A GIS-based approach to adaptation to regional climate change for local decision-making arrangements: A case study of Tokyo, Japan

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Abstract: Recently, local governments have an increasing need to take extensive and effective local measures to adapt to regional climate change. Despite emerging recognition of the necessity of climate change adaptation, many barriers still impede efforts to build local, regional, and national-level resilience. This study aims: 1) to develop a Geographic Information System (GIS) based approach to using observed and projected data for decision-making by non-expert government authorities, 2) to explore the value of regional priorities in climate change adaptation planning processes using GIS, and 3) to provide specialized yet understandable climate change projection to local decision-makers efficiently and equally by GIS, who are invoking the concept of resilience as a management goal. Tokyo, Japan (a megacity with a population of 13.23 million as of 1 April 2013), was chosen for this pilot study. In this paper, the most recent regional climate projections (5 km resolution) are transcribed into an understandable form. Moreover, a general approach has been developed to adjust the bias of model results using observations. The mean temperature increase at Okutama-machi, a sparsely populated mountainous region (area 225.63 km^2) to the northwest of the city of Tokyo, with the highest peak (2,017 m), is the greatest of any area in Tokyo. In comparing near future time period (2015–2039) and future time period (2075–2099) conditions, August monthly mean temperature will increase more than 0.7–0.9 °C and 2.6–2.9 °C, and monthly precipitation by 43–70 % and 25–41 %, respectively. Additionally, the RMS errors and bias of percentage change for monthly precipitation in summertime are 26.8 % and 4.3 %, respectively. These data provide an early warning and have implications for local climate policy response.

Keywords: climate change projection, geographic information system (GIS), local government decision-making, regional climate change, Tokyo

1 Introduction

Adaptation to climate change is largely time and scale dependent and this dependence is a function of both climate impacts on particular activities and its adaptive potential (Jones 2000). In recent years, there has been exponential growth in the amount of research published on climate change adaptation, vulnerability assessments and managing for resilience (Daniell et al. 2011; Yuan et al. 2013; Linnenluecke and Griffiths 2012; Benson and Garmestani 2011). For instance, Daniell et al. (2011) recommended that progress towards climate change aware regional sustainable development is affected by actions at multiple spatial scales and governance levels and equally impacts actions at these scales. Many reports indicate that decisions over policy, mitigation strategies and capacity for adaptation to climate change requires construction and coordination over multiple levels of governance to arrive at acceptable local, regional and global management strategies. However, existing literature rarely considers adaptation focused across multiple sectors as is found at the local government scale. Mounting evidence exists related to the need for basic tools to support local scientific policy dialogue as part of local decision-making processes for adaptation planning at the local scale (Hallegatte and Corfee-Morlot 2011).

After the 2003 European heat wave, climatologists, medical specialists, and social scientists expedited efforts to revise the European vulnerability assessment system and integrated risk governance frameworks for climate change adaptation (Schröter et al. 2004; Lass et al. 2011). Despite evidence of rapid growth in climate change adaptation planning across a range of geopolitical scales, critical examinations of this evidence suggest planning has yet to translate into substantive adaptation policies and measures. One reason is that local governments have an increasing need to take local measures to adapt to regional climate change, but have difficulty knowing how and when to adapt to such change. In particular, Jones (2000) recommended that the uncertainty which exists within projections of regional climate can be managed where it is unquantifiable. Tools for decision-making by non-expert government authorities are vital in understanding and managing the uncertainty which accompanies climate change assessments.

Furthermore, for decades, many international meteorological organizations have promoted the wide-ranging international cooperation frameworks to facilitate, data, information, products and services in real- or near-real time, free to the research community. These organizations include the World Meteorological Organization (WMO), Global Climate Observing System (GCOS) Surface Network (GSN), European Climate Assessment (ECA) and daily Global Historical Climatology Network (GHCN-Daily) (Alexander et al. 2006). However, there are three barriers to these organizations in the supply of adaptive information and understandable social-ecological resilience thinking based on projected database to local government and local decision-makers: (i) All expert knowledge, including data source, is a particularly useful resource for research; however, research findings usually do not include specific recommendations for local adaptation action; (ii) there is a lack of support framework or social learning program for local decision-makers to access the expert knowledge database; and (iii) a wide array of adaptation options, not field-specific, are provided by scientists. A basic tool to support decision-making by non-expert governors seems necessary, which would enable different branches of government to have common access to a huge variety of information, effectively and equally. A tool that exchanges high-quality climatic data and information about the science of climate change in understandable form to non-expert citizens would fit with a new resilient approach for local policymakers to meet the regional demand. If user-friendly software packages for using these increasing numbers of data sources from observations and high resolution simulations were provided, that would empower stakeholders or to influence adaptation and take appropriate actions themselves effectively by sharing expert knowledge and responsibility in participatory processes.

Currently, more and more scientists emphasize that developing and applying an advanced observational database and using the output of RCMs under Coupled Model Intercomparison Project—Phase 5 (CMIP5) as efficiently as possible is both essential and necessary, not only for climate scientists, but also for the growing number of stakeholders, policy-makers and the enlightened public. Based on advice given by Overpeck et al. (2011), "a new paradigm of more open, user-friendly data access is needed to ensure that society can reduce vulnerability to climate variability and change, while at the same time exploiting opportunities that will occur."

The objective of this paper is to develop a cost-effective, user-friendly GIS (geographic information system) based approach to aiding evidence-based decision-making processes and provide a basic tool to use observed and projected data easily by decision-maker for assessing regional vulnerability based on the GIS database. The Climatic Research Unit (IPCC Data Distribution Centre 2012a) has a free, high-resolution dataset. This dataset is available in NetCDF and GeoTIFF formats, which are both compatible. Recently, GIS has been increasingly used at all levels of government, in both developed and developing countries. We used high-quality daily data from the Japan Meteorological Agency (JMA), which are available to local governments (Japan Meteorological Agency 2012a). Projections were from a 5 km-mesh, non-hydrostatic, cloud system-resolving regional climate model (NHRCM-5 km, 5 km resolution), following the Special Report on Emissions Scenarios (SRES) A1B scenario. Those were dynamically downscaled results from the MRI-AGCM3.2S. The MRI-AGCM3.2S is an Atmospheric General Circulation Model for AMIP (Atmospheric Model Intercomparison Project).

We developed the basic tool with three GIS modules that can freely and easily produce a wide variety of data or maps, plus warning information, available in a GIS domain. In this paper, three major challenges for climate science revolving around data have been addressed. One is ensuring that the highest resolution projected climate change data (5 km resolution) become easier and cost-effective so that up-to-date information can be put into widespread use by a GIS database. Second is making sure these data and the results that depend on them are useful to and understandable by a broad interdisciplinary audience, especially by the local policy-makers. And third is aiding evidence-based decision-making processes and social learning frameworks equally. Because all GIS mapping output can be formatted into a Keyhole Markup Language (KML)/Keyhole Markup Language Zip (KMZ) file that can be readily used and displayed by Google Earth or other Earth browser programs. These greatly benefit local governments in undeveloped areas and depopulated regions, for obtaining information via the world wide web (WWW). Additionally, a similar approach can be achieved in both developed countries and developing countries using the GIS tool. These would improve routine decision-making and clarify regional priorities and issues effectively around the world.

To describe the methodological steps with GIS modules, Tokyo (area 2188.67 km^2; population 13.23 million as of 1 April 2013), a megacity in Japan was chosen for a pilot study. This paper describes the basic tool with three GIS modules and sources of projected daily data in "Data and Methods". In "Pilot Study of Tokyo", two case studies (Okutama-machi, a 225.63 km2 sparsely populated mountainous region and Shinjuku, the most famous business and entertainment area) in Tokyo metropolitan area are used to explain how to assess vulnerability and investigate adaptation to regional climate change through the GIS tool. This paper examines the challenges involved in providing an evidence-based decision-making processes equally and understandable uncertainty in climate change projections to local decision-makers.

2 Data and methods

2.1 Free international daily datasets at national levels in a digital format

As mentioned above, free international daily datasets including data applicable at national levels in digital form have been improved worldwide (Alexander et al. 2006) and these datasets include climate observations and climate models, have worldwide open-access, and are updated by IPCC Data Distribution Centre (http://ww.ipccdata.orgobs/index.html). Also, a number of new results have been published; RCMs can resolve features down to 20 km or less and many regional high-resolution (about 7 km) projections of future climate change have been developed (Feldmann et al. 2008; Berg et al. 2013).

In this study, we used a high-quality daily dataset from the JMA Observations (http://www.jma.go.jp/jma/en/Activities/observations.html) and projections (5 km resolution) from the NHRCM-5 km following the SRES-A1B scenario developed by the Meteorological Research Institute (MRI), JMA supported by Innovative Program of Climate Change Projection for the 21st Century (KAKUSHIN Program). The NHRCM-5 km is a dynamic downscaling of results from MRI-AGCM3.2S (20 km resolution). Also, we re-produced the GIS statistics conducted stepwise for local governments by the Ministry of

International Affairs and Communications, Japan (Statistics Bureau: Database of the national census).

2.2 Methods

This study had three main components: 1) developing a cost-effective, user-friendly GIS tool for local decision-making, 2) an empirical pilot study of regional adaptation measures designed for using the basic tool and 3) providing an evidence-based decision-making processes equally and understandable uncertainty in climate change projections to local decision-makers.

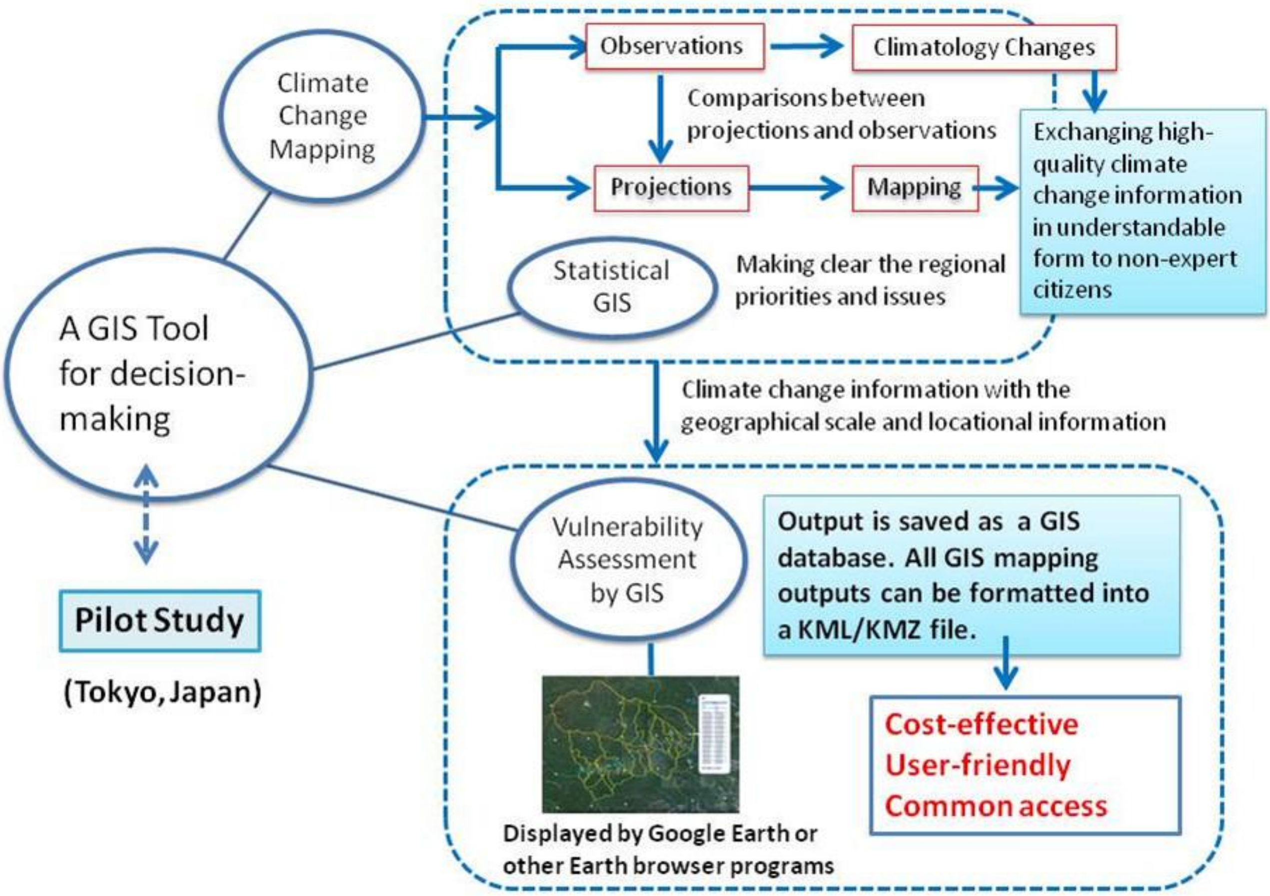


Fig. 1 Procedures adopted in this study

Figure 1 outlines the procedures adopted here and depicts the tool with three GIS modules. That is a mapping tool for managing an integrated spatial and attribute database, with a suite of climate change indices, regional statistics and regional vulnerability indices focused on extreme climatic events. New databases for decision-making were built using three different GIS modules consisting of spatial map layers with their spatial and attributes. These three modules are climate change mapping (climate change information with geographic scale and location information), regional statistical GIS, and vulnerability assessment by GIS. Vulnerability assessment by GIS includes natural, social and economic vulnerabilities, which are intended to inform decision-makers by analyzing current and potential impacts of global change and by recognizing pressures from other stresses. All data is computed and analyzed for regional tasks in the GIS domain, and output is saved as a GIS database. Moreover, the user can easily transform all output into a KML/KMZ file, which is available for presentation using freely available tools (e.g., Google Earth) and an internet connection.

The mapping tool presents observed (station data) and projected (grid mesh data) data together easily, using GIS (Fig. 1). Mapping the observed and projected data on the same GIS domain can allow the user to directly link other GIS data, such as societal and biological impacts and climate change. Climate-change mapping is a vehicle for readily depicting special distribution changes and trends across temporal and geographic scales. That can make projected information available to multiple users and encourage national and subnational governments to work closely with local authorities. All output is available for presentation on Google Earth by the DMT, as needed. It brings policy makers and citizens together and provide social learning frameworks equally.

2.2.1 Climate change mapping

Data quality and homogeneity is important to decision-making using the basic tool. We used a high-quality daily dataset from the JMA, and projections from the NHRCM-5 km following an SRES-A1B scenario. Several recent empirical studies have applied NHRCM-5 km output to date for months from June to October. For instance, research has been conducted related to summertime temperature extremes and daily precipitation across Japan in the late 21st century using the NHRCM–5 km (Murata et al. 2012; Kanada et al. 2010). These studies indicate that the NHRCM–5 km significantly improves the reproduction of the present climate. In particular, the bias of models with observations for daily mean temperatures in June, July, August, September and October was within 0.5 K (700 samples covering Japan) for the present climate (Murata et al. 2012; Nakano et al. 2012). Thus, we used only NHRCM-5 km output data for summertime (July to October data).

2.2.2 GIS statistics

Statistics often inform policy development. As Davidian and Louis (2012) stated, statistics is the science of learning from data, and of measuring, controlling, and communicating uncertainty; it thereby provides essential navigation for controlling the course of scientific and societal advances. Meanwhile, resilience is an emergent property of complex adaptive systems (Gunderson and Holling 2002). GIS statistics represents a mapping approach designed to present a regional development snapshot of governmental statistics information. The GIS mapping can analyze and explore the property of complex social-ecological systems. Mapping observed and projected data on the same GIS domain, using a common database that includes environmental and socioeconomic statistics, can be an effective and easy method to analyze and solve a particular problem. Also, multiple potential impacts on multiple sectors can be projected. These potential impacts combine with low adaptive capacity, based on a socioeconomic regional scale generic index.

After the 1990s, GIS statistical analysis was conducted stepwise for local governments in Japan. Datasets from GIS statistics are available for re-editing and visualization on Google Earth, as needed.

2.2.3 Vulnerability assessment by GIS

The IPCC Third Assessment Report "Climate Change 2001" (2003) clearly stated vulnerability to climate change is determined by two sets of factors; one external to the system, and the other internal. External factors consist of the character, magnitude, and rate of climate change, and variation to which the system is exposed. Internal factors are the sensitivity and adaptive capacity of the system itself. Unfortunately, empirical and theoretical evidence of how potential impacts and adaptive capacity can be combined into vulnerability measures is very limited. Here, we create environmental and socioeconomic statistics and then combine them with climate change observations and GIS projections. The resulting maps are useful in illustrating vulnerability in terms of negative potential impacts and limited adaptive capacity. All results are made available to stakeholders in the form of a digital atlas of potential impacts, adaptive capacity and dimension of vulnerability.

3 Pilot Study of Tokyo, Japan

The following is an illustrative example of adaptation to regional climate change for decision-making by a local government, using the GIS tool. For a pilot study, we chose Tokyo, Japan, a megacity with a population of 13.23 million as of 1 April 2013, and covers an area of 2188.67 km^2 (Tokyo Metropolitan Government HP 2013).

The number of people aged 65 or older in Tokyo is 2.64 million, or 20.4 % of the total population, which includes 9.0 % of the total population of the elderly in Japan; nationwide, the number of elderly people reached a record 29.25 million, or 23.01 % of the total population of 128.06 million, as of 1 October 2010). Similar to megacities in other developed countries, municipalities with aging populations are expected to suffer greatly from climate change and are vulnerable to global change because only a few people have sufficient information on which to base action. The continuing increase in size of the elderly population is an urgent issue for metropolitan governments. For example, Tokyo will become an ageing-megacity with the projected percentage of elderly people exceeding 25 % by 2030 (Ministry of International Affairs and Communications 2012). Meanwhile, in Tokyo, the population has continued to increase in the inner city (Tokyo's 23 wards) (Table 1). From 2005 to 2010, the population grew by 456,042 people, with a growth rate between 12.8 %–24.8 % (Ministry of International Affairs and Communications 2012). The concentration of population within the inner-city area (23 wards) has been a serious problem in the city.

On the contrary, as population and infrastructure became concentrated in the inner city of Tokyo, two surrounding localities (Okutama-machi and Hinohara Village; Fig. 2) have been depopulated. However, Okutama-machi is an unpopulated mountainous region accessible 2 hours northwest of Tokyo by train or car (Table 1 and Fig. 2). Lake Okutama (Fig. 3b), an impounded lake which feeds the Tama River which can hold 185 million m3 of water, supplies approximately 20 % of Tokyo's water supply.

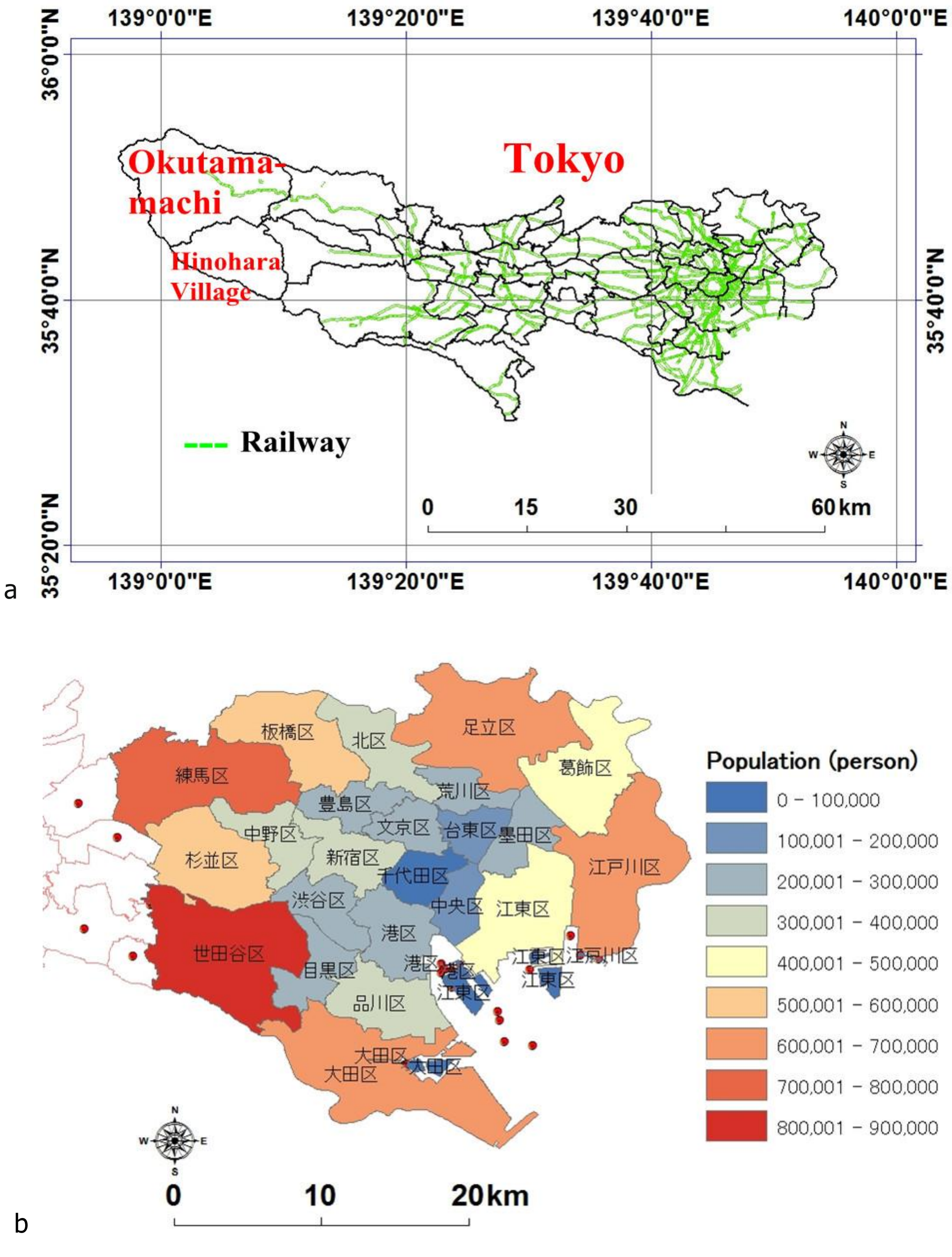
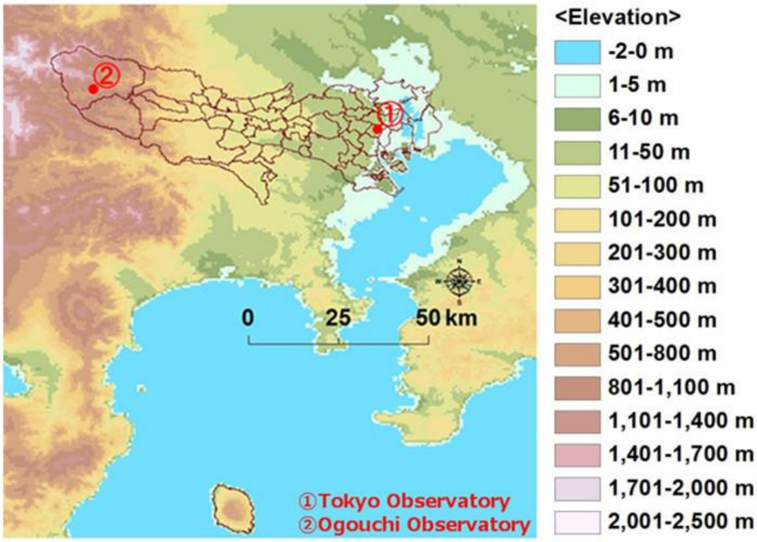


Fig. 2 Locations of unpopulated mountainous regions and transportation network in Tokyo (a), and population distribution (as of 1 October 2010) in Tokyo's 23wards (b)

a 

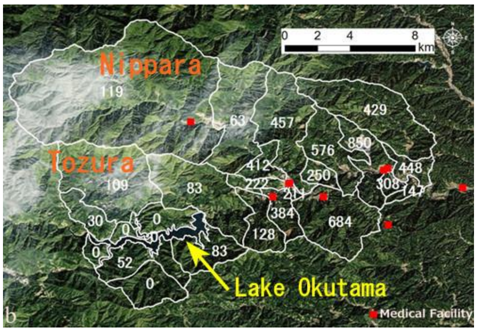
b 

Fig. 3 Elevations of observatories at Okutama-machi and Tokyo city center (a) and location of Lake Okutama (b). Tokyo Station (35°41.1′N, 139°45.6′E; elevation, 6.1 m above mean sea level); Ogouchi Station (35°47.5′N, 139°0.3′E; elevation, 530.0 m above mean sea level).

Figure produced by: Yingjiu Bai. Data

Source: Japan Meteorological Agency 2012b

Table 1 Comparison of population in the Tokyo metropolitan area and Okutama-machi (a sparsely populated mountainous region)

	Area (km^2)	Population (person)	Pop. density (per. / km^2)	Pop. growth rate from 2005 to 2010	Population aging (person) / rate	Number of households	Number of single-elderly person household (ratio)
Tokyo metropolitan	2,187.50	13,159,388	6,015.7	4.6%	2,642,231 (20.4%)	6,393,768	622,326 (9.7%)
Okutama-machi	225.63	6,045	26.8	-10.3%	2,498 (41.3%)	2,217	353 (15.9%)

Data Source: Ministry of International Affairs and Communications 2012.

Recent studies indicate global warming will be more marked at the mega-city scale, because of processes such as the creation of urban heat islands (Lemonsu et al. 2013). Figure 4a shows that annual mean temperature in Tokyo has risen about 3 °C over the past century, based on long-term observational data from the meteorological station in central Tokyo (Fig. 3a, ① (indicates the Tokyo station): 35°41.1′N, 139°45.6′E, elevation 6.1 m above mean sea level (abbreviated as AMSL); ② (indicates the Ogouchi station): 35°47.5′N, 139°0.3′E, elevation 530.0 m AMSL). Figure 4 show the climates of Tokyo and Ogouchi stations are warming based on changes in annual mean temperature records, although the annual mean temperatures and monthly mean temperatures at Ogouchi are more than 4 °C colder than those of Tokyo.

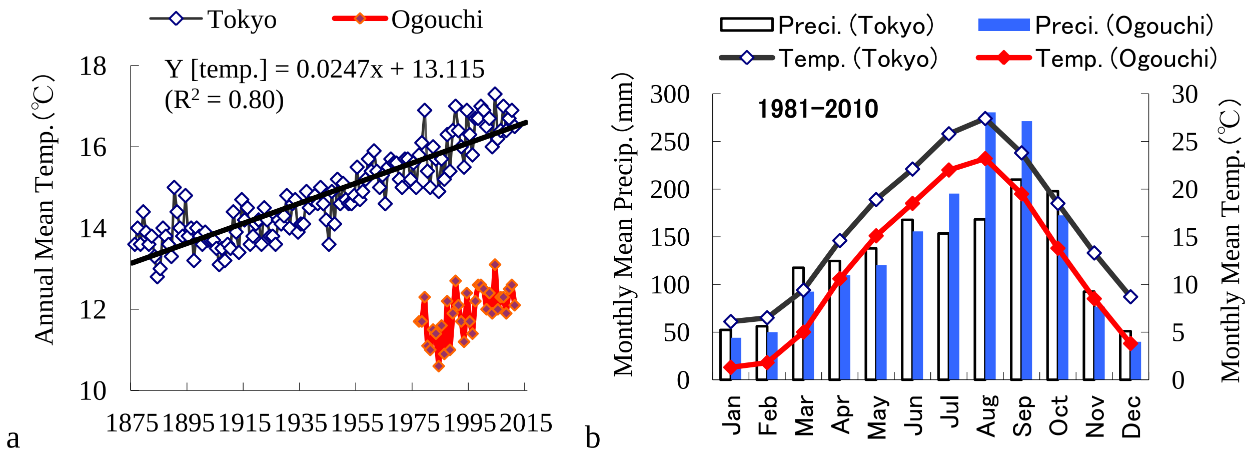


Fig. 4 Annual mean temperature increase (a), and observed trends of monthly mean precipitation and temperature during 1981–2010 (b) in Tokyo metropolitan area, based on average records from Tokyo (city center) and Ogouchi stations (rural area). Upper straight line in (a) denotes estimated trend of annual mean temperature increase for Tokyo station; slope = 0.0247°C/year, R^2=0.80. Tokyo Station (35°41.1′N, 139°45.6′E, altitude 6.1 m AMSL); Ogouchi Station (35°47.5′N, 139°0.3′E, altitude = 530.0 m AMSL.

Data Source: Japan Meteorological Agency 2012b.

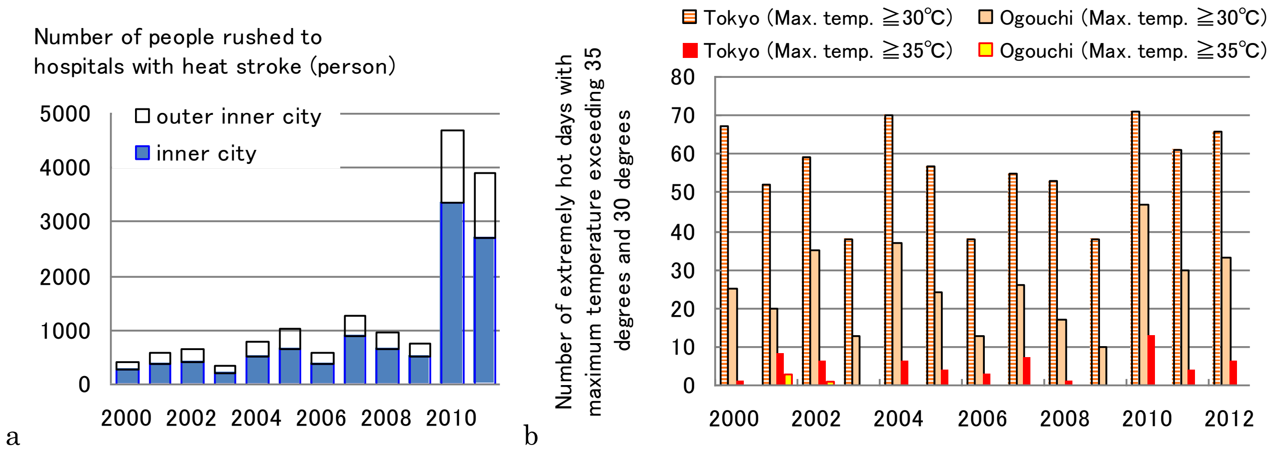


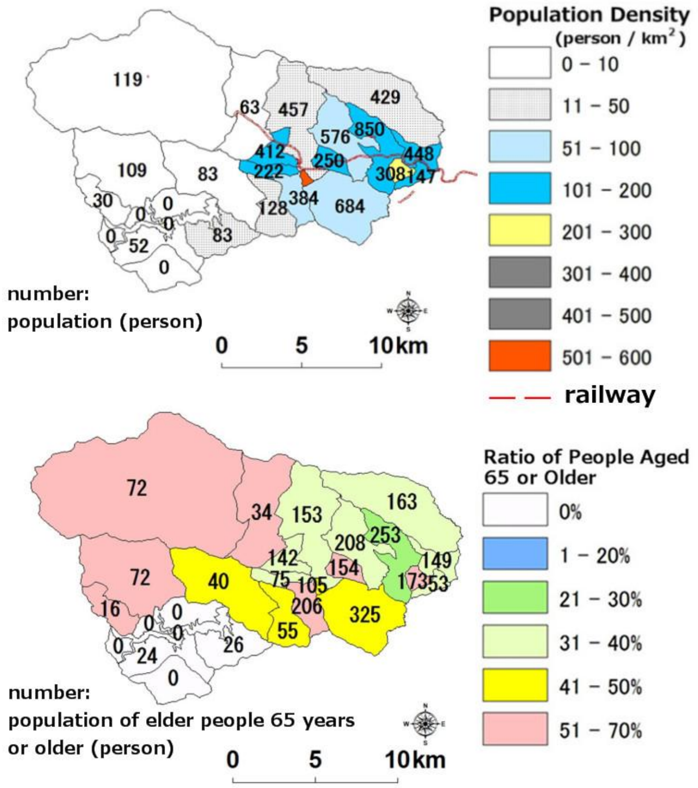
Fig. 5 Number of people hospitalized with heat stroke from 2000 to 2011 in Tokyo (a) and number of extremely hot days with maximum temperature exceeding 30 °C and 35 °C during 2000–2012 based on the records from Tokyo (city center) and Ogouchi stations (rural area) (b)

Data Source (a): Tokyo Fire Department 2012; Data Source (b): Ministry of Health, Labour and Welfare, 2011

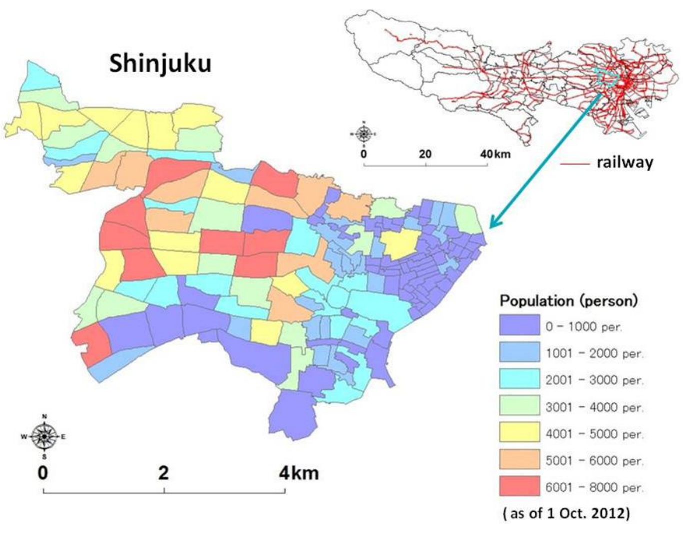
Figure 5(a) indicates the number of people hospitalized with heat stroke from 2000 to 2011 in Tokyo. In summer 2010, the monthly maximum temperature in August in Tokyo reached 29.6 °C. More than 70 days (or 10 days) had extremely high monthly maximum temperatures exceeding 30 °C (or 35 °C) during the entire summer (Fig. 5b). This heat resulted in 272 deaths and about 4,700 hospitalizations for patients with heat stroke (Fig. 5a).

3.1 GIS Statistics Modules

A DMT with GIS modules can serve our purposes, since GIS can manage enormous amounts of data conveniently, cost effectively and quickly. GIS statistics of the DMT furnish a mapping approach which can be used to produce a regional development snapshot based on governmental statistical information. As a sample, Figure 6 shows the population distribution (as of 1 October 2010) in Okutama-machi and Shinjuku (the most famous business and entertainment area). As Figure 6a, the lowest population density is 0–10 persons/km2, covers more than half the area in Okutama-machi as of 1 October 2010. The ratio of people aged 65 or older in Okutamamachi exceeds 25 % (compared to the nationwide ratio of 23.01 % as of 1 October 2010). There are two areas in Okutama-machi where this ratio is over 60 % (Fig. 6a).



a



b

Fig. 6 Population density and ratio of elderly people 65 years or older in Okutama-machi (a) and population distribution in Shinjuku (b)

Data Source: Ministry of International Affairs and Communications 2012

It seems obvious the Okutama-machi government is tasked with adaptation to climate change, along with addressing regional population issues and overcoming risks to the elderly. In contrast, Shinjuku is the most famous business and entertainment area with the maximum population density in the world. As transportation is convenient, many non-Japanese live in Shinjuku ward. Adaptive management must recognize the importance of environmental variability in contributing to social-ecological resilience and productivity. Hence, it is necessary to provide a common information base, including environmental and socioeconomic statistics and key climate change datasets to all levels of government, and allowing the merger of different indices and new datasets easily to facilitate policy-making as needed.

Moreover, GIS statistics modules can provide information related to regional public infrastructure, e.g., hospitals (Fig. 3b) and public transport information (Fig. 2a), as well as demonstrate the importance of such information at a geographic scale. Statistical mapping results can display the main regional issues in Okutama-machi and outline the crises faced by local governors. The primary concern is the continuous decline in population. The arrival of a "super-aging" society and a decline in birthrate may progress to the point of dampening economic activity, increasing the load on the social security system, and sapping the vigor of society as a whole. Second, even if the local government is well prepared for a super-aging society, it is unclear if it will be possible to sustain adequate levels of medical care and public welfare in Okutama-machi, given its transportation difficulties. Third, the Tokyo Climate Change Strategy and Tokyo Metropolitan Environmental Master Plan (Tokyo Metropolitan Government 2010) outlines specific policy directions, which represent a dramatic departure from the past and progress toward achievement of an announced target for the metropolitan area. However, concerns have been raised about whether the information and climate change report are effective for policymaking regarding responses to potential consequences of climate change in unpopulated mountain areas. GIS statistics modules present sufficient visual evidence to enable local government leaders to directly reflect local needs in their policymaking decisions. Furthermore, GIS mapping can be a process that promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood.

3.2 Climate change indices (1979–2003, 2015–2039, and 2075–2099)

A suite of climate change indices derived from daily temperature and precipitation data, including projected climate data, were computed and analyzed. To obtain accurate and detailed temperature and precipitation information on a daily time scale, all observed data were from an array of JMA surface observation networks. These networks are composed of automatic observation equipment collectively known as the Automated Meteorological Data Acquisition System (AMeDAS). All observational data are transmitted to JMA's data base (Japan Meteorological Agency 2012b).

Projected climate data are based on the NHRCM-5 km mesh regional climate model, with the SRES-A1B scenario. Sasaki et al. (2011), who developed the NHRCM-5 km, estimated its output in long-term climate projections and analyzed uncertainty based on model expert judgment. The bias of modeled annual mean temperature is −0.3 °C, and root mean square (RMS) errors are 0.7 °C. However, summer season output is almost the same as AMeDAS observations, except in mountainous areas (Sasaki et al. 2011). On the other hand, Sasaki et al. (2011) showed that NHRCM-5 km output in the summer season is nearly the same as AMeDAS observations, except in mountainous areas.

The climate informatics module consists of the spatial distribution of projected climatic indices and their change, using daily, monthly and annual weather data (focus on temperature and precipitation in summertime) from three study periods (1979–2003, 2015–2039 and 2075–2099). Figure 7 illustrates mean temperature changes in the months of July to October over Tokyo in the near future (2015–2039) and future (2075–2099) periods. Simulation results from the GIS mapping tool indicate that summer temperatures in metropolitan Tokyo will increase by more than 2.5 °C in the future period, and more than 0.5 °C in the near future period. The mean temperature increase at Okutama-machi is the greatest of any area in Tokyo during both periods.

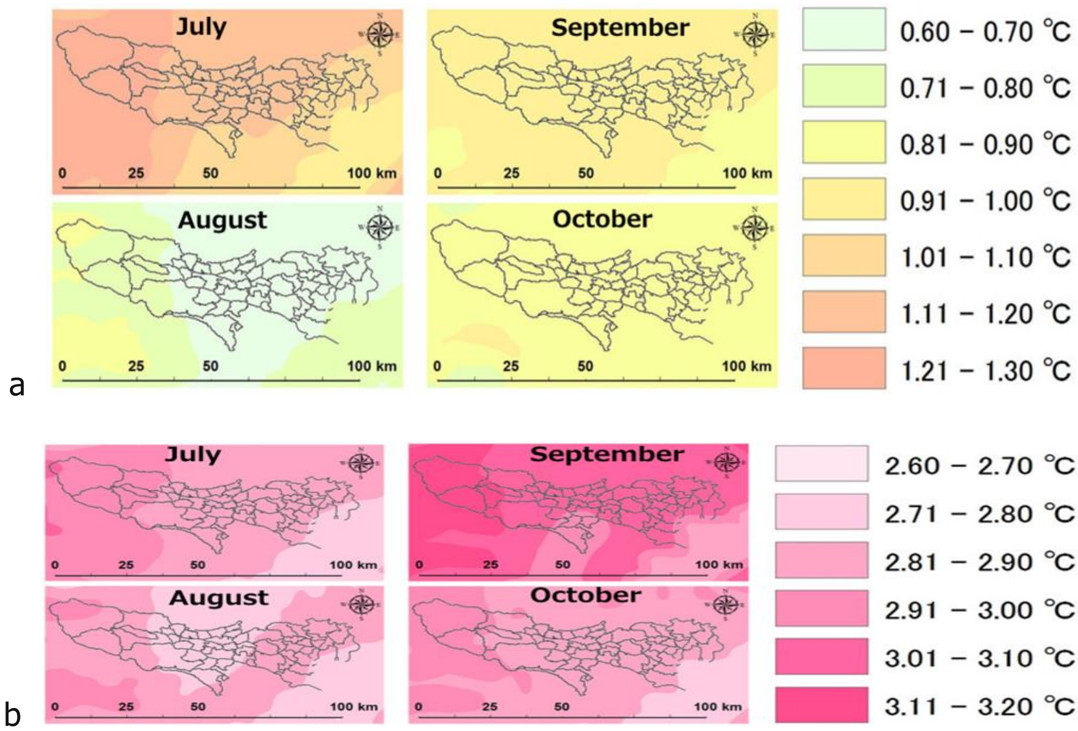
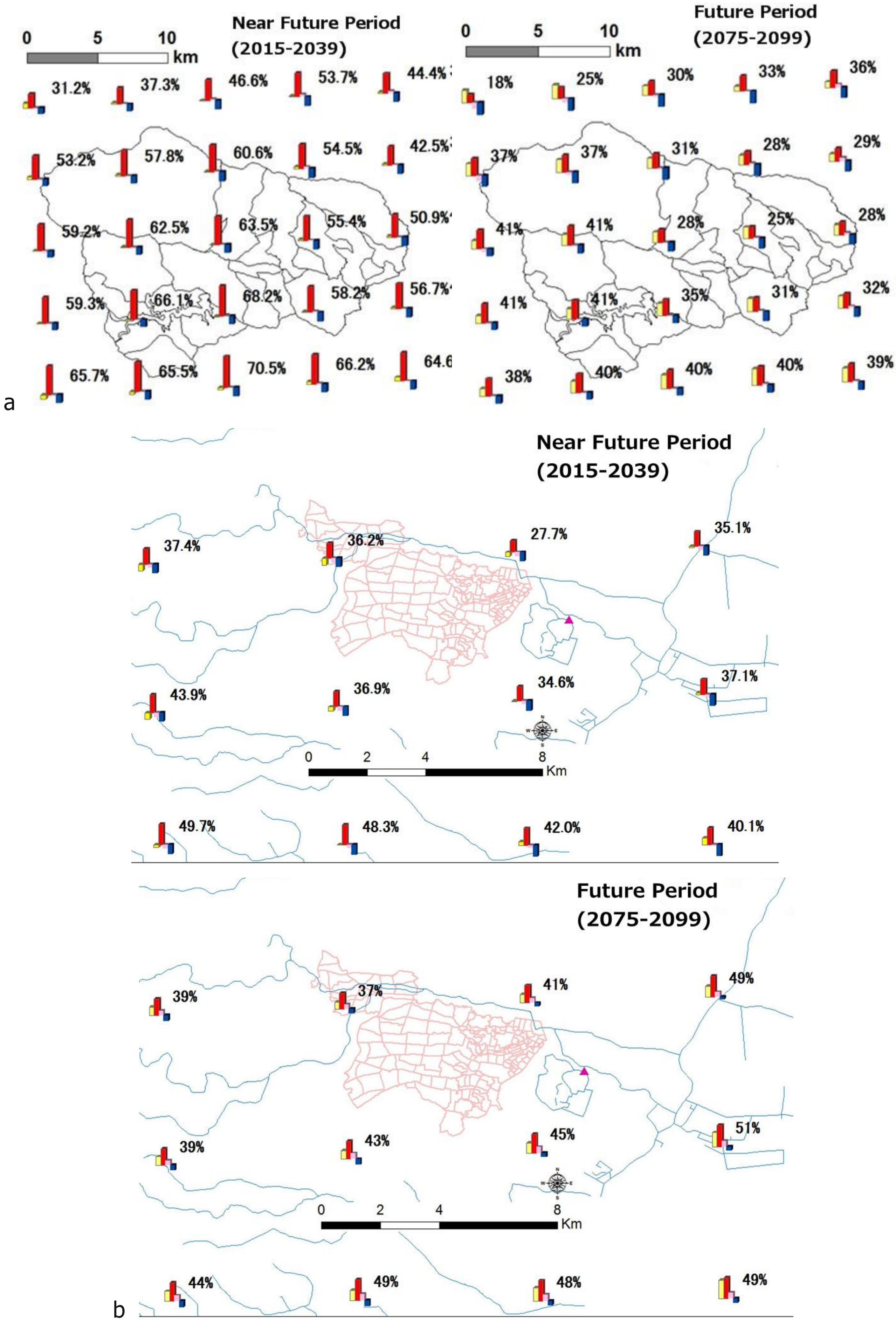


Fig. 7 Mean temperature changes in the months of July to October over Tokyo in the near future (2015–2039) and future (2075–2099) periods from NHRCM-5 km output



a
Near Future Period
(2015-2039)
0 5 10 km
31.2% 37.3% 46.6% 53.7% 44.4%
53.2% 57.8% 60.6% 54.5% 42.5%
59.2% 62.5% 63.5% 55.4% 50.9%
59.3% 66.1% 68.2% 58.2% 56.7%
65.7% 65.5% 70.5% 66.2% 64.6
Future Period
(2075-2099)
0 5 10 km
18% 25% 30% 33% 36%
37% 37% 31% 28% 29%
41% 41% 28% 25% 28%
41% 41% 35% 31% 32%
38% 40% 40% 40% 39%
b
Near Future Period
(2015-2039)
37.4% 36.2% 27.7% 35.1%
43.9% 36.9% 34.6% 37.1%
0 2 4 8 Km
49.7% 48.3% 42.0% 40.1%
Future Period
(2075-2099)
39% 37% 41% 49%
39% 43% 45% 51%
0 2 4 8 Km
44% 49% 48% 49%

Fig. 8 Percentage changes in monthly precipitation in July, August, September and October at Okutama-machi and Shinjuku during near–future (2015–2039) and future (2075–2099) periods from NHRCM-5 km output. Numbers indicate ratio of change in August precipitation (a and b)

Downscaled NHRCM-5 km output provides changes in July to October monthly mean temperature, along with percent changes in monthly precipitation for those months, during the near-future and future periods at Okutama-machi. Figure 8 shows percentage changes in monthly precipitation in July, August, September and October at Okutama-machi and Shinjuku during near–future (2015–2039) and future (2075–2099) periods from NHRCM-5 km output. In case study of Okutama-machi, August monthly mean temperature will increase more than 0.7–0.9 °C, and monthly precipitation by 50 % in the near–future period. For the future period, August monthly mean temperature will increase more than 2.8–2.9 °C, and monthly precipitation by 25–41 %.

Recent climate model improvements have enhanced the ability to simulate many aspects of climate variability and extremes. However, systematic errors and limitations in accurately simulating regional climate conditions remain (Easterling et al. 2000). Sasaki et al. (2011) gave bias and RMS error of annual mean precipitation difference between NHRCM-5 km and observations at −11 mm and 379 mm, respectively. Similarly, Kanada et al. (2010) reported bias of 10-year mean regional maximum precipitation in summertime between NHRCM-5 km and observations at 9 %, and bias in the number of wet days from June to October was 12 %.

RMS errors and bias are defined by formulas (1) and (2):

$$RMS = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(Mod_k - Obs_k)^2} \quad (1)$$

$$bias = \frac{1}{N}\sum_{k=1}^{N}(Mod_k - Obs_k), \quad (2)$$

where *Mod* is model simulations and *Obs* is observations; N is the number of data (number of observation stations × years × 4 months).

Data were analyzed for 25 years, from 1979 through 2003, and 4 months, from July through October. The RMS error of difference in July, August, September and October monthly precipitation between the model simulations and observations is 66.18 mm, and the bias of difference is −0.49 mm. We also computed RMS errors and bias of percentage change for monthly precipitation of these months, which were 26.8 % and 4.3 %, respectively.

3.2 Vulnerability assessment

Vulnerability information is useful to moderate potential damages and take advantage of opportunities to adjust strategy as needed. Hallegatte and Corfee-Morlot (2011) stated understanding of vulnerability at a local scale can help national and subnational governments work closely with city authorities. If this is addressed, enabling national policy frameworks can help city authorities and other local decision-makers to execute locally-tailored, cost-effective and timely solutions. Here, the DMT is a basic tool for representing regional physical vulnerability to the direct impacts of local climate change.
Figures 9 give examples of vulnerability assessment in Tokyo and Okutama-machi. As seen in Fig. 7, mean temperatures increase in Okutama-machi faster than any area in Tokyo during both the near-future and future periods. However, Figure 9 shows that the monthly average maximum temperature in Okutama-machi during the future period (2075–2099) will be less than 30 °C. There is no significant change in the number of extremely hot days with maximum temperature exceeding 35 °C. These results caution that it is necessary to examine links between national and local climate policy response.

Careful monitoring of these outcomes both advances scientific understanding and help adjust policies or operations as part of an iterative learning process. For example, the increase in August average maximum temperature during the future period is 2.7–2.9 °C at Okutama-machi. Thus, it appears that one legitimate policy decision, as an example of design and delivery of a climate policy solution by local government, is the construction of a medical facility or healthcare center in Tozura for the aged (Fig. 3b). These firsthand analyses clarify high-priority issues and provide critical input to planning for climate change. Particularly, in the Nippara and Tozura area (Fig. 3b), aging population ratios exceed 50 % and 60 % as of 1 October 2010 (Fig. 6a), respectively. This means that regions vulnerable to climate change are also under pressure from forces such as changing population demographics. The potential vulnerability links between human lives and climate change become obvious. Sufficient information is available for policymaking about responses to potential climate change consequences, and this indicates an explicit need for initiatives by local governors to design adaptation strategies and build adaptive capacities.

The RMS error of percentage change for July to October monthly precipitation between model simulations and observations is 26.8 %, and the bias of percentage change is 4.3 %. Figure 8b illustrates the drainage network in Shinjuku and percent changes of monthly precipitation from NHRCM-5 km, during the near-future (2015–2039) and future periods (2075–2099). In the near future, August monthly precipitation will increase by 30 % (Fig. 8b). First-priority specific adaptation measures should be implemented to limit flood risks in the area with the maximum population density. The vulnerability assessment can be used to guide policymakers.

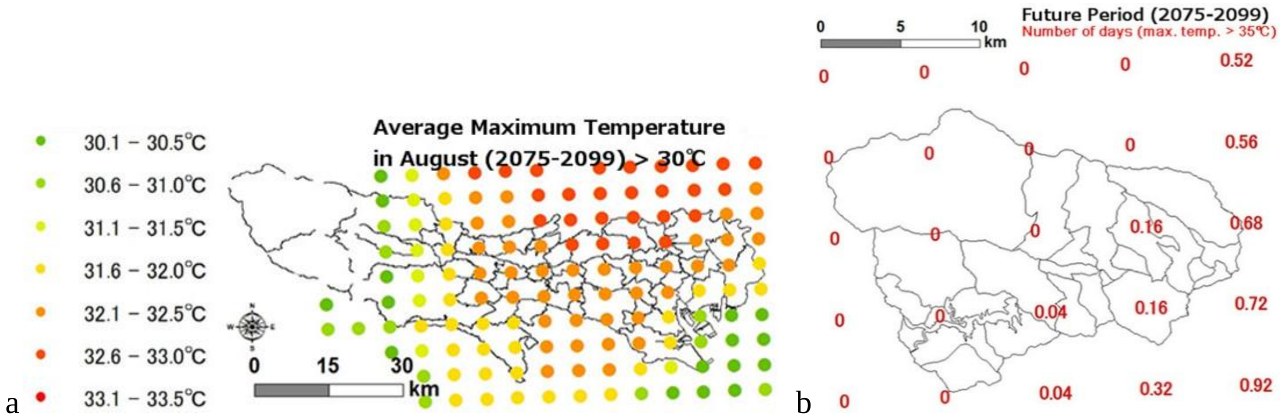


Fig. 9 Distribution of August average maximum temperature greater than or equal to 30 °C during 2075–2099 (a) and number of extremely hot days with maximum temperatures exceeding 35 °C and changes in average August maximum temperature during the future periods (b)

4 Results and discussion

In this paper, the ever expanding volumes of data (5 km resolution) are easily and freely available to enable new scientific research by a GIS-based tool. These data and the results that depend on them are useful to and understandable by a broad interdisciplinary audience, especially by the local policymakers. A similar approach can be achieved in the other areas/countries using observations and regional simulations for which the output can be downloaded freely.

The NHRCM-5 km output (only evaluates for Japan) is the most complete and current evaluation of projected climate change impacts on Japan. The pilot study leads to the following conclusions:

1) Using a GIS-based tool, the model promotes understanding of the most important consequences of climate change on local livelihoods. Williams et al. (2009) recommended "adaptive management does not represent an end in itself, but rather a means to more effective decisions and enhanced benefits. Its true measure is in how well it helps meet environmental, social and economic goals, increases scientific knowledge, and reduces tension among stakeholders". Figures 7, 8, and 9 present simple mapping of local impact analysis of climate change in Tokyo metropolitan areas. These results confirm the impacts of climate change are felt locally. Many attributes (Figs. 3, 4, 6 and 8) that determine human vulnerability and adaptive capacity are also local. Figures 3, 4, 6 and 8 display the main issues in the region and the crisis faced by local government leaders. Knowledge of adaptation is limited within existing literature. Successful adaptive management efforts will require that institutions have sufficient space and support for learning and experimentation (Gunderson and Light 2006).

2) The DMT facilitates two-way exchange of local knowledge between researchers and decision makers. Non-expert governors will benefit from the tool by understanding the projections graphically; bias and RMS errors of simulation can be clearly determined. For

example, as seen in Fig. 7, the mean temperature increase in Okutama-machi is the highest of any area in Tokyo during both near-future and future periods. However, Fig. 9 shows that the August monthly maximum temperature in Okutamamachi during the future period (2075–2099) will be less than 30 °C based on the climate change projections. It is important to define emergent properties of response variables that are sensitive to resilience (or lack thereof).

3) The pilot study tested several functions of the tool with GIS. The study outcome shows that the mapping tool can illustrate likely climate change during near-future (2015–2039) and future (2075–2099) periods, and can address different climate change adaptations needed on various time scales. These outcomes and the basic tool can facilitate good decision making. Further, hazard-specific adaptive actions will have potential knock-on effects for generic governance systems. These can become equitable (more inclusive decision making) to avoid increased disparity and inequality.

4) The pilot study outcomes also suggest that online systems with services (datasets from GIS statistics are available for re-editing and visualization on web browsers) are central to adaptive capacity, because these make real-time information available to multiple users and encourage national and subnational governments to work closely with local authorities. This means that building bridging capital (connections between groups in society) is most important for local governments in unpopulated mountain regions, especially for marginal villages.

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