. If not us, then our grandchildren's grandchildren, will have to learn to scan the sky for clear stars, for new ideas, in order for a new New York to function and flourish, all on solid ground. Or will floating cities become the norm?

Back to the present realities. Obviously any broad, fundamental, and hence probably costly adaptation solutions need wide public support, require intricate environmental and urban planning/landuse and community issues to be resolved; and for these reasons alone, apart from financial issues, they would need long lead times before they could be analyzed, planned, publicly accepted, designed, financed, implemented and then maintained in a sustainable way in the face of changing and often poorly predictable future climate and political/economic environment.

Engineering staff in the NYCT is aware of some of the listed fundamental risks and, to a lesser degree, of related adaptation options. But no agency and system-wide climate risk assessment plan is currently available, nor had it been contemplated.

A full climate risk assessment is urgently needed for the NYCT subway system and must have a high priority within a comprehensive, MTA-wide climate risk assessment and adaptation effort, involving all MTA member agencies.

Because the NYCT subway system has such a large portion of its costly assets at or below sea level, and is the backbone and lifeline for NYC's mass transit, *NYCT Subways* is the MTA agency most vulnerable not only from occasional flooding in the short run, but is quite fundamentally threatened in the long-run by the combination of sea level rise and storm surges. Many of its rail yards and maintenance shops are also located in potential high-risk flood zones.

All MTA adaptation measures for the subway system must increase the system's resilience against the *already currently existing risks from hurricanes and nor'easter storms*, which are steadily increasing because of sea level rise, as discussed in this chapter and at greater detail earlier for the entire metro region's transportation infrastructure (Jacob et al., 2000) as part of the broader Metro East Coast (MEC) study (Rosenzweig and Solecki, 2001).

***NYCT Bus* Division:** *Asset- vs. Operational Vulnerabilities.* The *NYCT Bus* division faces different – and on balance more manageable – challenges from weather and climate related events and trends. Some of the challenges and adaptation options are:

- *Snow, snow-removal, ice and winter conditions* are obviously a problem that require operational adjustments and sometimes slow down, or can even totally disrupt temporarily some service operations. It may take up to 12 hours for *Bus* operations to fully recover from a snow/ice storm. *NYCT Bus* maintains its own snow emergency teams and some equipment. While winter precipitation is likely to increase in frequency and intensity, eventually during this century below-freezing conditions may be reduced as the regional climate warms, and heavy rains may increasingly replace heavy snowfalls.

- During extended *weather related power outages or brown-outs*, likely to be associated with excessive *heat waves or thunderstorms*, stand-by power must be provided at bus refueling stations; but failure of street signals can slow down general street traffic or bring it to a near-halt. The number of stormy days and of excessively hot days per year is expected to increase. Whether this feature translates into more power and street signal outages depends on the capacity, resiliency and redundancy of power suppliers and distributors.

- Bus services with flexible routing options are less affected by *flooding and storm surge inundations* than are rail-bound services operating on fixed right-of-ways (ROW) and in underground tunnels. But street flooding can be quite common, for instance on bus routes in the Tottenville section of Staten Island; and in Jamaica, Queens. Unless buses encounter street flooding in excess of 3 feet (which can damage brakes and other components), buses can remain generally operative during lower-level flooding.

- The *rolling bus stock* can be readily moved to higher ground during *coastal storm surges*, although *exposure to wind* (flying objects) can be a problem. *Bus* has procedures in place to line up large portions of its fleet along more protected routes, e.g. along portions of 8th and 9th Avenue in Manhattan, when storms are forecast.

- *Urban or coastal flooding can effect fixed assets of NYCT Bus* such as bus depots and maintenance shops, many of which are located at low elevations and often close to the waterfront or inlets and streams. Sand bagging of entrance portals is the preferred current prevention, where applicable, but is only of limited utility, and would be ineffective during serious coastal storm surges, at least at some threatened locations. Installation of well-engineered floodgates at depots and shops should be evaluated for their feasibility and effectiveness.

- The bus fleet has an important pre-defined function during NYC-OEM-coordinated *hurricane/coastal-storm evacuation procedures* (OEM 2006). Mobilizing the necessary workforce under storm conditions could be a problem and requires sufficient lead-time and institutional preparedness, combined with sufficient and reliable advance warnings of imminent weather conditions.

- During weather related events *NYCT Bus* regularly incurs *overtime costs*, in addition to potential physical damages and lost fare revenues. NYC OEM emergency plans suggest suspending fare collection for declared pre-storm emergency conditions. Similar loss patterns are of course true for virtually all MTA divisions, but on a percentage base of a loss/revenue ratio normalized by capital assets, they may be more severe for *NYCT Bus*.

In summary, NYCT Bus is largely focused on (and reasonably well prepared for) maintaining reliable bus operations during extreme weather events, as long as these events are relatively short-lived so dependency on possibly flooded depots and shops does not come into play. NYCT-Bus seems to lack at this time discernable systematic plans, on any time horizon, to adapt to current and future coastal storm hazards and accelerating SLR to reduce flood risks to some of its <u>fixed assets</u> such as depots and shops located at low elevations not far from the waterfront. These risks are expected only to increase with time and definitely need attention.

<u>MTA Metro North Railroad (MNR).</u>

MNR's total assets, including 800 miles of track and roadbeds, stations, terminals, tunnels, rolling stock and others, are on the order of $ 10 Billion. MNR operates three main commuter rail lines *east* of the Hudson (i.e. the Hudson, Harlem, and New Haven Lines), all out of Grand Central Station in Manhattan, and has to the west of the Hudson River contracted to NJTransit the operations of the NY state portions of 2 commuter lines, the Pascack Valley, and the Main & Bergen Lines (also known as Port Jervis Line), with Hoboken, NJ, on the west shore of the Hudson as starting point for both. The two

MNR lines closest to tidal/estuary water front are the Hudson line to Poughkeepsie which largely follows the east shore of the Hudson, with this route's lowest critical elevation, LCE=6.5 ft; and the New Haven Line (LCE=9.8 ft), segments of which cross at low elevations numerous inlets along the NY and CT sections of the Long Island sound's northern shore. Numerous bridges and causeways lie along its low-elevation right of ways. Grand Central Station's LCE is 11.0 ft. All elevations given are with respect to the National Geodetic Vertical Datum (NGVD) of 1929 (Jacob et al., 2000).

Both Long Island Sound and the Hudson River are subject to coastal storm surges, and expected maximum storm surge heights are latitude/longitude-geocoded, tabulated and graphically displayed for many pertinent locations in Jacob et al. (2000), and listed at least by name in an early hurricane-transportation study by the US Army Corps of Engineers et al. (1995).

It takes about 4½ hours for storm surges to proceed up the Hudson from Battery Park, at the southern tip of Manhattan, to Poughkeepsie. Depending on its category and other details the surge may be reduced to about 20 to 50% of its surge height that it has at the south tip of Manhattan **(Fig. 5),** by the time it arrives in Poughkeepsie. Slightly lesser reductions (higher surge heights than along the tidal Hudson) apply generally to inlet points along the New Haven line, near the north shore of Long Island Sound, in Westchester County and Connecticut (Jacob et al., 2000).

Inquiries with its staff indicate that MNR focuses on the reliability of its day-to-day operations, and is currently mostly concerned with frequent minor flooding from run-off from terrain above its right of way, rather than coastal storm flooding. Track flooding from run-off occurs largely during excessive rains, e.g. at the crucial Mott Haven junction (MTA, 2007) in the Bronx, where the Hudson and New Haven lines bifurcate as they run north after having left Manhattan. MNR staff feels it can devote little time to projecting future climate hazards to design future strategic plans. MNR staff expressed the opinion, as did the staffs of most other MTA operating agencies, that climate change adaptation policies and performance standards should be mandated by the MTA central management across its family of operating agencies; that the technical expertise that is available in the individual operating agencies is generally not familiar with future climate trends, tides, flood probabilities, and related adaptation options; and that it has not sufficient engineering expertise to provide in-house the type of specialized analysis needed for its facilities' vulnerabilities to weather and climate. On the other hand staff may readily provide data on *past* operational experience during extreme weather events. These are necessary but insufficient to plan for *future* sustainable operations under different climate conditions. There is a willingness and eagerness to cooperate, but uncertainty how to approach adaptation strategies systematically and professionally, without the required scientific and technical support from the outside. Such arguments apply not only to assessing risks of MNR transit routes, bridges and stations, but also to yards and maintenance shops.

<u>MTA Long Island Rail Road (LIRR):</u> Arguments similar to those made for MNR apply to the LIRR operations and its in-house technical abilities to assess climate vulnerabilities of

LIRR facilities. The asset value of LIRR structures, shops and yards is on the order of $ 19 Billion, and the almost 600 miles of track, stations, and power facilities exceed $ 20 Billion. Rolling Stock is valued in excess of $ 3 Billion.

LIRR uses Penn Station in Manhattan as its western anchor with transfers to/from AMTRAK, NJTransit, NYCT subways and nearby PANYNJ PATH. The track levels of the MTA/LIRR West Side Hudson Yards (above which extensive development is in various stages of planning, southwest of Penn Station) are at elevations within reach of hurricane storm surge flood zones coming up the Hudson.

LIRR trains leave Manhattan eastward via the East River Tunnels, owned and co-used by AMTRAK for its Washington-Boston NE Corridor. The *East Side Access* project, currently under construction, will use a tunnel below the East River from Queens to Manhattan emerging at 63rd Street, with a planned extension to and under Grand Central Terminal (GCT). It will in the future directly connect commuting locations on Long Island with Manhattan's mid-town East Side; but it also may allow new underground floodways to connect into GCT; it is worth evaluating to what degree these risks exist, and what engineering options can be devised to minimize them.

Beyond Queens the LIRR lines branch to the north shore of Long Island on the *Port Washington, Oyster Bay, and Port Jefferson Lines*, and beyond the Jamaica Station, Queens take various routes to serve Long Island along its central spine (ending in the North Fork) and southern stretches; of these especially the *Long Beach Branch, and the Babylon and Montauk Lines* run at sometimes low elevations; the latter cross many river inlets and small bays straddling the northern perimeter of Great South Bay. Many of these near-shore routes are lying in mapped hurricane storm surge zones (NYSEMO, 2006). However unless the exact track elevations are inventoried in these mapped storm zones, the actual vulnerability and risks cannot be quantified. In some instances the rail bed may be sufficiently elevated to act as an unintended levee. This may lead to overtopping (either during incoming storm surges, or during the backflow while storm tides retreat), to erosion, washout and even destruction of the rail bed, tracks and signal and control installations. Bridges may also be at risk since they are typically not strongly secured against lateral forces, despite them being capable of carrying substantial vertical loads. Similar losses from *Katrina* to rail beds, tracks and bridges along the Gulf Coast in Mississippi and Louisiana were substantial and took many months to repair at great cost. The freight carrier CSX alone spent in excess of $300 million to repair rail beds and tracks along the Gulf Coast after *Katrina* and *Rita* had passed in 2005 (National Academies, 2008)

LIRR staff voiced special flood concerns about the East River Tunnels (LCE= 9.0 ft); Long Beach Branch (LCE=6.2 ft); Hunters Point Ave Station, Queens; Shea Stadium Station and Yard, Queens; route segments near Amagansett and Montauk, Suffolk County; Atlantic Avenue Tunnels, Brooklyn; and the future East Side Access tunnels and route. To this list could be added the Penn Station Tunnel (LCE=10.0 ft) especially when considering accelerated SLR combined with storm scenarios and looking more than a few decades ahead.

MTA Bridges and Tunnels (B&T). *Bridges and Tunnels* is in a somewhat different position. It does not operate mass transit with rolling stock. It owns 9 large toll-collecting facilities (2 tunnels and 7 bridges) at key locations, each with a very high replacement value. Total built assets are approaching $ 25 Billion. *Annual* toll revenues from all B&T facilities amount to about $ 1.2 Billion (URS, 2008). The 9 key assets and their lowest critical elevations for storm surge flooding (LCE) are: Queens Midtown Tunnel (LCE=10.6 ft), Brooklyn Battery Tunnel (LCE=8.6ft); Verrazano Narrows Bridge (with one approach at LCE=8.0ft); Throgs Neck Bridge (approach LCE=10.0ft); Bronx-Whitestone Bridge (approach LCE=12.0ft); plus the Triboro Bridge, the Marine Parkway and Cross Bay Bridges in Queens, and the Henry Hudson Bridge across the Harlem River in northern Manhattan.

Since B&T has only few but high-value facilities it has a great interest in managing risk to these facilities by proper engineering upgrades and maintenance to make them resilient against *major* structural losses, whether from seismic, wind or other natural or man-made hazards. The major climate-related risks are:

- Flooding of its two Tunnels (Queens Midtown and Brooklyn-Battery)
- Possible interference from flooding for some of the low-lying bridge access roadways.
- A long-term concern may be the reduction in bridge clearance for ships under rising sea level conditions, especially when combined with sagging of the suspended main spans especially of the Verrazano-Narrows Bridge on hot days. This clearance controls the entry height (and in extreme cases the timing) into the NY/NJ harbor for large container and passenger ships with high profiles. The same applies in principle to the Bronx-Whitestone and Throgs Neck Bridges although ships passing through the East River are generally of lower profile, tonnage and less draft. Both the number of hot days and SLR are accelerating with climate change, so clearance issues must be monitored and evaluated before they become safety and broader economic concerns of restricting ship traffic and harbor activity.

In Summary: Despite B&T's general engineering tradition, the evolving and future risks from climate change are not currently addressed in its capital-spending and facility-upgrading programs, with perhaps the exception of improving the aerodynamic performance of , for example, the Bronx-Whitestone Bridge. Retrofits to bridges are typically best combined with seismic retrofits. Innovative engineering solutions for preventing or reducing the risks of flooding of the two Tunnels during hurricanes and related storm surges will be a challenge that needs to be addressed; the urgency for such preventive measures may increase with rising sea levels, unless the option for regional storm barriers (with earlier discussed risks from questionable long-term sustainability in the face of SLR with no clear upper limits) will temporarily obviate such preventive actions at the two tunnels. Reduction in bridge clearance because of SLR and increase in the number of very hot days causing sagging needs to be evaluated both from a bridge safety aspect, but also because of its importance for the economic viability of New York/New Jersey as a global harbor. Some consideration in the context of climate change and energy policy should be given to the projected toll revenue stream at B&T's facilities. As fossil fuel prices may increase, commuter and other vehicular road traffic may decrease and partially shift to mass transit and rail or barge freight (to the extent *possible). In addition, hurricanes (as was the case for Katrina and Rita in 2005) can at least temporarily decrease refining and production in the US coastal areas, with national impact on fuel prices. Hence, climate change and resulting changes in the physical, political and economic environment, and events sometimes far beyond the New York's immediate reach, may potentially put a damper (both episodically and as a long-term trend) on the revenues that B&T may be able to expect.*

MTA Long Island Bus. Much of the generic issues discussed for NYCT Bus apply to MTA Long Island Bus, modified of course by the geographies of its route system and of some of its fixed structures, such as depots and shops. Snow and ice seem at this time of greater concern than flooding because the former conditions can last for days or a week, while flooding (as experienced in the past) tends to dissipate often within hours or less. Under both conditions stalled cars can be a problem. Advance operational planning and preparedness is generally better developed (and easier) for bus operations than for rail transit. LI Bus may assist under power outages or other events to take up impeded LIRR and other County traffic as directed, and has special contingency plans for such situations. Cooperation with Emergency Services (NYC OEM and Counties) is well established.

Specific concerns are persistent trouble spots for flooding such as along service routes near the South Shore of Nassau County, but rerouting plans whether on short or advance notice are generally effective and well planned and executed. Some fixed installations are subject to coastal and river flooding, prominently the Rockville Center Bus Depot (along LIRR's Babylon Branch, in Nassau County).

MTA Capital Construction was formed in 2003 to centrally manage the largest capital construction projects for the entire MTA family of agencies. Current projects in planning or under construction are: 1st phase of the 2nd Ave Subway; the East Side Access project bringing LIRR into Grand Central Station; modifying the subway stations and train routing at the South Ferry Terminal; future extension of the #7 (Flushing Line) subway to the West Side of Manhattan; design and construction of a direct rail link between Lower Manhattan, Jamaica and JFK International Airport; and redesigning the Fulton Street Transit Center serving many lines in Downtown Manhattan. Obviously several of these projects have been planned and designed over quite a number of years and some are in various stages of progressing towards construction, or even completion. To insert new design and performance demands that take into account climate change, and in particular long-term SLR, is a challenge, and has its limits to what is possible. It will be one of the most critical tasks for the MTA, requiring boldness, tenacity and perseverance, and carefully balancing the costs and benefits over short, medium and long time horizons, to insert these sustainability considerations into Capital Construction's planning, design, financing, and construction processes.

It should be one of the highest priorities for the MTA as part of addressing climate change adaptation, to assess at the earliest possible time, what portions of these major projects are still flexible enough to allow for modifications, where necessary and/or prudent, to account for SLR, storm surges, and for increased temperature and precipitation extremes, risks that past planning and designs were largely not aware of.

Just as terrorism posed on short notice new demands, so will climate change pose new conditions, albeit more gradual, but eventually more relentless and persistent than even terrorism. Ignoring these foreseeable climate factors and forces, many accelerating in pace, magnitude or frequency, will be expensive if such long lasting and costly facilities freeze-in any vulnerabilities they may have, only to require modifications after they are completed according to their present or past plans and designs.

These decisions cannot be made without looking beyond the transportation system. Coordination, with PlaNYC and other planning and complex development processes that address the long-term sustainability and viability of the City and the region, needs to take place in a holistic way. The stakes are high, and timing is pressing and precious; certainly for some of the major projects with long lead times and life cycles, if not all capital projects.

To interface the functioning of new projects adhering to new climate-conscious design and performance standards with the existing infrastructure that does not live up to these standards is another problem to be solved. Since old and new elements must work together and be resilient as a system, there will arise for some time situations where the weakest links can trip the entire system, making those elements that were designed to higher standards not perform to their capacity. But this interdependency of old and new cannot be used as a blanket excuse for not making a start to address the problem. Whenever costly key structures are built, they should be designed to perform their functions preferably over a good part of their entire expected lifetime during which they will encounter great changes in their physical environment. Future generations should not be unduly burdened to pay for our mistakes. At the same time, we should not be unduly burdened in carrying all the costs today for reducing all the risks for future generations. But some balance will need to be struck. This balancing must have a beginning, and it so happens that history has put this task squarely on the shoulders of this generation, starting now.

MTA Insurance Program. This topic has already been covered in earlier sections of this Chapter. The key issue is to find the right balance in reducing losses and vulnerabilities of MTA's built assets by either investing in capital projects and rolling stock performing at higher standards than current or past climate conditions demanded; or paying ever higher insurance premiums and still face the issue of not being able to deliver services to the public once an extreme event strikes. (Smaller events will demand perpetual upgrading costs and incremental fixes to avoid unreliable services subject to weather conditions.) The balancing cannot be done just by looking at the costs and benefits for the MTA books. The costs to MTA, one way or the other, must be shared by the public if it wants to reap the benefits. MTA leadership will need to sell this idea on the local, state and federal level, and the public in large, and do so at its managerial best. But most likely a blend of investing in more climate resilient infrastructure and distributing the remaining risk to the insurance market (in whatever innovative form) will be the likely solution to emerge. This section points more to the problems rather than offering specific solutions. The solutions can only be as optimal as the problem is understood in step with evolving information and external circumstances, whether environmental or economic, that often are hard to predict, especially for long time horizons. Therefore insurance will always play an important role as a more flexible complement to the very slowly changing infrastructure, often cast in inflexible and not easy adaptable steel and concrete. But insurance cannot fix this infrastructure, it only may smooth out the financial pains from uneven hardware performance under sometime extreme conditions. For the sake of delivering reliable services to the public, the focus ought to be on *preventive medicine*, not on emergency triage covered at some marginal levels by post-disaster insurance payments, while services remain diminished until the system is restored and functional again; and then the public still has to pay for the upgrades of the systems to standards that they should have met in the first place. The issue of self-insurance has been addressed in earlier sections.

MTA HQ: Provide Leadership, Set Policy, and Monitor and Adapt Institutional Processes. By now it is clear that the limbs and parts that make up the body MTA can only carry out their movements safely and efficiently to the degree that they are led by a conscientious, alert, cautious, reflective and forward looking central guiding system that steers the flux of sustaining resources for the individual muscles to flex and work together for the entire body to move forward in a way adaptive to the environment in which it lives and fulfills its assigned mission and purpose. Sometimes the brain will direct a muscle to flex in a different pace or direction. Sometimes the muscle will report back some pains and ask for relief or refreshing nourishment so it can continue to do its chores. But if the brain and its connected eyes and ears do not recognize that some parts of its body are in a danger zone, then the entire body may eventually suffer. The direction in which the body moves must come, if not by instincts to survive, first by careful observation, contemplation and assessment, then by making risk conscious decisions and giving directives to its limbs and muscles to take action.

How to translate this metaphor into a process for the MTA to steer and manage its adaptation strategies and actions is the task at hand. The challenges to cope with the various aspects of changing climate are reviewed and summarized in the next section, this time not grouped by MTA agency, but by the nature of climate processes, which can turn at some point in time into a severe hazard or threat, if the organization exposed to it cannot cope with its timing, frequency, magnitude and spatial distribution. One thing is clear: MTA leadership at the headquarters needs to take the lead to: set an adaptation vision; develop a policy that translates this vision into agency-specific missions and tasks; these tasks must lead to solutions within a framework that paces the necessary investments under financial constraints with the timing and severity of risks as dictated by the changing climate whose forecasts need regular scientific updating. Inaction is not a choice; or more to the point, inaction will be the most expensive choice.

Vulnerability by Type of Climate Process or Hazard:

Temperature / Humidity: In most cases, excessive levels of temperature or humidity will affect less the built environment than it will affect:

- MTA customers and workforce alike; this means commuters longing for the next cool train on an unbearably hot and humid ‘local’ subway station with barely any motion of air, until on the opposing track a rattling express train rushes by to stir a lukewarm breeze just for a precious moment; or workers sweating to replace some tracks in a tunnel with stifling heat and humidity. Remember: some 70 days per year with more than 90ºF are forecast by the ‘business-as-usual’ greenhouse gas emission scenario (Fig. 1), the global trajectory we still are on right now. Heat, heat stroke and related health issues (including asthma, heart attack) will become an increasing concern with potential operational impacts for mass transit operations.

- More hot days will call for more energy to cool and vent trains, buses, perhaps even subway stations, but certainly offices, workspaces and shops. The vicious circle closes. More use of energy feeds back into more global warming, unless we find energy sources that do not contribute to enlarging the carbon footprint.

<u>Precipitation and Urban/Street Flooding:</u> The days with extreme rainfalls will increase. The consequences are:

- Flooding of streets, subways, road tunnels, shops and building basements will increase unless the capacity of culverts, street-level storm sewer drainage systems, holding tanks, subway underground pumping and disposal systems, and city waste water treatment and control plants (in case of joint sewer systems) are adjusted to cope with the increased precipitation; or unless we find ways to avoid excessive run-off, and increase infiltration into the ground by using permeable roadways and parking lot pavements.

- Sufficiently effective curbs, berms and swales are often a good start, but frequently provide only local or temporary fixes, rather than systemic solutions

- More pumping of water from subway and road tunnels means more energy use: again, the vicious circle.

- Pumping to stay dry on your property often means flooding your down-slope neighbor, unless the discharge is well engineered and thought out. Avoiding runoff from public roads onto rail tracks and switch yards (Mott Haven Juncture, as a Metro North example) may require effective interaction with the Highway, Environmental Protection, or Sanitation Departments of the respective community. Therefore many of the best solutions will need coordination and joint actions by multiple stakeholders. There is a limit to what can be fixed by the ‘do it yourself’ approach within MTA’s own turf. Coordination with external stakeholders will be essential to solve many of the drainage and flooding problems.

<u>Coastal Flooding from Storm Surge and Sea Level Rise.</u> Storm surge alone, even under current climate and sea level conditions, is already a serious risk with potential for huge losses in New York City in general, and for MTA in particular. A single storm with the “right” track can leave the City or smaller coastal communities in the region struggling

for survival. While it is fortunate that no truly severe hurricane has made a direct hit on New York for several decades, there is no guarantee that luck will hold for another few decades or centuries. The FEMA flood insurance rate maps are outdated for most of the MTA service area, since sea level rise is not accounted for. Certainly the outdated FEMA maps should not be used without a (to be determined) safety margin of a magnitude where expected lifetime of the system is matched with the SLR that can reasonably be expected to add an appropriate safety margin.

The notion currently conveyed by FEMA flood insurance rate maps (FIRM) that flood hazards have annual probabilities on the order of 1 and 0.2 % per year for the respective flood heights indicated on the maps, is misleading for any future planning scenarios. Yet these FEMA FIRM elevations are used for environmental impact statements, and before planning and zoning boards, and for granting zoning variances for projects with often long future life times, despite the fact that the FIRM elevations were never intended as a *planning tool*, rather than for setting insurance rates for *current* conditions. Yet MTA agencies use FEMA's FIRM elevations widely for planning purposes. This practice must end, and MTA must develop policies and new planning and construction guidelines, in cooperation with the PlaNYC Infra-structure Task Force initiatives, and do so at the fastest possible pace while taking climate change factors into account. Fixed elevation safety margins may not provide the most suitable planning and construction guidance, but solutions ought to be found that pursue several goals:

(i) elevation safety margins need to take into account the importance of the structure for maintaining safe system operations;

(ii) safety margins need to take into account both expected lifetime of the structure (or system) and the expected climate-conditioned flood elevations as they increase with time; and

(iii) the engineering should attempt to build into the project design some flexibility (whenever and wherever possible) to adjust to new flood elevation forecasts as new climate information, including forecasts on precipitation, sea level rise and storm patterns will become available.

Another storm- and SLR hazard-related risk management issue is to optimize adaptation measures depending on whether they rely on multiple distributed, but individually site-specific defenses, vs. centralized mega-defenses that –in the absence of redundancy- and in case of failure, can lead to catastrophic losses in the entire area they are meant to protect. The Dutch "Delta Plan" is an integrated national flood and storm protection program built over time since the devastating 1953 North Sea storms and floods. The Delta Plan designs the coastal defenses to be safe against occurrences at annual probabilities as small a 1 in 10,000 (or 10^{-4} per year). For comparison: New Orleans' defenses were intended for (but were not performing at) much lower safety margins, i.e. for events with annual probabilities of 1/100 (or 10^{-2} per year), that is, two orders of magnitude (or a factor 100) less safe. And yet, the Dutch now realize that climate change and sea level rise are chipping away on their originally intended safety margins. Only half a decade after many of the defenses were planned the Dutch must (and do) start to rethink their defense strategies. Politically they have the advantage of a nearly united national consensus that is aiming for the Netherlands to stay more or less where they are. In the U.S., it can be questioned whether up-state taxpayers, or corn farmers in Iowa will join New Yorkers in helping to defend their city with Dutch and Delta-type solutions, and for unforeseeable open-ended times and SLR scenarios. Hence, New York City, and the MTA with its distributed transportation network reaching far beyond the city, needs to think about alternative solutions for the long run. Basically speaking, the non-barrier long-term options are:

(i) raising the flood-prone infrastructure systems and critical components more or less in place (i.e. at the same location in map view) above yet to be agreed upon elevation levels. This means that the building stock and commerce that the infrastructure serves, will need to move much of their support systems often from below grade to higher floors above what will become acceptable flood elevations, thereby giving up valuable prime floor space;

(ii) for both infrastructure systems and the building stock finding architectural and engineered solutions to seal them off temporarily from flood intrusions – a challenging task, especially if such solutions require power for pumping when power cannot be guaranteed, unless the systems are self-sufficient and fail-safe.

(iii) moving infrastructure systems (in concert with relocating businesses and residences) laterally to higher ground. In built-up areas, like Manhattan, that means that the average height of buildings would have to increase further; at the same time new infrastructure right of ways above ground would have to be carved out.

(iv) a partial, and by no means universal option may be, that floating or floatable structures and infrastructure will become more common near the water front, with new design principles for flexible connection of utilities, and the need to anchor such floats safely in the face of strong winds, waves, currents and floating debris, all designed to be robust under hurricane conditions.

(v) the wait-and-see "non-action" default, which sooner or later will lead to catastrophic system or community collapse (often after ever more frequent smaller losses from climate-related events). Because of its high risks it really is a non-option, in which responsibility would be entirely delegated to future generations.

(vi) the wait-and-see "action", i.e. anticipating future losses including catastrophic ones, but combined with a mandatory *pre-disaster planning of a post-disaster renewal plan (PDP-PDR). Call it a pre-planned climate "Marshall Plan". It must include financial, urban renewal, and infrastructure recovery designs. They must be based on a pre-disaster consensus, preferably cast into binding legislation that may assign federal, state and local functions and responsibilities. It needs a mechanism by which contingency resources are instantly accessible so that "The Plan" can be implemented without delay in the immediate aftermath of the catastrophic event. (Counter examples are: neither New Orleans after Katrina, nor –of course less foreseeable-- New York after 9/11 had a consensus master plan, or a vision for what it would strive for in case of such mega-disasters. Valuable time was lost, and in both cases recovery is still partly unresolved, or at least severely delayed, for how best to turn such disasters into a better, less vulnerable future. In other words, the disaster must not lead merely to recovery to the vulnerable state that existed before the "event"; rather the event becomes the opportunity and vehicle to build a new, climate-resilient, less vulnerable, and otherwise better and more sustainable future of the community and of its infrastructure systems; and realize the vision of a future it may have had for a long time anyhow, but where the event becomes* *the trigger to realize this vision: Pre-Disaster Planning – Post Disaster Renewal (PDP-PDR).*

(vii) in practice, a blend of the above listed solutions is likely to emerge, in which barriers may have perhaps a place, albeit quite likely as a temporary one to be outpaced by SLR, driven in turn by the collapse of ice sheets in Greenland and Antarctica, until and unless global warming will be contained, either by man-made action or natural cycles leading to global cooling, and re-glaciation of land masses many millennia from hence.

NYC will not be the only coastal city, and MTA the only transportation authority having to struggle with such sea level adaptation issues that are endemic to coasts and estuaries around the globe. The creation of the MTA's Blue Ribbon Commission for Sustainability, and the City's PlaNYC show, however, that both entities are now determined to take on this adaptation challenge, at least conceptually. It will, however, require tenacity, resources and political will, besides science and engineering ingenuity to translate this intent into a sustained and sustainable reality.

Other Climate Change Processes (Wind, Snow, Ice, Drought, Weather Induced Power Demands and Failures).

Compared to the storm surge and sea level rise threats, other climate change processes not heretofore much discussed seem to pale in severity, although they will dominate operational adaptation needs and measures now and in the near future: severe winds, snow, ice, drought, and weather-induced peak power and power failures.

MTA Vulnerabilities and Climate Change Adaptation Measures as seen in the Context of the Blue Ribbon Commission for Sustainability's five Working Groups.

Energy/Carbon:

The recommendations by the Energy/Carbon Working Group seek a continued shift to cleaner and alternative energy sources to reduce MTA's carbon footprint; and to reduce its overall energy needs and consumption. Some of the adaptation measures proposed here will, however, counteract these energy reduction goals.

For instance, the necessity for increased pumping frequency and capacity to remove excess ambient and flood waters from subway tunnels will require larger amounts of energy as the number of days with heavy rains or storm surges increases, and as sea level rises. To find ways to avoid seepage or flood waters entering into the tunnels in the first place, are therefore preferable over conditions that require pumping the water, just from an energy aspect alone.

The demand for electric peak-power to serve air-conditioning needs in subways, trains, shops, facilities and offices will rise sharply with the increased number of very hot days per year; also the energy demand for air conditioning buses will rise, whatever their fuel source; similar trends are associated with additional venting by fan plants of subway tunnels and stations should the subway system be transformed into a closed or closeable system to reduce the risk of flooding. In this context, elevated transportation systems replacing underground systems may be more energy efficient since they avoid both venting and pumping, and perhaps even less air conditioning of trains, apart from being less prone to flooding.

The roofs of elevated-train cars and stations may be surfaced with photovoltaic cells to meet some of the air-conditioning and other needs during day time. At fixed installations, geothermal heat pumps may be considered requiring shallow wells for circulating the fluids for cooling in summer and heating in winter.

Facilities:

The Facilities Working Group recommends green buildings (LEED standards). When implemented, emphasis should be on reducing run-off; and increasing the permeability of parking and other paved surfaces to delay and reduce run-off during heavy precipitation events. Gray water usage fed from roof catchments can enhance this flood-reducing function. Such catchments should be able to collect the first ½ inch of a rainstorm.

Buildings and other structures must not be designed to meet only current climate standards, but must have the ability to meet or adapt to the future increased demands with the number of hot and wet days increasing, and more extreme storms and flooding conditions. Taking future conditions into account implies the placement outside future flood zones of such structures and facilities. Their design and performance features must meet future climate norms with respect to wind, temperature, humidity, and precipitation extremes. The target climate for new designs should be commensurate with the upper bound for the expected lifetime of the structure, facility or equipment.

Green roofs can serve both to reduce run-off and achieve easier cooling, and in addition they minimize the facilities' contributions to citywide heat island effects.

Materials Flow

Recommendations of the Materials Flow Working Group focus on reducing waste streams and enhance green procurement. From an adaptation perspective the materials and products procured need to meet the more extreme temperature demands (e.g. to avoid buckling of thermally expanding rail tracks); pumping equipment needs to have the capacity to cope with more extreme rainfalls; fan and air conditioning equipment needs to be able to handle more days at extreme temperatures, yet do so with the highest achievable energy efficiency. Design and procurement of roofing, whether at fixed surface installations (shops, yards, depots, offices, or even of the rolling stock) should contribute to reduction of heat absorptions to minimize cooling demands below, and/or contribute to photovoltaic or hot water energy production, and where applicable, reduce or delay run-off during extreme precipitation events. Buses should be resilient to street flooding to the maximum height technically possible. Increase in salt content of ambient surface or groundwater at facilities or rolling stock near coastal areas at or below sea level, whether as air spray or in ground water or in water pumped from tunnels, should not lead to excessive corrosion of structural elements and equipment. This can be achieved either by the proper choice of load carrying materials, or by proper surface treatment and coating.

Water

From a climate change adaptation point, water enters the picture in two forms: too much and too little; too much during rainstorms and floods, and too little during potential droughts. Consideration should be given to where the water is drained after it has been pumped from subway (NYCT), rail (LIRR and MNR) and roadway (B&T) tunnels. It should not contribute to street flooding nor lead to overflow conditions in combined sewer systems, which in turn may cause the water to flow back into the subway system or rail tunnels. Can the water that is pumped from tunnels be used as gray water in some locations and for some purposes? Are there procedures in place for how to reduce water used for cleaning and washing the rolling stock in depots and yards while drought conditions prevail? Is grey water available instead of fresh water, under drought conditions that stress the public water supply?

Smart Growth and Transit-Oriented Development (TOD).

Climate Change Adaptation is a key factor for planning and implementing Smart Growth and TOD projects. First and foremost, new TOD communities, and their building stock and infrastructure should not be placed in current or future expected flood zones, taking into account the latest projections of combined threats from coastal and estuarine storms and sea level rise, but also anticipating extended flood zones near rivers and streams because of more extreme precipitation events and land use changes in the upstream sections of the watershed. Nor should any new transportation infrastructure be located in such existing or projected flood zones when serving new TODs.

In general, MTA has no jurisdiction or mandate to make the decisions for the placement of TODs. But it should use its best ability to make the developers, and local governments with jurisdictions for such decisions, aware of the climate risks, and contribute the adaptation-aware arguments for these jurisdictions and developers to promote climate-smart, sustainable decisions. All smart-growth and TOD projects should minimize run-off and have permeable pavements and roadways to enhance infiltration, recharge of ground water tables, and reduce surface and street flooding. The sewer systems and wastewater treatment plants serving the TODs should have the capacity to take the flow during extreme rainstorms. TOD communities should have green roofing to reduce local heat island effects and minimize air conditioning needs.

Opportunities for TODs may exist near-shore along the service routes of LLIR and MNR along the Hudson River, the North- and South Shore of Long Island, and along the inlets of the Long Island Sound in NY and CT. These shores are affected by SLR and storm surges during hurricanes and Nor'easter winter storms. As discussed earlier, the rail beds of LIRR and MNR are themselves already at risk from increasing climate hazards. TODs should not be exposed to similar risks, but instead should seek higher ground (either natural or engineered). Such new TODs should be designed by anticipating that at a future time, MTA may want to raise the rail tracks and/or beds in place to higher elevations to reduce its own exposure to the rising, combined storm surge/SLR risks.

V. Summary Findings and Recommendations.

- **Finding 1:** As of 2008 MTA had not in place an agency-wide policy for climate change adaptation. Without such a policy for guiding principles it is difficult for its member agencies to develop coherent and technically sound adaptation plans for how and when to cope with the challenges from climate change to its transportation infrastructure systems, operations, and capital projects; and how to set priorities for this adaptation process. This lack of a stated policy also deprives MTA leadership of opportunities to tenaciously convey long-term strategies, needs and opportunities to its customers, the public, and to governments on the local, state and federal levels whose support it needs to make climate change adaptation happen.

- **Recommendation 1**: *At latest by mid-2009, the agency shall have a basic adaptation policy in place*. In announcing the policy MTA may state that (i) it is aware that adaptation to climate change is a necessity without which a stable prosperous and sustainable economy of the region, and a reliable functioning of its transportation infrastructure cannot be achieved; (ii) MTA is committed to develop a strategic adaptation master plan with basic performance standards and milestones to achieve them; (iii) MTA will coordinate its adaptation efforts with those of other infrastructure operators, utilities, and local and regional planning efforts to foster a coherent action plan for the region, in which the transportation sector cannot proceed in isolation, but has a key role to play; (iv) MTA is committed to take a leading role and set a national example for making the largest mass transit system in the Nation resilient to the challenges of climate change; and (v) MTA is fully aware of the interplay of adaptation to, and mitigation of global warming and climate change; and that both approaches need to be balanced and pursued to achieve a sustainable future.

- **Finding 2:** Climate change and related weather events have already affected MTA operations and facilities in its service area. Projections of future climate change scenarios indicate that trends will increase in magnitude and pace, and so will the frequency associated with extreme events. They include increases in the number of days per year with extreme temperatures, rainfalls, storms, and costal storm surges. Sea level rise (SLR) may approach 1m (3ft) during this century, and may exceed this amount in the century thereafter.

- **Recommendation 2***: At latest by the end of 2010, MTA shall have established a climate data base (or secured access to such a base). It shall contain information on future trends of climate parameters including but not limited to temperature, precipitation, storms and coastal storm surge patterns, and of sea level rise forecasts*, for *which it needs to undertake meaningful adaptation measures.* The information shall be in a form that serves MTA's needs to provide a sound scientific-technical foundation for making the best strategic, operational, engineering and management decisions as to how to optimally adapt to these forecast climate changes. Both mean trends and parameter variability quantifying the magnitude and frequency of extreme weather and climate events shall be included. This compilation of climate forecasts shall be updated on a regular basis at least every 5 years, or earlier when important new scientific data or forecasts become available. It should have enough spatial resolution, must serve the entire MTA service area, and shall include forecasts out to at least 100 years, and in some cases longer to the extent that this is scientifically feasible. An essential part of the effort is to quantify the uncertainties by providing a measure of confidence for the provided forecasts and for different time horizons. The climate forecast data shall be readily accessible to MTA staff preferably in electronic form, and in standard formats (where applicable for use in GIS or CAD applications) to foster ready use for strategic and operational decision-making on a day-to-day routine basis. MTA shall explore partnering with other infrastructure operators and entities in the region towards a coordinated regional data base effort, and may want to do this in cooperation with similar efforts facilitated by, for instance, the PlaNYC's Climate Change Adaptation Task Force and its New York Panel on Climate Change (NPCC).

- **Finding 3:** Like most other infrastructure operators in the region, MTA has not yet developed the capacity to *systematically* asses and quantify the vulnerability and risk exposure of its various systems, facilities and operations to climate change and weather events, nor has it commissioned such assessments. Therefore the magnitude and projected rate of impacts and losses associated with the predicted climate risks are unknown, for present conditions and future times.

- **Recommendation 3:** *At latest by 2012, MTA shall have completed a thorough, quantitative vulnerability and risk assessment vis-à-vis climate hazards of the systems, assets, facilities, operations and income streams of tolls and fares of its various operating member agencies, and of its centralized insurance program.* This assessment should include the climate vulnerability of the existing systems and of all new capital projects in their various stages of construction, engineering design, and/or conceptual planning. The vulnerability and risk assessment should be both scenario-based for typical expected events but must also be performed probabilistically to allow to obtain estimates of *annualized losses* integrated over the range of climate event magnitudes and their probabilities, and over the current and planned range of assets and operations for the entire MTA family. The assessments shall be made for the current asset inventory, and for the inventory and climate conditions as projected for the 2020s and 2050s. For major system elements found most vulnerable to sea level rise and coastal storm surge flooding, such as tunnels, rail beds, subways near or below sea level, additional risk assessments under the climate conditions projected beyond the 2050s and at least to the end of this century shall be produced.

- **Finding 4**: Since neither the climate hazards nor the vulnerability of MTA assets are known at this time, and consequently the already incurred losses or potential future risks cannot be meaningfully assessed, it is not now possible to formulate optimal cost-effective strategies for adapting MTA's assets to current and future climate conditions. While some ad-hoc initiatives have been undertaken to fix, for instance, some flood prone sections of its rail and subway mass transit systems, these efforts generally carry only short-term benefits.

- **Recommendation 4:** *At latest by 2015, the MTA shall have completed a strategic climate change adaptation master plan for how the MTA envisions its regional mass transit system will be transformed to cope with the progressive demands from climate change and provide cost estimates for the various options to make the system robustly adaptive and resilient to climate change.* This master plan shall take into account the results originating from Recommendations 2 and 3 (climate data base, and vulnerability risk assessments, respectively) as a basis for arriving at optimal adaptation measures along various, sometimes overlapping decision paths and time horizons, out to at least 100 years into the future. The specificity of this master plan will decrease with time. But fundamental decisions on long-term capital projects, including those currently under construction, design or planning, and fundamental strategic decisions, are required. In particular, complex decisions will have to be faced as to whether transportation systems relying on tunnels and rails with elevations at or below rising sea levels, and which are increasingly exposed to storm surge flooding, can be made resilient to such threats in their existing locations; or whether such systems need a fundamental redesign and transformation to a network that operates above-grade and at elevations above projected flood heights. If such elevated relocations are found feasible or necessary, then they must be planned with accounting for the fact that such flood zones will grow in vertical and horizontal reach as sea level keeps rising. Part of such a strategic master plan will be to take a decisive position on whether or not the New York/New Jersey harbor estuary (including the tide-controlled sections of the Hudson River to Troy/Albany) barriers are a viable, albeit temporary protective solution with some marginal potential for catastrophic failure under the most extreme storm conditions); or, because of the prospect that open-ended sea level rise scenarios will make the barriers eventually ineffective and unsustainable, that they should not be included as a strategic option for making at least part of the region and MTA service area for some time more resilient against coastal flooding from combined storm and sea level rise threats. It should be noted, that portions of MTA mass transit systems operating in Brooklyn, Queens and Long Island, and in Westchester and Connecticut would *not* be protected by the barriers as currently conceived.

- **Finding 5:** Neither the MTA, nor local or state governments in the Metropolitan Tri-State Region (NY, NJ, CT) have currently a vision, much less actual plans and procedures, for how to renew the economic base, livelihood, and the infrastructure of this region should a major disaster such as a hurricane of category 2, 3 or even 4 directly strike this region. As examples have shown from other parts of the Nation (e.g. New Orleans after *Katrina*), or from New York itself after 9/11, it is essential that such a pre-disaster vision exists; that legal, administrative, fiscal and technical/operational instruments and procedures are in place *before* the disaster strikes (subject to modifications to fit the circumstance of the event). The goal is to renew the economy and livelihood as fast and efficient as possible, and *not* rebuilt communities to their vulnerable state in which they were before the disaster, but to a state and trajectory in which climate change becomes a sustainable process rather a constant threat.

- **Recommendation 5:** *At latest by 2015, MTA shall establish a framework Pre-Disaster-Plan for Post-Disaster-Redevelopment (PDP-PDR), in concert with local, state and federal governments, and with input from communities and the public and private sectors.* While an earlier completion date is desirable for a PDP-PDR internal to MTA, such plans need to go far beyond MTA's principle mission to provide efficient, safe, reliable and affordable public transportation to the region. Basic landuse, urban design, and broad economic and social issues are at stake, apart from dealing with scientific, technical and engineering issues. For this reason a PDP-PDR may have to be developed in conjunction with the regional adaptation master plan of Recommendation 4. Again, the opportunities provided in conjunction with PlaNYC and other equivalent local, state and federal, and private sector initiatives should be used to the greatest possible effectiveness for this far-reaching goal. The purpose of the PDP-PDR is to transform the disaster into a one-time opportunity for realizing the heretofore unachievable vision for a better future that without the disaster was unachievable because of lack of political will to act preventively by incremental steps. But without this vision and institutional preparedness to realize it, the opportunity that a disaster can provide can be easily squandered.

- **Finding 6**. Adaptation, by necessity, occurs on different times scales and is tied to opportunities and risks in an environment with fiscal, political, economic, social, and also technical and engineering processes at work. MTA can within current operational and capital spending budgets strive to address some 'low-hanging fruit' adaptation measures, especially when tied to existing maintenance and refurbishing activities and projects.[3] Examples include increasing pumping and fan capacities for subway

[3] After the August 8, 2007 storm, MTA has undertaken a thorough review of its operating systems and procedures by planning, engineering, and implementing measures to reduce its systemic and operational vulnerabilities to extreme weather events, and increase its readiness and internal and external communication capacity to manage, and effectively cope with, extreme weather events and other emergency situations. An internal tracking system of the remedial measures undertaken has been established to keep track of the progress and implementation schedule. Its *MTA Storm Status Report* of September 2008 (MTA, 2008) lists a total of 17 major initiatives with more than two dozen projects that fall into 3 major categories: operations, engineering and communications. In *Operations* they include the establishment of *early warning and response capabilities, procedures and teams*; the creation of a MTA *emergency response center (ERC);* and a revision of the *agency storm operating protocol.* Under the *Engineering* initiatives corrective engineering and procedural measures have been undertaken at some of the most notorious flood-prone locations, requiring in many cases close interagency cooperation with, and capital expenditure by the NYC Department of Environmental Protection and Department of Transportation. Under *Communications* a contract was approved to install wireless communication capabilities to allow the usage of cell phones in subway stations. The first 6 stations are scheduled to be operational by year-end of 2010. All 270 subway underground stations should have this capability within 6 years (2014). These measures improve internal

and other tunnel operations to achieve greater resiliency to flooding and environmental hazards. It is also possible to replace buses with clean and energy-efficient vehicles, at which time their capacity to cope with increased street flooding and air-conditioning demands during ever more hot and wet days can be reassessed to meet future challenges. But apart from these incremental adaptation steps at opportune times, there are priority decisions to be made for projects already built into the current capital spending plans (examples are the East-Side Access Project to connect MNR into Grand Central Terminal; or subway extensions for the 2nd Ave line on the East Side, and #7 line on Manhattan's West side; amongst several others). For these projects timing of decisions is crucial in order to avoid freezing in risks vis-à-vis climate change processes that are expensive to rectify at a later time. Therefore a special task force whose task is to establish priorities linked to opportunities for minor or major projects already underway seems highly advisable.

- **Recommendation 6.** *The MTA should establish, at latest by mid-2009, an 'Adaptation Priority Task Force' (APT) that identifies by the end of 2009 unique opportunities for adaptation measures*. Some current and ongoing projects may provide unique one-time opportunities during the operational maintenance cycle, for new construction, or during the ongoing design and planning stages of capital projects to which MTA is currently committed. Such critical opportunities must not be missed to include adaptation measures to the extent still possible. This Adaptation Priority Task Force has to act on a fast track and must not be held back by the more fundamental and time consuming initiatives proposed under Recommendations 2 to 5, although APT must establish a strong working liaison with these other initiatives.

- **Finding 7:** Multiple organization-specific and some multi-institutional initiatives to address climate change mitigation and adaptation issues are underway in the greater NYC metropolitan region. Often they are tied to achieving broader economic and environmental sustainability goals. They take place at a variety of local, state, and federal government and non-government organizational levels. The PlaNYC's Climate Change Adaptation Task Force was mentioned as an example, but there are numerous others. Since MTA will benefit greatly from interacting with these efforts, both to inform such efforts of its own adaptation plans, but also to bring back best practices, and to negotiate common adaptation performance standards and guidelines that are needed for an entire metropolitan region to work as an integrated network, MTA should institutionalize such cooperation and assign in-house expert staff to such integrative efforts. This expert staff should then be used as internal facilitators in the various MTA agencies to help advance sound adaptation efforts. This internal process should be enhanced by an education and knowledge transfer process by teaming with existing expertise in academia, professional organizations and by specialized

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operational and response capabilities but also satisfy the needs of the riders, not only during emergencies, but also on a day-to-day basis. Operating personnel at LIRR, MNR, and B&T were equipped with additional communications devices to achieve communication redundancy. The various measures include and affect all MTA operating divisions and MTA headquarters.

consultants in the scientific, technology, engineering and social fields to complement and enhance the MTA's staff capacities to address adaptation most effectively.

- **Recommendation 7**. *MTA should assemble a designated internal Adaptation Team (AT). This can be done immediately and should be completed by February 2009.* There is a two-fold purpose to this AT. First, it shall represent MTA outside its jurisdiction in multi-institutional, locally, regionally or even nationally coordinated sustainability and adaptation efforts such as setting policies, common performance standards and guidelines, and goals for technical research and data collection or monitoring projects that serve common needs of diverse stakeholders of adaptation in the region. The second objective is that the AT has sufficient representation from, and standing in the key MTA member agencies so it can perform the much needed educational and knowledge transfer functions in these agencies. The AT should partner for these "in-reach" efforts with expertise available in academia, professional organizations and specialized consultants in the appropriate fields. The AT will need an operating budget and establish goals and milestones for its activities not later than mid-2009. It should be operative for a period of at least three years and be reviewed in its third year (2012) for possible continuation depending on its achievements, effectiveness and on the challenges that still need to be tackled.

- **Finding 8:** MTA's Blue Ribbon Commission for Sustainability (BRCS) has set some ambitious goals by its five Working Groups (WGs) for: energy/carbon; facilities; materials flow; water management; and smart growth/transportation-oriented development (TOD). The realization of these goals must be designed and performed not to interfere, but rather enhance adaptation strategy; vice-versa, adaptation measures should be designed and performed to enhance green policies to achieve sustainability, reduce the carbon foot print and energy consumption and meet other environmental goals. Unfortunately adaptation and mitigation measures sometimes lead to contradictory outcomes. For instance, increasing the pumping capacity to drain flood waters in subway tunnels will require more energy consumption; increasing the air-conditioning needs in mass transit rolling stock and offices or other facilities has the same effect. Vice versa, some adaptation measures may provide opportunities to achieve energy benefits. A hypothetical but interesting example (largely outside MTA's direct mission) could be to explore what opportunities for *tidal power generation* may be built into the earlier discussed storm surge barriers, should they be contemplated, but without jeopardizing the reliability of their protective function.

- **Recommendation 8:** *Each mitigation project MTA undertakes needs to have a checklist as to how it enhances or hinders adaptation for short and long time horizons. Each adaptation project needs a checklist to show how it enhances or hinders mitigation and energy conservation efforts and improves environmental performance.* Depending on identified adverse cross-impacts, the project designs and implementation plans must seek modifications to strike a well justified and documented balance if the outcomes are still mutually incompatible after modifications or project redesign and no viable and innovative alternatives can be found.

- **Finding 9:** It will take time setting climate change adaptation performance standards and guidelines, especially if they are formulated to apply to multiple interdependent infrastructure service providers (transportation, water, power, sewer, communication and others) so the region becomes resilient and can perform robust under climatic stresses (e.g. reduce power outages after severe weather events). Therefore MTA, in concert with others, may think about interim procedures that will have precautionary effects without specifying a particular solution. These procedures would trigger a review of any new project or major alteration and investments for existing operations and projects. For instance, MTA in concert with others, may set a target elevation x (say, of the order of 15 ft above MLLW measured at the tide gauge at the Battery, NY, in the year 2000). If new projects are planned, designed, budgeted, or constructed in the region; or if major upgrades and maintenance of existing facilities are undertaken that have any major structural or critical operational components at or below this elevation, then they will trigger a review process in addition to and/or separate from standard environmental impact statements or checks against FEMA flood zone regulations; FEMA flood zone elevation maps (also known as flood insurance rate maps - FIRM) are unfortunately used for many planning purposes to set critical project elevations. FIRMs were not intended as a planning tool. FIRMs do not recognize at this time that sea level rise is upon us. They barely predict flood heights correctly at two annual probability levels (1% and 0.2% per year) because they were derived using climate information and land use conditions of the last century. Certainly they fail to predict future climate and landuse conditions under which infrastructure will need to perform robustly.

- **Recommendation 9:** *MTA should establish by the end of 2009, preferably in concert with local governments and other infrastructure providers, a procedure called CARE (Climate Adaptation Resiliency Evaluation).* It will be triggered when any new projects or major alterations to existing projects are undertaken whose load-bearing structural components, or non-structural components critical for its uninterrupted operation and functioning are located below a critical trigger elevation x above an established measure of sea level of the recent past. The elevation x needs to be negotiated; it is recommended not to be less than 15 ft above the mean-lower-low water (MLLW) mark measured –say-- in the year 2000 at the Battery, NY, tide gauge. MTA should promote the establishing of CARE procedures and guidelines internally and externally, recommend its usage in Smart Growth/TOD projects, and certainly shall adopt CARE for all MTA projects and planning in-house.

- **Finding 10:** The MTA is the largest mass transit provider in the U.S. and serves the most densely populated region of the Nation. MTA's existence and operations have contributed to make the New York Metropolitan region the one with, as measured in

2005, the smallest per capita carbon footprint in the US east of the Mississippi, and the 4th lowest in the nation (those lower in their footprint are mostly in more temperate climates). Moreover, the average New York resident emitted in 2005 some 0.664 tons from automobiles (1st rank, with the lowest output among the US metro regions), compared to 1.004 tons per resident as the average of the100 largest metro regions in the US (Brown et al, 2008). Because of this achievement, but also because of the extraordinary concentration of assets, and risks from climate change to the region, it is in its own interest and the interest of the Nation, and of many other large coastal cities around the world that either have or aspire to such an effective, albeit aged and matured, mass transit system, *that the MTA take a leadership role nationally and globally*. This leadership should show the way and set an example for how a major city and its mass transit system in a precarious situation because of storm surges and sea level rise faces this threat, develops innovative adaptation strategies and solutions, and develops and follows policies that turn an untenable situation into an opportunity for urban renewal.

- **Recommendation 10:** *The MTA leadership should fearlessly pursue and promote a path towards sustainability in the face of climate change. It should take a strong stand on these issues on the local, state, federal, even global level. It should not shy from helping to develop prudent adaptation and mitigation policies and be a voice to promote on all government levels the importance for renewal of the nation's infrastructure, and especially in its largest cities. It should see to it that it can speak with a credible voice as one of its strongest implementers of such policies.* MTA has started on this path by enlisting the *Blue Ribbon Commission on Sustainability* to help develop such a vision and basic strategy; and to set some interim goals and milestones on this long path into an uncertain future. This is only the beginning. MTA shall carefully balance the use of its limited resources when making decisions between acting by mitigation of, vs. adaptation to, climate change. Mitigation must be a global mandate, adaptation remains a local necessity. Local adaptation measures by and for the NY City metropolitan region will not only make it survive the challenges from climate change, especially sea level rise, but flourish and renew itself over and again – a typically New Yorker trait we should not relinquish in the face of the global climate challenge. MTA can and must lead on this path.

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Note Added in Proof: This report was produced largely in the summer of 2008. Since then considerable work has been carried out by various groups in and around New York City, and New York State. Some of the latest climate projections and other related consensus products for adaptation and mitigation for the MTA's operating regions may potentially supercede those stated in this report.