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Climate change and multi-dimensional sustainable urbanization

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Abstract: Global large-scale urbanization and climate change have become indisputable scientific facts yet are unresolved issues, and are a common concern for mankind. The relationship between these two topics is unclear and it is not known how to deal appropriately at the scientific level with climate change in the process of urbanization. Further exploration of the science, management and practice, are needed to achieve global and regional sustainable development. This paper first considers the basic facts concerning mass urbanization and climate change and summarizes the interactions and possible mechanisms of urbanization and climate change. Urbanization leads to the heat island effect, an uneven distribution of precipitation and extreme weather, together with a local-regional-global multi-scale superposition effect, which aggravates the consequences of global climate change. The impact of climate change on urbanization is mainly manifested in aspects such as changes of energy consumption, mortality, and the spread of infectious diseases, sea level rise, extreme weather damage to infrastructure, and water shortages. This paper also briefly reviews relevant international research programs and action coalitions and puts forward an analysis framework of multi-dimensional sustainable urbanization which can adapt to and mitigate climate change, from the perspective of the four key dimensions—population, land use, economy, and society. It is imperative that we strengthen the interdisciplinary activities involving the natural and social sciences, take urbanization and other human activities into consideration of the land - atmosphere system, and explore the human-land-atmosphere coupling process. The adaptation and mitigation from the perspective of human activities, as represented by urbanization, might be the most critical and realistic way to deal with climate change.

Keywords: sustainable urbanization; global change; interaction; human-land-atmosphere coupling; land-atmosphere coupling; adaptation and mitigation

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1 Introduction

Many studies have demonstrated that human activities, as represented by the urbanization process at the global scale, are important driving factors of climate change. Specifically, the rapid growth of the urban population, land use change, and a large number of fossil-fuel based energy development and utilization programs, not only promote the rapid development of the economy and society but also lead to a series of changes in climate systems. Several studies have shown that climate change has some positive effects to a certain extent in some regions such as reducing the demand for heating and the dependence on heat energy (Yalew *et al*., 2020), as well as increasing agricultural crop yields (Wu *et al*., 2019), and increasing plant growth and biosphere activity (Peñuelas and Filella, 2001). However, research has demonstrated that climate change brings great risks and challenges to human survival and sustainable development in the future. In the process of urbanization, fossil fuel utilization contributes to three quarters of global greenhouse gas emissions, which directly affect the process of climate change and its trends in the future. Urbanization can have a strong impact on the local climate, such as the heat island effect (Oke, 1973; Karl *et al*., 1988; Peng *et al*., 2005; Zhong *et al*., 2017), uneven spatial distribution of precipitation (Shepherd and Burian, 2003; Li *et al*., 2008), and frequent extreme weather such as floods and storms (Huff and Jr., 1972; Jauregui and Romales, 1996; Kong *et al*., 2018). Meanwhile, cities with more than half of the world's population act as the main conduit of human economic and social activity, which is greatly affected by climate change (Zhai *et al*., 2019). Climate change impacts on urbanization with respect to changes in energy consumption (LCCP, 2002; Giannakopoulos and Psiloglou, 2006), an increase in mortality and the spread of infectious diseases (Alcoforado *et al*., 2015; Wu *et al*., 2016), the security of coastal and island cities (De Sherbinin *et al*., 2007; Hunt and Watkiss, 2011; Takagi *et al*., 2016), the destruction of infrastructure (Kirshen *et al*., 2008; Huong and Pathirana, 2013), and a shortage of water resources (Milly *et al*., 2005; Kummu *et al*., 2010). The interaction between global climate change and human activities is an important bottleneck that restricts the future sustainable development of typical urban agglomerations (Zhu *et al*., 2017).

In response to the huge challenge of climate change, the Intergovernmental Panel on Climate Change (IPCC) was established in 1988 with a remit to undertake scientific research on climate-related issues such as impacts, adaptation, mitigation, and vulnerability. Subsequently, a number of cross-regional and multi-center network organizations emerged, such as the local government council for sustainability (1990), the C40 Cities Climate Leadership Group (2005), and the 100 resilient cities (2013) (Bai *et al*., 2019). In 2015 with the signing of the Paris agreement, various countries pledged to implement energy saving and emission reduction measures, in order to significantly reduce the impact and risk of climate change. At present, adaptation and mitigation are two major international strategies to deal with climate change. Adaptation is generally described as the adjustment of natural or human systems to a new or changing environment (IPCC, 2007). Mitigation is defined as the action or method of reducing greenhouse gas emissions or entering the atmosphere (IPCC, 2014a). In the past, research on urban problems and countermeasures for climate change has been limited to certain fields such as the urban drainage system design based on an adaptation strategy (Eckart *et al*., 2017; Xia *et al*., 2017; Gimenez-Maranges *et al*., 2020), green space planning (Hamada and Ohta, 2010; Maimaitiyiming *et al*., 2014), application of green infrastructure (Demuzere *et al*., 2014; Chen, 2015b; Derkzen *et al*., 2017), urban governance (Broto *et al*., 2015), reduction of meteorological disaster risks and hazards (Zimmermann *et al*., 2016), as well as low energy consumption buildings based on mitigation strategies (Wende *et al*., 2010; Lim and Yun, 2017), application of new technologies like the cool roof and the green roof (van Bijsterveld *et al*., 2001; Akbari and Matthews, 2012; Santamouris, 2014; Qi *et al*., 2019), and development of alternative energy and adjustment of energy structure (Creutzig *et al*., 2015; Paszkowski and Golebiewski, 2017; Wang *et al*., 2018). Combining adaptation and mitigation, systematic measures that superimpose on multiple aspects of city vulnerability, exposure, social adaptability, risk, and hazards to produce synergy can ensure long-term sustainable development goals. On the whole, pertinent research is now conducted mainly in fields such as engineering technology, meteorology and climatology, architecture, and energy, which focuses on discovering new facts associated with climate change processes and understanding the functional relationship and driving mechanism of the land-atmosphere system. It is still insufficient to analyze the relationships among the human urbanization process, and the land use change and climate change systems. The adaptation and mitigation from the perspective of human activities, as represented by urbanization, may be the most critical and realistic path to deal with climate change. The shift from a land-atmosphere coupling to a human-land-atmosphere coupling is the trend and direction for new research in order to gain a full understanding of the impact of the large-scale urbanization process (Chen *et al*., 2019c). It is clearly important to enhance our understanding, from an interdisciplinary perspective, of the interplay between natural and social sciences and to further promote the transformation from extensive urbanization to a "people-oriented" new type of urbanization (Chen *et al*., 2016; Chen *et al*., 2018; Chen *et al*., 2019a), as well as the transformation from an unsustainable urbanization which adversely impacts climate change into sustainable urbanization having much less of an impact in order to achieve a reduction in the risk and harm of meteorological disasters and urban vulnerability and exposure, mitigate against climate warming, as well as improve urban social adaptability.

This paper first gives a brief account of global large-scale urbanization and climate change, and then summarizes the interaction mechanisms and relationships between urbanization and climate change. We then construct a multi-dimensional analysis framework of sustainable urbanization that can adapt to and mitigate climate change in order to provide a scientific basis and an acceptable pathway for the realization of global and regional sustainable development goals.

2 Key facts on global large-scale urbanization and climate change

In recent decades, the planet has been experiencing a large-scale and rapid urbanization process, which has occurred mainly in developing countries and regions. According to the UN's world urbanization prospects for 2018, 55% of the world's population live in urban areas, and this proportion is expected to reach 68% by 2050 (UN, 2018). Although the urbanization rates for Asia and Africa are at the low level of 50% and 43%, respectively, the urban population is growing rapidly. The global urban population has grown rapidly from 751 million in 1950 to 4.2 billion in 2018, and nearly 90% of this growth has occurred in Asia and Africa (Figure 1). Sub-Saharan Africa, East Asia, West Asia, Latin America, and the Caribbean and other underdeveloped regions have experienced faster urbanization than the historical trend for developed countries, among which East Asia experienced the fastest urbanization with the proportion of the urban population increasing from 18% to 60% from 1950 to 2015 (UN, 2018). Based on the current rates of growth, it is estimated that 230 new cities will be formed in middle-income countries by 2050 (UNDP, 2016). The results show that the impervious surface area of human settlements in the world will have reached 797,076 km² in 2018, which is 1.5 times that of 1990. During this period of nearly 30 years, the impervious surface area of human settlements in Asia has increased nearly three times, becoming the fastest growing continent in the world (Gong *et al*., 2020).

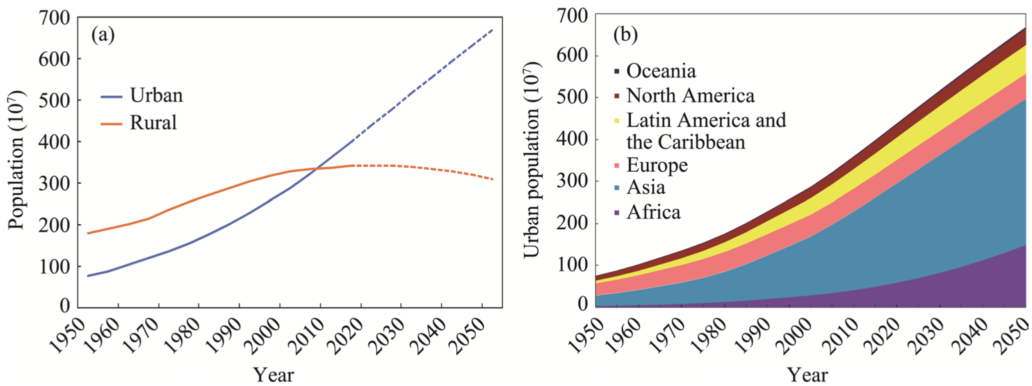

Figure 1 Urban and rural populations (mid-year) for the period 1950–2050 (a); urban population (mid-year) by regions (b) for the period 1950–2050 (data provided by the Population Division of the UN Department of Economic and Social Affairs (UN, 2018))

Since mankind created the industrialized society, a series of problems, such as frequent extreme weather, ocean warming, melting of glaciers and ice sheets, and rises in sea level have aroused global attention to the issues of global climate change. The fifth assessment of the IPCC reported that from 1880 to 2012, the global average surface temperature of lands and seas increased by 0.85°C, which reconfirmed that global climate change is an indisputable fact and that the climate system will continue to warm. The warmest 5 years from 2015 to 2019 according to meteorological observation records shows that the global average temperature for this 5-year period was 1.1°C higher than that of the 1850–1900 period. Many places in Europe suffered from a heat wave in July 2019, making it the hottest month in the history of modern meteorological records (Figure 2). The temperature of the upper 75 m of ocean has increased by 0.11°C every 10 years from 1971 to 2010. Meanwhile, global warming has led to widespread shrinking of polar ice caps, with average global glacier mass loss rates of 275 Gt per year over the period 1993 to 2009. The concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are the main greenhouse gases in the atmosphere, increased by 40%, 150%, and 20%, respectively from 1750 to 2011, reaching unprecedented levels for at least the past 0.8 million years. Due to factors such as the melting of glaciers and ice sheets and the thermal expansion of the ocean from warming, the global average sea level rose by 0.19 m from 1901 to 2010. Since the middle of the 19th century, the sea level has risen at a higher rate than the mean rate over the past 2000 years, thus seriously threatening many coastal areas and low-altitude islands in the world (IPCC, 2014b). As climate change will profoundly affect the human social economy and natural systems, climate action has become one of the key objectives of the UN's Sustainable Development Goals (SDGs).

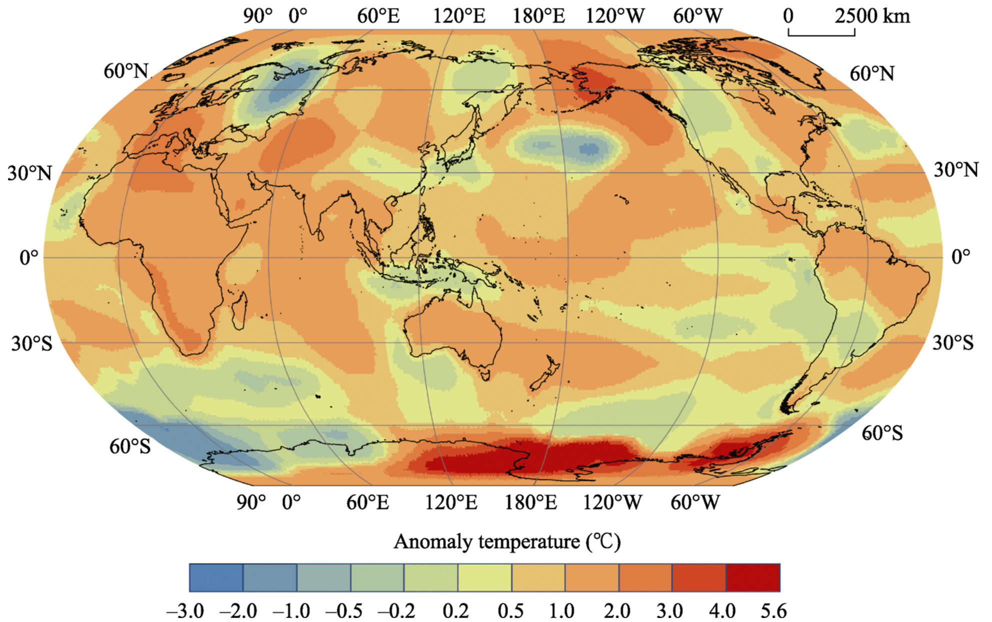

Figure 2 Global temperature anomalies in July 2019 (*vs* 1951–1980) (data from GISTEMP (2020); world map from http://bzdt.ch.mnr.gov.cn/, with code GS (2020) 4395

3 Interaction between urbanization and climate change

3.1 Impact of urbanization on climate change

3.1.1 Effect on temperature

The heat island effect has a significant impact on local warming because of urbanization. A large number of studies have shown that urban areas have experienced a more intense warming trend than non-urban areas (Sun *et al*., 2016). The urban heat island (UHI) effect can be detected even in small towns with a population of less than 10,000 (Karl *et al*., 1988). Studies have shown that the local warming effect of the UHI is related to factors such as the geometric shape of buildings, land cover, the impervious surface, anthropogenic heat, vegetation, and a reduction in the water cover area (Oke, 1973; Peng *et al*., 2013; Luo and Chen, 2019). Land urbanization leads to a decrease in the urban surface albedo yet an increase of surface roughness makes the city absorb more short wave radiation in the daytime which it gradually releases at night, leading to muggy nights (Si *et al*., 2014). In the case of strong solar radiation, urbanization will induce extreme heat waves (Zhong *et al*., 2017). A poorly planned urban layout may hinder urban air flow and slow down heat dispersal (Lau and Ng, 2013). The expansion of urban populations leads to an increase of anthropogenic heat from various sources such as transportation and residential energy consumption, resulting in a surface energy surplus (Mahmood *et al*., 2014).

3.1.2 Effect on precipitation

Urbanization leads to local changes in the spatial distribution of precipitation, especially in the downwind regions. From analysis of the trends in climate change associated with the urbanization process in Beijing, Li *et al.* found that precipitation areas had shifted from the west to the northeast of the city since the 1970s (Li *et al.*, 2008). A large number of studies have reported that urbanization leads to more precipitation in the downwind areas (Shepherd and Burian, 2003). Huff and Jr. (1972) found that the maximum precipitation in the summer in eight cities in the USA, including St. Louis, Chicago, Houston, and Washington, increased by 7 to 19%, and occurred mainly in the downwind regions at 16 to 56 km from the city centers. The increase of urban surface roughness promotes precipitation by enhancing the atmospheric convergence of updraft (Thielen *et al.*, 2000), while a large number of impervious surfaces reduce urban evaporation and inhibit precipitation. Meanwhile, industrial emissions increase the aerosol load and enhance atmospheric stability, thus reducing precipitation (Zhong *et al.*, 2017).

3.1.3 Effect on extreme weather

Urbanization increases the frequency and harm of extreme weather including severe convective weather events such as high temperatures, heat waves, rainstorms, and hail (Jauregui and Romales, 1996). Huff and Jr. (1972) found that urbanization increased the intensity maxima of rainstorms by 13 to 47% and hail by 90 to 350% in St. Louis and the surrounding areas in the Midwestern United States. Based on the daily precipitation data of 544 meteorological stations in China from June to August for the period 1961–2010, Kong *et al.* concluded that urbanization in China upgraded the extreme precipitation threshold by 1.68% nationwide (Kong *et al.*, 2018). Meanwhile, a large number of impervious surfaces shorten the time of surface runoff and makes the peak value of runoff greater than the threshold of the drainage system, causing frequent urban waterlogging and even floods. Owing to tensions between people and land, many cities in river deltas occupy large areas of the flood buffer zone, which includes even lakes and rivers, thus making cities more vulnerable to flood disasters under the same precipitation conditions (Wei *et al.*, 2020). Surface runoff will bring a large number of pollutants into rivers or into the groundwater systems in a short time, leading to deterioration of water quality and reduction of dissolved oxygen concentrations (Astaraie-Imani *et al.*, 2012). It is estimated that the frequency of extreme high temperature events in summer in eastern China has improved more than 60-fold since the 1960s due to enhanced UHI effect brought by greenhouse gas emissions and rapid urbanization (Sun *et al.*, 2014). Wang *et al.* (2013) found that urbanization raised the average temperature of heat waves in the Beijing-Tianjin-Hebei region by about 0.6℃.

3.1.4 Impacts on local-regional-global multi-scale climate change

Urbanization can not only cause local and regional climate change such as the UHI and extreme weather but also affect global climate change through atmospheric circulation (Luo and Chen, 2019; Zhai *et al.*, 2019). Since 1750, cities have been responsible for about three quarters of the world's energy consumption and greenhouse gas emissions though they only account for about 0.4 to 0.9% of the surface area, which is an important reason for global warming. In the process of urbanization, fossil fuel combustion and automobile exhaust emissions lead to ultra-high concentrations of nitrogen oxides in the atmosphere. Chase *et al.*, through computer simulations, showed that regional land use change is not limited to the local area and even may give rise to a global climate chain reaction (Chase *et al.*, 2000). Urbanization can directly cause local or regional climate change, as well as affect local or regional climate change indirectly by influencing the global climate, generating a multi-scale superposition effect as depicted in Figure 3.

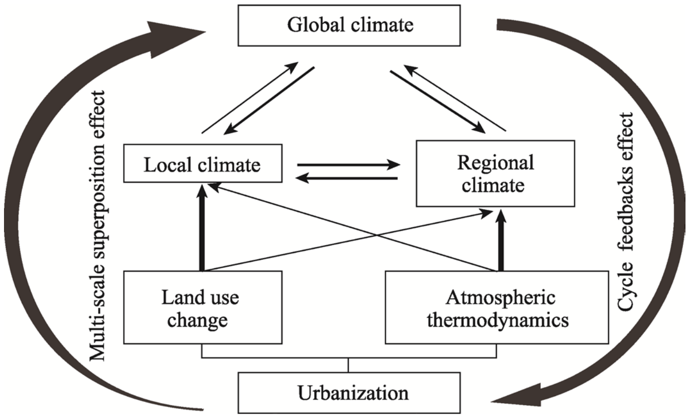

Figure 3 The multi-scale superposition effect of urbanization on climate change

3.2 Impact of climate change on urbanization

Climate change affects urbanization mainly through global warming, sea-level rise, extreme events, and redistribution of precipitation. The impact is mainly manifested in five aspects: a change in energy consumption, the spread of health and infectious diseases, the security of coastal and island cities, the destruction of infrastructure, and a shortage of water resources (Figure 4). With an acceleration of climate change, this effect may result in a rapid non-linear increase in climate change rather than a linear one.

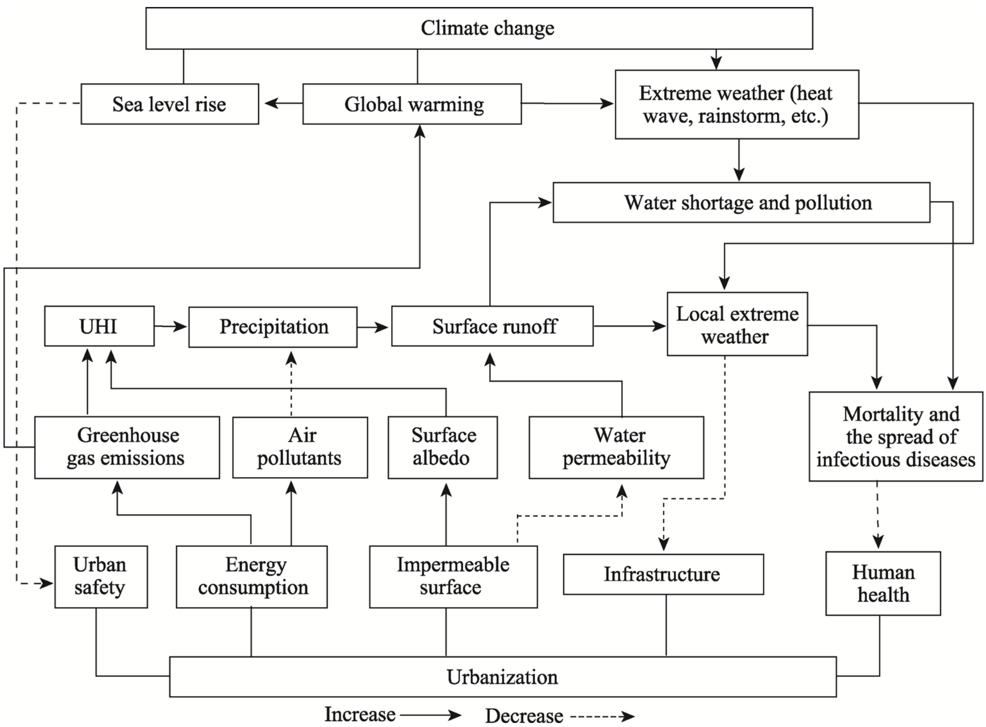

Figure 4 Overview of the interactions of urbanization and climate change

3.2.1 Global warming changes energy consumption

Warming changes the seasonal demand for residential energy consumption. It is predicted that the energy required for heating buildings in middle and high latitudes regions will decrease, but the energy used for indoor cooling in urban areas will rise significantly for temperature rises of 1 to 5℃. For example, due to the extensive use of air conditioning, energy demand in Athens will increase by 30% by July 2080 (Giannakopoulos and Psiloglou, 2006). By 2050, office buildings in London are expected to add energy consumption for cooling by 10%, and by 20% in 2080 (LCCP, 2002). An average annual temperature rise of 1℃ in the Yangtze River Delta will increase the air conditioning energy consumption of the textile industry by 10% (Gu *et al*., 2011). In addition, temperature rises will reduce the capacity of thermal power generation capacity and transmission, resulting in more energy loss.

3.2.2 Climate change and human health

Global warming and extreme climate events affect peoples' physical and mental health directly via heat waves or an increase in mortality or indirectly through the spreading of infectious diseases, and lowering of virus survival rates. Studies have shown that strong heat waves lead to high mortality in the elderly who have cardiovascular or cerebrovascular diseases, causing a secondary peak of mortality in the summer (Alcoforado *et al*., 2015). High temperatures would also densify the content of ozone and other pollutants in the air, thus aggravating cardiovascular and respiratory diseases (Paz *et al*., 2016). Kovats *et al*. (2004) modeled the impact of heat wave on the hospitalization rate for Greater London and observed that the mortality rates grew by 3.3% for every 1℃ increase on the basis of 21.5°C. Climate conditions seriously affect water-borne diseases, mosquito borne infectious diseases such as dengue fever, Ross River virus diseases, food borne infectious diseases caused by salmonella, campylobacter, and many other microorganisms and diseases transmitted by other cold-blooded animals (Wu *et al*., 2016). Climate change has expanded the range of zoonotic parasites and improved the prevalence of parasitic diseases (Gordon *et al*., 2016). In general, urbanization and related urban land expansion augment the summer heat index by about 75% and reduce the comfort of residents (Wang *et al*., 2019).

3.2.3 Security of coastal and island cities

Sea-level rise threatens the security of coastal and island cities. Data show that about 65% of cities with a population of more than 5 million are located in coastal areas at low altitudes (McGranahan *et al*., 2007). More than 50% of the world's population live in low-lying areas, which are potentially vulnerable to rises in sea-level (IPCC, 2007). The direct impacts of rises in sea-level include flooding, coastal erosion, storm tides, salt tides, the rise of coastal water levels, and blocked drainage systems which give rise to damage to buildings and infrastructure, land loss, and other disasters, while the indirect impacts include changes in the distribution of bottom sediments, the structure and function of coastal ecosystems and leisure activities (Hunt and Watkiss, 2011). It is calculated that the seawall in the Yangtze River Delta will have to be raised by at least 1 to 1.5 m by 2030, because the whole of Shanghai, the Taihu Lake Basin, Nantong and Jiaxing will be submerged once the seawall is breached (Gu *et al*., 2011).

3.2.4 Climate events such as extreme weather destroy infrastructure

Extreme weather, such as floods and storms, brings about property losses and casualties in cities and towns, and also causes great damage to infrastructure, industrial production, waste water treatment systems, and other public facilities (Kirshen *et al*., 2008). Climate change accelerates the water cycle and aggravates extreme precipitation, which directly influences the frequency and intensity of surface runoff and floods (Arnone *et al*., 2018). Cities are more vulnerable to waterlogging, floods, and other disasters due to large impervious surfaces and the limited capacity of drainage systems (Huong and Pathirana, 2013). Considering the agglomeration of the population and the economy, global metropolis and urban agglomerations will face greater risks. In 2010, the flood disaster area of Jiangsu and Zhejiang provinces in the Yangtze River Delta reached 7.73 million hectares, with the land area with no harvest up to 226,000 hectares. In 2013, the economy of Zhejiang Province has lost 12.405 billion yuan affected by Typhoon “Fitow” (Zhu *et al*., 2017). In addition, natural disasters related to extreme weather such as hurricanes, landslides and debris flows are more harmful for urban areas (Douglas *et al*., 2008).

3.2.5 Deterioration of water quality and water shortage

Climate change makes water shortage more critical in some areas by affecting the availability and quality of the earth’s freshwater resources . As a result of changes in precipitation patterns and boosting evaporation through temperature rise, some areas will become more humid while others will be drier, especially in arid and semi-arid areas, where freshwater resources are more vulnerable to climate change. Climate change has contributed to desertification in 12.6% of the arid areas, involving 213 million people, 90% of whom are in developing countries (Burrell *et al*., 2020). Moreover, the rapid growth of the urban population and large-scale industrialization immensely worsen the problem of water shortages (Kummu *et al*., 2010; Lu and Chen, 2015). Research shows that the global population under the impact of water shortages will increase by 7% for every 1℃ warming (Qin, 2014). In addition, during heavy rainfall runoff carry a larger number of pollutants to rivers and groundwater systems, leading to a decline in the urban water quality.

4 Regulation of multi-dimensional sustainable urbanization for adaptation and mitigation of climate change

4.1 International research and coalition actions on sustainable urbanization

The Brundtland Report in 1987 put forward a sustainable urban model, a path which not only meets the needs of the present without compromising the ability of future generations to meet their own needs, and safeguards human well-being from the three dimensions of society, economy, and environment. In response to the problems faced by the sustainable development of cities, more than 200 multi-scale and cross-regional urban networks have been established in the world, to breakdown the traditional static and isolated pattern of scientific research, practice, and policy, interchanged ideas of stakeholders across systems such as urban governance, knowledge innovation, and urban action. Many outstanding examples are listed in Table 1 (Bai *et al*., 2019). These networks can be divided into two types. One is research cooperation such as the IPCC and urban climate change research network, which provides a scientific basis for urban adaptation and mitigation decisions. The other is action cooperation such as the C40 climate leadership group that supports inter-city peer-to-peer learning and institutions. These networks strengthen the interaction among science practitioners and decision makers so as to create powerful conditions for the transformation of sustainable urbanization (Rosenzweig and Solecki, 2018). The "Future Earth" plan was proposed in 2012 to achieve global sustainable development through the global research network spanning natural, human, social, and engineering disciplines (Zhou *et al*., 2019). Interdisciplinary and interregional cooperation is a general trend for addressing the problems of human sustainable development.

4.2 Multi-dimensional sustainable urbanization

4.2.1 From land-atmosphere coupling to human-land-atmosphere coupling

Man and Nature, written by P M George in 1864, first paid attention to the role of mankind in global change. Nobel Prize winner Crutzen proposed the concept "Anthropocene" in 2000, which relates to the fact that human activities play an important role in many aspects of the global process, and in so doing promoted widespread interest in the topic within the scientific community (Crutzen, 2002). In 2009, the International Commission on Stratigraphy established the Anthropocene Working Group (AWG) to study whether to include "Anthropocene" in the geological time scale, during which human activity characteristics may be distinguishable from the other geological time layers such as the new signatures of black carbon, plastic, concrete, and $^{239+240}Pu$ deposits (Waters *et al*., 2016). Global biodiversity is changing geographically among which marine biodiversity is the most intense and variable because of human activities (Blowes *et al*., 2019). Although researchers are still in debate over whether the concept of Anthropocene can be formally used, it is necessary to regard human activities as an important driver of global change and change the overreaching analytical framework from land-atmosphere coupling to human-land-atmosphere coupling. Recently, many natural sciences have paid attention to the importance of human activities, but they lack a comprehensive understanding and analysis of complex human activities. Yet, the social sciences engaged in the research of human activities often do not pay enough attention to the global changes caused by human beings. (Zalasiewicz *et al*., 2011). Therefore, taking human activities as a key factors of global and regional climate change, promoting the combination of interdisciplinary research, introducing a humanistic perspective, and shifting from the past land-astmosphere coupling system research to the human-land-atmosphere coupling, can obtain a more comprehensive scientific view on global change issues. (Chen *et al*., 2019c). Large-scale urbanization is a concentrated performance of human activities. Urban agglomerations, and urban belts with populations in excess of 10 million is also one of the main characteristics of the concept of Anthropocene. Urbanization from a geographical perspective is the process and spatial evolution of human production and lifestyle changes from rural to urban, including the urban-rural population structure, land cover, mode of production, and social adaptation. Urbanization and urban sustainability will play a key role in global and regional adaptation and mitigation of climate change and sustainable development in the future.

Table 1 Examples of cross-regional urban cooperation networks at different scales (after Bai *et al*., 2019)

	Core areas	Examples of key initiatives
Global networks		
UN Sustainable Development Goals (SDGs)	Global comprehensive sustainable development goals	2030 Program
Intergovernmental Panel on Climate Change (IPCC)	Assessment of scientific, technical and socio-economic information on global climate change	Synthesis and thematic assessment report
Future Earth	A global research network across disciplines such as nature, humanities, and engineering, and solutions to sustainable development	Scientific planning, Chinese National Committee for Future Earth and other regional committees
100 Resilient Cities	City action, resilience solutions, local leaders, global influence	100 Resilient Cities Network
C40 Cities Climate Leadership Group	Climate adaptation, mitigation implementation, air quality, energy & buildings, food, waste & water, transportation & urban planning	Deadline 2020
Cities Alliance	Global south cities, urban slums, cities and sustainable development	Innovation Programme
Coalition for Urban Transitions	Economics, policy, options, finance	Financing the Urban Transition
Global Covenant of Mayors for Climate and Energy	Data, finance, innovation for addressing climate change	Innovate 4 Cities
ICLEI Local Governments for Sustainability	Low-emissions, nature-based, circular, resilient, equitable and people centered development pathways	Talanoa Dialogues, 100% RE Cities and regions network
Metropolis	Urban diplomacy and metropolitan advocacy, capacities for metropolitan governance	Metropolis Urban Innovation, Metropolis Observatory
United Cities and Local Governments (UCLG)	Metropolitan areas, intermediary cities, territories, Localizing SDGs	Learning UCLG
Urban Climate Change Research Network	Scientific assessment on urban climate change issues specific to urban climate change needs (UHI, air quality, urban design etc.)	Urban Climate Change Assessment (ARC3)
Urban Knowledge Action Network	Link urban science to urban policy and practise, capacity building for co-designing sustainable urban futures	Cities and Climate Change Science Conference, Nature and the Urban Century Assessment, Urban Planet Book Project
Regional Networks		
African Center for Cities	Convener and central knowledge hub driving evidence-based policy influence across the African continent	City-lab programme, NOTRUC initiative, MOVE program
Federation of Canadian Municipalities	Organizer, convener and municipal funder representing all of Canada's municipalities	Municipalities for Climate Innovation
Urban Resilience to Weather-related Extremes Sustainability Research Network	Linking urban science to urban policy, planning, and management, and building capacity through codesign of resilient urban futures with local and regional stakeholders	

4.2.2 Multi-dimensional sustainable urbanization regulation

As one of the key scientific issues in geography, urbanization has rich connotations, a synthetical process containing rural-urban migration, land use change, economic non-agricultural activities, social urbanization and other factors (Chen *et al*., 2010; Chen *et al*., 2019b). From the perspective of adaptation and mitigation of climate change, this paper attempts to deconstruct the multi-dimensional process of urbanization, and take scientific measures based on population, land, economy, and society, in order to realize adaptation and mitigation of climate change and global sustainable development goals (Figure 5).

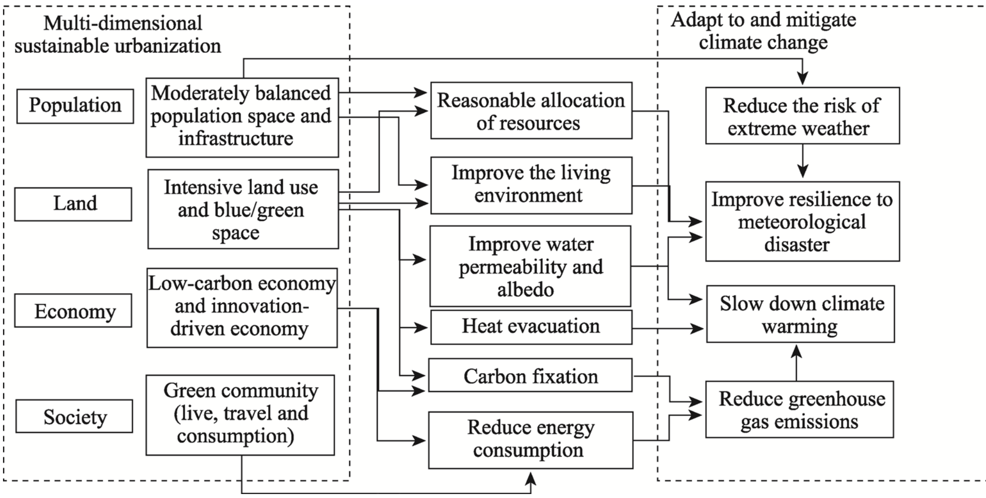

Figure 5 Overview of multi-dimensional sustainable urbanization as response to carbon storage

(1) Population dimension: moderately balanced population space and infrastructure.

A moderately balanced population space could alleviate the environmental pressure of mega cities and improve their adaptability to climate change. Research shows that anthropogenic heat generated by large-scale populations aggravates the UHI effect. With more populations concentrated in big cities, the spatial distribution of population creates a higher urban average heat island intensity compared to one that is in spatial equilibrium (Yang *et al*., 2016; Chen *et al*., 2020). More than half of the world's mega cities or urban agglomerations are located in coastal areas where more and more people are gathering (McGranahan *et al*., 2007), thus increasing urban exposure, vulnerability, and risk to climate change. Paying attention to the development of medium-sized cities and approaching the spatial equilibrium of population can reduce the impact of climate on cities and the risk level of climate change.

A moderately balanced population space is a relative concept which combines urban resources and environmental carrying capacity instead of taking an equitable distribution approach. It has been found that a negative correlation between population scale and climate change adaptability is not significant when cities have a low unemployment rate and good infrastructure conditions (Filho *et al*., 2019). A rapid increase of population in urban areas makes migrant workers and low-income groups to being squeezed into marginal zones with low land prices, high risks, and weak infrastructure and public services, with these areas being more vulnerable to the impact of climate change (O'Brien and Leichenko, 2000). Therefore, careful planning of urban infrastructure in the context of climate change is needed to improve the living environment of vulnerable groups in order to significantly reduce urban risks, exposure and vulnerability (LCCP, 2002).

Infrastructure construction and transformation that can adapt to and mitigate climate change includes sustainable water management systems and new buildings. A traditional drainage system finds it difficult to cope with extreme weather events such as rainstorms and floods given the uncertainty of climate change (Stancu *et al*., 2017; Jato-Espino *et al*., 2019). Currently, there are ongoing experiments and research on sustainable water management systems at home and abroad, such as low impact development (LID) in the USA (Eckart *et al*., 2017), sustainable drainage in the EU Water System (SUDs) (Gimenez-Maranges *et al*., 2020), and sponge cities in China (Chan *et al*., 2018). The main principles involve the use of green/blue space, infiltration filters, impounding reservoirs, and flood control buildings to simulate the natural water cycle in order to improve urban land infiltration and the evaporation rate and then to reduce surface runoff and the river pollutant load. Ozerol *et al*. (2020) believe a water management framework adapted to climate change should be established, which is divided into water sensitive communities and networks, catchment areas and ecological services, as well as the development of evaluation indexes to facilitate monitoring and management.

New types of infrastructure such as building walls, roofs, and roads transformed with new materials and technologies will effectively alleviate the UHI effect (Rossi *et al*., 2014; Creutzig *et al*., 2015). Santamouris (2014) found that the green roof and cool roof make the urban albedo increase by 0.1, and the average rate of decrease of temperature is expected to be 0.3 to 3 K and 0.1 to 0.33 K, respectively. A cool roof can save typical residential buildings about 170 kwh to 700 kwh energy consumption, and about 500 to 1000 kwh for office buildings (Akbari and Matthews, 2012). Heat storage materials with high heat capacity such as PCMs (phase change materials) and photovoltaic (PV) cells can reduce the heat released to the environment and slow down the temperature rise (van Bijsterveld *et al*., 2001). Sealing chips, colored concrete, grass concrete, and drainage permeable pavements and other modern road surfacing materials can also slow down the impact of cities on the local climate (Akbari and Matthews, 2012).

(2) Land dimension: compact city, intensive land use, and blue/green spatial layout.

Characterized by a relatively high density, mixed land use, high-intensity development and utilization, and enhanced connectivity through an efficient public transport system (Stevens, 2017), the compact city helps urban residents to minimize undertaking long-distance travel and thus saving on energy consumption for travel purposes. The expansion of residential areas near the location and route of effective transportation and infrastructure would encourage people to use public transportation more often. For cities in the stage of rapid development, compact urban development can promote a higher population density, appropriate land use planning, reduction in infrastructure investment, protection of green space and ecological environmental carrying capacity, thus restraining the UHI effect (Creutzig *et al*., 2015; Yuan *et al*., 2021). Second, a compact spatial layout helps to reduce the energy consumption of residential and service buildings thus saving on infrastructure investment. Wende *et al*. (2010) found that compact and high-volume buildings are more energy-efficient than low volume buildings; for example, the energy demand for banded townhouses is only about 56% of that for detached family houses with the same number of households.

Intensive land use relates to the rational distribution of urban elements to achieve the highest efficiency of land output and the best use of resources (Ma and Jin, 2011). The process of urban expansion should adhere to "smart growth" with intensive use of land resources including the three-dimensional space above ground and underground to avoid an extensive and disorderly development of cities. New compact urban areas near the original urban center will effectively reduce the urban average heat island intensity for megacities or large cities (Yang *et al*., 2016) and also avoid the waste of resources caused by repeat of infrastructure as well as high energy consumption and high pollution caused by long-distance transportation. Medium-sized cities have more plasticity and less path dependence and are appropriate for more compact urban design and intensive land use.

Parks, greenways, private gardens, green roofs, lakes, rivers, etc., as part of the urban green/blue space undertake a variety of key functions such as the regulation of climate, a reduction in urban temperature and urban carbon emissions, as well as providing an increase in community habitability, which contributes to the biodiversity of the urban ecosystem (Guo *et al*., 2012). Green/blue spaces reduce air and surface temperatures by providing shading and increasing evapotranspiration (Demuzere *et al*., 2014; Zimmermann *et al*., 2016). It has been demonstrated that the surface temperature of green land is significantly lower than that of other types of land cover, such as residential buildings, factory buildings, and paved built-up areas (Li *et al*., 2011; Guo *et al*., 2012), yet the cooling range of the green area is about several hundred meters, and its relatively cool air flow will be hindered by crowded traffic or towers (Hamada and Ohta, 2010). Green/blue space is used to build urban air ducts to promote urban air circulation and heat dispersal. In addition, urban greening can store carbon dioxide to reduce carbon emissions. For example, the total amount of carbon stored in urban vegetation per hectare in Leicester, UK is 31.6 tons (Davies *et al*., 2011). Chen (2015b) found that the average carbon density was 21.34 t/ha, and the average annual carbon sequestration rate was 2.16 t/ha in 2010 based on an analysis of green infrastructure in 35 major cities in China. Urban green space and green roofs can also slow down runoff velocity (Jacobson, 2011) and intercept rainwater. With an increase in soil infiltration and water storage capacity as well as a decreased pollution load in surface runoff, urban drainage is greatly improved (Davis *et al*., 2009; Zimmermann *et al*., 2016).

(3) Economic dimension: low-carbon economy and innovation-driven economy.

Urban economic development depends on energy production and consumption. Fossil fuel combustion in traditional industries is the main source of greenhouse gases and the main factor for global warming. In 2003, the UK put forward a development model for a low-carbon economy in the White Paper "Our Future: Creating a Low-Carbon Economy," which sought to achieve low consumption, low pollution, and low emission through the adjustment of energy structure, innovation of industrial structure, and improvement of energy conservation and emissions reduction technology.

With a diversified energy structure, a low-carbon energy or non-carbon energy structure being adopted, such renewable energy sources will gradually replace the traditional fossil fuel based structure such that a sustainable energy system will be established (Wang *et al*., 2018). Given that the calorific value of coal is the highest of the fossil fuel energy sources, a reduction in carbon emissions will effectively be achieved by reducing the proportion of coal used in energy consumption, improving oil and natural gas alternative technologies and low-carbon and non-carbon treatments for coal. Currently, national policies play a huge role in deciding the proportion of energy efficiency and renewable energy, such as the strategic action plan for energy development (2014–2020) in China, the 2020 climate and energy package in the EU, and the clean energy plan in the USA (Ge *et al*., 2018). Research reveals that price and market-based policies are more conducive to technology research and innovation, improvement of industrial energy efficiency, and reduction in industrial energy intensity. Market-based policies include a carbon tax, carbon emission trading permits, low-carbon labeling of products, such as for the sulfur dioxide market in the USA and the carbon emissions trading system in the EU (Mi *et al*., 2019).

Industrial manufacturing, transportation, and construction consume a lot of energy while tertiary industries have the lowest carbon footprint (Isman *et al*., 2018). Therefore, adjustment of the industrial structure to develop an innovation-driven economy would reduce the dependence of economic growth on heavy chemical industry and industrial energy intensity yet increase employment opportunities.

(4) Social dimension: green community.

The green community includes green transportation, a reduction in residential energy consumption, moderate consumption, and other aspects of green lifestyles and concepts to achieve the goal of low energy consumption and low emissions.

The first green community aspect concerns transport. A design plan for a people-oriented green transportation system within an urban city and with a multi-mode transportation network consists primarily of walking, bicycle, and public transportation routes, which would encourage more people to adopt green travel practices as compared to those used currently in a typical urban setting designed for vehicles (Nieuwenhuijsen, 2016). Building urban roads deucedly will cause “traffic guidance” and create a dependence on cars, thus stimulating the further expansion of urban roads (Wang *et al*., 2018). In addition, a reduction of short-term traffic emissions can be achieved through mandatory policy measures such as alternate days for car use, limited parking spaces, and increased public transport in cities such as Paris, Milan, Chengdu, Brussels, and Copenhagen (Nieuwenhuijsen and Khreis, 2016). However, compulsory reduction of the use of motor vehicles will result in the travel inconvenience for residents and new inequalities. Therefore, with a multi-mode humanized transportation system, sustainable urbanization would improve the accessibility and convenience of public transportation and thus meet the needs of population mobility.

The second aspect is low energy consumption. Currently, many countries and regions have established energy consumption standards for buildings, such as the ASHRAE standard of the USA and the nearly zero energy building (nZEB) of the EU. Technology for low energy consumption in buildings includes the use of energy-saving building materials, improved residential insulation performance, Intelligent central air-conditioning control system (HVAC), thermoelectric integration systems, and natural ventilation (Wende *et al*., 2010; Akbari and Matthews, 2012; Lim and Yun, 2017). The use of an integrated intelligent energy design in buildings will reduce energy consumption and greenhouse gas emissions by 30 to 40% (Brown and Southworth, 2008). Taking northern China as an example, it is estimated that if 10% of the areas that have 500 million m^2 of residential buildings meet the passive low energy consumption standard, the northern region can save about 8.5 billion kw·h of primary energy every year and decline carbon dioxide emissions by 2.83 million tons.

The third aspect relates to moderation of consumption. An awareness of social sustainable development in consumption can be highlighted by transitioning from the luxury consumption mode to the moderate consumption mode, such as cutting down the purchase of “one-time” consumable items, clean plate campaign, avoiding the purchase of non-essential goods, and choosing low-carbon products through publicity and education. Excessive consumption boosts the pressure on resources, produces too much domestic waste, and adds energy consumption in manufacturing. Thus, the promotion of green travel and reduction of a dependence on cars will effectively reduce an individual’s carbon footprint (Isman *et al*., 2018).

5 Conclusions and discussion

(1) A large number of studies have demonstrated the scientific facts regarding global large-scale urbanization and climate change, and as a matter of urgency there is a need to introduce adaptation and mitigation measures. Human activities represented by urbanization are the principal drivers of climate change. Urbanization linked to the human-land-atmosphere coupling rather than consideration of just the land-atmosphere coupling helps us to better understand the process and future trends of climate change and deal with it accordingly knowing all the scientific facts.

(2) There are complex interactions and scale effects which link urbanization and climate change. Urbanization leads to the heat island effect, an uneven spatial distribution of precipitation and frequent extreme weather events through fossil fuel consumption and underlying surface modification, which also leads to climate warming and regional air pollution through scale superposition effects. Climate change has an impact on urbanization mainly through global or regional warming, sea-level rise, extreme events, and shortages in water resources. The impact is manifested mainly by changes in energy consumption, health and infectious disease transmission, security issues relating to coastal and island cities, infrastructure damage, and water shortages.

(3) Sustainable urbanization is an inevitable choice for human society to make in order to cope with climate change. Based on coordination of the human-land relationship and the full understanding of the connotation of sustainable urbanization, an analysis framework of sustainable urbanization with climate resilience may be constructed from the four key dimensions of population, land, economy, and society. Sustainable social concepts such as a moderately balanced population space, the construction and transformation of infrastructure, compact city, intensity of land use and green/blue spatial layout, low-carbon economy, innovation-driven economy, green community, low energy consumption, and moderation in consumption collectively represent the path that needs to be followed to realize a climate resilient city and sustainable development for human beings.

In general, the current understanding of the relationship between urbanization and climate change is still at the exploratory stage, and our understandings of the key scientific issues such as the critical interaction mechanisms between urbanization and climate change, local-regional-global multi-scale effects, the human-land-atmosphere coupling process, and complex interface processes are incomplete. There is an urgent need to adapt to and mitigate climate change and promote the realization of sustainable development goals. Thus, how to establish the analysis paradigm and the perspective of the human-land-atmosphere coupling system and how to adapt to and mitigate climate change through multi-dimensional sustainable urbanization provides a possible solution, but requires further in-depth interdisciplinary research. The interdisciplinary interplay between nature and humanities, as well as the close cooperation of science, policy, and practice to deal with climate change is needed. Offering comprehensive and interdisciplinary elements, geography is well placed to further interdisciplinary endeavors related to the climate, hydrology, populations, cities, the economy, society, and other disciplines, which will help to provide comprehensive scientific solutions in response to the climate emergency and enable sustainable urbanization (Chen, 2015a; Fu, 2017).

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