Urban Hazards Forum
Jan 22-24, 2002; John Jay College, New York City

Multi-Hazard Mitigation Needs and Opportunities for the Greater New York City Metropolitan Area with Examples for Earthquake and Coastal Storm Surge Hazards

Klaus Jacob
Lamont Doherty Earth Observatory, Palisades NY 10964
jacob@ldeo.columbia.edu

Abstract

The high concentration of built, economic, institutional and cultural assets in the New York City Metropolitan region inevitably poses an extreme risk exposure for catastrophic events, even when the annual probability for any given hazard is only moderate - as is the case for earthquake and coastal storm surge hazards. Rare extreme natural disasters such as a direct hit by a Hurricane of category 3 or 4, or an earthquake of magnitude 6 or larger are likely to surpass the losses suffered during the WTC attacks at least in economic terms, but not necessarily in fatalities. GIS-based loss modeling tools are now available to quantify the impacts of such events. We present a few examples for earthquakes and coastal storms and address the inferences for mitigation needs and options for the Metropolitan area. Probable maximum losses for very rare single events ($=10^{-4}$ per annum) can exceed US$ 100 Billion which is a substantial fraction of the local economy expressed as the annual gross regional product of about US$ 1 Trillion/year.

Introduction

We assess the hazards and risks to the Greater New York City Metropolitan Region (for short "Metro East Coast" region or MEC). We do this in an abbreviated form for two specific natural hazards: storms /storm surges, and earthquakes. For the storm hazards we use the results from the MEC climate change impact study (Rosenzweig and Solecki, 2001), and in particular its chapter on infrastructure (Jacob et al., 2001a). For the earthquake loss assessment we rely on the results from the study by NYCEM (New York City Area Consortium for Earthquake Loss Mitigation; see Tantala et al. (2001); and this conference volume). The pertinent websites for these two assessments show the methods used and the results obtained in great detail. They can be found for the MEC and NYCEM studies at http://metroeast_climate.ciesin.columbia.edu and http://www.nycem.org, respectively. While some mitigation activities are proceeding in this region, they are slow and sparse. Therefore, the region will be exposed largely unmitigated for many decades to come. The events of the September 11, 2001 attacks on the World Trade Center have alerted the responsible government and private sector stakeholders to the magnitude of losses to which the region is exposed, whether they stem from natural or man-made events. This is simply a function of the asset concentration which is typical for other global megacities as well.

Quantifying Risk :

Risk of a region (the expected future loss) is defined here as the product of 3 locally varying factors, integrated over the region of interest:

$$\text{Risk} = \text{Sum}(\text{Hazard} \times \text{Asset} \times \text{Fragility}_{\,|\,\text{Hazard}}) \qquad (1)$$

The *hazard* for storms can be the height and duration of a coastal storm surge, or the wind velocity of tropical storms, measured on the Saffir-Simpson scale. For earthquakes the hazard would be typically the horizontal ground shaking level in terms of fractions of the gravitational acceleration g (1g = 981 cm/s/s). The hazard can be deterministically defined for given scenario events, or probabilistically for given levels of annual exceedance probabilities.

The *assets* are taken as the replacement values of all built structures such as buildings, their contents, and infrastructure. It is easier to estimate in advance the direct physical losses, and much harder to estimate the indirect economic losses, not to speak of the even more difficult estimation of the "intangible" losses such as impact on the culture and urban fabric.

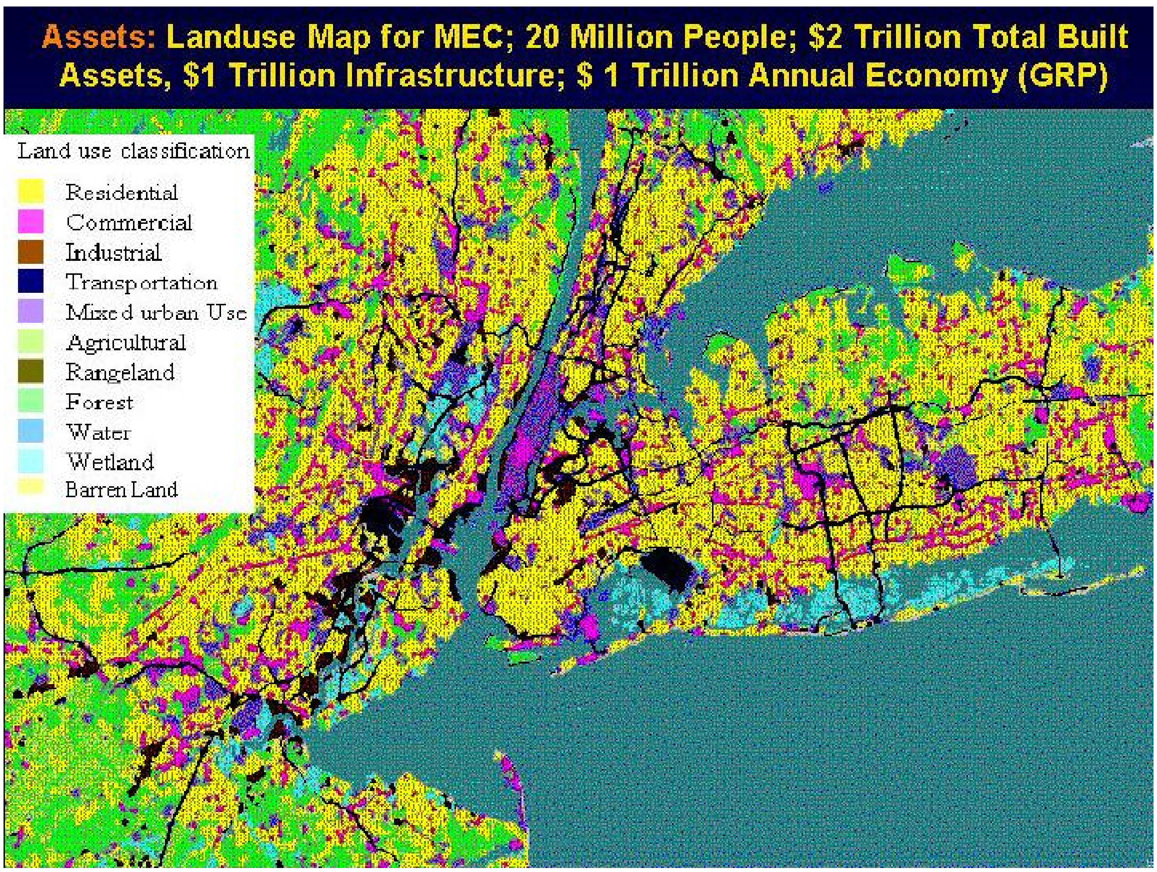

Figure 1 : Schematic land use map and some vital statistics for the region investigated.

The landuse of the area is sketched in Figure 1 and some of the basic facts are given for the region which we define as "MEC": About 20 million people live and work in the 31 counties in three states (NY, NJ, CT), of which about one third or 8 million people live in the five boroughs (counties) of New York City itself. The built assets according to

HAZUS (1999) are about US$ 2 trillion of which about half is in buildings, and the other half in infrastructure and essential facilities (utilities) from highways, bridges, sewage facilities, airports to nuclear power plants.

The *fragility* is specific to each piece of asset and for each hazard and hazard level. It is a function (actually a multi-dimensional matrix) with values between 0 and 1. Zero means no damage occurred, one means the entire asset is lost, and fractional losses occur between those two extremes. Fragility can be expressed also probabilistically as a distribution of likelihoods for levels of fractional damage to occur.

Storm Hazards and Risks

For the MEC region we focus on two types of storm impacts: those from tropical storms (hurricanes, see Figure 2) whose intensity according to barometric pressure and wind speed is measured on the Saffir-Simpson (SS) scale, and for extra-tropical winter storms locally known as "nor'easters". First we investigate deterministic scenarios based on "SLOSH" model computations of storm surge heights by NOAA and US Army Corps of Engineers (USACE) teams and then compare these estimates to some recent historic events of coastal storm inundation.

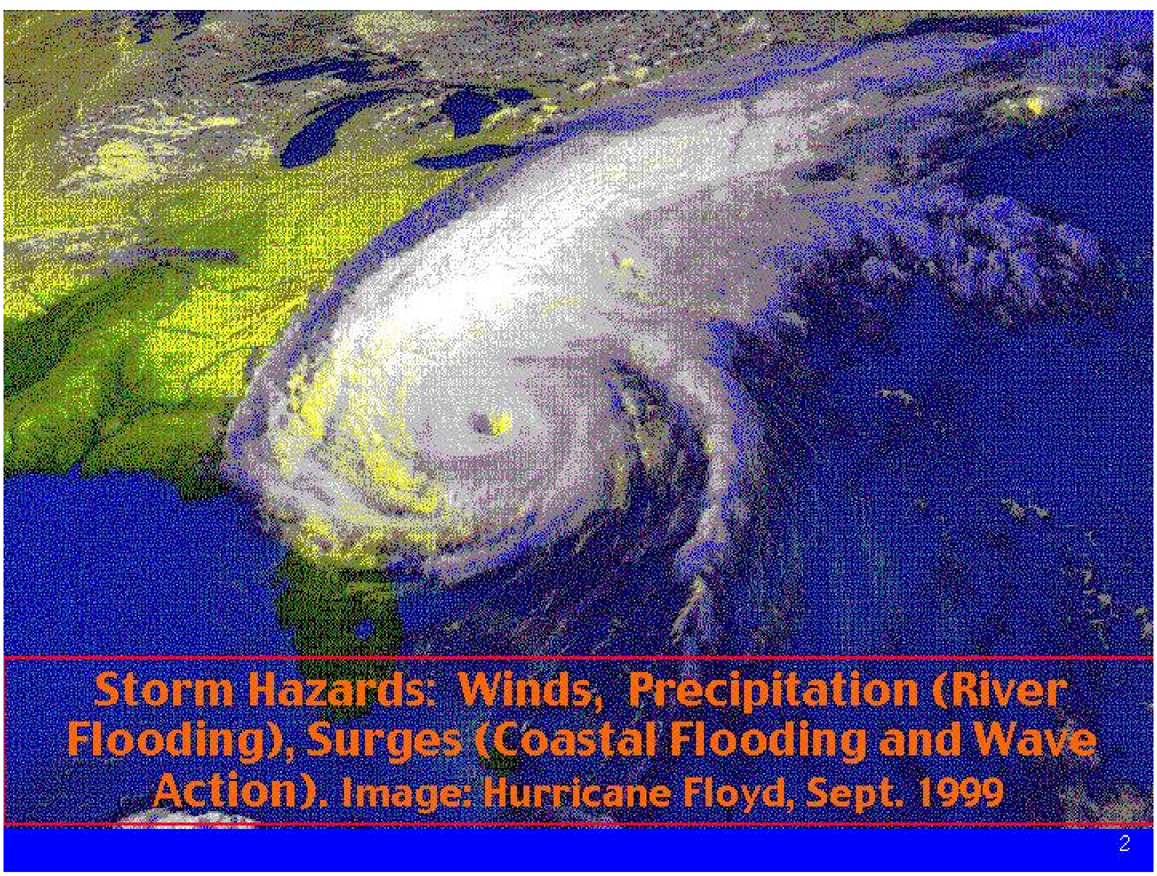

Figure 2: Hurricane Floyd, here seen centered over South Carolina, moved up the US east coast during September 1999. By the time it arrived in New York, it had degraded to a *tropical depression*, causing mostly inland flooding rather than a coastal storm surge.

From the many SLOSH computations for SS storm categories 1 through 4 (5 is considered unlikely in these latitudes) and for a large variety of possible storm tracks with different land fall locations, one can choose "worst case" storm tracks. When a hurricane has a landfall just south of New York City, i.e. somewhere in middle New Jersey, then the storm's right arm of the counter-clockwise rotating air mass around the low-pressure system hits the New York area in an optimal way to maximize the surge height in this area. Expected storm surge heights at the southern tip of Manhattan, at the Battery Park tide gauge, are given as 10.5 ft, 16.6 ft, 23.9 ft and 28.7 ft for SS 1 through 4 storm categories, respectively, and for worst case track scenarios.

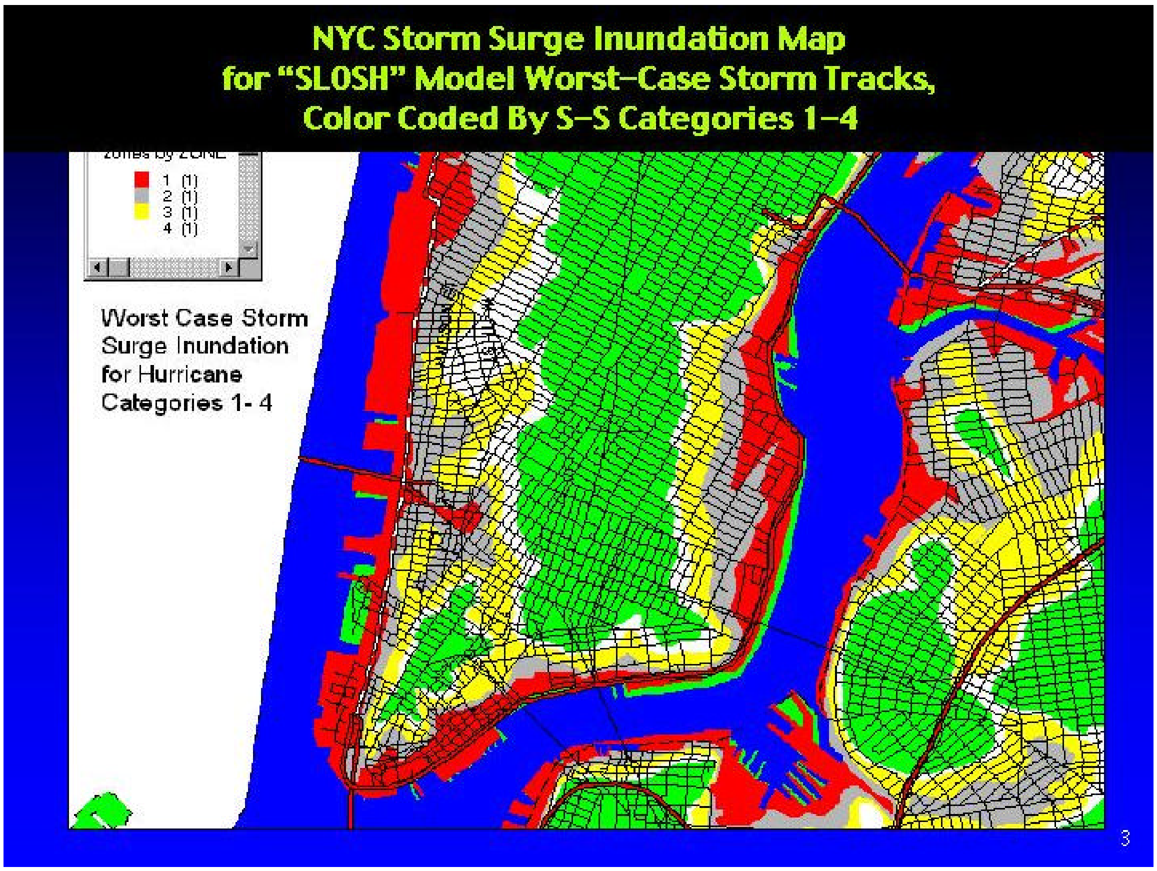

Figure 3 shows the extension of expected flood areas for SS category 1 through 4 in lower Manhattan based on "SLOSH" model worst case storm tracks. Red=SS1; gray = SS2; yellow = SS3; white = SS4 flood zones. Green area is not expected to flood ever.

The distribution of inundated areas during the cresting of the worst-track storm surges is shown in Figure 3 for lower Manhattan and portions of Brooklyn. Note that for a SS 2 worst case storm track, Manhattan will be divided into two islands along Canal Street. The southern island will included the Wall Street financial district and City Hall, while the rest of Manhattan will be north of Canal Street, and north of the flooded entrance to Holland Tunnel (marked as red incursion for a SS 1 storm, near the west side of Manhattan, facing the Hudson River). Examples of transportation systems expected to be flooded for varies storm categories are shown in Figures 4 and 5.

Figure 4: (Left): Expected storm surge level at Manhattan entrance of the Brooklyn-Battery Tunnel for a worst case storm track of a SS Category 1 storm.
Figure 5: (Right): Same for the South Ferry number 1 & 9 subway station entrance, at the southern tip of Manhattan, for a SS Category 2 storm. Both cases apply to current sea levels. Below we address the increased flood heights for various models of sea level rise.

No probabilities were associated with the worst case scenarios of the NOAA / USACE computations using the SLOSH model. Simple estimates indicate these probabilities are expected to be low. We will revisit the probability issue.

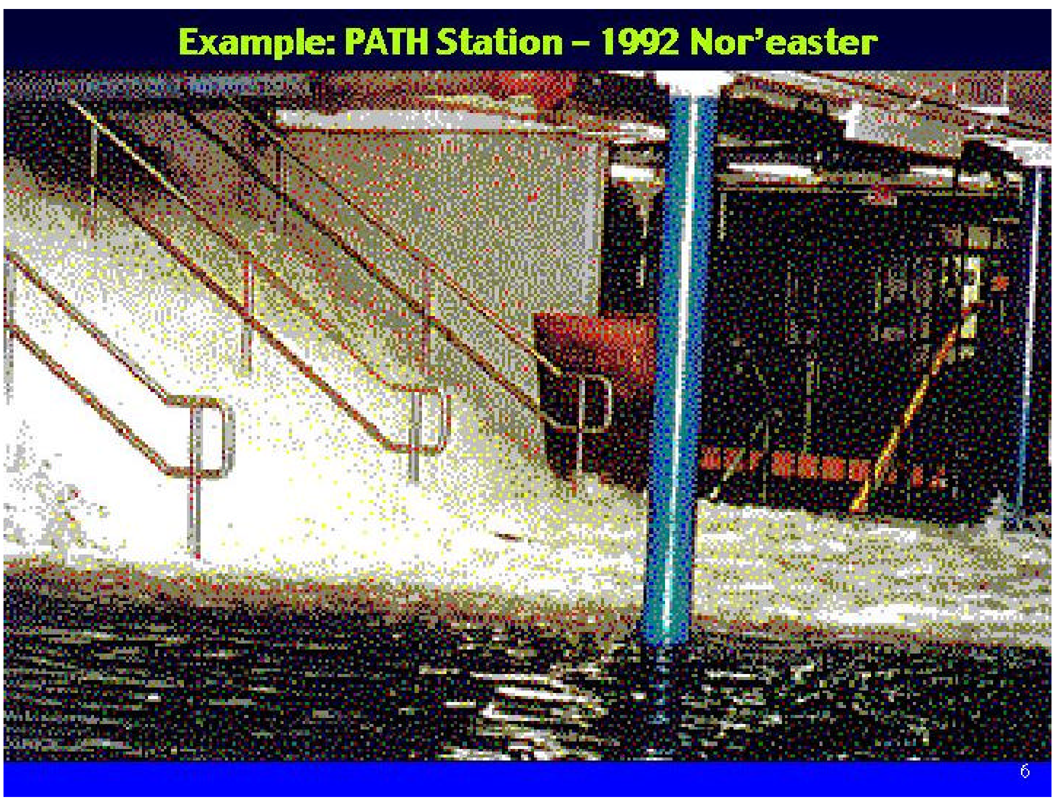

Figure 6: PATH train entrance in Hoboken, NJ, flooded during a 1992 “Nor’easter” winter storm. Repairs kept the commuter traffic through the PATH tunnel under the Hudson to the World Trade Center in Manhattan interrupted for 10 days, until the Port Authority of New York and New Jersey could restore this crucial service.

Flooding during storms in the MEC region is documented for several cases from the recent past. Figures 6 through 8 show locations where 'nor'easters' inundated different transportation systems in the New York -MEC region.

Figure 7 (left): The FDR-drive along the East River of Manhattan during a 1992 "Nor'easter" winter storm. **Figure 8 (right):** The La Guardia Airport flooded on Nov. 25, 1959 during a "Nor'easter".

The detailed report by Jacob et al. (2001a) presents additional examples and provides detailed information on SLOSH model computations by NOAA/ASCE teams for storm surges in the entire NY-NJ-CT tri-state area of the MEC region.

So far deterministic scenarios and actual events have been discussed, without addressing any rates of occurrence or probabilities. Also we assumed sea level to be static at its observed state in the 1990-2000 decade. We now turn to a probabilistic approach and superimpose the effects of sea level rise projections on increasing future storm surge heights and occurrence rates.

Probabilistic Storm Surge Heights and the Effects of Sea Level Rise.

The first step is to determine recurrence periods of historic storm surges in the NY City coastal area. We rely on a regression of observed storm heights vs. frequency near Coney Island, NY, obtained by the USACE (see Gornitz, 2001). The resulting probability distribution is discussed below.

The second step is to account for the effects of sea level rise. There are several contributions to sea level rise. Global warming is at least partially caused by the release of man-made green house gases such as CO_2. The warming climate thermally expands the water in the oceans. This expansion contributes anywhere from about 1/2 to 2/3 of the rate in sea level rise near New York. Other contributions come from melting glaciers. A third contribution originates from glacial unloading and rebound of the North American continent's lithospheric crust since the last glacial period about 10,000 years ago. The North American ice sheet extended then as far south as New York City. Around Hudson Bay in Canada, the continent still rises, while near New York City the continent continues to "sink into the ocean" (actually into the Earth's viscous mantle) because of isostacy, elastic properties of the Earth's "lithosphere", and the disappearance of the ice load many thousand years ago. Figure 9 shows the sea level rise curves for the 21st century in the vicinity of New York City for various climate model scenarios (for details see caption of Figure 9, and Gornitz, 2001).

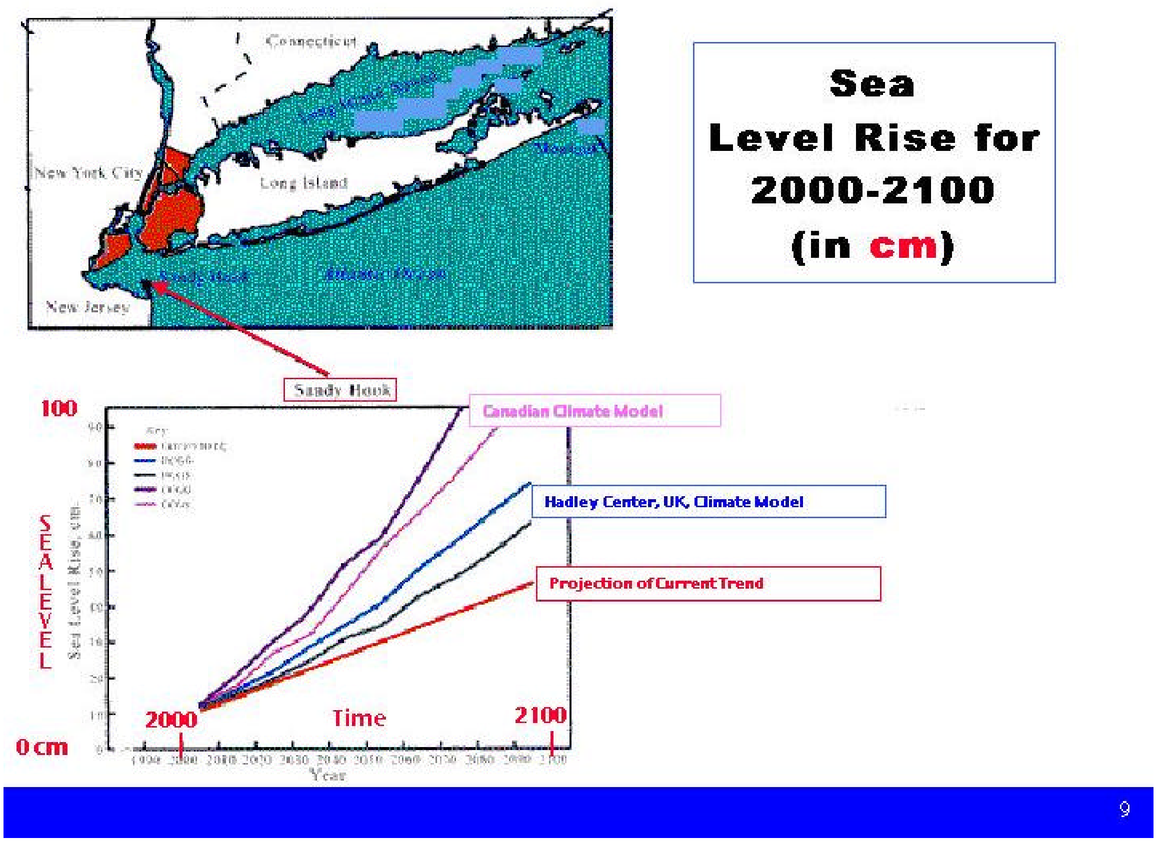

Figure 9: Area map with location of Sandy Hook (top) to which the five sea-level rise curves (bottom) apply. The upper pair of curves in the bottom graph are for the Canadian Climate (CC) model, the middle pair of curves are for the Hadley Center (HC), UK, climate model; the single lower curve is the forward projection into the 21st century of the empirical sea-level rise trend from several decades prior to the Year 2000. The stronger sea level rise in the CC and HC pair is for warming due to green house gases (GG) only - without accounting for additional aerosols being released into the atmosphere, while the lower ones account for the reduced warming from additional aerosols. For the average effect of sea level rise on frequency of storm surges we use the mean of these models, closely coinciding with the upper curve of the HC pair .

Let us now focus on the sea-level rise curve associated with model CCGG (Fig. 9, bottom graph's upper-most curve). This model has the steepest sea level rise (SLR) of the five models used in this study. We combine this SLR model with a list of lowest critical elevations of important transportation systems to evaluate their probabilities of being flooded by storm surges. The CCGG model provides the following properties for the storm surge heights as a function of time (Figure 10):

• The increase in surge heights between the decades starting in 2000 and 2090 amounts to at least 1m (3ft).

• Surge heights associated with an average recurrence period T at the beginning of this century (2000) will be reached at the end of this century (2100) with an average recurrence period T/10, i.e. about 10 times shorter.

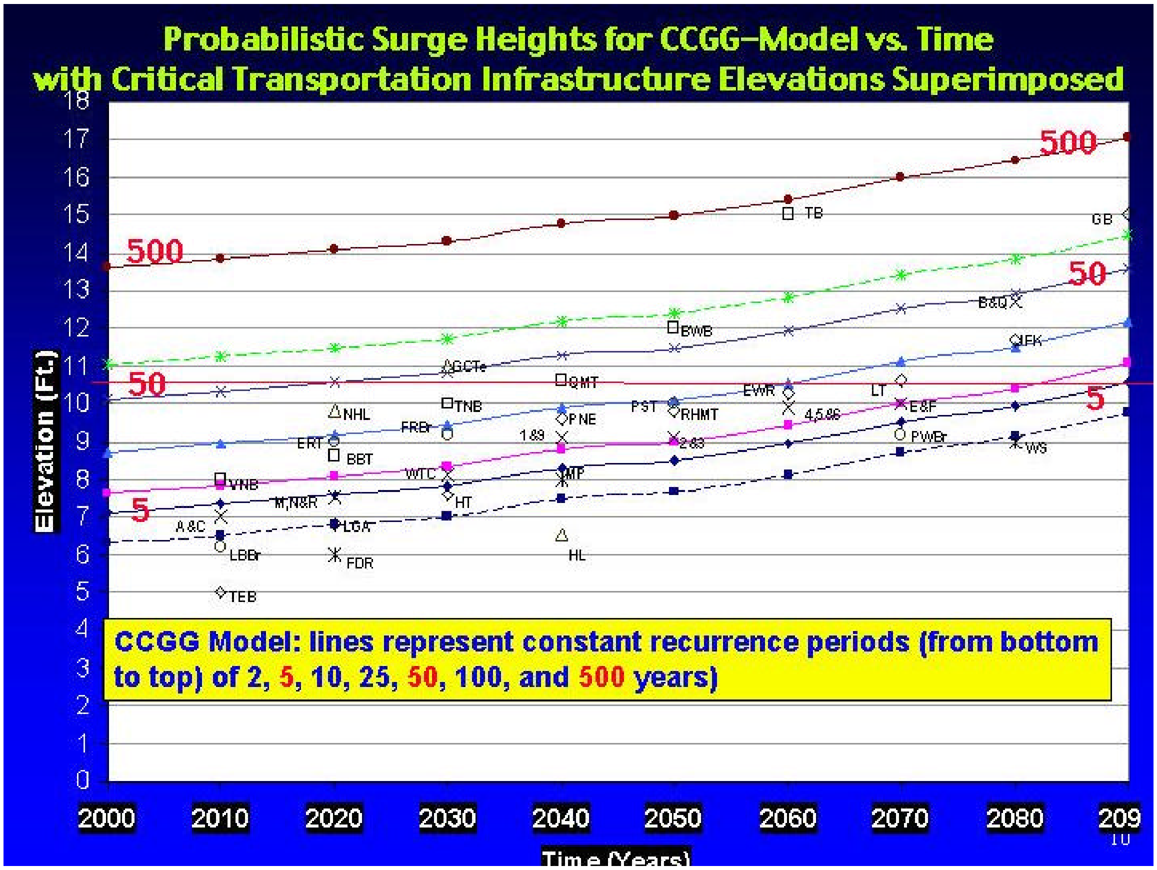

Figure 10: Seven storm surge height curves (in ft) plotted vs. time between 2000 and nearly 2100. There is one curve per constant recurrence period (i.e. for 2, 5, 10, 25, 100, and 500 years, respectively). The crosses show the lowest critical elevations of important transportation systems in the NYC – MEC region. Note that a 10 ft flood in 2000 is about a 50-year event; but it becomes a 2- to 5-year event by the year 2100.

For instance, for the CCGG model, a 10-foot surge height in 2000 requires a 50-year storm; the same 10-ft surge is being produced in the decade starting in 2090 by a storm with a 2 to 5-year recurrence period. In other words, weaker storms will then achieve the same flood level as a stronger (and rarer) storm does today. This drastic shortening of the recurrence periods of surge heights is simply due to the SLR, not due to any change in meteorological storm frequency, which we assume to be constant throughout the century. Should the storm frequency also increase, then this may contribute a further shortening of the average recurrence period for a certain storm surge height to be reached. If we keep the wind storm frequency constant (as we do in this study), SLR has the effect that weaker wind storms (which are more frequent than stronger ones) in the year 2100 reach the same flood levels as stronger (i.e. less frequent) storms in the years 2000. That is to say, even if (wind) storm frequencies stay the same, the surge frequencies increase with SLR (and time). To fully appreciate this result, it is important to distinguish between (wind) storm frequency and the surge height frequency, where surge height is defined relative to a given object or vertical reference datum attached to the solid Earth in this region (as all built structures or geodetic markers are).

Critical Transportation Facilities, Sea Level Rise, and Storm Flood Hazard Curves for the Decades between 2000 and 2100.

Superimposed on the probabilistic surge height curves in Figure 10 are the lowest critical elevations of transportation infrastructure systems in the MEC region. This graph provides insight into the likely consequences of SLR on the flooding hazards for the MEC's transportation infrastructure. Figure 10 uses the CCGG climate / SLR model together with the MEC's key transportation systems' lowest critical elevations. The fact that we plot the facility elevations as a function of time serves only the visual convenience to spread them out to avoid overlap, and no particular meaning should be attributed to this feature. Only their elevations are of significance. The main results from this juxtaposition of SLR-modified surge heights with. critical heights of infrastructure systems are:

• Factors by which the storm surge recurrence periods shorten between 2000 and 2100 for the extreme CCGG model measure about 10 . However when the mean of all sea-level rise models is taken (not shown), then a mean value for shortening the recurrence periods for the entire ensemble of five SLR models is about a factor of 3.

• Most of the critical lowest elevations of the infrastructure systems listed are between 6 and 20 ft above NGVD, with a majority towards the lower elevations of this range. Therefore, there are very few transportation systems that may escape to be flooded during the century that just began. In fact for the two thirds of the facilities whose elevations are at or below 10ft above NGVD, flooding by the end of the 21st century may occur on average at least once every decade, and for some facilities every few years.

Storm Risks and Expected Future Losses.

In contrast to computer models for earthquake losses, quantitative models for storm losses are in an early stage of development. Jacob et al (2001a) use instead a semi-empirical heuristic method to obtain first-order estimates of future losses from storms expected to hit the MEC region. Losses from past storms in the region, corrected for past inflation and growth of the asset base, plus storm losses from elsewhere in the US, normalized to their respective asset base, were used to derive approximate expected loss estimates for the NYC – MEC region. For details see Jacob et al. (2001a). In Table 1 we label the storms by their approximate Saffir-Simpson categories, although SS categories do not apply for nor'easters which contribute to the loss estimates. The more important relation is between losses and their expected recurrence times (also known as risk curve). Two recurrence periods are listed because of SLR, one applying to the beginning, and the other to the end of the current century.

The expected losses for the given recurrence periods, when measured in Billions of US $, amount to about 1/3 (in 2100) to 1/10 (in 2000) of the recurrence periods measured in years. Hence, a Category 4 storm with an *average* recurrence period between 800 and 2500 years, depending on SLR, is estimated to produce a probable maximum loss (PML) in excess of US$ 250 Billion.

To obtain the total annualized loss one has to integrate over all losses weighted by (i.e. divided by) their respective recurrence periods. This yields an annualized loss on the order of about US$ 1 Billion per year, which would be easily absorbable by the $ 1 Trillion annual economy of the region since it constitutes only about 0.1 % thereof. The problem lies of course in the fact that the losses do not occur in neatly apportioned small annual rates of $ 1 Billion / year. The risk lies in a large loss exceeding tens of billions of dollars, or perhaps even $ 0.25 trillion to occur in a single year, albeit with low probability.

Table 1: Approximate Storm Risk Estimates for the NYC – MEC region:

SS Category	Recurrence Period (Years)	Loss ($Billion)
1	15 - 50	5
2	30 - 100	10
3	150 - 500	50
3-4	300 - 1000	100
4	800 - 2500	250+
	by Year: 2100 2000	

Annualized Loss $ 1 Billion/Year = 0.1% of GRP (Absorbable)
Probable Maximum Loss (PML) up to 25% + of GRP !!!

Summary of Storm Hazards and Risks.

To sum up the findings of the storm-hazard segment of this study:

• Critical components of infrastructure systems (so far the assessment is limited to mostly transportation infrastructure) are found to be currently located at elevations of 6 to 20 ft above the National Geodetic Vertical Datum (NGVD of 1929). At these low elevations many of the systems are, at present, known to be flooded every few decades.

• The expected sea level (SLR) rise of 1to 3ft by the Year 2100 increases flood frequency by factors of 2 to 10 (with a mean of 3).

• Without mitigation, probable maximum losses (PML) of US$ 10 to 250 Billion are expected every few decades to centuries, becoming more severe in the second half of the 21st century. All measures are in Year 2000-dollars.

• Annualized losses of 0.1% of the gross regional product (GRP) would be absorbable by the region’s US$ 1 Trillion annual economy.

• The problem is that the losses do not occur at this moderate annualized rate, but large losses occur in single catastrophic events (1-25% of GRP) with likely national and international economic ripple effects.

Earthquake Hazards and Risks

Earthquake Hazards. New York City is not known to be an earthquake town. In the public's mind this accolade is associated with San Francisco, Los Angeles, perhaps Anchorage, and certainly Tokyo. But New York? The problem is that the hazard, while small compared to those of the most active regions of California, is not zero; it is definable. Figure 11 shows the seismicity in the northeastern US as recorded by seismic networks for a period of only 22 years. Most of the events are moderate to small (magnitudes smaller than 4 which rarely cause any damage). But some of the events, even in this short period are above magnitude 4.

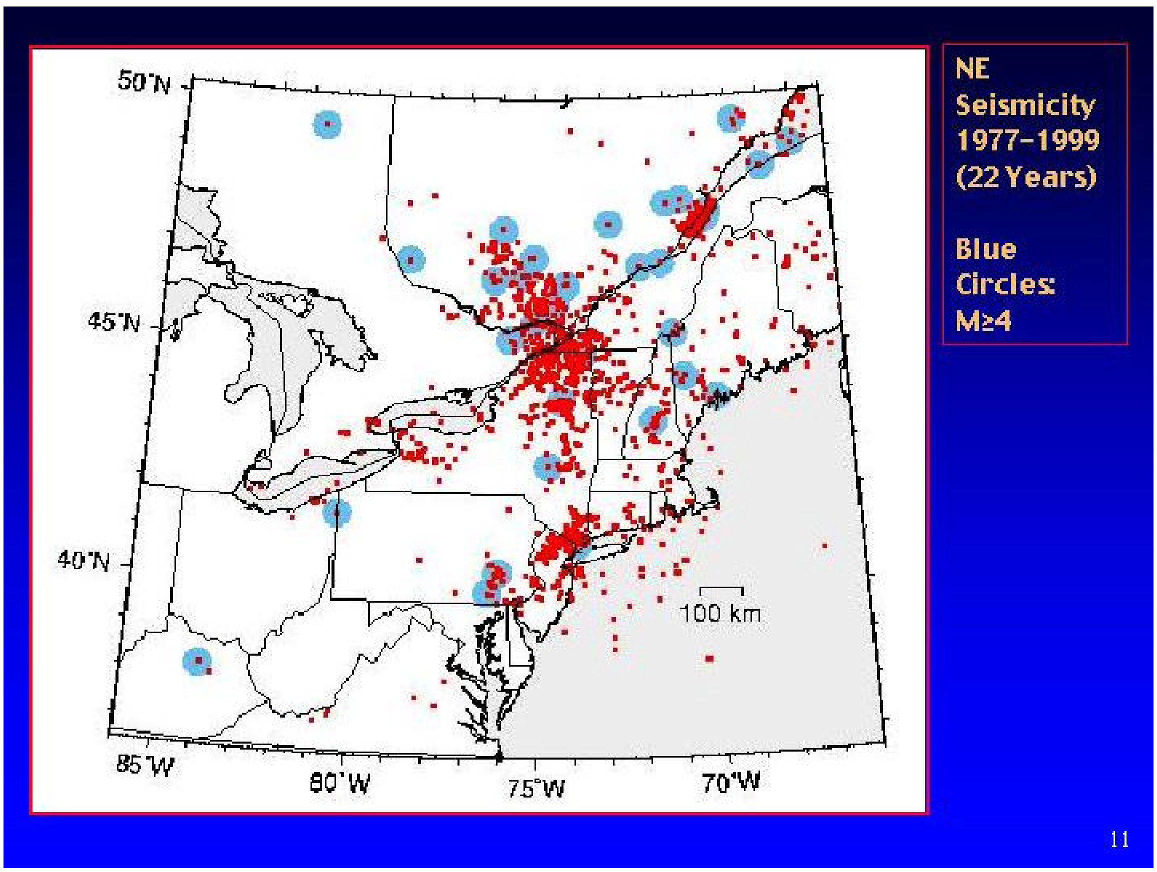

Figure 11: Instrumentally located earthquakes for a 22-year period in the northeastern US surrounding the NYC – MEC region. During this period the large majority of events has magnitudes smaller than 4. Only the events in blue have or exceed magnitudes of 4.0.

When one combines the instrumentally recorded seismicity with earlier historic seismicity largely based on felt and damage reports, one can quantify an estimated rate of seismicity for the magnitude range of damaging M5 to M7 earthquakes. One can, by global experience, extrapolate the rate estimates even for magnitudes beyond the largest historic earthquake of New York, which was a M5.2 in 1884, offshore New York, about 10 miles off Brooklyn's Rockaway section. This event toppled chimneys from northern New Jersey, throughout New York City, into Connecticut, but caused no structural collapses, and no fatalities were associated with this event. The rate of M5 events in the New York City MEC is about one event every 100 to 200 years.

These seismicity rates and spatial patterns, when combined with established ground motion attenuation relations can be translated into a probabilistic seismic hazard map. Ground motion attenuation relations tell how ground motion shaking diminishes with distance for any given magnitude. The probabilistic hazard map tells the ground motion level that will be reached or exceeded with a predefined probability in a pre-defined exposure time. The combination of the latter two translates into an average recurrence period for the ground motion.

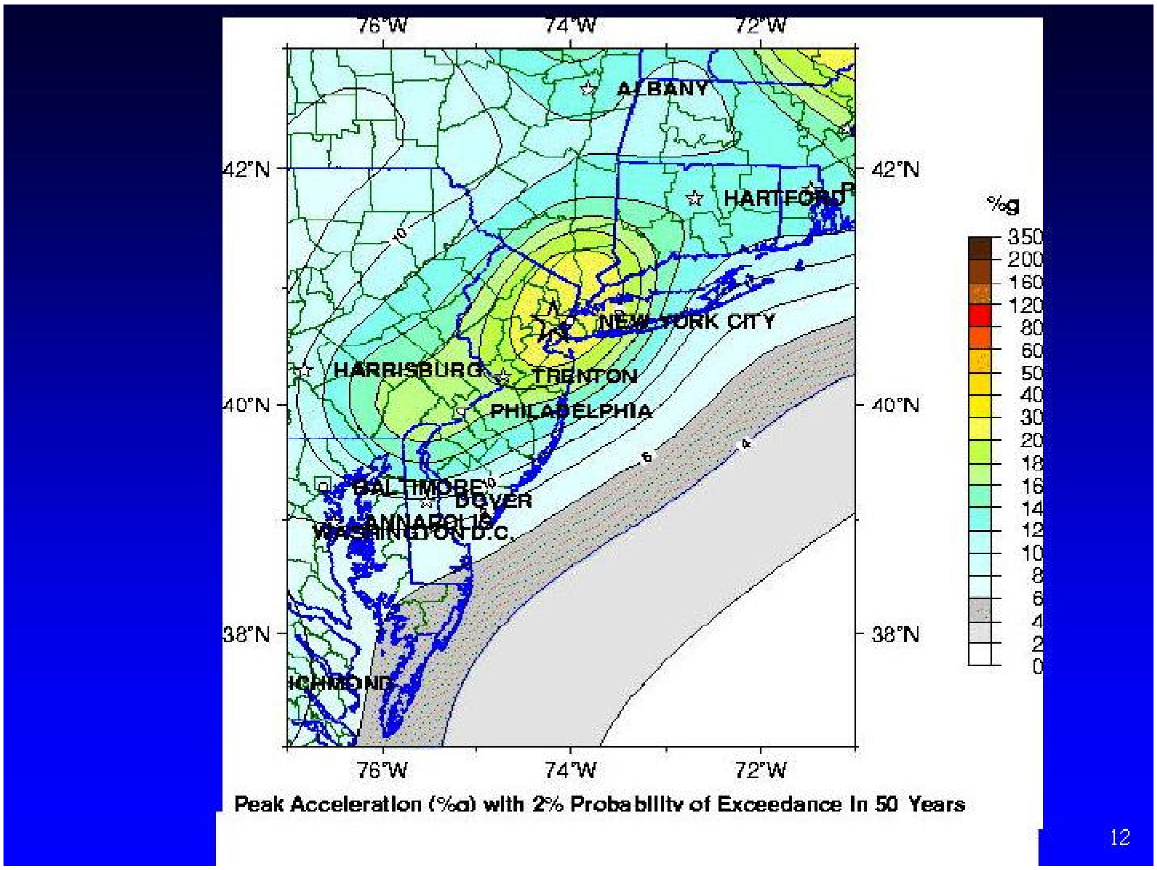

Figure 12: Probabilistic seismic hazard map produced by the USGS showing the expected horizontal peak ground acceleration (PGA) measured in %g (1g = 981 cm/s/s is the Earth's gravitational acceleration). The mapped values are for an exceedance probability of 2% in 50 years (which corresponds to an average recurrence period of about 2500 years). The shaking values apply to a specific surface rock condition as a reference. Actual shaking values need to be modified for other soil or rock conditions.

Figure 12 shows such a probabilistic seismic hazard map produced by the USGS for the New York City – MEC region. The ground motions are defined in terms of acceleration and measured in % of g, where g is the Earth's gravitational acceleration (1g = 981 cm/s/s). The exceedance probability chosen for this map is 2% in 50 years, which implies a 98% chance that the depicted ground motions will NOT be exceeded in that exposure period. It also implies an annual probability of about 0.0004 = 1/2500 per year , or an average recurrence period of about 2500 years for the mapped horizontal peak ground accelerations.

This kind of map depicting probabilistic seismic hazard is used as the basic input for seismic building codes in giving guidance how to design structures to be resilient against earthquakes. However, some additional information is needed to assess the level of shaking at a given construction site. The type of rocks or soils at and near the surface highly modify the ground motions. Hence the shown map (Figure 12) is only for a given reference geology or site condition that may be defined as "firm rock", or in code language, site class B. There are harder rocks and softer soils than this reference site class. For these the National Earthquake Hazard Reduction Program (NEHRP) defines in its seismic building code provisions the site classes A through E, based on soil parameters in the upper 100 feet below grade. Each of these site classes is associated with a set of multipliers that diminish or amplify the ground accelerations according to the stiffness of the materials at this site, and for various spectral frequency bands.

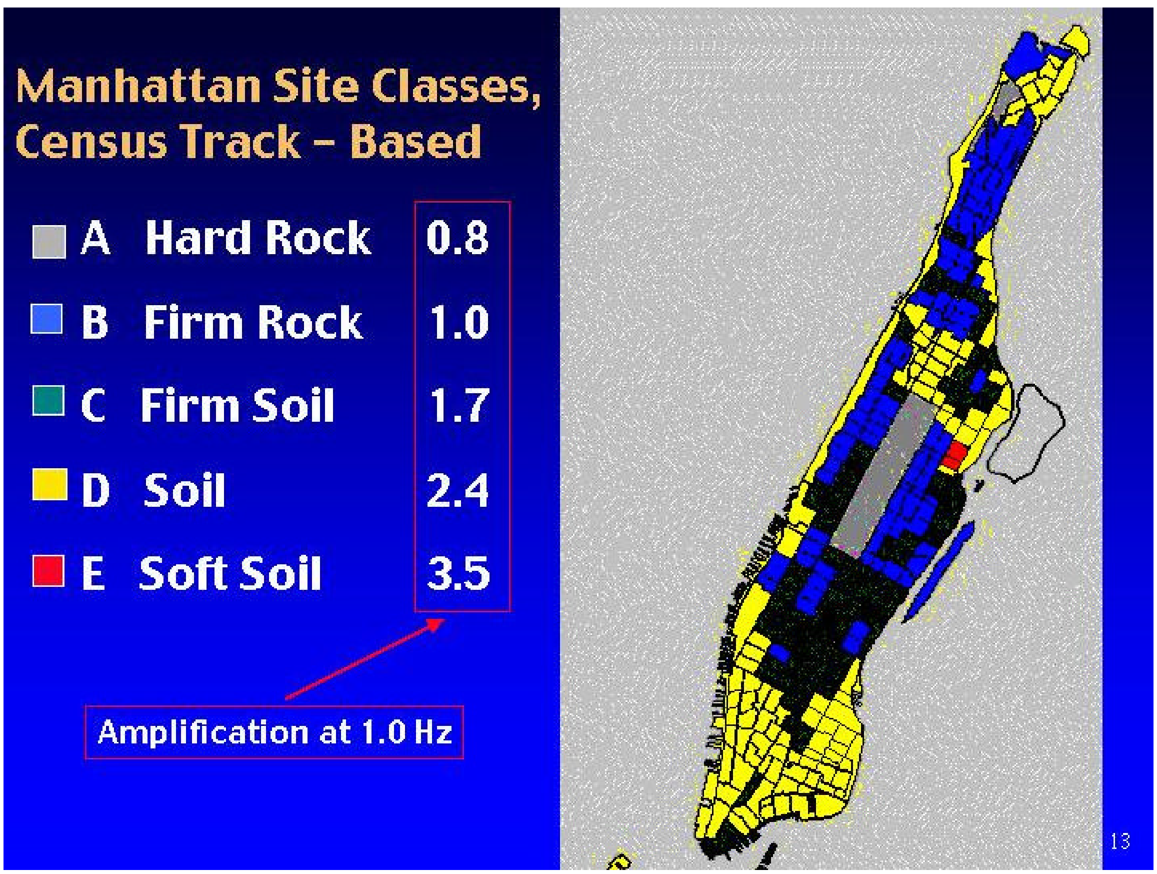

Figure 13: Microzonation map for Manhattan showing the color-coded NEHRP site class for each census tract (on the right), and (on the left) the site amplification factors for all NEHRP site classes that the scenario or probabilistic ground motions need to be multiplied to account for the modification of shaking by the local soil and rock conditions. These amplification factors apply for a spectral building period of 1.0 sec (which implies buildings about 10 stories high).

Figure 13 shows a site classification map for Manhattan, derived as part of the "NYCEM"-project (Jacob et al., 2001b). The map shows for each census tract in Manhattan the dominant NEHRP site class and, in the legend on the left, the site amplification factors associated with the site classes. These factors are, in general, dependent on the input ground motion level and on the spectral period of the ground motions. The factors depicted in Figure 13 apply to the spectral ground motion period of 1.0 sec (that is the natural period to which buildings with a height of about 10 stories are most sensitive), and to ground motions typical for NYC for a 2% in 50years exceedance probability.

Earthquake Risk Estimates.

As pointed out earlier, and as defined in equation (1), hazard is only one component to risk. The other components are the *assets* exposed to the hazard, and the *fragilities* of these assets, defined at various hazard levels (ground motion acceleration levels). The NYCEM project aims at mitigating against, and reducing, earthquake losses in the NYC-MEC region. NYCEM uses as one of its tools the HAZUS (1999) software package to compute estimates of expected losses, either for given scenario earthquakes with given magnitude and location, or of probabilistically defined annualized losses using the USGS probabilistic seismic hazard maps as hazard input in conjunction with soil site maps as shown in Figures 12 and 13, respectively.

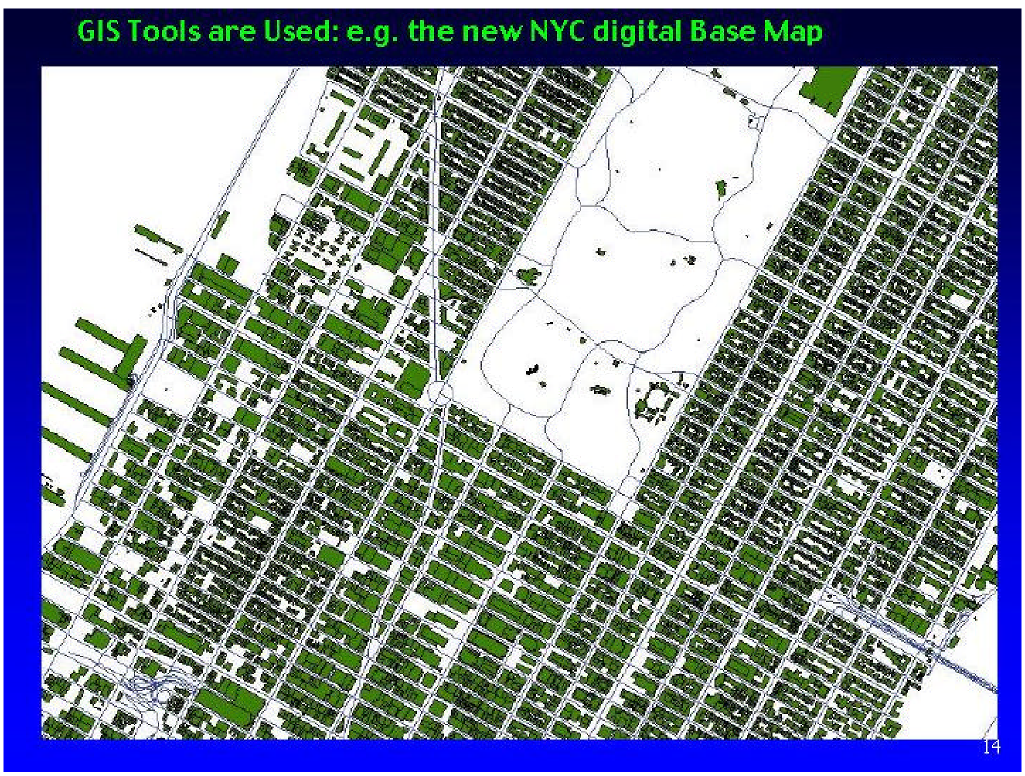

Figure 14: To obtain an accurate inventory of assets, and to map these in detail, a number of different data sources were used. Some consisted of tax-records for the real estate properties in NYC, others involved new high-resolution digital base maps used in conjunction with Geographical Information Systems (GIS). The example above shows the mid-town area in Manhattan near the South end of Central Park.

To obtain an accurate inventory of built assets, a variety of sources were used, including real estate tax records and modern GIS-based mapping tools. Figure 14 shows such a Geographical Information Systems (GIS) based map of the buildings in a section of

Manhattan. It straddles the southern portions of Central Park, and covers the business district in mid-town Manhattan. It is largely based on the new digital base map of New York City. At many locations outside the city boundary, less accurate data bases had to suffice.

The fragilities had to evaluated and modified from the default value input data sets provided by HAZUS (1999). For details see Tantala et al. (2001, and this volume).

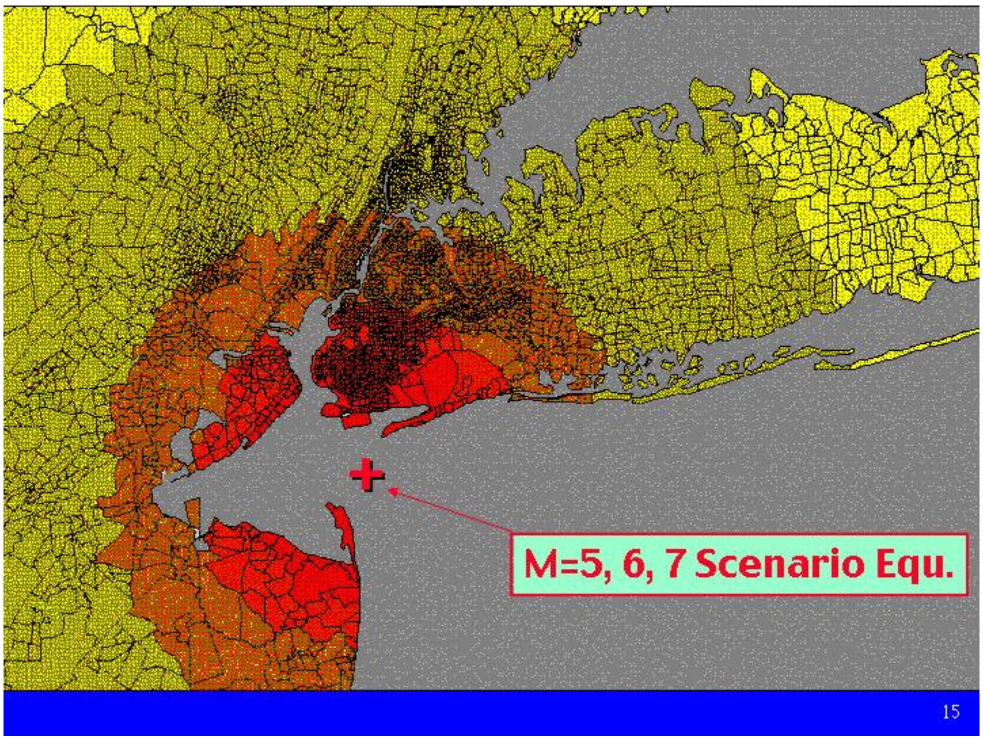

Figure 15: Map of the scenario event location coinciding with the M=5.2 earthquake of 1884 near the entrance to New York Harbor. The magnitudes of the scenario earthquakes for the HAZUS loss estimation runs are M=5, 6, and 7. Colors show schematically the reduction of ground shaking with distance, yet unmodified for site conditions exemplified in Figure 13.

The risk or loss estimates were computed for several hazard inputs, including the scenario events of M5, M6 and M7 shown in Figure 15 . Their location coincides approximately with that of the historic 1884 earthquake of M5.2. The computed building-related losses are shown in Figure 16. They amount, just for Manhattan alone, to US$ 0.7 Billion, 10 Billion, and 43 Billion, respectively for the three magnitudes. These estimates leave out the infrastructure- and lifeline-related losses. When figured in they may almost double the losses related to all direct physical damage. Many other disaster aspects have been modeled for these events such as impacts on hospitals to function, schools in their capacity to provide shelter for people displaced from damaged homes, and for the water distribution system and fire houses for their capacity to fight fires. For details see Tantala et al. (2001, and this volume).

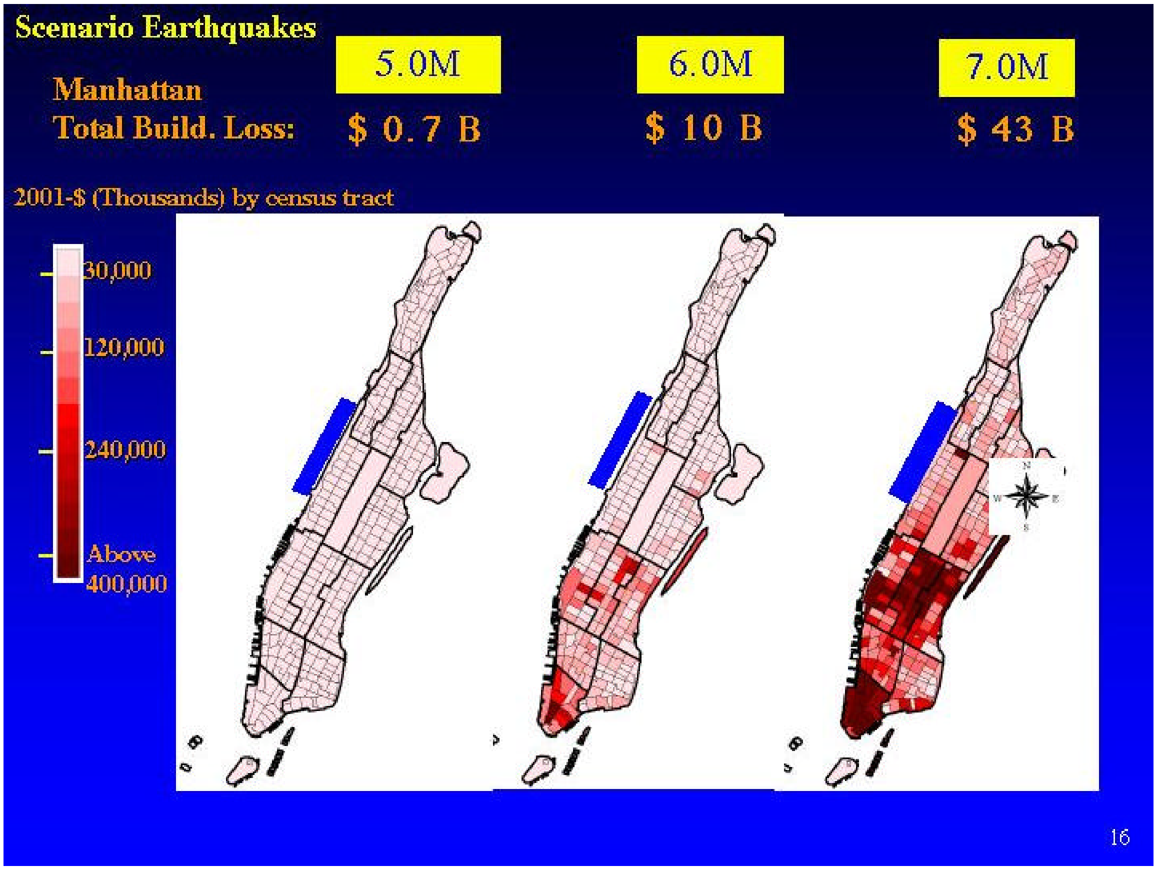

Figure 16: Maps of building-related earthquake losses, by census tracts in Manhattan, for (from left to right) the M=5, M=6, and M=7 scenario earthquakes at the location depicted in Fig 15. The total building-related losses for all of Manhattan are $ 0.7 billion, 10 billion, and 43 billion for the M5, 6 and 7 quakes, respectively.

We show here only one other result, i.e. the debris produced by building damage (Figure 17). The estimates, again for Manhattan alone yield about 0.1, 6 and 27 megatons of debris, for the three events, respectively. This implies, when carried by 10-ton truck loads each, about 9-thousand, 600-thousand , and 3-million truck loads respectively. For comparison, note that the debris from the 9/11/2001 attacks on the World Trade Center (WTC) towers resulted in debris of about 1.2 Million metric tons, about $1/5^{th}$ of what the scenario M6 is expected to produce just for Manhattan alone, excluding additional debris outside Manhattan.

Comparing at this early stage of preliminary results the magnitude and annual probabilities of economic losses from storms and earthquakes, it appears that storm risks outpace earthquake risks in the NYC-MEC region. This applies to both the annual average losses and to the probable maximum losses (PML) for the most extreme events. Additional work needs to be done to refine these preliminary findings. If the currently available loss estimates for the 9/11/2001 WTC attacks in the order of US$ 80 to 100 Billion, of which about $60 Billion are insured losses, should be confirmed, then it follows that maximum losses from extreme natural scenario events, albeit with annual probabilities of less than 10^{-3} per year, could *exceed* those of the WTC disaster. The main difference would be that the damage would be spatially more distributed, compared to the highly concentrated physical damage in lower Manhattan during the 9/11/2001 events and their aftermath. Depending on insurance penetration for the specific natural hazards, which differs for flood, wind and earthquake, the insured losses could be lower or higher than for the WTC. Storm-related fatalities are expected to be lower because warning should allow timely evacuations and other precautions. Any warnings are highly unlikely in case of an earthquake.

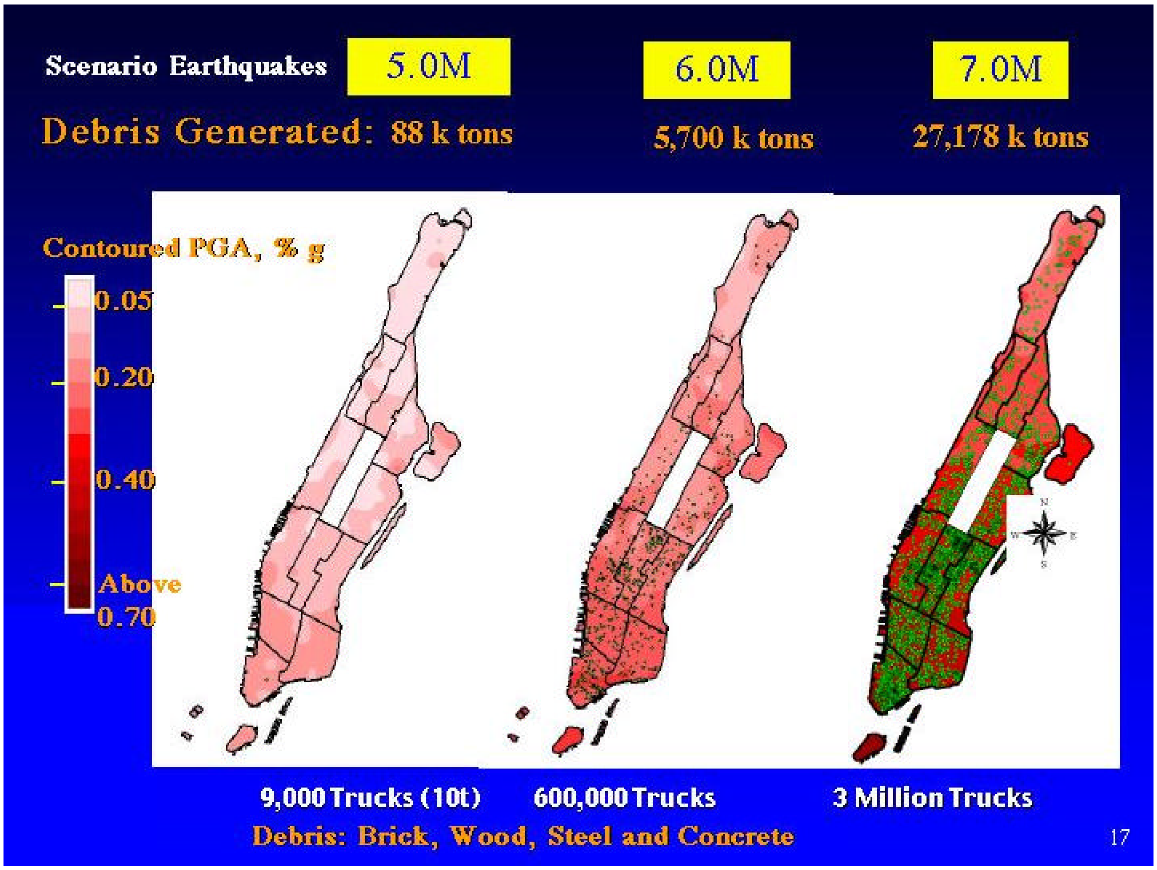

Figure 17: Amount of debris generated just in Manhattan for the three scenario earthquakes M5, M6, and M7. Amounts measure 88-thousand 5.7-million, and 27-million metric tons of debris, respectively. When transported by 10-ton trucks they would require about 9-thousand, 600-thousand and 3-million truck loads, respectively. For comparison, the WTC collapse of Sept. 9, 2001 produced about 1.2 million tons of debris.

Risk Management Options

How can the risks outlined here be managed? Windows of opportunity for engineered risk mitigation often arise *after* major disasters, during the reconstruction phase. It is therefore prudent and urgent for those in charge of rebuilding lower Manhattan's WTC facilities and related infrastructure systems to take the outlined flood and earthquake hazards fully into account. The flood potential for the entrances to the subway and PATH systems in and around the WTC "ground zero" sites must be by all means avoided, and can be achieved with prudent planning for raising the critical minimum elevations (entrances, ventilation shafts etc.). A minimum value of 20ft above NGVD of 1929 would eliminate the more likely floods, and 30ft above NGVD would eliminate virtually every flooding. Apart form this special case in the aftermath of the 9/1//2001 events, what can be done and what is being done or already has been done, and what has *not* been done?

Seismic Building Codes. In New York City a seismic building code became effective February 1996. It applies only to new construction and hence it may take more than a century before a considerable fraction of the building stock is replaced by more seismically resilient structures. In particular the large percentage of unreinforced masonry ("brownstones" and other older town houses) are of great concern and pose a considerable threat to lives, especially for local events approaching M6 or larger. A few federal buildings of pre-1996 vintage have been retrofitted as part of a general upgrading program. Amongst them is the Federal Court House in Manhattan. New Jersey and Connecticut have adopted seismic building codes, *but New York State has not yet. This is a situation which needs to be rectified urgently.*

Bridges and Other Essential Facilities. With federal encouragement and support, the NY State and NY City Departments of Transportation have adopted internal guidelines for seismic construction of highway and bridge structures and for retrofits during regular upgrades and major repairs. Other regional bridge owners such as the Metropolitan Transportation Authority, the Port Authority of New York and New Jersey and others have started to investigate the seismic performance characteristics of their existing bridges. There are several thousand highway and rail bridges in the NYC-MEC region, and they include some of the larger suspension and steel bridges in the nation. Nuclear reactors (e.g. Indian Point some 30 miles north of NYC on the Hudson) are designed for seismic events and periodic reviews of their seismic performance criteria are undertaken by the US Nuclear Regulatory Commission (USNRC).

Table 2: Examples of Critical Structures & Facilities in the extended NYC-MEC region that are Undergoing, Scheduled or have been Completed for Seismic Retrofit./Design:

- Major Bridge Retrofit Work & Studies:
  - Delaware Memorial, NJ/DE
  - Whitestone NYC
  - Tappan Zea, NY
  - Queensboro NYC
  - Williamsburg. NYC
  - Manhattan, NYC
  - George Washington NY/NJ
  - Other smaller bridges across the Harlem River and numerous non-river highway crossings and elevated overpasses especially in NYC.
- Nuclear Power Facilities, Indian Point
- JFK Airport International Arrival Bldng.
- Federal Court House in Manhattan
- West Point Military Academy

Table 2 lists some of the critical facilities in the greater NYC-MEC region that are currently undergoing seismic reviews, design, retrofits or are scheduled to be investigated. One of the structures already undergoing seismic redesign and retrofit is the Queensboro Bridge connecting Manhattan with Queens across the East River and Roosevelt Island, and is shown in Figure 18.

Figure 18: One of the many bridges in New York City requiring seismic retrofitting, currently underway. This is the double-cantilevered 5-span Queensboro (or 57th Street) bridge across the two arms of the East River with Roosevelt Island at the center-span, and mid-town Manhattan in the background.

Storm Surge and Flood Mitigation. Most of the flood and storm disaster planning has concentrated largely on evacuation of populations at risk, especially during an approaching hurricane. Very little has been done to tighten up zoning laws that would prevent new building in low lying areas. In fact large assets have been added to risk-exposed water front zones in the New York Harbor and lower Hudson Valley, and on Atlantic barrier islands, both in the states of NY and NJ. Sea level rise has not been taken into account in existing flood zonings. *This is an issue of utmost urgency*. Many tens of billions of US $ in assets are exposed. It is only a matter of time before a major coastal storm surge disaster will strike the area with losses in the tens to hundreds of billions of US $.

General Guidelines for Reduction of Risk Exposures: Some general guidelines for both, the private and public sectors (the latter including state and local governments, counties, cities, towns and villages) emerge from the basic relation we already discussed:

Risk = ? (Hazard x Assets x Fragility)

An important part of risk management is to minimize the spatial sum of these three factors. Some of the consequences from this relation for risk management can be summarized as:

- Update Hazard Maps for the Most pertinent Hazards in the Region / Jurisdiction.
- Be Aware of Tails of Probability Distributions -> Extreme Catastrophes.
- Evaluate Hazards and Risks at the Appropriate Probability Level Especially for Critical Facilities.
- Avoid Placing Valuable Assets into Hazardous Zones.
- Implement Regional/Urban Planning, Landuse, Zoning, Regulations & Codes.
- Reduce Asset Fragility, Increase Toughness and Provide Redundancy
- Set Clear Priorities for Comprehensive Retrofit Programs
- All Major Capital Spending Programs, Whether for New or Existing Facilities Need to be Evaluated for their Risk Exposure and Should Include Risk-Minimizing Design Principles.

Other risk management principles include:

- Sound emergency response planning and preparedness help to minimize post-event losses.
- Post-event recovery / reconstruction using federal and other disaster relief funds provide unique opportunities for including mitigation measures.
- Risks for assets that cannot be resolved by proper engineering measures can be transferred and distributed by insurance, assistance & mutual support agreements and networks.

Conclusions.

Two sets of conclusions can be drawn: one for the NYC-MEC region; the other for other global megacities by learning from the NYC-MEC experience, but modifying them for conditions in often less developed, less affluent and often outright poor nations and cities.

<u>Summary and Conclusions for the New York City Metro Region.</u>:

The Greater New York City Metropolitan Region has

- low earthquake and moderate storm hazards
- high population and asset concentrations
- high fragilities of existing built assets to both earthquake and storm hazards

Therefore it follows that New York represents a classical example for

- low probability - high consequence conditions
- substantial risk exposure (tens of billions of dollars / event)
- extreme rare events (approaching 10^{-4} annual probability) may cause losses exceeding US$ 100 billion.

In particular, the greatest *seismic* risk is to extensive unreinforced masonry with high risk of collapse and threat to lives. *Storm surge* risks to transportation infrastructure systems are substantial because low elevations at critical points make these systems highly vulnerable to flooding. The flooding frequency will increase by about a factor of 3 during the coming century because of sea level rise. Given these hazards and risk exposures, emergency preparedness must be high until vulnerability will be gradually reduced through zoning, reconstruction and other measures, all of which require a systematic risk reduction master plan for the entire region. The public and private sectors must participate in this endeavor.

Generalized Conclusions for Global Megacities

1. Urbanization increases the risk from disasters on a global scale. Especially it shifts the distribution of loss size per event towards ever higher probable maximum losses (PML).

2. Hazard is probabilistically quantifiable on a global scale with current data. Microzonation of hazard requires detailed local geotechnical data for earthquake hazards, and high-resolution (cm to dm) near-shore topography for mapping out areas prone to storm surge flooding.

3. Risk/Loss modeling is reasonably well developed for some hazards but needs full inventory of built assets and their fragilities. This is marginally achievable at some significant costs for the New York City Metro region, but on a global scale, and especially in developing countries, population and per capita income may have to suffice initially as a proxy for full asset inventories.

4. Vulnerability is a complex quantity, strongly tied to lack of resources, redundancy and coping capacity. In developing countries it is often tied to poverty, income-inequities, and the exclusion of large sectors of civil society from the political process. It is hard enough to quantify vulnerability just for a single hazard. While there may be common causes for vulnerability to different hazards (e.g. for earthquakes, floods, storms, draughts, ….), vulnerability has clearly hazard-specific aspects.

5. Risk Management: Pre-event preparedness and mitigation are as important as post-event recovery. Any remaining unmitigatible risks can be distributed via insurance which in developing countries is not readily available or affordable for a large sector of the population and economy. Unclear land title rights often exacerbate the situation. Risk management requires strong institutions and resources that are not readily available in developing countries. This is a major development issue of global scale.

References.

Gornitz, V., (2001) Chapter 3: Sea-Level Rise and Coasts (pp. 19-46). In: C. Rosenzweig and W. Solecki (Edit.), Climate Change and a Global City: The potential consequences of climate variability and change. Metro East Coast (MEC). A Report of the Columbia Earth Institute for the U.S. Global Change Program. Columbia University, July 2001. ISBN 0-9713347-0-6.

HAZUS (1999). FEMA Tool for Estimating Earthquake Losses, NIBS/FEMA, Washington D.C., 2 Basic CDs (Eastern & Western US), and User Manual. plus 1CD per State; for Windows OS., 1999.

Jacob, K.H. N. Edelblum and J. Arnold., (2001a) Chapter 4: Infrastructure (pp. 47-65). In: C. Rosenzweig and W. Solecki (Edit.), Climate Change and a Global City: The potential consequences of climate variability and change. Metro East Coast (MEC). A Report of the Columbia Earth Institute for the U.S. Global Change Program. Columbia University, July 2001. ISBN 0-9713347-0-6.

Jacob, K.H. N. Edelblum and J. Arnold., (2001b). NEHRP Site Classes for Census Tracts in Manhattan, New York City. NYCEM 2nd-Year Technical Report: December 31, 2000. Earth Science Tasks: October 1, 1999 - September 30, 2000. Lamont Doherty Earth Observatory, Palisades NY.

Rosenzweig, C. and W. Solecki (Edit., 2001), Climate Change and a Global City: The potential consequences of climate variability and change. Metro East Coast (MEC). A Report of the Columbia Earth Institute for the U.S. Global Change Program. Columbia University, July 2001. ISBN 0-9713347-0-6.

Tantala, M. W., Nordenson, G.J.P., and Deodatis, G., (2001), "Earthquake Loss Estimation Study for the New York City Area," NYCEM Year 2 Technical Report, 1999-2000.

Webresources

Storm Surge Hazards: http://metroeast_climate.ciesin.columbia.edu
Earthquake-Hazards: http://www.nycem.org
Risk management as a global sustainable development issue:
http://www.columbia.edu/cu/sipa/COURSES/2001-2002/u6760.html