Climate Change Impacts on Built Environment

Jolanta Dąbrowska1*), Anna Rawska-Skotniczny2), Maciej Kaźmierowski3), Małgorzata Biniak-Pieróg4)

1) Wrocław University of Life and Environmental Sciences, Department of Civil Engineering, 24 Grunwaldzki Sq., 50-363 Wrocław, Poland; email: jolanta.dabrowska@upwr.edu.pl; https://orcid.org/0000-0002-6017-6919

2) Wrocław University of Life and Environmental Sciences, Department of Civil Engineering, 24 Grunwaldzki Sq., 50-363 Wrocław, Poland; email: anna.rawska-skotniczny@upwr.edu.pl; https://orcid.org/0000-0002-0997-5029

3) Wrocław University of Life and Environmental Sciences, Department of Civil Engineering, 24 Grunwaldzki Sq., 50-363 Wrocław, Poland; email: maciej.kazmierowski@upwr.edu.pl; https://orcid.org/0000-0002-8977-4154

4) Wrocław University of Life and Environmental Sciences, Department of Environmental Protection and Development, 24 Grunwaldzki Sq., 50-363 Wrocław, Poland; email: malgorzata.biniak-pierog@upwr.edu.pl; https://orcid.org/0000-0001-8704-5532

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Abstract

We are currently in the period of an intensive climate change, resulting from changes in the heat balance of the earth's surface and causing an increase in the temperature of the lower troposphere levels. According to the latest IPCC report of 2021, it is human activity that has indisputably caused the increase in atmospheric concentrations of greenhouse gases, responsible for this process. The consequences of climate change under Polish conditions, apart from a rise in temperature especially in the spring and winter months, are also changes in the amount and distribution of precipitation totals. A slight increase in precipitation totals is observed, however heavy rainfall is significantly more frequent, interspersed with periods of droughts and heatwaves. Ground frost-free periods are prolonged, and a negative trend in the duration and thickness of snow cover is recorded in most parts of the country. Although extreme phenomena occurring in Poland are permanently inscribed in its climatic conditions, the threat of strong winds has been increasing in recent years, and the intense precipitation that often accompanies them is the cause of peak discharges and flooding. Forecasts for progressive climate change are not optimistic, either on a global scale or for the country in question. The article examines the impact of climate change on the design, construction and maintenance of engineering structures globally and for Poland. Changes in design standards, selected examples of disasters and solutions to adapt and build resilience to climate change have been analysed. For most building disasters, climatic factors were the direct cause of the disaster, although in the course of the analysis it has usually turned out that the disasters exposed human errors in the design, construction and, to a lesser extent, the improper maintenance of engineering structures. However, there is an increasing number of new approaches to creating a climate change resilient built environment, including the latest one, which proposes to use the grey infrastructure of cities to build resilience to climate change.

Keywords: climate change impacts, built environment, engineering structures, Poland

Introduction

In the era of climate change, engineering structures are increasingly exposed to weather-related hazards: droughts, extreme temperatures, pluvial, fluvial and coastal floods, rainstorms, snowstorms, hailstorms, thunderstorms and lightings, windstorms, including hurricanes, cyclones, typhoons, tornadoes and whirlwinds, sandstorms, landslides, avalanches, sea level rise, fires and bush fires, overturning of trees. Moreover, climate changes increase the risk of earthquakes, tsunamis, and volcanic eruptions [1–8]. Numerous up-to-date scientific articles and industry reports discuss the threats posed by climate change as well as the effects of malfunctions and disasters induced by climate-related hazards [2,6,7,9–15]. Early warning systems are constantly being improved, as well as mitigation and adaptation strategies to elevate resiliency of engineering structures to climate change [5,7,8,13,16,17]. The adverse effects of climate change are taken into account during the design, construction, operation, and also repairing and replacing of engineering structures, unfortunately very often based on lessons learned from previous failures and collapses. When analyzing these risks, future climate change should be taken into account and preventive action should be taken [7,8,15]. Weather-related hazards also pose a threat to historical constructions and cultural resources, which require special treatment and protection [6,17].

Climate change resilience is built at a local, regional, national and supra-national scale i.e. engineering structure, its surroundings, city, region, EU member state and EU as a whole. The importance of scale is described in the work of Landauer et al. [18]. New construction materials and technologies are used in mitigation and adaptation measures. Grey infrastructure is being combined with green and blue infrastructure and nature-based solutions, new urban planning policies are being created [19–22]. In their paper, Qi et al. propose a new approach – utilizing grey infrastructures (GREIs) to mitigate urban heat island (UHI), this is different from the traditional viewpoint that believes GREIs create and exacerbate UHI [23]. Despite the numerous analyses carried out and the creation of new materials, technologies and strategies, there are still many areas of knowledge deficit for climate change impact on built environment, as well as a need to bridge the gap between knowledge and action.

Climate Change from The Global and National Perspective of Poland

Climate change is identified on the basis of changes in features or a variability in their characteristics over a long period of time, relating to at least decades [24]. They may occur as a result of natural processes, i.e. volcanic eruptions or changes in solar cycles. External causes include anthropogenic changes to the composition of the atmosphere or land use. The latest report of the Intergovernmental Panel on Climate Change (IPCC) [24] identifies human activities as the cause of the increase in atmospheric concentrations of greenhouse gases. They are responsible for changing the heat balance of the earth's surface, resulting in a rise in the temperature of the lower troposphere. The most recent data for two key climate elements indicate a human-induced temperature increase of between 0.8°C and 1.3°C compared to 1850-1900. There has been a distinct increase in global mean precipitation, especially since the 1980s. The observed changes are resulting in an intensification in the number and frequency of extreme weather events practically worldwide [25]. These comprise heat extremes, including heat waves, heavy rainfall, droughts, tropical cyclones [26–29]. What is more, individual phenomena occur simultaneously, such as heat waves and droughts, fire weather and multi-causal floods.

The effect of climate change under Polish conditions is an increase in temperature especially in the spring and winter months. According to the study by Tomczyk et al. [30], an increase of its extreme values in winter – minimum and maximum – is observed, however, it is more noticeable in the case of the latter. Kejna and Rudzki [31] indicate an increase in air temperature in Poland between 1961 and 2018 of 0.33°C/10 years on average, with the greatest increase in the Silesian, Greater Poland and Mazovian lowlands and in the central part of the Baltic coast, exceeding 0.4°C/10 years. The authors point out that warming was observed in both the summer and winter months (the greatest in July and January). The increase in temperature has resulted in increasingly frequent heat waves (most common in the central and southern parts of Poland) and increasingly rare frost waves (most common in the north-eastern and southern parts of the country and least frequent in the west and on the coast) [32]. According to Wibig [33], heat waves may occur in Poland from April to September, but are most common in July and August.

Koźmiński et al. [34] on the example of the multiannual period 1971-2020, indicated that the observed climate change contributed to the lengthening of periods without ground frost (from approximately two more days in north-eastern Poland to about eight more days/10 years in Pomerania). The authors observed a distinct shortening of the spring ground frost period for the area of the Lublin Lake District, Wielkopolska Lowland and Sandomierska Basin. The autumn ground frost period starts much later in Pomerania, among others.

In the case of precipitation, a slight increase in totals is observed, but its seasonal and monthly distributions are clearly changing. According to Szwed [35], its increase is most evident in the cooler half of the year in south-western and western Poland, while no such changes are observed in the eastern and south-eastern regions. However, the proportion of summer rainfall in the annual sum of precipitation is decreasing, which is most evident in southern Poland. Pińskwar et al. [36] indicate much more frequent occurrence of intensive rainfall, especially in the north-west of Poland. The authors showed an increase in daily maximum precipitation at many stations, more pronounced in the summer half-year than in the winter half-year. At the same time, they are interspersed with prolonged periods without precipitation accompanied by high air temperatures and heat waves.

The increase in temperature in the winter half-year is not without effect on the occurrence of snow cover. According to Szwed et al. [37], during a typical winter in Poland (based on the years 1952-2013), the depth of snow cover varies from 2.2 to 11.8 cm (except in mountainous areas, where it is much thicker) and increases towards the north-east. The average number of days with snow cover increases from west to east (north-east) and ranges from about 30 to 60 days during the winter. Higher values are recorded at mountain stations. On average, snow cover is present from 26 November to 26 March. A study by Tomczyk et al. [30], based on the years 1966/67–2019/20, shows a clear decreasing trend in the duration of snow cover for most stations in Poland. However, such a pronounced tendency is not observed for snow cover depth, which should not be related to air temperature but rather to the amount of precipitation reaching the surface in the solid state. In general, southern Poland showed a decrease in snow cover depth at lower altitudes and an increase at higher altitudes. Similarly, Falarz and Bednorz [38] indicate a decreasing trend in the number of days with snow cover in Poland for the years 1950/51 to 2017/18, noting that the negative trend in maximum snow cover thickness is not as significant in Poland as the average in Europe.

Although extreme phenomena occurring in Poland are permanently inscribed in its climatic conditions, the threat of strong winds has intensified in recent years. This type of hazard in the years 2010-2019 became one of the most frequent causes of interventions by the State Fire Service [39]. The greatest risk arises from October to April, which is due to general circulation conditions. In addition to the coastal strip, areas exposed to strong winds include the western and central parts of Poland, mountain areas and the Suwalszczyzna region. On average in Poland (excluding mountain areas), the number of days with a high wind risk reaches six [40].

Climate Change Impact on Structural Loads - Lessons Learned from Poland

Engineering activities require decisions to be made with a relatively high degree of risk, which is due, among other things, to the uncertainty and frequent lack of complete data on the climatic actions (Figure 1), that affect engineering structures [10]. A prediction of actions that are highly likely to occur during building maintenance in a country is included in the design standards. These comprise actions characteristic of the climatic zone in which the building is designed, with a certain intensity established on the basis of long-term meteorological measurements and statistical analyses. In Poland and other countries with a similar geographical location

(Germany, Denmark, Scandinavian countries, etc.), these will include wind, snow, temperature (Figure 1) or icing. In other countries, e.g. those closer to the equator, these climatic actions will not occur at all or will occur with less intensity (e.g. snow or icing), but other will, e.g. seismic activity [6,7,9].

Apart from typical climatic actions, standards classify also actions during execution (arising during the construction, conversion or demolition phase) and accidental actions, which are much less likely to occur and may be much more intense. These include, but are not limited to, actions related to rainwater, which may accumulate as a result of drainage obstruction, inadequate drainage, uneven surfaces, sagging and/or damage to drainage facilities.

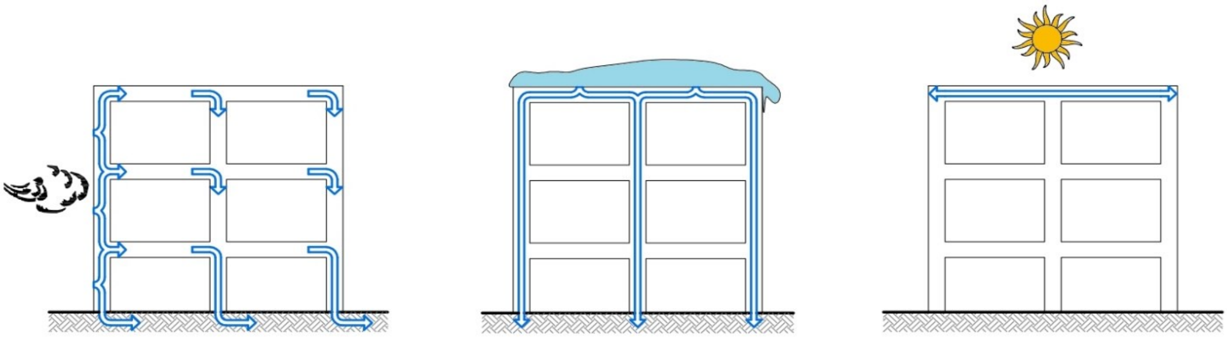
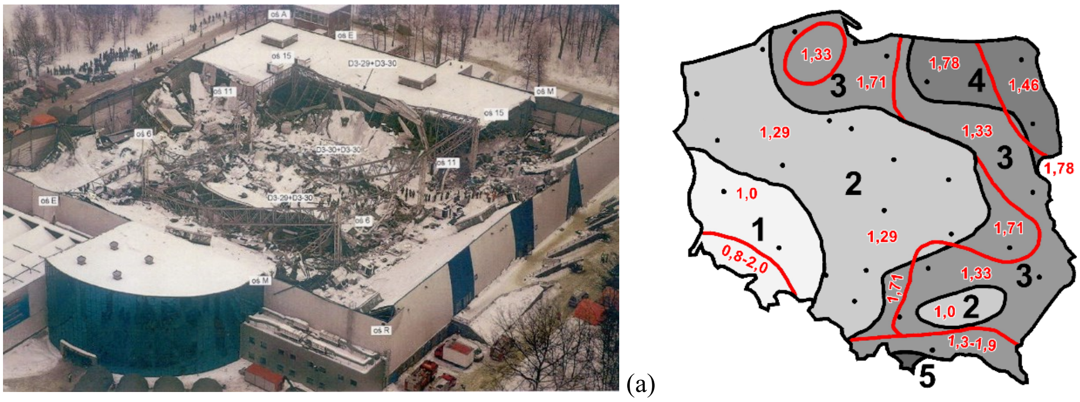

(a) (b) (c)

Fig. 1. Climatic actions affecting buildings, a) wind, transmitted horizontally to the foundations through bracing which ensures structural stability, b) snow, water, transported by gravity from top to bottom through bending or compression of floors, beams, columns and walls, c) uniform temperature distribution

The causes of construction disasters tend to be complex, due to the fact that the process of erecting building structures is complicated and multi-stage. Ensuring the assumed reliability of a structure is achieved through the implementation of a differentiated quality control system, covering the design, execution and maintenance of engineering structures. At each of these stages, undesirable actions may occur due to human errors [10]. If some of these errors are not detected during the various stages of supervision, there is a high probability that they will be detected by normative or super normative climatic phenomena. Conclusions from such catastrophes always trigger discussions within the engineering community, which sometimes lead to changes in regulations and/or normative requirements.

One of the biggest building disasters in the history of modern Poland happened in Katowice in 2006. The roof of the MTK exhibition hall, which was heavily laden with snow, suddenly collapsed (Figure 2a), killing 65 people and injuring more than 170. Forensic engineers proved that the cause was a number of design flaws, which were detected by the accumulated snow [5,10]. However, the tragic consequences of the catastrophe prompted scientists to re-analyze the meteorological data, as a result of which the layout of the snow zones on the map of Poland was changed (Figure 2b), increasing this load in some places almost twofold.



(a) (b)

Fig. 2. Catastrophe of the exhibition hall a) general view, photo GUNB (public domain) [41], b) changes to snow zones after the disaster, adapted from [42]

The demands of the engineering community to increase the level of safety in the use of buildings were fulfilled by increasing the safety coefficients of climatic actions and amending the provisions on periodic inspections, especially of large-scale structures. A principle was introduced, according to which the owner or manager of a structure is responsible for its safe use not only in terms of its technical performance, but also with regard to the impact of various external factors, including the action of forces of nature.

Another high-profile catastrophe caused by climatic factors was the collapse of one of the discs of the meteorological observatory at Mount Śnieżka [43]. At the summit, four high-intensity actions were impacting the structure at different intervals and in different configurations: snow, ice, wind and temperature (high in summer, low in winter). As a result, alternating compressive and tensile stresses occurred in the welds connecting the steel trusses of the disc to the stem, leading to fatigue cracking of the welds. The designer, however, was not accused of causing the disaster, as in the year of the building's construction, the obligation to design welds with consideration of the effects of fatigue loading had not yet been included in the design standards for steel structures. This disaster confirmed the validity of taking into account the variability of climatic actions in design standards.

In recent years, winters in Poland have been getting milder and less snowy. As a result, the vigilance of those involved in the construction process has been dulled, and engineering structures that do not have the required snow resistance began to be designed and built. Due to low price, tent halls with tarpaulin roofs are increasingly visible in the Polish landscape. However, sporadic snowfalls that currently occur are quickly verifying the over-optimistic design assumptions (Figure 3), as it is technically impossible to effectively remove snow from roofs with loose sheathing, and such a condition is often written into the instructions for use of such tents [44].

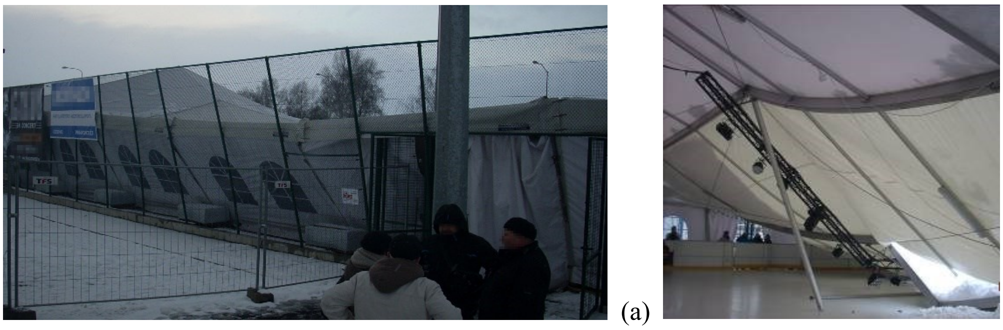


Fig. 3. Disaster of tent hall laden with snow a) external view, b) damaged aluminum girders of ice rink roof in Szczecin, photo PINB Szczecin (public domain) [45]

Snow is not the only precipitation that causes problems for building users [7,9,46]. Climate change also causes alterations in the intensity of rainfall [7], which may take the form of catastrophic rainfall in excess of 100 mm/day, and sometimes even storm rainfall (catastrophic rainfall occurring in a short period of time). Rainwater should run off roofs under gravity thanks to slope and drainage systems consisting of gutters and downpipes, and in most roofs there is no problem with this. The situation is different for concave or flat roofs with attics, where runoff depends on the efficiency of the drainage system. In such roofs, EN 12056-3 standard [47] enforces the design of overflow and emergency outlets (Figure 4a), which allow accumulated water to be discharged outside the building. Such safeguards, reducing the risk of rainwater overflowing into the building or overloading the structure, have long been known as principles of technical know-how and can be found in many historic buildings (Figure 4b). Unfortunately, sometimes designers forget these important architectural details, with tragic consequences (Figure 4c).

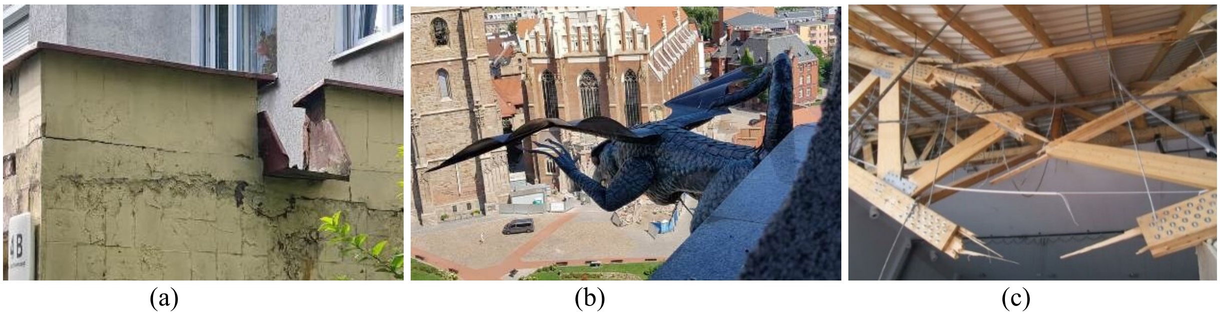


Fig. 4. Emergency overflows in flat roofs with attics, a) overflow opening in the attic of a vestibule of a multi-family building, b) historic gargoyle on a town hall tower, c) the consequence of the lack of emergency overflow in a school sports hall in the event of catastrophic rainfall, (a. and b. photo by A. Rawska-Skotniczny, c. photo PINB Poznań (public domain) [48]).

Changes to the standards after 2006 also applied to wind loads, although in this case only the safety factor was increased. The climatic maps of Poland were left virtually unchanged, though more emphasis is now placed on loads acting at edges such as wall corners, eaves or ridges, where turbulent air masses are generated. This action is regarded as one of the most difficult to predict and still poses many design problems. It is worth mentioning that one of the most famous disasters, the Tahoma Bridge in 1940, which proved the great importance of the dynamic effect of wind on structures, still provides scientists with material for mathematical analysis today [49]. Tornadoes and hurricane-force winds have been appearing sporadically in Poland for some time, but they are treated as above-normal actions (so-called force majeure). Hurricane-force winds usually result in torn-off roofs, hence the recommendations to minimize the impact of air masses on building partitions [50].

Conclusion

In conclusion, the time trends of the basic climate components in Poland indicate that the climate is changing. It is important to identify those areas for which the effects of this change may be crucial, to identify opportunities for their mitigation and ways of adapting to them.

Construction disasters, in which climatic phenomena were one of the causes, are constantly classified and analyzed by structural engineers, national authorities and standards committees. The conclusions drawn from these become a contribution to updating the national annexes to design standards and thus to improving the reliability of engineering structures.

References

1. T. Tanaka, K. Kiyohara, Y. Tachikawa, “Comparison of fluvial and pluvial flood risk curves in urban cities derived from a large ensemble climate simulation dataset: A case study in Nagoya, Japan”, J. Hydrol. 584, 124706 (2020).
2. L.M. Abadie, L.P. Jackson, E. Sainz de Murieta, S. Jevrejeva, I. Galarraga, “Comparing urban coastal flood risk in 136 cities under two alternative sea-level projections: RCP 8.5 and an expert opinion-based high-end scenario”, Ocean Coast. Manag. 193, 105249 (2020).
3. J.E. Norris, A. Stokes, S.B. Mickovski, E. Cammeraat, R. van Beek, B.C. Nicoll, A. Achim, Slope Stability and Erosion Control: Ecotechnological Solutions (Springer, Dordrecht, Holland, 2008), pp. 1-288.
4. D. Anelli, F. Tajani, R. Ranieri, “Urban resilience against natural disasters: Mapping the risk with an innovative indicators-based assessment approach”, J. Clean. Prod. 371, 133496 (2022).
5. Z. Zięba, J. Dąbrowska, M. Marschalko, J. Pinto, M. Mrówczyńska, A. Leśniak, A. Petrovski, J.K. Kazak, “Built environment challenges due to climate change”, IOP Conf. Ser. Earth Environ. Sci. 609, 012061 (2020).
6. M. Mosoarca, A.I. Keller, C. Petrus, A. Racolta, “Failure analysis of historical buildings due to climate change”, Eng. Fail. Anal. 82, 666–680 (2017).
7. V. Mishra, A. Sadhu, “Towards the effect of climate change in structural loads of urban infrastructure: A review”, Sustain. Cities Soc. 89, 104352 (2023).
8. A. Nasr, E. Kjellström, I. Björnsson, D. Honfi, O.L. Ivanov, J. Johansson, “Bridges in a changing climate: a study of the potential impacts of climate change on bridges and their possible adaptations”, Struct. Infrastruct. Eng. 16, 738–749 (2020).
9. P. Croce, P. Formichi, F. Landi, F. Marsili, “Climate change: Impact on snow loads on structures”, Cold Reg. Sci. Technol. 150, 35–50 (2018).
10. I. Tylek, K. Kuchta, A. Rawska-Skotniczny, “Human errors in the design and execution of steel structures-a case study”, Struct. Eng. Int. J. Int. Assoc. Bridg. Struct. Eng. 27, 370–379 (2017).
11. H. Hao, K. Bi, W. Chen, T.M. Pham, J. Li, “Towards next generation design of sustainable, durable, multi-hazard resistant, resilient, and smart civil engineering structures”, Eng. Struct. 277, 115477 (2023).
12. S.B. Guerreiro, R.J. Dawson, C. Kilsby, E. Lewis, A. Ford, “Future heat-waves, droughts and floods in 571 European cities”, Environ. Res. Lett. 13, 034009 (2018).
13. J.S. Tan, K. Elbaz, Z.F. Wang, J.S. Shen, J. Chen, “Lessons Learnt from Bridge Collapse: A View of Sustainable Management”, Sustain. 12, 1205 (2020).
14. J. Fluixá-Sanmartín, L. Altarejos-García, A. Morales-Torres, I. Escuder-Bueno, “Review article: Climate change impacts on dam safety”, Nat. Hazards Earth Syst. Sci. 18, 2471–2488 (2018).
15. K.E. Haslett, J.F. Knott, A.M.K. Stoner, J.E. Sias, E. V. Dave, J.M. Jacobs, W. Mo, K. Hayhoe, “Climate change impacts on flexible pavement design and rehabilitation practices”, J. Transp. Eng. Part A Syst. 22, 2098–2112 (2021).
16. S. Szewrański, J. Chruściński, J. Kazak, M. Świąder, K. Tokarczyk-Dorociak, R. Żmuda, “Pluvial Flood Risk Assessment Tool (PFRA) for Rainwater Management and Adaptation to Climate Change in Newly Urbanised Areas”, Water 10, 386 (2018).
17. X. Xiao, E. Seekamp, J. Lu, M. Eaton, M.P. van der Burg, “Optimizing preservation for multiple types of historic structures under climate change”, Landsc. Urban Plan. 214, 104165 (2021).
18. M. Landauer, S. Juhola, J. Klein, “The role of scale in integrating climate change adaptation and mitigation in cities”, J. Environ. Plan. Manag. 62, 741–765 (2019).
19. A. Hurlimann, S. Moosavi, G.R. Browne, “Urban planning policy must do more to integrate climate change adaptation and mitigation actions”, Land Use Policy 101, 105188 (2021).
20. B.J. He, J. Zhu, D.X. Zhao, Z.H. Gou, J. Da Qi, J. Wang, “Co-benefits approach: Opportunities for implementing sponge city and urban heat island mitigation”, Land Use Policy 86, 147–157 (2019).
21. J.G. Carter, G. Cavan, A. Connelly, S. Guy, J. Handley, A. Kazmierczak, “Climate change and the city: Building capacity for urban adaptation”, Prog. Plann. 95, 1–66 (2015).
22. I.M. Voskamp, C. De Luca, M. Budding Polo-Ballinas, H. Hulsman, R. Brolsma, A. Pagano, E.L. Gunn, L. Kapetas, B. Mayor, “Nature-Based Solutions Tools for Planning Urban Climate Adaptation: State of the Art”, Sustain. 13, 6381 (2021).
23. J. Da Qi, B.J. He, M. Wang, J. Zhu, W.C. Fu, “Do grey infrastructures always elevate urban temperature? No, utilizing grey infrastructures to mitigate urban heat island effects:, Sustain. Cities Soc. 46, 101392 (2019).

24. IPCC, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, Cambridge, United Kingdom and New York, NY, USA, 2021), pp. 1-2409.
25. B. Clarke, F. Otto, R. Stuart-Smith, L. Harrington, "Extreme weather impacts of climate change: an attribution perspective", Environ. Res. Clim. 1, 012001 (2022).
26. K.J.E. Walsh, S.J. Camargo, T.R. Knutson, J. Kossin, T.-C. Lee, H. Murakami, C. Patricola, "Tropical cyclones and climate change", Trop. Cyclone Res. Rev. 8, 240–250 (2019).
27. D.F. Balting, A. AghaKouchak, G. Lohmann, M. Ionita, "Northern Hemisphere drought risk in a warming climate", Clim. Atmos. Sci. 4, 61 (2021).
28. O. Lhotka, J. Kyselý, A. Farda, "Climate change scenarios of heat waves in Central Europe and their uncertainties", Theor. Appl. Climatol. 131, 1043–1054 (2018).
29. S. Pfahl, P.A. O'Gorman, E.M. Fischer, "Understanding the regional pattern of projected future changes in extreme precipitation", Nat. Clim. Chang. 7, 423–427 (2017).
30. A.M. Tomczyk, E. Bednorz, K. Szyga-Pluta, "Changes in air temperature and snow cover in winter in Poland", Atmosphere (Basel) 12, 68 (2021).
31. M. Kejna, M. Rudzki, "Spatial diversity of air temperature changes in Poland in 1961–2018", Theor. Appl. Climatol. 143, 1361–1379 (2021).
32. A.M. Tomczyk, E. Bednorz, M. Półrolniczak, L. Kolendowicz, "Strong heat and cold waves in Poland in relation with the large-scale atmospheric circulation", Theor. Appl. Climatol. 137,1909–1923 (2019).
33. J. Wibig, "Heat waves in Poland in the period 1951-2015: trends, patterns and driving factors", Meteorol. Hydrol. Water Manag. 6, 37–45 (2018).
34. C. Koźmiński, J. Nidzgorska-Lencewicz, A. Mąkosza, B. Michalska, "Ground Frosts in Poland in the Growing Season", Agric. 11, 573 (2021).
35. M. Szwed, "Variability of precipitation in Poland under climate change", Theor. Appl. Climatol. 135, 1003–1015 (2019).
36. I. Pińskwar, A. Choryński, D. Graczyk, Z.W. Kundzewicz, "Observed changes in extreme precipitation in Poland: 1991–2015 versus 1961–1990", Theor. Appl. Climatol. 135, 773–787 (2019).
37. M. Szwed, I. Pińskwar, Z.W. Kundzewicz, D. Graczyk, A. Mezghani, "Changes of snow cover in Poland", Acta Geophys. 65, 65–76 (2017).
38. M. Falarz, E. Bednorz, "Snow Cover Change", in: Climate Change in Poland. Past, Present, Future. Edited by M. Falarz (Springer, Cham, Switzerland, 2021), pp. 375–390.
39. E. Siwiec (Ed), Atlas skutków zjawisk ekstremalnych w Polsce (IOŚ-PIB, Warsaw, Poland, 2023), pp.1-79.
40. IMGW, Informatyczny System Osłony Kraju, Silny Wiatr. Zróżnicowanie Sezonowe i Przestrzenne. https://imgw.isok.gov.pl/mapy-zagrozen-i-ryzyka/zagrozenia-meteorologiczne/silny-wiatr/zroznicowanie-sezonowe-i-przestrzenne.html. (Accessed 12.12.2022).
41. GUNB, Wyciąg ze sprawozdania z działalności komisji powołanej przez Głównego Inspektora Nadzoru Budowlanego w sprawie ustalenia przyczyn i okoliczności katastrofy budowlanej w dniu 28 stycznia 2006 r. pawilonu wystawienniczego przy ul. Bytkowskiej 1 na terenie Miedzynarodowych Targów w Katowicach, Warszawa, 2006. https://www.gunb.gov.pl/sites/default/files/attachment/katowice_wyciag.pdf. (Accessed 01.12.2022).
42. B. Lewicki, J.A. Żurański, "Obciążenie śniegiem w nowych normach polskich", Wiadmości Proj. Budownictwa 1, (2007) 18–21.
43. J. Gierczak, R. Ignatowicz, W. Lorenc, "Steel structure of the roof in lower saucer of the Śnieżka Meteorological observatory in the context of the state of emergency", in: 26 Int. Conf. Stuctural Fail. Międzyzdroje, 21-24.05.2013, 2013, pp. 1–8.
44. A. Rawska-Skotniczny, A. Marynowicz, M. Nalepka, "Errors in the design of temporary and solid fabric structures", in: 28 Int. Conf. Stuctural Fail. Międzyzdroje, 22-26.05.2017, 2017, pp. 1–12.
45. PINB Szczecin, Documentation of the tent hall disaster 04.02.2015, 3/5/7 Szafera St., Szczecin, (documents made available to the authors by the authority).
46. J. Geis, K. Strobel, A. Liel, "Snow-Induced Building Failures", J. Perform. Constr. Facil. 26, 377–388 (2012).
47. CEN, EN 12056-3 Gravity drainage systems inside buildings - Part 3: Roof drainage, layout and calculation, 2000.

48. PINB Poznań, Katastrofa budowlana sali gimnastycznej w Poznaniu, to nie tylko sygnał ostrzegawczy, to też pytanie o skuteczność przepisów, (2021). http://www.pinb.poznan.pl/index.php/115-dzialalnosc-inspektoratu/artykuly/469-katastrofa-budowlana-sali-gimnastycznej-w-poznaniu-to-nie-tylko-sygnal-ostrzegawczy-to-tez-pytanie-o-skutecznosc-przepisow. (Accessed 01.12.2022).

49. G. Arioli, F. Gazzola, "A new mathematical explanation of what triggered the catastrophic torsional mode of the Tacoma Narrows Bridge", Appl. Math. Model. 39, 901–912 (2015).

50. J.A. Żurański, M. Gaczek, S. Fiszer, "Measures for minimising windstorm damage to buildings", in: 25 Int. Conf. Stuctural Fail. Międzyzdroje, 24-27.05.2011, 2011, pp. 1–10.