Developments in the Built Environment 4 (2020) 100023

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.editorialmanager.com/dibe/default.aspx

# How to bring urban and global climate studies together with urban planning and architecture?

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ARTICLE INFO

*Keywords:*
Urban climate
Climate change
Urban planning
Building design
Adaptation
Meteorological perspective

ABSTRACT

Climate friendly urban planning plays a key role in climate change mitigation and adaptation and allows for sustainable development of living conditions for future generations. It has been long understood that measures such as urban greening, planted facades and roofs or highly reflecting building materials are able to dampen excess heat and help reducing energetic costs. Transferring scientific and often theoretical knowledge into actual urban planning however necessarily involves an interdisciplinary dialogue. This paper intends to provide a review of existing literature from a meteorological perspective in order to answer the question how results from urban climate studies can be linked to architectural design of future urban areas. Results from state of the art research are evaluated and critically addressed, hence providing a catalogue for urban planners and stakeholders which should serve as basis for a re-evaluation of the term ‘smart city’.

## 1. Introduction

Urban agglomerations are very complex entities which are difficult to govern. An efficient governance is nevertheless indispensable, because more than half of mankind is presently living in urban areas and this share is ever increasing. Urban and global climate on the one hand and urban planning together with building design on the other hand should thus be important and interconnected fields of research and action in order to shape sustainable cities for tomorrow. This manuscript looks at the situation from an atmospheric scientist’s point of view. It intends to provide suggestions for sustainable urban planning under present and future climate conditions. Rather than defining specifically dedicated and detailed measures or technical realizations, this document aims to display and offer a pool of efforts and ideas summarizing results from five decades of scientific research in the field of urban planning with regard to local air quality and to local and global climate. Readers are encouraged to evaluate the effectiveness of the measures provided for dedicated urban planning, architecture and building design in their city.

For several thousands of years - since the sedentarisation - mankind has built cities; Jericho is said to have existed for ten thousand years now (Bonine, 2016). Traditional city design has been the result of a long evolution. As the local climate had been one of the major external factors for city design in ancient times, climate-adapted city designs evolved in many parts of the world. Just to name a few examples for cities in very warm and hot areas, one could look at white Greek cities or at the densely built desert cities in the Sahara and the Middle East. More examples can be found in, e.g., Linhares de Siqueira (Linhares de Siqueira, 2015). Also technical installations such as towers serving as wind catchers were used in some hot places to keep cities cool and inhabitable (Azami, 2005).

In modern cities of our times other factors impacting the city design have become more dominating. Economic interests, transportation needs, and political prestige have taken over as major driving factors in city planning and architecture. This seems to be even true for what is often seen as one of the few exceptions: the design of Masdar city (see, e.g. (Nader, 2009),) which is said to be strictly planned as a sustainable city. Cugurullo (2016) argues that Masdar has been planned around economic and political targets. In this, sustainability has been understood as reflections of broader policy priorities. The meaning of the term sustainability, introduced into the modern discussion by Brundtland (1987), is strongly dependent on the context in which it is applied and on whether its use is based on a social, economic, or ecological perspective (Brown et al., 1987). This has to be seen in light of the fact, that cities of today present requirements that are different from those of the past. This calls for certain measures to be re-evaluated in order to shape sustainable cities to be simultaneously economically viable, socially just, politically well managed and ecologically sustainable to maximize human comfort

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https://doi.org/10.1016/j.dibe.2020.100023
Received 2 July 2020; Received in revised form 7 August 2020; Accepted 7 August 2020
Available online 11 August 2020
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(Panagopoulos et al., 2016). Sustainable urban planning as such has to be treated with respect to the historical stage of development of the city or region in focus, thus enabling a 'fitness-for-purpose'.

This paper is structured as follows: First, in Section 2, a short look on existing urban studies from atmospheric and sustainability sciences is given followed by a brief comparison of the terms "smart" and "sustainable". Subsequently a few recent examples of modern building design are listed in Section 3 which have found larger public interest and thus have been noted by atmospheric scientists as well. These introductory sections are followed in Section 4 by a longer structured and ranked list of suggestions how local and global climate features could be incorporated into today's and future building and city design. Section 5 giving some recent numerical model approaches to urban air quality and urban climate and some final remarks conclude this paper.

## 2. Existing urban studies

### 2.1. Studies from atmospheric sciences

Atmospheric sciences have dealt with the special features of urban climate for about 200 years starting with the seminal book of Howard (Howard and Phillips, 1818). The most important features of urban climate include higher air and surface temperatures, changes in radiation balances, lower humidity, and restricted atmospheric exchange that causes accumulations of pollutants from local sources. The four main causes of a special urban climate are: (1) replacement of natural soil by sealed surfaces, mostly artificial and having a strong 3-D structure, (2) reduction of the surface area covered by vegetation, (3) reduction of long-wave emission of the surface by street canyons, and (4) release of gaseous, solid and liquid atmospheric pollutants, and waste heat. These factors all have severe impacts on the urban energy budget, water storage, and atmospheric exchange in near-surface layers (Marzluff et al., 2008).

Urban climate studies in the last decades have usually focused on specific features such as urban heat islands (UHI, (Hidalgo et al., 2008), (Levermore et al., 2018), (Li et al., 2019)), air quality (emission, transport, chemical transformation, and deposition of reactive gases and particles (Parrish et al., 2011), (Parrish, 2016), (Andrade et al., 2017)), pedestrian comfort (e.g., local wind conditions (Stathopoulos et al., 2004)), or thermal comfort (Chatzidimitriou and Yannas, 2016) often in connection with public health issues (Tan et al., 2010), (Salmond et al., 2018), (Steeneveld et al., 2018). Some of these studies discussed the interrelation to the regional and global climate and climate change (Cleugh and Grimmond, 2012), (Akbari et al., 2016), (Ward et al., 2016), (Founda and Santamouris, 2017).

### 2.2. Studies on sustainable cities

Sustainability studies mainly concentrated on energy consumption and greenhouse gas emissions. About 80% of all greenhouse gas emissions is generally attributed to cities (Martos et al., 2016). That means, according to (Satterthwaite, 2008), most likely less than half of the anthropogenic greenhouse gas emissions are actually generated within the city boundaries. However, cities account for a significantly higher percentage of these emissions, if emissions from power stations or industries are assigned to the location of the actually consuming persons or institutions. Some studies also addressed matter fluxes and cycles (water, energy, commodities) but rarely recyclable buildings and infrastructure (see, e.g. (Petit-Boix et al., 2017),).

There seems to be consensus in several studies from the last two decades that nearly none of these studies, neither climate studies nor sustainability studies, had considerable influence on actual city planning and/or building design so far (Eliasson, 2000), (Mills et al., 2010), (Parsaee et al., 2019). The low impact is said to be a result of several constraints which could be related to five explanatory variables i.e. conceptual and knowledge based, technical, policy, organisational, and the market (Eliasson, 2000). While a substantial body of knowledge on the science of urban climates has been developed over the past fifty years, there is little evidence that this knowledge is incorporated into urban planning and design practice (Mills et al., 2010). UHI mitigation strategies have had negligible contributions to urban development policies and action plans (Parsaee et al., 2019) as they necessarily have to involve the dynamic nature of the urban landscape with regard to social and economic aspects. Bringing together concepts from various disciplines, sustainability of cities, leading to human health and well-being should be manifested in economic viability, social justice, ecological sustainability and transparency of political management (Panagopoulos et al., 2016). These assessments fit to the arguments given in Cugurullo (2016).

Amado et al. (2016) even state that current urban planning is not a process that ensures energy efficient cities and then demand both reducing energy consumption and supporting the integration of solar energy systems and smart grid technologies in urban context should be part of urban planning. Martos et al. (2016) analysed more specifically that the impact on the environment and the elevated energy consumption generated by the dominant use of private motor vehicles in the cities is one of the most pressing demands on making urban policies more sustainable. Notwithstanding the high interdependences between the urban issues and sustainability strategies, cities have not been analysed comprehensively from a life cycle perspective so far due to their complexity (Petit-Boix et al., 2017).

### 2.3. Smart vs. sustainable

Another development has been the hyping of the term 'smart city' in recent years. It usually implies that better information and communication infrastructure and enhanced IT applications lead to better governance. But smart does not necessarily mean sustainable. Often social sustainability dominates over environmental and economic sustainability in smart cities (Ahvenniemi et al., 2017). Bibri and Krogstie (2017) give a literature review on the designations 'smart' and 'sustainable' (and all possible combinations thereof) for cities. A recent review (Angelidou et al., 2018) analyses that the links between smart applications and sustainable cities are fragmented and that there are at least six fields of action which need further research. These are: (1) green mobility, (2) waste management, (3) air pollution, (4) energy consumption, (5) urban biodiversity, and (6) water management. At least the fields (3), (4), and (6) are in line with the issues which are in the focus of this paper.

Fig. 1 summarizes urban issues which seem to be obvious from a climate, matter cycle and energy point of view and which should be addressed more in urban planning and architecture. Fig. 2 summarizes such issues from a life-cycle and sustainability point of view (adapted from Petit-Boix et al. (2017)). A comparison of Figs. 1 and 2 shows that

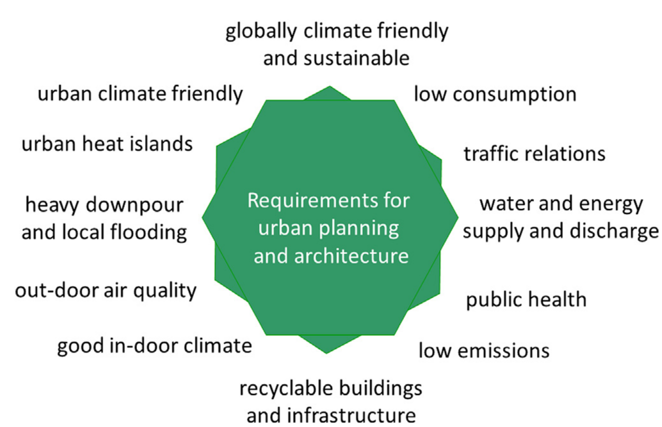


**Fig. 1.** Major issues in sustainable urban governance. Atmospheric and climatic issues are listed on the left-hand side, technical and energetic aspects are listed to the right and below.

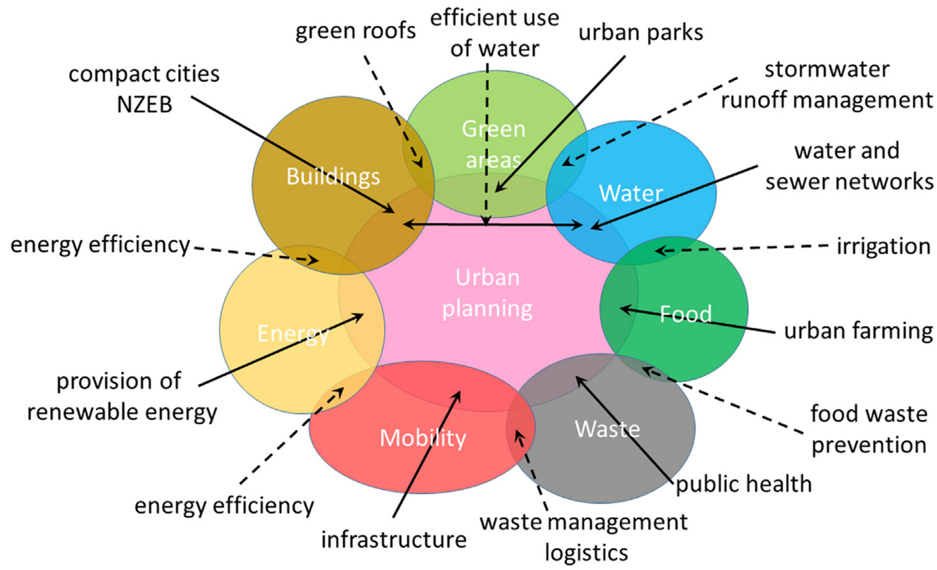


**Fig. 2.** Interrelations among urban issues towards sustainability and presence in life cycle studies. The bubbles depict the overlaps among two or more urban issues and an example for each overlap is provided. NZEB = "nearly zero-energy building" (modified from (Satterthwaite, 2008)).

although many issues appear in both graphs, climate issues - either global or local - are nearly completely absent in Fig. 2.

## 3. Recent examples

Nevertheless, there are ongoing progressive ideas in building design which have found widespread interest across disciplinary borders. E.g., 'biophilic design' is said to enhance human well-being by fostering connections between people and nature in the built environment. Studies report, that people living in proximity to natural spaces report fewer health and social problems, independent of rural and urban residence, level of education, and income (Kellert et al., 2011). The 'Bosco Verticale' in Milano, Italy (completed in October 2014), and several buildings in Singapore are listed as examples in (Hayles and Aranda-Mena). The Bosco Verticale, which means 'Vertical Forest', are two buildings in Milan, Italy. The buildings consist of two separate towers reaching heights of 111 and 78 m. The towers are composed of 26 and 18 floors respectively and the façades are covered with plants, shrubs and trees. The buildings were designed by the Milanese architect Stefano Boeri in cooperation with the architects Giovanni La Varra and Gianandrea Barreca (Visser, 2019). Biophilic design can be viewed as the missing link in prevailing approaches to sustainable design when working in complementary relation with low-environmental-impact design, thus achieving true and lasting sustainability. With major objectives of low-environmental-impact design focusing on goals such as energy and resource efficiency, sustainable products and materials, safe waste generation and disposal, pollution abatement, biodiversity protection, and indoor environmental quality. A detailed specification of design strategies to achieve these goals for instance has been incorporated into certification systems such as the U.S. Green Building Council's 'Leadership in Energy and Environmental Design' (LEED) rating approach (Kellert et al., 2011). Biophilic design can thus be an overarching strategy, incorporating various needs for sustainable building design thus providing holistic solutions for sustainable planning needs.

Although not explicitly noted by Hayles and Aranda-Mela (Hayles and Aranda-Mena), biophilic design helps to meet some of the requirements due to atmospheric and climate impacts mentioned in Fig. 1, e.g., reducing urban heat islands, enhancing outdoor air quality, and, via shading, also providing a better indoor climate. In reducing the needs for air conditioning biophilic design also helps to create more sustainable cities by reducing energy consumption, and by this reducing greenhouse gas and gaseous reactive nitrogen compounds emissions. Biophilic design also fits into Fig. 2 and could be sorted into the scheme as an extension of the issue "Green roofs".

Another trend is using wood as building material. Tupenaite et al. (Tupėnaitė et al., 2019) give an overview on existing buildings made from timber. Their ranking of the buildings also includes the saved carbon dioxide in comparison to concrete buildings. The highest timber building is presently the Mjøsa Tower in Norway, an 18-floor building which is 85 m high. Recently, the Sumitomo Forestry Co. in Tokyo, Japan, announced plans to build a 70-story, 350 m tall skyscraper made of 90% wood and 10% steel (Buffi and Angelini, 2019), (Naser, 2019). The project called "W350" is planned to be completed only in 2041. Again, it seems that nearly no climate or sustainability arguments are driving the architects. The undoubtedly good rationale given instead tells that avant-garde designers are reshaping the historical relationship between nature and architecture fostering a natural approach to design which results in structural lightness, rational use of energy and elegance. Wood seems to be a perfect material to engage with this new period of design research, and while timber towers are getting higher, there is a strong interest in understanding to which extent wood can represent a valuable alternative to those materials that have characterized the recent architectural debate (Buffi and Angelini, 2019).

Additionally, skyscrapers made of timber instead of metal and concrete involve less carbon dioxide emissions during the production of these materials and the construction phase of the building. And in addition timber buildings store biologically extracted carbon from the atmosphere for a long time. $CO_2$ emissions from the global cement production sum up to about 4% of those from fossil fuel combustion and contributed 1.45 Gt $CO_2$ in 2016 (Andrew, 2019). Buffi and Angelini (2019) briefly mention this and give a share of 8% of the global $CO_2$ emissions for the combination of global cement and steel production. Because atmospheric issues such as climate are completely missing in Fig. 2, advantages of timber buildings cannot be entered into the sorting of Fig. 2. But it perfectly fits to the top issue "globally climate friendly and sustainable" in Fig. 1.

## 4. Suggestions for urban planning and building design

Changes in building design in order to adapt to a changing climate are often narrowed down on issues caused by extreme winds, lightning and extreme precipitation (e.g., in Germany (Wallbaum et al., 2011), see also the intersection of “Water” and “Green areas” in Fig. 2). In this context, “extreme precipitation” comprises phenomena such as local flooding due to heavy downpour, hail and heavy snow loads. This definitely helps to erect resilient buildings which can withstand extreme weather events and reduces the costs for owners and insurance companies.

But resilience to extreme weather events is only a small facet of a sustainable city which is to become resilient in a changing local and global climate and with respect to changes in local and global energy and matter fluxes. Stress to human health by high temperatures, bad air quality and noise has to be reduced as well in order to shape resilient cities. Unwanted interactions between strategies and actions to achieve each of these goals have to be paid attention to (e.g., air quality can become worse as a consequence of heat island mitigation measures (Fallmann et al., 2016)) and require holistic approaches which assess the overall impact of several (or ideally all) strategies and actions together.

Climate resilient cities should come into existence by coordinated efforts and not just as beneficial side effects of other sustainability efforts. The following section of this paper lists ideas and options to directly address air quality and local and global climate issues. The listed measures are sorted into four fields from the building scale to the nationwide scale: measures to modify building design, measures to enhance urban green and blue, measures to replan cities, and finally measures to secure the overall resilience of urban areas. Within each of the action fields, the measures are sorted by descending importance from an atmospheric scientist point of view.

### 4.1. Building design

(1) **Changing urban surfaces.** White and reflecting (Akbari et al., 1997), (Akbari et al., 2009), or green and transpiring (Georgescu et al., 2014) roofs and walls prevent urban structures from heating up. PV and solar thermal devices count in the category “reflecting”, as they prevent heating up of underlying structures as well (and additionally produce electrical and thermal energy). In addition, green façades and roofs can help to remove particulates from the urban air by dry deposition. Road pavements could be substituted by reflecting materials as well (Santamouris, 2013), (Rossi et al., 2016). Modified surfaces reduce the UHI and the energy demand by air conditioning. Biophilic design mentioned above belongs to this action point. Nevertheless, it has to be kept in mind that green roofs and façades need sufficient water supply (Cascone et al., 2019), getting even more important in a warming climate. With generally broad confirmation of positive effects of green roofs and facades (e.g. (Besir and Cuce, 2018)) also with regard to high rise buildings however some authors state limitations in that sense. Estimates of (Tan and Ismail, 2014) showed that high-rise and high-density buildings reduced daily PAR by almost 50% when compared to fully exposed conditions. The reduced PAR levels were correlated with lower vegetative and reproductive growth of several species of shrubs, and increased slenderness of two tree species Amongst others (Zhang et al., 2012) mention increased maintenance costs.

Further, water consumption can be a significant limitation to green roof implementation in dry areas with high water costs (William et al., 2016). Comparing green facades and roofs at high-rise buildings worldwide (Wood et al., 2014), found suitability of greening at nearly every height but however pointed out as well that at some locations, high wind load due to ‘vortex shedding’ could lead to impairment of root systems and plant structure. Further, sufficient, constant water pressure has to be guaranteed for irrigation of higher building levels. In places, accessibility and staff needed for maintenance might be an issue as well.

(2) **Passive solar architecture - Cooling.** Protruding roofs in the direction of the sun’s daily culmination point reduce sunshine into the windows in summer but enabling it in winter (GOETZBERGER and SCHMID, 2010). This reduces the energy demand for air conditioning and heating. An adaptation to the uniqueness of the place and climate is mandatory to increase the response of architecture to cooling. Well insulated lightweight constructions for instance reduce heat gain and loss, making energy use more efficient but will not optimize the interior environment. A heavy mass building damps temperature amplitudes inside the building during the day. In hot, humid climates however, long-wave heat losses are low and night-time temperature is not much lower than at day. Night-time evaporation from wet surfaces would be the only passive cooling mechanism there, which could be achieved by allowing sufficient air flow through the building (Haggard et al., 2016).

(3) **Passive solar architecture - Heating.** Darker wall colours for those parts of the façade which are only hit by the sun in winter supply radiative heat gains in this cold season. They should be coupled with protruding roofs or should be limited to those parts of the walls which are set back from the main façade, e.g., at balconies. An enhancement of this idea are Trombe walls named after the French inventor Felix Trombe. Trombe walls are walls coated with a dark surface shortly behind glazing. Heat conduction through the wall and airflow driven by natural convection transport the energy absorbed by the walls into the interior of the building (Dimassi and Dehmani, 2012). There could also be co-benefits, if these dark surfaces allow simultaneous power production when PV structures are used (Pedrero et al., 1206). Heavy mass buildings mentioned in action point (4) can release heat at night to warm interior space (Haggard et al., 2016). Clear orientation of buildings with respect to the sun’s daily culmination point is one of the prerequisites for some of the measures listed here. Building orientation has first been formulated by Tony Garnier for his ‘Une Cité Industrielle’ in 1917 (Rudlin, 2010). According to Garnier (Rudlin, 2010), residential quarters were to be laid out in east-west blocks allowing all housing to face south. Narrow streets were not to have trees, with wider streets only being allowed trees on the southern side to avoid shading. This is one of the first attempts at passive solar design in modern times, although at that time the motivation was based on the health-giving properties of sunlight rather than on energy efficiency. Nevertheless, negative side effects through, e.g., high reflection from façades hampering the comfort of urban dwellers or glaring road users should be avoided. Furthermore, buildings should not be arranged in a way that they produce wind channelling and nozzle effects between building structures which decreases pedestrian comfort. Fresh air corridors should be kept free where possible (see action point (15) below).

(4) **Passive solar architecture – Phase change materials (PCM).** Phase change materials such as salts or paraffin may be integrated into building walls without increasing the wall mass or using additional insulating materials as suggested in action point (2). The melting temperature can be adjusted as necessary. If PCM is made to store heat at a useful temperature it will maintain that temperature level until the whole phase change process has taken place, thereby reducing overheating or cooling of the internal air (Gillott et al., 2010).

(5) **Building materials - Greenhouse gases.** Reduce or even avoid the usage of steel and concrete wherever possible. Steel and concrete production are responsible for a considerable part of global greenhouse gas emissions. Shares between 4% and 8% are reported (Buffi and Angelini, 2019), (Andrew, 2019). One solution could be the following action point. See also the last paragraph of Section 3 above.

(6) **Building materials - Wood.** Buildings at least partly made of wood (Tupėnaitė et al., 2019), (Buffi and Angelini, 2019) help to store carbon for a long time and to exclude this carbon from the atmospheric circulation. As this carbon has been extracted mainly

from the atmosphere by trees, buildings made of timbers are a means of carbon capture helping to reduce atmospheric carbon dioxide concentrations. See also the last paragraph of Section 3 above.

(7) **Building materials - Recycling.** Even if the action points (4) to (6) above can be implemented, the selection of building materials and building construction methods should already have in mind the recycling of these materials later. This will help to reduce the demand for commodities and will support the measures in point (5). Even sand and gravel are no longer unlimited resources (Torres et al., 2017).

(8) **Passive aeolian architecture.** Wind catchers (Azami, 2005) should be reconsidered as a meaningful technology for cities in hotter areas with regular winds, e.g., near sea shores or closer to larger mountain ranges. As a passive technology they do not require additional energy consumption.

(9) **Roof shape.** It has been stated by various experiments, that in-canyon flow conditions are strongly dependent on geometric features of buildings and the shape of the roofs (Llaguno-Munitxa et al., 2017). Turbulent structures in the urban canopy can affect pollution levels inside the urban canyon. It has been reported, that pollution levels were found to decrease with increasing roof slope, which is related to the rotational speed of the canyon vortex and the aerodynamic roughness decrease (Takano and Moonen, 2013).

### 4.2. Urban green and blue

(10) **Green close to buildings.** Urban green among and close to buildings clearly help to moderate the local climate. But they should not be much higher than the buildings themselves for two reasons. Firstly, in order to avoid damages from falling trees due to extreme wind gusts, and secondly, in order not to obstruct the effects of reflecting or green roofs for cooling and/or renewable energy supply (see action point (1) above). Urban green in front of buildings on the side lighted by the midday sun should consist of deciduous trees and shrubs in order to allow for shade in summer and incoming light in winter. Coniferous trees could provide shelter against cold winds on the opposite side. Such vegetation meaningfully complements the passive solar architecture mentioned in action points (2) to (4).

(11) **Urban green.** Small parks in city centres reduce urban heat islands (Fallmann et al., 2013) and offer recreation spots. Urban green requires sufficient water resources. Chosen shrub and tree species should be resistant against heat, temporal water shortage and air pollutants (Quigley, 2004) as plants can suffer from bad environmental conditions similar to animals and humans. On the other hand, dense tree canopies in narrow streets can reduce aerodynamic roughness which could lead to weaker turbulent mixing of air masses and to a relative warming of near surface temperature respectively (Meili et al., 2019). Furthermore, trees in narrower street canyons with large amounts of traffic exhausts should not impede the lateral and vertical air exchange in such canyons too much. Otherwise the trees would contribute to worsen air quality at the bottom of these canyons (Vranckx et al., 2015). Hedgerows in urban street canyons with heavy traffic can improve air quality, whereas height and porosity influence the strength of improvement. The greatest improvements have been reported for hedgerows at the centre of urban canyons, when the approaching wind was perpendicular to these hedges (Gromke et al., 2016). Tree species known to emit hydrocarbons such as isoprene (e.g., plane trees/sycamores) should not be planted in urban environments, because sunshine into air masses polluted with nitric oxides from combustion processes and isoprene from inappropriate urban green leads to rapid formation of ozone on the leeward side of the emissions (Simon et al., 2019). For the same reason, also planting larger numbers of isoprene emitting trees (e.g., poplars) upstream of larger cities should be avoided (Zhang et al., 2016). In terms of a climate perspective, there is evidence for carbon sequestration by urban green e.g. from urban eddy covariance studies (Velasco et al., 2016) or urban green roof experiments (Heusinger and Weber, 2017).

(12) **Urban blue.** Water in cities is often seen as one option to moderate temperature extremes due to the large heat capacity of water. Although this is true and water bodies could be an ideal part of recreational areas in cities, it will not be easy to maintain the water quality of lakes with small water exchange. Additionally, water bodies can be breeding areas for insects which could serve as vectors for diseases. Therefore, urban blue may be limited to areas with sufficient fresh water supply. With regard to building material and design (see action point (1) above), roof ponds could act as passive heating and cooling systems (Sharifi and Yamagata, 2015). The key elements of such a concept are the use of water for heat storage and as interim heat sink, thermal coupling of the water with the occupied spaces, exposure to sunshine for heating during the day and cooling under the night-sky.

(13) **Urban Gardening.** Local supply through urban farming may help to provide fresh food (Valley and Wittman, 2019), (Martin and Molin, 2019), (Feola et al., 2020) in addition to greening the city. Urban gardening can contribute to perceived attractiveness of urban areas (Lindemann-Matthies and Brieger, 2016) and within the frame of the compact city, aiming at an efficient and resource-saving (re)organization of urban space (Tappert et al., 2018).

### 4.3. City planning

(14) **Energy supply.** Cities with reduced urban heat island (due to some of the measures listed above) have to be cities with strongly reduced combustion processes (neither fossil nor renewable fuels (with the exception of green hydrogen) should be used for any purposes), because cooler cities do not foster so much thermally-driven vertical ventilation which otherwise helps diluting high pollutant concentrations due to local emissions in cities. One option for heating could be the use of electrical heat pumps. A good heat reservoir is the urban heat island in the groundwater underneath cities. Extracting surplus heat from groundwater for heating (Bayer et al., 2019), (Zhu et al., 2011) also helps to bring the groundwater body back to normal, usually healthier conditions. Particularly high rise buildings with undisturbed view towards incoming solar radiation offer a great potential for PV energy supply. However, it should be noted that dark surfaces underneath PV installations could counteract local climate. Therefore, we recommend the combination of green roofs and PV installations. Alternative technical realizations exist to provide energy from wind flow around the buildings (Grant et al., 2008) discusses the installation of roof-mounted ducted wind turbines, which use pressure differentials created by wind flow around a building. Small wind turbines at roof level in our opinion can also serve as additional source of power production, after potential risks of high wind shear for turbines and connected technical failures have been assessed, e.g. through intensive observations of roof level micro-meteorology

(15) **Fresh air corridors.** Extension of existing city quarters and planning of new quarters should not hamper the free flow of air from regional environments into cities. Nocturnal venting of fresh and cooler air from the outside into cities, e.g., gives relief from nocturnal heat stress and enhances human living conditions and air quality (Schau-Noppel et al., 2020).

(16) **Reduce urban sprawl.** Cities should be built in a rather dense way in order to avoid urban sprawl which in turn helps to reduce traffic needs and to save the natural environment of cities. But this

should not happen in contradiction to the previous action point (15). Part of such strategies has to be to keep shopping malls within residential areas and not to erect them off city limits (see the next point (17) as well). In a second step it could be even considered to distribute shops more into the housing areas rather than concentrating them into one big building which attracts a lot of traffic.

(17) **Overcome strict functional separation.** Today's industries do not emit so much detrimental substances as they did in former times and most of them are no longer noisy. Thus residential areas and industrial areas could be closer together than they are today. This will help to reduce commuting traffic and air pollution related to this traffic. From the air quality point of view, city planners should overcome the paradigms of CIAM (Congrès International d'architecture moderne) and the charter of Athens (1933) (Gold, 1998). Based on intensive discussions Le Corbusier and other contemporary architects had developed the idea of a functional city which strictly separated residential, industrial, recreational and transport areas in the early 1930s. The Leipzig Charter of 2007 (Eltges, 2010) is a first and considerable step away from the Athens Charter and towards more sustainable cities. This action point and the previous point (16) are closely linked to each other.

(18) **Privileged public transport.** Public surface transport has to be privileged in larger cities in order to reduce pollutant emission from individual traffic. The organization of public transport will become easier, if the previous point is put into reality.

### *4.4. Nationwide planning of infrastructure*

(19) **Traffic.** Larger cities should be interconnected by efficient high-speed railway lines, separated for passenger and goods transport. Air traffic should be reserved for intercontinental passenger transport.

(20) **City planning - Sea level.** New cities and industrial plants must not be planned directly at low sea shores. Cities and many industrial plants are usually designed to exist for centuries. But on this time scale sea level rise will become a major problem from Global Warming. The present rate (2011–2020) of sea level rise is close to 5 mm per year and is expected to increase further (see, e.g., http://www.cmar.csiro.au/sealevel/sl_hist_last_decades.html for the newest data). Existing cities and industrial hubs have to be prepared and hardened to rising sea levels.

This list is probably not complete and future research will definitely identify further possible actions. Although the sequence of the measures in the action fields above have been ranked according to their importance for air quality and climate, the actual choice of appropriate measures from the above list and their importance for a given city may depend on the specific characteristics of the city in question.

The topics listed in Figs. 1 and 2 can be combined into a new graph. Fig. 3 is an example of a possible graph which can emerge from such a combination. Essentially, three bubbles have been added in Fig. 3: 'Urban Climate', 'Global Climate', and 'Air'. Full arrows point to intersections of the outer bubbles with the central bubble 'Urban Planning', dashed arrows point to intersections between neighbouring outer bubbles. The addition of the three bubbles now allows for an attribution of local climate, global climate and air quality issues in this graph and gives a much more complete image than Fig. 2.

Figs. 2 and 3 should not be misinterpreted. The world is not two-dimensional. This means, there are many intersections between bubbles which are not direct neighbours in Figs. 2 and 3. But such intersections are not presentable in Figs. 2 and 3. Just to give one example for this multi-dimensionality: 'Mobility' has a strong influence on 'Air'. The way we organise traffic in a city has strong repercussions on urban air quality. Although these intersections cannot be plotted in Fig. 3, they have to be taken into account in the abovementioned holistic approaches exploring and paving the way towards more sustainable and climate-friendly cities.

## 5. Model approaches

Climate sciences have started to pave the way for holistic numerical model approaches by designing Earth system models (Bonan and Doney, 2018), (Claussen et al., 2002) in order to bring together the atmosphere, the oceans, the ice masses, the vegetation and other forms of land use on a global scale. Urban areas are one special form of land use. Fully coupled (ocean, wave, atmosphere, land) earth system type models have lately also been developed for regional scale applications in the UK (Lewis et al., 2018) and their potential to improve the forecast of small scale atmospheric features in the order of 1–10 km has been assessed (Fallmann et al., 2017).

Convective-scale (i.e. resolving spatial scales of a few hundred metres


**Fig. 3.** Interrelations among urban issues towards sustainability. The bubbles depict mutual overlaps among the urban issues and one example for each overlap is provided (full arrows point to overlaps with the central bubble and dashed arrows to overlaps between the outer bubbles). NZEB = "nearly zero-energy building" (Modified from (Satterthwaite, 2008)).

to a few kilometres and temporal scales of minutes; in atmospheric sciences the term convection denotes thermally driven upward vertical motions such as in showers and thunderstorms) atmospheric and chemical transport models have recently been used in atmospheric sciences to analyse urban features mentioned in Section 2.1, covering a range of modelling systems and research questions. Though not being able to provide ready-to-use applications for urban planning purposes, they however can offer sophisticated information on urban rural interactions and on the feedbacks between regional climate, meteorological processes and small scale phenomena such as sea-breeze, urban heat island, mountain-valley circulation etc. Thanks to efforts in the development of more detailed urban canopy parametrizations for these kind of models (e.g. WRF-BEP (Chen et al., 2011), TERRA_URB (Wouters et al., 2015), WRF-TEB (Meyer et al., 2020), BEP-Tree (Krayenhoff et al., 2020) and COSMO-BEP-Tree (Mussetti et al., 2020a) or more recently CCLM-DCEP (Mussetti et al., 2020b) and various evaluation studies (Jandaghian and Berardi, 2020), (Trusilova et al., 2016)), the urban energy balance and the diurnal features of the urban boundary layer are widely understood at the convective scale. With more and more studies critically assessing the sources and quality of input data and model systems needed (Masson et al., 2020) in order to also provide sophisticated information for societal needs (Hidalgo et al., 2019), the link between the regional and the local scale (meso- and microscale) and the transfer to actual planning processes remains an ongoing challenge. Current studies try to overcome the scale dependency of processes and link atmospheric and planning perspectives by coupling meso-scale models with CFD-based approaches e.g. analysing microscale flow patterns during heat wave episodes (Piroozmand et al., 2020), investigating the evolution of extreme wind induced by building structures (Javanroodi and Nik, 2020), or with Lagrangian modelling systems e.g. evaluating urban NOx pollution (Veratti et al., 2020).

Recent efforts in downscaling climate simulations to a sub-kilometre resolution have been made by several communities and weather services (Schau-Noppel et al., 2020) in order to generate climate impact studies for a selected urban region with results underpinning decisions at a municipal level. Although providing more insight in features relevant for regional scale urban planning such as the definition of cold air catchments or areas particularly prone to climate extremes (by linking model results to population statistics one can analyse the vulnerability of certain city quarters to urban heat stress), these kind of models fail to allow for a street-scale analysis.

Fully integrated CFD-based 3D-microclimate models have recently been developed e.g. for analysing the benefit of reflective pavements at building scale, for isolated street canyons under dry and wet conditions (Ferrari et al., 2020), investigating street ventilations (Shirzadi et al., 2020), or drag induced by street trees (Zeng et al., 2020). First steps towards a holistic street-scale and building-resolving urban climate model covering spatial scales from metres to many kilometres and temporal scales from seconds to years have recently been made in Germany (Scherer et al., 2019). Also including air chemistry, such a model can simulate the interactions between buildings and the atmospheric flow, the urban radiation and heat budget, and the urban air quality. With this tool, many of the suggestions listed in Section 4 above can be tested for their suitability and effectiveness in given urban situations. Coupling such urban climate models with regional and global Earth system models will offer the opportunity to consider climate change issues in urban planning as well (Sharma et al., 2020). Assessing requirements and case studies to evaluate the practicability and usability of these systems for local stakeholders and societal needs is subject for current analysis among atmospheric and climate communities (Halbig et al., 2019).

## 6. Conclusion

As decisions in urban planning often involve a dialogue amongst an inter- and multidisciplinary field of actors, this review offers a starting point for bringing together impulses from research and application thus fostering collaborations amongst different communities and strengthen argumentations with stakeholders. For example, after Superstorm Sandy in 2012, many cities in the US and globally installed dedicated climate resilience officers which transfer information into the generation of resilience plans. With the constraint to reduce carbon emission to zero by 2050, many cities in Europe also have followed with the installation of climate managers in urban planning. Model approaches such as those mentioned briefly in Section 5 will help climate resilience officers and urban climate managers to fulfil their tasks in the future. These positions are particularly important, when official directives such as the announcement of the climate emergency are to be transferred from a symbolic statement to applied action.

However, current legislative regulations and also architectural views on the representativeness of buildings still limit the implications of certain measures. In our opinion, the financial barrier for private households is still too high and more financial benefits and support has to be provided e.g. through national programs (e.g. as already in place for Berlin, Germany). Further, we think that the perception of public space has to change in a way, that greening has to be considered in the preplanning phase as we find especially new city quarters still lacking of green space. That aspect should be manifested in dedicated legislative regulations.

Nonetheless it is mandatory to evaluate climate sensitive urban planning measures with regard to their cost-benefit factor both environmentally and economically. Climate action in urban planning has necessarily to happen in light of social and economic equality, which can be hard to obtain in some places. The expected benefits of intended urban planning actions have to communicated in a proper way and accompanied by actual numbers highlighting the mitigation, adaptation and risk reduction potential. The dialogue between science and application has therefore to be guided by official bodies such as the above mentioned climate managers. Sustainable development has to cover many fields and span different spheres of interests, which makes holistic actions hard to construct in light of both climate change and population growth happening simultaneously. Extreme events often are followed by side effects and communities have to be best prepared against unforeseen feedbacks. With having been responsible for over 70000 deaths in Europe, the 2003 heat wave has shown dramatically the expected impact of a changing climate on urban population. At about the same time, the East-Coast of the US suffered the most severe electrical outage in history affecting about 60 million households, which was due to overheating electrical circuits due to excess heat.

Sustainable urban planning has to cover different scales, from local to regional and from short term to climate scale. Cities have to be prepared for short term effects, requiring immediate action but also long term strategies in light of these extreme events happening more often in the future. In doing so, it has to be kept in mind that the impacts of different measures from Section 4 do not add linearly. Some measures even counteract others. Therefore, model studies with elaborated and sophisticated systemic models are necessary in order to assess the consequences of selected measures before realizing them in reality. This document aims to fertilize the design of dedicated case studies and the transfer to action in order to allow for sustainable, climate sensitive urban planning.

**Funding sources**

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**Declaration of competing interest**

The authors share no conflicts of interest.

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