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Urbanization, climate change and flood policy in the United States

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Abstract The average annual cost of floods in the United States has been estimated at about $2 billion (current US dollars). The federal government, through the creation of the National Flood Insurance Program (NFIP), has assumed responsibility for mitigating the societal and economic impacts of flooding by establishing a national policy that provides subsidized flood insurance. Increased flood costs during the past two decades have made the NFIP operate at a deficit. This paper argues that our current understanding of climate change and of the sensitivity of the urban environment to floods call for changes to the flood policy scheme. Conclusions are drawn on specific examples from cities along the heavily urbanized corridor of northeastern United States. Mesoscale and global models along with urbanization and economic growth statistics are used to provide insights and recommendations for future flood costs under different emissions scenarios. Mesoscale modeling and future projections from global models suggest, for example, that under a high emissions scenario, New York City could experience almost twice as many days of extreme precipitation that cause flood damage and are disruptive to business as today. The results of the paper suggest that annual flood costs in the United States will increase sharply by the end of the 21st Century, ranging from about $7 to $19 billion current US dollars, depending on the economic growth rate and the emissions

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scenarios. Hydrologic, hydraulic and other related uncertainties are addressed and a revised version of the NFIP is suggested.

1 Introduction

The United States has a long history of catastrophic flooding. In the last half of the 20th century (1950–1997), the National Weather Service reports an average of 110 deaths per year in flood-related accidents. For almost the same period (1950–2003), the most comprehensive analyses of annual flood costs in the United States suggests an annual average of $2.0 billion current US dollars (Pielke et al. 2002; Pielke and Downton 2000). More recent research results based on insurance data suggest this number to be $2.7 billion current US dollars per year (Changnon 2008). Similar research shows that weather-related losses steadily increased in the last half of the 20th century with a sharp increase in the period 1989–1997 where the sum of insurance costs and disaster assistance funds averaged $9.8 billion per year (current US dollars, Kunkel et al. 1999).

Floods in the conterminous United States are caused by a broad range of weather phenomena (see e.g. O'Connor and Costa 2003, 2004; Droegemeier et al. 2000; Changnon et al. 2001). Quantifying the geographic variation in flood risks associated with hurricanes, organized thunderstorm systems and extratropical cyclones is a daunting scientific challenge. This challenge is made more difficult by the emerging consensus (IPCC 2007a) that human-induced climate change will alter the frequency of extreme rainfall and that the nature and degree of alteration will exhibit pronounced regional variations (Milly et al. 2008). Equally important to the quantification of regional variation of flood risks is the continuing trend to concentrate people and property in urban environments. Alterations of the land-surface environment associated with urbanization markedly increased flood magnitudes in the US during much of the 20th century for many urban watersheds (Leopold 1968). Increasing attention has also been given to the impacts of the urban environment on weather systems that produce extreme rainfall (Jin et al. 2005; Ntelekos et al. 2008; Shepherd 2005; Shepherd and Burian 2003; Changnon 1980).

In response to catastrophic riverine flooding, the federal government assumed responsibility for flood prevention with the establishment of the Flood Control Act of 1936. In its initial formulation, the Flood Control Act called for the use of engineering solutions for flood prevention. In the years that followed, floods kept occurring and annual flood costs increased (see Section 2). It was then recognized that a broader approach of floodplain management was more appropriate for dealing with flooding. This led to the creation of the National Flood Insurance Act in 1968 that established the National Flood Insurance Program (NFIP). The NFIP's main purpose was to create governmental subsidized flood insurance for qualifying communities (see Section 2) on a voluntary basis. Subsequent revisions of the NFIP made flood insurance purchase mandatory for the communities situated in the 100-year floodplain. The NFIP was last revised in 1994, providing more stringent measures of compliance and requiring a mandatory revision of the flood maps every five years (NFIP 2002).

In some respects, the NFIP provided an effective policy framework for preventing flood damage and enhancing the overall understanding and awareness of the public about floods (Sylves and Kershaw 2004; NFIP 2002). Nevertheless, the NFIP has its weaknesses and has, in the past, shown its inability to self-finance. This paper attempts a critical evaluation of the NFIP, as currently formulated, in the light of research results pertaining to the vulnerability of the urban environment to flooding and to our enhanced understanding of the climate system (see Changnon et al. 2001; Pielke 2000; Downton and Pielke 2000; Hudgens 1999 for related studies). Conclusions are drawn from analyses of flood hazards in the Baltimore metropolitan region (Ntelekos et al. 2007, 2008; Smith et al. 2005a, b, 2007; Nelson et al. 2006; Javier et al. 2007) and in the New York City metropolitan area (Ntelekos et al. 2009). The Baltimore Ecosystem Study (BES), which is an urban component of the US National Science Foundation's Long-Term Ecological Research (LTER) program, provides an exceptionally dense network of hydrologic monitoring systems for examining flood hazards.

The paper is organized as follows: Section 2 presents a historical overview of flood policy in the United States and the NFIP's current formulation and major operating components. Section 3 presents current research evidence for the implications of urbanization and climate change for flood policy. Section 4 combines results from global and mesoscale models to draw conclusions and make inferences about future flood costs. In Section 5, a low-cost modernization of the NFIP is presented. Concluding remarks are presented in Section 6.

2 United States flood policy

Major changes in US flood policy have typically followed major floods. The massive flood of the Ohio River in 1913 led to the creation of the "Committee on Flood Control" by the U.S. House of Representatives and the establishment of the Miami Conservancy District (Morgan 1951). The Miami Conservancy provided a model for subsequent flood control programs in drainage basins throughout the US, including the Tennessee Valley Authority. In 1917, Congress approved the "Flood Control Act", by which federal responsibility of floods is first acknowledged. The protection against floods was based on a "levees-only" system that was soon proven inadequate by the major disaster of the Great Mississippi River flood in 1927. In response, the Flood Control Act was refined in 1928 to include other engineering solutions (e.g. as embankments and dams) to protect against floods while the first major allocation of funds ($325 m) towards flood protection was made.

One of the most important consequences of the 1927 flood from the perspective of flood policy in the US was the decision of private insurance companies to stop providing flood insurance (FEMA 2005), due in large part to the difficulties in accurately pricing policies (see also Mills 2005). This provided an important backdrop for debate during the following decades over the federal role in mitigating the societal and economic consequences of flooding.

The first coordinated effort to deal with the adverse effects of floods was established by the Flood Control Act of 1936, which was stimulated by the Ohio River basin flooding in March 19, 1936 (NFIP 2002; Sylves and Kershaw 2004; FEMA 2005). The 1936 Act ushered in a massive program of dam building, organized by the U.S. Army Corps of Engineers, but in the years that followed flood damage costs continued to increase. The engineering structures had a two-fold impact on flood damages: On the one hand, they dramatically changed the hydrologic response of drainage basins across the US, but on the other hand, more people chose to settle in flood-prone areas because of the mistaken public perception that levees, embankments and dams would protect against any flood (White 1945; Hoyt and Langbein 1955).

The continuing cycle of devastating flooding in the decades following the Flood Control Act of 1936 led to consideration of a federal program of flood insurance (FEMA 2005). Following unsuccessful attempts at federal level for a stimulus of a private flood insurance industry in the 1950's, the National Flood Insurance Act of 1968 created the National Flood Insurance Program (NFIP). The main objectives of the 1968 Act were to create federally subsidized flood insurance for qualifying communities, to reduce future flood damages by engaging communities in floodplain management practices, and to reduce federal expenditures for disaster assistance and flood control. In its early stages, the program was voluntary and participation by communities was very limited. Revisions to the Act, typically in response to major flood episodes, expanded participation by requiring the purchase of mandatory flood insurance on all grants and loans relating to building construction or acquisition projects in what the NFIP designated as the 100-year floodplain (NFIP 2002; FEMA 2005). A major stimulus for changes to the NFIP was the Great Flood of 1993 in the Mississippi River basin (see Myers and White 1993; Gumley and King 1995).

The NFIP is administered by the Federal Emergency Management Agency (FEMA) and its mission is to identify flood-prone areas, to promote safe floodplain management practices, and to provide flood insurance to qualified communities (for more details see NFIP 2002). A major responsibility of FEMA is to create maps that identify the flood-prone areas of the nation. In carrying out this task, FEMA has adopted the 100-year recurrence flood criterion nationwide. A 100-year flood is a flood event that has 1% chance of occurring each year and has a specific inundated area associated with it. This area is identified on the flood maps of a region and is the area in which flood insurance purchase is enforced. The 100-year floodplain is calculated by both empirical methods and hydraulic modeling depending on data availability and funding. A Flood Insurance Study (FIS), which provides maps of both the 100-year and 500-year floodplain, is the most comprehensive product of floodplain delineation based on hydraulic modeling, data analysis and empirical methods. These maps are used routinely by FEMA and other officials to identify the areas in which floodplain practices are promoted as part of the NFIP, to calculate premium rates for flood insurance, and to identify areas where flood insurance purchase would be required when loans for construction and acquisition of property are granted.

Communities participating in the NFIP are required to adopt a series of minimum floodplain management measures. All development is regulated for any building/structure that lies in the 100-year floodplain zone (designated as Special Flood Hazard Area—SFHA), and strict review processes have been established to verify that new development does not conflict with safe floodplain management practices. The program is estimated to save \$1 billion annually in flood damages (Sylves and Kershaw 2004).

Property owners of NFIP participating communities are eligible for purchasing flood insurance that covers, up to specified limits, building and personal property damage. If a building was built before a Flood Insurance Rating Map (FIRM) was available for the area, Congress authorizes NFIP to provide subsidized flood

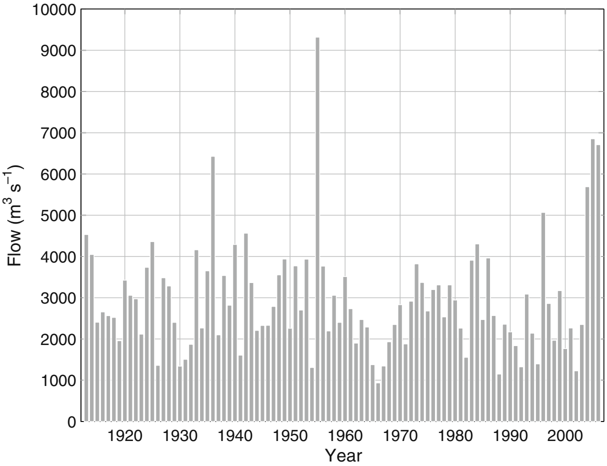

Fig. 1 Annual peak flow data measurements for the Delaware River station at Trenton (Station ID: 01463500, observation period: 1913–2006, in m^3s^{-1}, source: USGS)

insurance to the owner at a rate that is about 30 to 40% of the full actuarial rate. One of the largest financial burdens to NFIP results from repetitive flood damages to buildings that were built before the creation of flood maps. A repetitive loss is defined generally as a policy that had two or more losses of more than $1,000 each within any 10 year period. Although only about 1% of the total number of NFIP policies is classified as "repetitive losses", these policies account for about 33% percent of all paid losses (NFIP 2002).

A consequence of flood policy in the US during the past century has been to create a complex and changing environment for flood hazards. The complexity of flood hazards is illustrated by the public and technical debate over causes for three near-record flood episodes in the Delaware River basin in September 2004, April 2005 and June 2006 (Fig. 1). The Delaware River above Trenton, NJ drains portions of New York, Pennsylvania and New Jersey, has an extensive network of dams and reservoirs and exhibits diverse patterns of development. The sequence of successive flood peaks has been attributed to the impacts of development, climate change and even operation and maintenance of the reservoir system. This is fundamentally linked to the difficulties in characterizing changing flood frequency in urban environments (see Villarini et al. 2009). Although simple answers to the causes of the Delaware River flooding are difficult to obtain, one of the clear implications is that flood management policy and the methods used in implementing flood management policy must broadly account for the changing environment of flood hazards.

3 Urbanization and climate change implications

A shortcoming of the NFIP is its inability to address the inherent vulnerability of the urban environment to floods. Examples of recent, devastating flash floods in urban environments are numerous (see, e.g. Vieux and Bedient 1998; Ogden et al. 2000; Smith et al. 2002, 2005b; Ntelekos et al. 2007, 2008; Sharif et al. 2006; Changnon and Westcott 2002). Urbanization trends are increasing globally; the United Nations predict that there will be a total of 5.1 billion urban residents by 2030 (United Nations

2006). In the United States, 50 metropolitan areas exceeded one million people in 2000 compared to the 14 in 1950 (Hobbs and Stoops 2002). The NFIP currently makes no distinction in the way it applies the measures for floodplain protection between rural areas and highly urbanized cores.

The altered flood hydrology of the urban environment is illustrated through analyses of a large flood event over Baltimore, MD on July 7, 2004 (Ntelekos et al. 2008). Figure 2 shows the 100-year and 500-year FEMA floodplain maps for Dead Run, a small urbanized watershed in Baltimore, MD. Dead Run is a mixed urban-suburban watershed with a drainage area of 14.3 km^2 at the U.S. Geological Survey (USGS) stream gage located immediately downstream of the reach shown in the figure. Also shown in Fig. 2 is the mapped inundation from the July 2004 flood, showing extensive areas in which flood inundation exceeds both 100 and 500 year FEMA floodplains. Urban infrastructure, including roads, bridges, and embankments play a major role in determining floodplain extent in urban cores (Fig. 2). Conventional flood frequency analysis techniques applied to the stream gauging record from Dead Run yield a return interval of less than 100 years for the 7 July 2004 flood. The above example is illustrative of the uncertain relationship between rainfall and flood frequencies in urban settings, and of the difficulties introduced in estimating flood frequency through the combination of rainfall frequency analyses and hydrologic modeling. Estimating the 100 year and 500 year flood magnitudes is exceedingly difficult in urban watersheds like Dead Run. For related studies in different regions that deal

Fig. 2 Innundated area (*yellow*) from a July 2004 storm over an urbanized watershed (Dead Run) in Baltimore, MD and FEMA derived 100-year (*dark blue*) and 500-year (*light blue*) floodplains

with the issues treated in the watershed example presented above see the studies of Vieux and Bedient (1998) and Smith et al. (2002).

Standard design storms used by NFIP to predict a flood peak of a given recurrence interval, frequently, fail to reflect the durations that urban streams are usually more sensitive to (short rainfall durations, close to 1 h, see also discussion below). Rainfall accumulations for the 7 July 2004 storm had return intervals exceeding 200 years for time periods of 1–2 h. For shorter and longer time periods, the return interval of rainfall accumulation decreased rapidly. The characteristic response time of the Dead Run watershed at 14.3 km^2 basin scale is approximately 1 h. Estimating 100 and 500 year flood peaks, given the modification of hydrologic response due to the urban infrastructure impacts, requires development of hydrologic and hydraulic modeling tools that address the characteristic alterations of flood response in urban watersheds (Bates et al. 2006; Nelson et al. 2006; Smith et al. 2005a).

In the Baltimore metropolitan region, striking contrasts in flood magnitude are tied to the history of stormwater management policy. A small urban watershed in Baltimore City, Moores Run, has the highest frequency of "unit discharge" flood peaks exceeding 100 $ft^3s^{-1}mi^{-2}$ (1.1 $m^3s^{-1}km^{-2}$) in the streamgaging record of the USGS (Smith et al. 2005b). "Unit discharge" is the flow rate divided by the drainage area of a watershed and a unit discharge of 100 $ft^3s^{-1}mi^{-2}$ has a return interval exceeding 100 years for many USGS stream gaging stations. In Moores Run, however, the return interval of a 100 $ft^3s^{-1}mi^{-2}$ flood peak is approximately 1 month. Moores Run is an extreme case in the flood response spectrum of urban watersheds and reflects urban development prior to stormwater management policies instituted by the sequence of legislative actions tied to the Clean Water Act. Portions of the Baltimore metropolitan region developed following the introduction of stormwater management regulations exhibit larger flood peaks than natural, pre-development watersheds, but significantly smaller flood peaks than in watersheds like Moores Run (Ntelekos et al. 2007). The Dead Run watershed (Fig. 2) in Baltimore reflects the typical setting of urban environments in which hydrologic response associated with extreme flooding reflects a heterogeneous mix of development types and histories.

The NFIP does not systematically employ tools for addressing the heterogeneity of hydrologic response in urban regions, partly because of the high degree of complexity associated with urban flooding. There are several issues that need to be addressed in this respect. Flood frequencies are poorly understood, partly because of short flow records on most urban streams, but also because of the non-stationarity of the records due to changing infrastructure and changing climate (Milly et al. 2008, see also discussion below). Currently, the flood risk in most urban sites is assessed using regional frequency curves. Although these regional curves have coefficients for percent impervious area, they cannot be refined to account for different patterns of stormwater management infrastructure.

Urbanization can alter not only the hydrologic response of urban watersheds but also the precipitation climatology of urban regions. Alterations of precipitation climatology through atmospheric processes tied to the Urban Heat Island (UHI), the Urban Canopy Layer (UCL), and the different aerosol composition over urban areas (see reviews of Lowry 1998; Shepherd 2005; and Collier 2007) could have significant impacts on the climatology of floods. Mesoscale modeling studies of the 7 July 2004 storm in Baltimore-Washington D.C. metropolitan area, suggest that the urban environment can have a significant impact on rainfall distribution, and thus flooding, even in cases of complicated topography and for extreme magnitude events (Ntelekos et al. 2008). In this study, rainfall accumulations of 30% of the total on the southwest part of Baltimore, were attributed to alterations of precipitation associated with the urban environment itself. These research results illustrate the increased vulnerability of the urban environment to extreme events and point to the challenges in quantifying extreme flood hazards in urban settings. They also point to the utility of mesoscale atmospheric modeling as a tool for characterizing the spatial variation of extreme rainfall hazards over urban areas.

After almost two decades of scientific examination, overwhelming evidence points to the fact that global warming is a reality with dangerous implications for the future of humanity (e.g. IPCC 2007a; Oppenheimer 2005; Loaiciga et al. 1996). After the release of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), the question has shifted from "Is there global warming" to "What do we do about global warming?" and to "What are the policy implications of global warming?".

In its AR4, the IPCC projects an increase in the frequency of heavy precipitation events (and thus flooding) during the 21st century. Annual precipitation is expected to increase by as much as 20% in the high latitudes of the northern hemisphere (IPCC 2007a) with serious implications for flood occurrence in the United States. The frequency of low intensity rainfall events is predicted to decrease in the 21st century, under increased CO_2 concentration scenarios (Milly et al. 2002; Meehl et al. 2000), and an increasing fraction of annual rainfall will be "*very likely*" delivered in short duration, high-intensity events (IPCC 2007a). These findings are especially important in connection with the sensitivity of the urban environment to short duration, high intensity rainfall events discussed earlier in this paper. There is also debate concerning the potential increase of the frequency of intense tropical cyclones but the uncertainty associated with these findings is high (IPCC 2007a). The implications of these and the previously discussed findings for future costs of flood losses, that will most likely be driven by losses in large urban cores, are analyzed in Section 4. As noted in the "future impacts" section of Working Group's II Summary for Policy Makers report on impacts, mitigation and vulnerability:

> "*The most vulnerable industries, settlements and societies are generally those in coastal and river flood plains, those whose economies are closely linked with climate-sensitive resources, and those in areas prone to extreme weather events, especially where rapid urbanisation is occurring*" (IPCC 2007b).

Subsequent research results, after the AR4 cut-off date, reinforce the statements of the IPCC and indicate an agreement of the climate models on an increase of the extreme rainfall events' frequency and intensity, with obvious implications for flooding, in the 21st century (Milly et al. 2005, 2008; Sun et al. 2007).

A compilation of official FEMA data (Fig. 3) gives a sense of the continuously increasing financial pressure on the NFIP in the last 29 years (1978–2006). FEMA categorizes losses into a) losses from "major" events (classified as these events for which the total number of claims exceeded 1,500) and b) losses from "non-major" events. The first category includes essentially all hurricanes and tropical storms but also some major winter storms and large synoptic systems that caused excessive flooding to property insured by the NFIP. The second category includes intense storms of localized nature. Non-major events, these for which both the intensity and frequency are expected to increase in the 21st century (IPCC 2007b), are driving a significant percentage of the total annual losses of the NFIP. As Fig. 3 suggests, the number of NFIP policies is steadily increasing with more than 2.5 million new policies in the last 15 years. In both major and non-major events, this has not led neither to a change in the amount paid per policy nor to a reduction of the inter-annual variability of this amount. The financial burdens of the NFIP have significantly increased since 1994, when the General Accounting Office noted that "*the overall income of the program is not enough to build reserves that can cover anticipated flood losses*" (GAO 1994).

Figure 3 also suggests that non-major events are currently not driving the NFIP losses and that major events have been increasing in the last 15 years. Despite that, the causes of the recent increase in tropical cyclone activity have been heavily debated in the literature and are not necessarily attributed to climate change (see for example Vecchi and Soden 2007; Goldenberg et al. 2001; Vecchi and Knuston 2008).

In relation to climate change, research results suggest that future hurricane activity will depend on the combined effect of warming sea surface temperatures (SST) and increased vertical wind shear (Nyberg et al. 2007). The two mechanisms act as positive (warming SST) and negative (vertical wind shear) feedbacks for hurricane activity and they are both expected to increase under a warming 21st century climate (Vecchi and Soden 2007). Although most recent research results suggest that the increased vertical wind shear could dominate over increased SSTs, leading to an overall reduction of tropical cyclone activity under a warming climate (e.g. Knuston

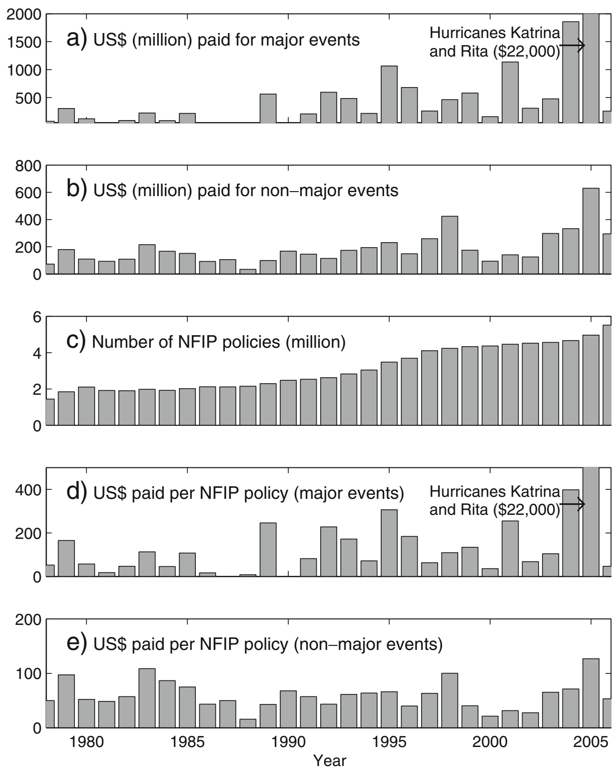

Fig. 3 Annual losses for major (**a**) and non-major (**b**) events, number of effective policies (**c**), losses per effective policy for major (**d**) and non-major (**e**) events of the National Flood Insurance Program from 1978 to 2006 (Source: FEMA)

et al. 2008; Gualdi et al. 2008), the question remains open and additional research is needed to address it (Vecchi et al. 2008). Simultaneously, the frequency of extreme rainfall events, as elaborated above, is expected to increase under a warming climate with a good level of certainty (IPCC 2007b; Milly et al. 2005, 2008; Sun et al. 2007).

Although not conclusive, the above suggest that the impact of non-major events on flood losses will increase in the future under a warming climate. Moreover, a good percentage of flood losses from major events (hurricanes, and winter storms) are due to the effects of urbanization which include the development across coastlines and the increase of impervious areas that accentuate flood losses. Urbanization is inherently connected to both major and non-major events.

4 Projections of future flood costs

As noted in the previous section, costs of the NFIP have been continuously increasing over the past years. An interesting problem concerns the potential for increase in costs during the the 21st century under different climatic change scenarios. Analyses from global circulation models can be used in conjunction with mesoscale models to provide insights to this problem. Global circulation models face several challenges, mainly due to the coarse resolution that they operate on (in the order of two degrees). For example, all of them fail to adequately reproduce the observed increase in extreme precipitation events over the last two decades (Wilcox and Donner 2007; Sun et al. 2007). Despite that, there is a unequivocal agreement between global climate models on an increase in extreme precipitation events at the end of the 21st century (IPCC 2007a). Mesoscale models, although very useful for short-term weather forecasting (in the order of a few days), have high computational requirements and their application is generally limited to sub-continental domains.

Sun et al. (2007), have examined the results of all 17 coupled global climate models used by AR4 create ensembles of monthly and daily precipitation frequencies under three emissions scenarios of the IPCC for the end of the 21st century. The three emissions scenarios are representative of a low (B1), an intermediate (A1B), and a high (A2) emissions projection. Based on the results of Sun et al. (2007) for land-only areas globally, the frequency of 60 *mm* (about 2.4 in.) daily rainfall accumulation events will increase by 30% for B1, 49% for A1B, and by 58% for A2 emissions projection scenario by the end of the 21st century (Fig 1(b) of Sun et al. 2007). These values are the average of all the available models.

The Weather Research and Forecasting model (WRF V2.2, see Skamarock et al. 2007; Jankov et al. 2005; Chen and Dudhia 2001; Mesinger 1996) was used to obtain regional estimates of the average number of days in a year exceeding 60 *mm* of daily rainfall accumulation in the last 5 years. The study area (Fig. 4) is focused over the heavily urbanized northeast corridor of the United States. The model setup included two domains with 9 and 3 *km* resolutions respectively. The time-step of the finer domain (3 *km*) was 18 *s*. The highest available spatial and temporal resolution analysis data was used for initial and boundary conditions (40 *km* every 3 *hrs* Eta model output, see Rogers et al. 1996). The model simulation period included the warm seasons of five years (2003–2007). For each one of the five years, the model was initiated on April 1st and was let to run continuously until September 31st. After the daily statistics were calculated, the coefficients of Sun et al. (2007) were used to

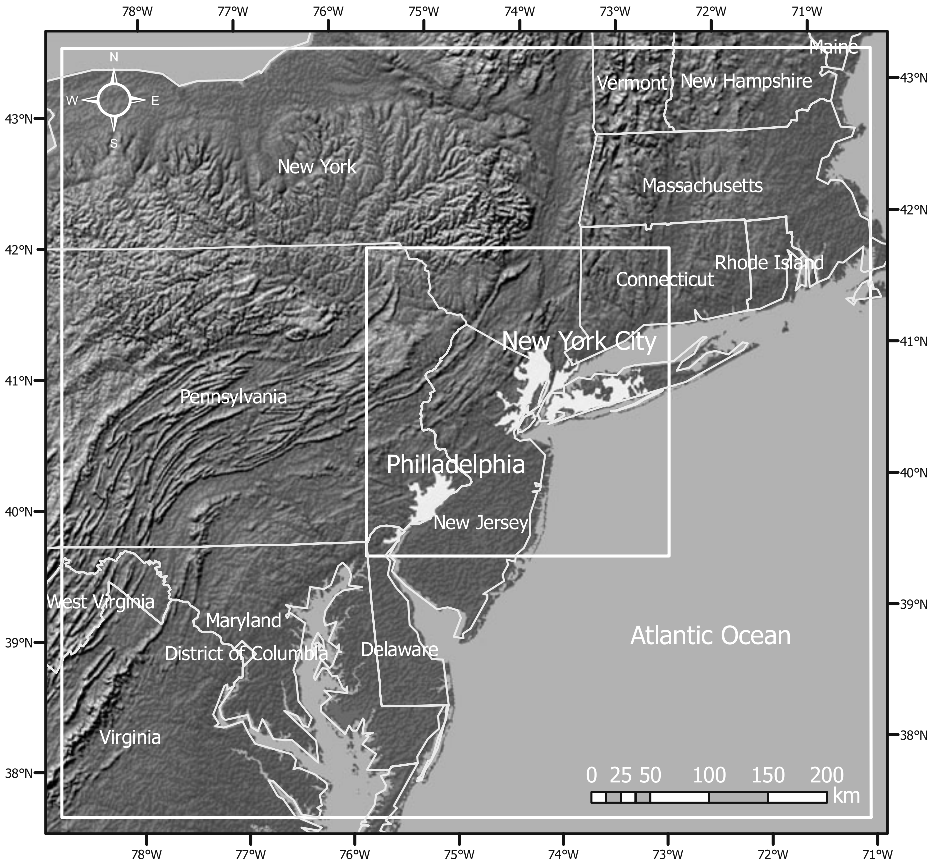

Fig. 4 Mesoscale modeling domains focused over the northeastern United States. *Large white rectangle* shows domain 1 with a resolution of 9 *km*; *smaller white rectangle* shows domain 2 with a resolution of 3 *km*. *Shaded areas* are the New York City Metropolitan area (north) and the Philadelphia Metropolitan area (south). State boundaries are shown in *white*

calculate the number of days that will exceed 60 *mm* at the end of the 21st century under the three different emissions scenarios.

There are two main points that need to be clarified in respect of the modeling approach that was adopted: 1) The decision of not directly coupling a specific global model with the mesoscale model was taken partly because global models frequently fail to provide high quality long-term boundary conditions for the mesoscale models and partly because the ensemble information from all 17 global models was judged to be a more representative metric of future precipitation frequency (IPCC 2007a). 2) A basic assumption was made that the mesoscale model, although not as precise as rainfall observations, captures the basic elements of rainfall distribution and provides a seamless rainfall product over this large area (see Fig. 4) that is representative of rainfall climatology over the last decade (see for example Gallus and Bresch 2006; Jankov et al. 2005; Kain et al. 2006; Otkin and Greenwald 2008 for model validation studies).

The results presented in Fig. 5 have important implications for future flood damages. Most extreme rainfall events (daily rainfall accumulations exceeding 60 *mm*) are concentrated on the mountainous area at the northwest part of the domain in Fig. 5. Based on model-derived rainfall climatology, this area currently experiences three or four days of extreme precipitation per year (Fig. 5a). The mesoscale modeling results suggest that during the last five years, the greater New York City metropolitan area experiences on average one or two days of extreme precipitation, being along the path of the northeastern storm-tracks. The area of the Philadelphia metropolitan region experiences two and in some rare occasions three days of extreme precipitation per year. For the different emissions scenarios, these numbers are altered based on the global models' coefficients presented above, assuming that the same patterns of rainfall persist. The situation is substantially changed for the high emissions scenario (A2, Fig. 5d). Based on this scenario, at the end of the 21st

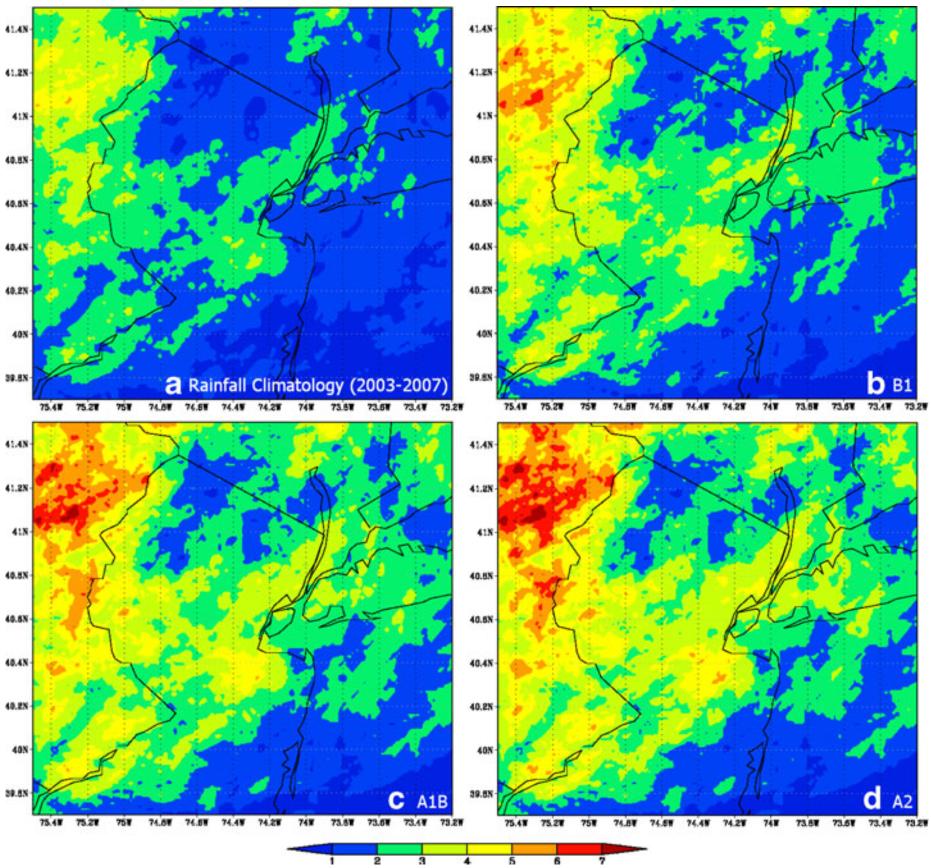

Fig. 5 Colormaps of average number of days in a year (see color legend) with extreme rainfall events (over 60 *mm* accumulation) for **a**) current climate—based on model-dervided rainfall climatology—and for the end of the 21st century under three different emissions scenarios: **b**) B1 (low), **c**) A1B (medium) and **d**) A2 (high) over domain 1. See Fig. 4 for geographical location of domain 1 and of urban centers within. *Black lines* represent state boundaries

century, the New York City area will be experiencing three to four days of extreme precipitation in an average year. Aside from the flood costs, these types of events are particularly disruptive for businesses and local communities as the recent flood of August 8, 2007 over New York City has shown (Sender 2007).

A detailed calculation of floods costs at the end of the 21st century is virtually impossible not only because of the climatic input uncertainty, but also because of the lack of vulnerability data and other economic parameters. For example, only short-term projections of growth of wealth are available, while projections that exceed a few years are highly uncertain. A back-of-the-envelope calculation of future flood costs, with an emphasis on urban areas is, however, possible. The expansion of the urban cores, as detailed in Section 3, will lead to an increase to the number of people and property exposed to floods. For developed regions, such as the United States, the United Nations projects an increase in the urban population of about 6% (from about 75% today to 80.8% in 2030, United Nations 2006). Given that population density in urban cores will not dramatically change by the end of the 21st century, and that urban expansion will slow down after 2030, a 6% areal increase in urbanized regions typical of the northeastern corridor of the United States was hypothesized. A one-to-one relationship between urban areal expansion and flood costs was assumed; A linear relationship was also assumed to hold between future flood costs and the coefficients of Sun et al. (2007) for the distribution of extreme precipitation under different climatic scenarios. Such an assumption is only one among many plausible approaches, particularly since flood risk is sensitive to direct human interventions independent of climate change (like management of wetlands and the built environment). It is also noted here that the current annual flood costs in the US are calculated to be between \$2.0 billion (Pielke et al. 2002) and \$2.7 billion (Changnon 2008). For the purposes of the calculations carried out herein, the average of these two estimates is used (\$2.35 billion per year).

Finally, indicators of wealth show that the economy of the United States expanded with a rate of about 2.6% for the period 1999–2008 (International Monetary Fund 2007, www.imf.org). Projections of the growth with an 80 year horizon are not available, and thus a range from 1% to 2% average growth were investigated. It could be argued that the 1% to 2% average growth is a conservative yet realistic range for the purposes of this study. Note that the different emissions scenarios could have varying impacts on economic growth (e.g. Stern 2006). A one-to-one relationship between wealth and flood costs was assumed. Such a relationship has been claimed, by previous researchers, to explain a large part of the increase of flood costs in the last decade (Downton and Pielke 2000).

In summary, for the calculation of US flood costs at the end of the 21st century the following formula was used:

$$F(N) = E \cdot F(0) \cdot (1 + g)^N \cdot U \tag{1}$$

where $F(N)$ are the projected annual flood costs at year N ($N = 80$ for the end of the century) in billion dollars of today, E is the coefficient for different emissions scenarios (B1 − 1.30, A1B − 1.49, A2 − 1.58), $F(0)$ is today's annual flood costs in billion dollars ($F(0) = \$2.35$ billion per year), g is the average growth rate (ranging from 1% to 2%), and U is the coefficient for urban expansion (1.06).

Figure 6 shows the results of the calculations discussed above. The estimated spread of future flood costs is wide starting from about \$7 billion (current US dollars)

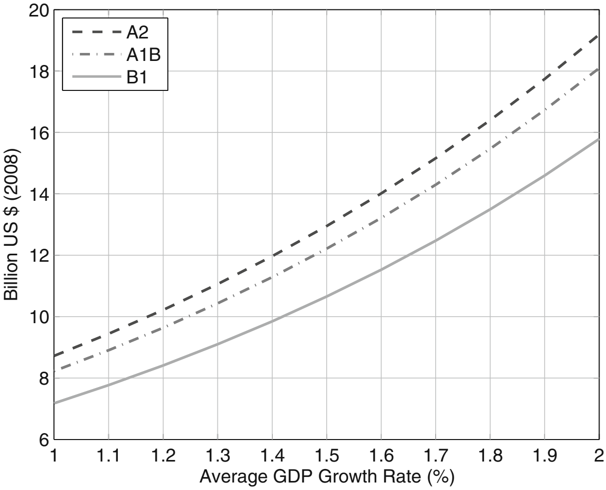

Fig. 6 End of the 21st century estimates of annual flood costs in the United States for three different emissions scenarios (B1 (low, *solid line*), A1B (intermediate, *dash-dot line*), and B2 (high, *dashed line*)), taking into account urban expansion and the climatic change that these emissions scenarios will be accompanied by (in billion US dollars of 2008)

of projected annual flood costs, for 1% average growth rate and low emissions (B1), to over $19 billion (current US dollars) annually for an average growth rate of 2% and high emissions scenario (A2). For an average growth rate of 1.5%, that lies in the middle of the range investigated, the low emissions scenario (B1) would create savings in annual flood costs of about $2.3 billion per year (current US dollars), compared with the high emissions scenario (A2). Despite the large degree of uncertainty and some lumping assumptions, the results of Fig. 6 provide some additional insight as to why a modernization of the NFIP, as discussed in the next section, is necessary for the financial viability of the program in the 21st century.

5 National Flood Insurance Program modernization

In recent years, some countries of the European Union have moved forward in changing their flood policies to reflect our better understanding of the climate system and/or the way floods impact areas of high value such as the urban environment. The new policies' names such as "Room for the River" in the Netherlands (see Samuels et al. 2006; Nijhuis 2006) and "Making Space for Water" in the United Kingdom (see Samuels et al. 2006) give a good sense of the change in attitude to dealing with floods in the light of the high risk of future years. In the United States equivalent measures of sustainable floodplain practices are being developed, but are limited to communities and local governments that decide to go over and above the typical NFIP requirements. Innovative measures adopted by local jurisdictions around the US look at ways of applying low-impact development measures that reduce the frequency of flooding. One example would be the situation in Maryland after Tropical Storm Agnes in 1972. Many of the affected riparian corridors had the buildings removed so that the flood-prone areas today are parks and open areas along much of their length.

The NFIP is the product of long-term efforts of multiple governmental agencies and experts in several fields of science and policy. It is designed to be a self-financing program that does not rely on taxpayer funds for disaster relief. To date, the program has helped thousands of people to recover from flood disasters without having to bear the heavy burdens of loans or bankruptcy. Increased flood awareness via education of the general public ("Project Impact" in 1999 or the "Mid-Atlantic Flood Insurance Summit" in 2004) has likely resulted in saved human lives to which it is difficult to assign a monetary value. In terms of flood damage costs, floodplain management practices, as enforced by the NFIP, are estimated to be saving $1 billion dollars annually. FEMA have also taken initiatives to increase the participation to the Program and strengthen its partnerships by nationwide campaigns ("Cover America" and "Cover America II"). It is thus recognized that a complete restructuring of the program is not necessary or viable, not only because of its long existence and relative success, but also because of the long timescales associated with radical changes of these systems. A revision of the currently established NFIP program that accounts for the shortcomings analyzed in Sections 3 and 4 could make the Program financially more secure and allow for more efficiency and flexibility in protecting human lives and property from the catastrophic consequences of floods. The proposed modernization includes the following elements.

- **Flood hazard identification and risk assessment modernization:** The following changes are suggested:
  - Extension and expansion of the mapping program for floodplain topography and floodplain land use and cover for urban regions. Although LIDAR techniques are part of the map-modernization program of the NFIP it is clear that a system-wide program of high-resolution lidar topography for urban regions is needed to improve 100-year floodplain calculation accuracy. A similar approach should be applied for land use and land cover datasets. The dynamical and rapidly changing nature of the urban environment require that such datasets be updated at least every 10 years.
  - A national program of hydrologic and hydraulic modeling for urban watersheds should be established. The modeling program should provide systematic capabilities for evaluating the 100 year and 500 year floodplains in heterogeneous urban regions. Characterizing the error associated with both the 100 and year 500 year floodplains is also of crucial importance in relation with the hydrologic uncertainties discussed above. The standardization of methods and techniques for characterizing the urban floodplain is also instrumental in creating a cohesive nation-wide catalog of urban watersheds.
  - Detailed hydrometeorological studies focused over urban environments should be included as part of the Program's modernization as a means of characterizing the variability in rainfall over urban regions. Advances in mesoscale modeling and remote sensing of precipitation should be integrated into the routine calculation of the current and future flood risk of urban environments.
  - Analyses based on global and mesoscale atmospheric models, as demonstrated should be used to evaluate future regional flood impacts and to update and assess the risk of the NFIP in the years to come. As more scientific evidence becomes available and as uncertainty is reduced, these tools could play an instrumental role in forecasting long-term losses and ensuring the financial security of the Program.

- **Floodplain management modernization:** Changes in floodplain management come about both from experience in current NFIP practice and from the proposed flood hazard identification and risk management changes presented above. These changes include the following:
    - The biggest financial burden on the NFIP comes from repetitive losses (1% of total number of NFIP policies accounting for 33% of annual paid losses). Moreover, flood insurance premiums are heavily subsidized for these Pre-Flood Insurance Rating Map (Pre-FIMR) buildings. As an alternative to existing practice, it is proposed that after a specified grace period, structures that experience repetitive losses will be subject to full actuarial rates to reflect the real risk associated with these structures. In alleviating the financial burden of the owners for upgrading their flood-prone structures, attractive financing options through the already established NFIP funds for upgrading and relocating should be made available to the participants.
    - Flood impact analyses for urban cores, as described above, should be used to more effectively enforce floodplain regulations in those areas of the urban environment that are found to be in greater danger. Although a significant reduction in flood risk might be obtained without additional regulations, flood awareness and education campaigns, as well as more stringent monitoring, should be directed to these areas.
    - Enforcement of floodplain management regulations should be linked to assessments of flood climatology in urban regions. Increased enforcement efforts in many urban settings of the US should reflect the increased flood risk of the urban environment from warm-season thunderstorm systems. The implementation of these changes can be done at essentially no cost since the NFIP has already established mechanisms to monitor community compliance. The advantage of the impact studies is that they provide focus and prioritize the monitoring efforts.
- **Flood insurance modernization:** Changes in this part of the Program are mainly possible by the implementation of a more accurate calculation of the 100-year floodplain. In urban environments, the more flexible use of floodplain mapping information, arising from more accurate estimates of the 100 year and 500 year floodplains and the integration of their associated errors, can lead to more effective pricing of flood insurance.

6 Concluding remarks

This paper argues that flood policy in the United States should be reevaluated to reflect our current understanding of flood impacts and future climatic change scenarios but also to secure the financial prosperity of the NFIP. An analysis of the rising flood insurance costs of the last decades along with projections of future flood costs suggest that the NFIP is entering a phase where changes need to be made. Scientific and financial evidence and experience in practice with floods should now be enough to initiate an effort that will soon change the way flood policy is done in the United States. Countries in the European Union have already started applying changes in their policies in acknowledgment of the new situation. The United States, in many ways, led the way in flood policy with the establishment of the NFIP in 1968 but has, since then, done little in securing the financial sustainability of the Program into the 21st century. The increasing flood insurance costs are pushing the NFIP to its limits and taxpayer money will most likely have to be funneled to flood disaster assistance more often in the future.

The proposed changes provide directions that the Program could follow with relatively low cost and high return value in both the short and long term. These changes could potentially allow the NFIP to continue covering its operating expenses in the future without having to frequently resort to large loans from the Treasury. Most importantly, this study aims to initiate more discussions and gather momentum for a change in flood policy that will secure the financial future of the Program and help alleviate the financial and physical burdens of people impacted by floods.

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