

# Introduction to eco-efficient materials for reducing cooling needs in buildings and construction

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## 1.1 Climate emergency and global warming runaway patterns

According to [Watts \(2018\)](#), in February of 2017 the temperatures in the Arctic remained 20°C above average for longer than a week, increasing the melting rate. As a consequence, the replacement of ice by water led to a higher absorption of solar radiation, making the oceans warmer and being responsible for basal ice melting ([Tabone et al., 2019](#)) and also for a warmer atmosphere ([Ivanov et al., 2016](#)). This constitutes a form of positive feedback that aggravates the aforementioned problem. [Wadhams \(2017\)](#) already stated that an ice-free Arctic will occur in the next few years and that it will likely increase the warming caused by the CO<sub>2</sub> produced by human activity by 50%. The latest data on rates of melting combined with new models suggest that an ice-free Arctic summer could occur by 2030 ([Screen and Deser, 2019](#); [Bendell, 2019](#)). The warming of the earth will also result in extensive permafrost thaw in the Northern Hemisphere. With this thaw, large amounts of organic carbon will be mobilized, some of which will be converted and released into the atmosphere as greenhouse gases. This, in turn, can facilitate positive permafrost carbon feedback and thus further warming ([Schuur et al., 2015](#); [Tanski et al., 2018](#)). Turetsky reported that permafrost thawing could release between 60 and 100 billion tonnes of carbon. This is in addition to the 200 billion tonnes of carbon expected to be released in other regions, which will thaw gradually.

Also, recent fires in the Arctic region (Siberia and Alaska) have emitted millions of tons of CO<sub>2</sub>, constituting another positive feedback situation, and it is expected that in future fires will occur more frequently ([Chen et al., 2016](#); [Riley et al., 2019](#); [Schirmeier, 2019](#)). Vicious cycles of drought, leading to fire, leading to more drought have a positive feedback effect that further aggravates carbon dioxide emissions and global warming.

[Gasser et al. \(2018\)](#) stated that the world is closer to exceeding the budget (cumulative amount of anthropogenic CO<sub>2</sub> emission compatible with a global temperature-change target) for the long-term target of the Paris Climate Agreement than previously

thought. Also, according to [Xu et al. \(2018\)](#), three lines of evidence suggest that the rate of global warming will be faster than projected in the recent IPCC special report. First, greenhouse-gas emissions are still rising. Second, governments are cleaning up air pollution faster than the IPCC and most climate modelers have assumed, but aerosols, including sulfates, nitrates, and organic compounds, reflect sunlight so the aforementioned cleaning could have a warming effect by as much as 0.7°C. Third, there are signs that the planet might be entering a natural warm phase, because the Pacific Ocean seems to be warming up, in accord with a slow climate cycle known as the Interdecadal Pacific Oscillation, which could last for a couple of decades. These three forces reinforce each other.

[Kareiva and Carranza \(2018\)](#) stated that positive feedback loops represent the gravest existential risks, and the risks that society is least likely to foresee. To make things worse, the current climate emergency is also impacting microorganisms, not only exacerbating the impact of pathogens and increasing disease incidence, but also having a positive feedback effect on climate change ([Cavicchioli et al., 2019](#)). Recently [Bamber et al. \(2019\)](#) found that future sea level rise with the inclusion of thermal expansion and glacier contributions results for 2100 will exceed 2 m, which is more than twice the upper value put forward by the Intergovernmental Panel on Climate Change in the Fifth Assessment Report. This is especially worrisome, because 90% of urban areas are situated on coastlines, making the majority of the world's population increasingly vulnerable to the current climate emergency ([Elmqvist et al., 2019](#)).

At the same time, the United Nations estimates that by 2030, 700 million people will be forced to leave their homes because of drought ([Padma, 2019](#)). Drought and heat waves associated with this climate emergency are responsible for damaging crop yields, deepening farmers' debt burdens, and inducing some to commit suicide. A study by [Carleton \(2017\)](#) shows that in India over the last three decades, the rising temperatures have already been responsible for over 59,000 suicides. And this raises the additional issue of determining which countries should take responsibility for climate refugees ([Bayes, 2018](#)).

It is no wonder that [Wallace-Wells \(2017\)](#) wrote about catastrophic scenarios that include starvation, disease, civil conflict, and war. Even the discreet and circumspect Joachim Schellnhuber, professor of theoretical physics, expert in complex systems and nonlinearity, and founding director of the Potsdam Institute for Climate Impact Research (1992–2018) and former chair of the German Advisory Council on Global Change, spoke out more strongly in his foreword for the paper by [Spratt and Dunlop \(2018\)](#), in which he wrote: "climate change is now reaching the end-game, where very soon humanity must choose between taking unprecedented action, or accepting that it has been left too late and bear the consequences." [Torres \(2019\)](#), on the other hand, has gone beyond the pessimistic forecasting by mentioning a hypothetical "double catastrophe scenario" in which an ongoing "stratospheric geoengineering project" is interrupted by a destabilizing event—e.g., a terrorist attack, or interstate or civil war—that could have unpredictable consequences for the global climate, for instance bringing about massive agricultural failures. And these are not unrealistic scenarios, because the world economy is so entangled that any random event could have massive consequences, especially for poor people. Coincidentally or not, on September of 2019

several drones attacked the Abqaiq facility in Saudi Arabia, the most important oil processing facility in the world, worsening an already unstable world economy (FT, 2019). This is a clear sign of the consequences of a world economy addicted to nonrenewable resources that are located in one of the most unstable regions in the world.

In July of 2018, Professor Bendell authored a dramatic piece warning of the probable social collapse, articulating the perspective that it is now too late to stop a future collapse of our societies because of the current climate emergency, and that we must now explore ways in which to reduce harm. He called for a “deep adaptation agenda” that would encompass: “withdrawing from coastlines, shutting down vulnerable industrial facilities, or giving up expectations for certain types of consumption” (Bendell, 2018). The essence of this deep adaptation lies in the “four Rs”:

1. Resilience: What do we most value and want to keep?
2. Relinquishment: What must we let go of?
3. Restoration: What skills and practices can we restore?
4. Reconciliation: What can we make peace with to lessen suffering?

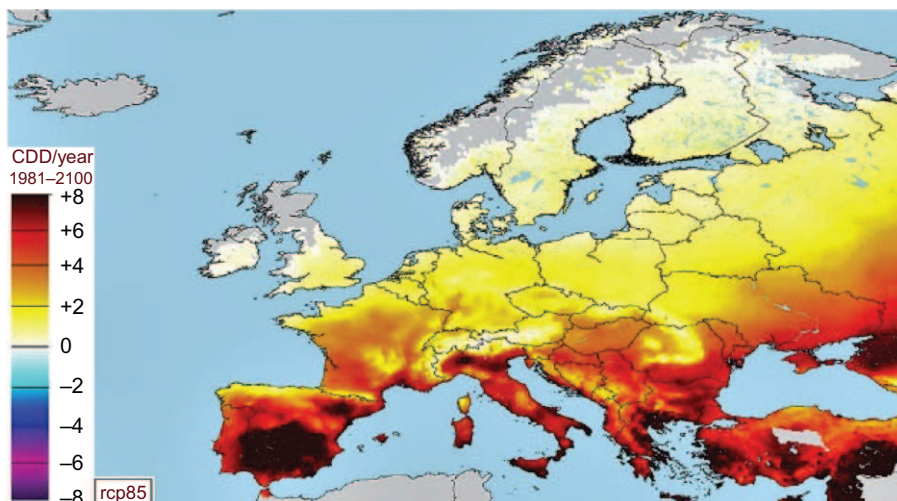
And in December of the same year, Read (2018) also shared his views about the dramatic future of our planet and the fate of humanity. Some say Bendell has gone too far in his pessimistic views, but a professor of physics at the University of Oxford wrote the following in a paper published in August of 2019: “Let’s get this on the table right away, without mincing words. With regard to the climate crisis, yes, it’s time to panic” (Pierrehumbert, 2019). In a presentation that Bendell gave in May of 2019 at the European Commission, he mentioned the importance of technologies for deep adaptation (Bendell, 2019), but of course he only named a few. Be that as it may, he was not even considering long-term scenarios defended by Baum et al. (2019). Also on November 5, 2019, Ripple et al. (2019), along with several thousand scientists, issued a warning: “Clearly and unequivocally the planet Earth is facing a climate emergency,” which is none other than tacit support for Bendell’s views.

## **1.2 Heat waves, urban heat island, and cooling materials as a way to save lives in the context of the coronavirus recession**

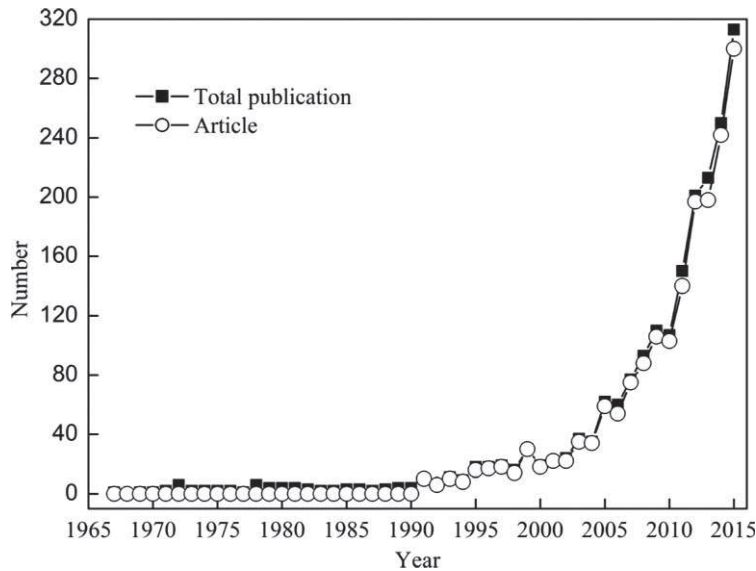
According to the IPCC, heat waves are the most important and dangerous hazard related to the current climate emergency. Kew et al. (2019) reported that anthropogenic climate change has increased the odds of heat waves at least threefold since 1950, and across the Euro-Mediterranean the likelihood of a heat wave at least as hot as summer 2017 (responsible for temperatures above 40°C in France and the Balkan region and nighttime temperatures above 30°C) is now on the order of 10%. The negative impacts of extreme heat, which are more acute in urban areas, include health risks, higher concentrations of pollutants (Meehl et al., 2018), lower water quality, and decrease in labor productivity. Ironically, Belkin and Kouchaki (2017) even found that heat increases fatigue, which leads to reduction in positive affect, subsequently

reducing individual helping. Also, those most affected are the most vulnerable groups among the urban dwellers: the elderly, the individuals with preexisting chronic conditions, communities with weak socioeconomic status, people with mental disorders, and isolated individuals (Smid et al., 2019). In this context it is worth remembering that in 2003 a European heat wave claimed the lives of several thousand people and in 2010 Moscow was hit by the strongest heat wave of the present era, killing more than 10,000 people. Europe, with its growing aging population trend, a population which is more susceptible to heat-wave effects, will in that context be hit in a harder way (Fig. 1.1).

If no adaptation measures are undertaken, this could mean an additional several thousand deaths/year from heat waves (and their synergistic effects with air pollution). The consequences associated with heat wave predictions do not even take into account the effect associated with urban heat islands (UHIs). This phenomena is triggered by absorption radiation due to artificial urban materials, transpiration from buildings and infrastructure, release of anthropogenic heat from inhabitants and appliances, and the airflow blocking effect of buildings (Mirzaei and Haghighat, 2010; Pacheco-Torgal et al., 2015). The dark-colored surfaces used (such as dark asphalt pavements) have low reflecting power (or low albedo characteristics); as a consequence they absorb more energy and in summer can reach almost 60°C, thus contributing toward greater UHI effects. UHI is probably the most documented phenomenon of the current climate emergency for various geographic areas of the planet, with a huge increase in the number of publications appearing on this topic since 1990 (Fig. 1.2). This may have something to do with the beginning of the sustainable development movement after the publication of the Brundtland report (*Our Common Future*) (Brundtland, 1987). As



**Fig. 1.1** Linear trends of cooling degree days (CDDs) per year under the RCP8.5 radiative forcing scenario, i.e., radiative forcing values at the end of the 21st century, relative to preindustrial values of  $+8.5 \text{ W m}^{-2}$  (Spinoni et al., 2018).



**Fig. 1.2** Characteristics by year of UHI-related publications (Huang and Lu, 2018).

a result of massive urbanization and industrialization of human civilization in the last few decades, UHI has gained a dramatic dimension that jumpstarted the publications in this field. In the future this urbanization trend is expected to become even worse; according to [Guerreiro et al. \(2018\)](#) by 2050 urban systems will be home to 66% of the global population, with the proportion being even higher in the European Union, where currently 75% of the population resides in cities with expected growth to 82% by 2050. At that point, UHI will become more and more important, having more dramatic consequences. Some authors have reported a 10°C temperature increase in the city of Athens due to the UHI effect ([Santamouris et al., 2001](#)) and an 8.8°C increase in London ([Kolokotroni and Giridharan, 2008](#)), while a recent 3-year investigation in the city of Padua reported an increase up to 6°C ([Busato et al., 2014](#)). According to [Li et al. \(2014\)](#), even the waste heat discharged by air conditioners alone was responsible for an increase of almost 2°C in Beijing average air temperature in 2005.

Recent projections show that in the northwest area of the United Kingdom, summer mean temperatures could rise by 5°C (50% probability, 7°C top of the range) by the 2080s ([Levermore et al., 2018](#)). The expected rise in global temperature is likely to increase the energy needed to cool buildings in the summer. [Balaras et al. \(2007\)](#) mentioned an increase of energy cooling needs more than 2000% between 1990 and 2010. Also, the synergistic effect between heat waves and air pollution causes worse outdoor air quality in the summer and prevents natural ventilation, thus increasing cooling needs. In the heavily polluted city of Beijing, [Li et al. \(2014\)](#) reported that 28.88% of the total air-conditioning energy consumption is due to the UHI effect. [Manoli et al. \(2019\)](#) studied data from some 30,000 cities worldwide, and concluded that cities having a more desert-like surrounding countryside can more easily achieve cooler temperatures by use of careful plantings than cities surrounded by tropical forests,

which need far more green spaces to reduce temperatures, thus creating more humidity. In these latter areas, other cooling methods are therefore expected to be more effective, such as increased wind circulation, more use of shade, and new heat-dispersing materials. [Shandas et al. \(2019\)](#) used a combination of ground-based measurements and satellite data that accurately identified areas of extreme urban heat hazards. The results showed that the urban microclimate was highly variable, with differences of up to 10°C between the coolest and warmest locations at the same time. [Sailor et al. \(2019\)](#) reported that building occupants in many US cities rely only on air conditioning, to a degree that their health and well-being are compromised in its absence. They found that residential buildings are highly vulnerable to heat disasters and that situation will be exacerbated by intensification of UHIs. A recent review by [Santamouris \(2019\)](#) included a projection that the mortality of the elderly population in Washington State will increase between 4 and 22 times by 2045, and heat-related mortality in three cities in the northeastern United States will increase six to nine times by 2080 under the high-emission scenario, RCP 8.5. Of course, these projections do not account for the economic recession caused by the coronavirus ([Michelsen et al., 2020](#); [Fernandes, 2020](#); [Leiva-Leon et al., 2020](#)), which in turn will reduce the number of those who can afford air conditioning. Some estimates are so pessimistic ([Sraders, 2020](#)) as to imply that air conditioning could become a luxury expense.

On the positive side, [Macintyre and Heaviside \(2019\)](#) concluded that cool roofs could reduce heat-related mortality associated with the UHI effect by ~25% during a heat wave. This shows how cooling materials can be important in saving lives, especially in the context of the coronavirus recession. [Bai et al. \(2018\)](#) advocated that research on mitigating urban climate change and adapting to it must be supported at a scale commensurate with the magnitude of the problem, and that funding agencies need to provide grants for cross-disciplinary research and comparative studies, especially in the global south. [Sharma et al. \(2019\)](#) also stated that there exists a huge gap in the literature on such topics. Of particular concern are cities located in developing nations with arid or semiarid climate conditions that are already experiencing very hot and dry summers and, due to low adaptive capacities, are more vulnerable to changing climate. All of these factors constitute a strong justification for this book. In addition, books already on the market do not present a comprehensive review of the full innovative range of eco-efficient materials capable of mitigating UHI effects and meeting building cooling needs. Some publications contain almost no information on cool pavements and others are deficient on subjects such as switchable glazing-based materials ([Santamouris, 2019](#)). This book, however, has a balanced coverage of eco-efficient materials for pavements, façades, and roofs, with a section especially for phase change materials (PCMs) and switchable glazing-based materials. With special contributions from a team of international experts, this book provides an updated state of the art on eco-efficient materials for reducing cooling needs in buildings and other construction.

### 1.3 Outline of the book

This book provides an updated state-of-the-art review of eco-efficient materials to reduce cooling needs in building and construction.

Part One encompasses an overview of pavements for mitigation of urban heat island effects (Chapters 2–4).

Chapter 2 covers particular applications aimed at mitigating the heat-related concerns using high albedo materials. First, albedo significance and relevance and its usefulness for effectively producing thermally optimized pavements are analyzed. After a short contextualization, the physics of albedo is discussed, in order to better understand its theoretical meaning and function in determining the radiative properties of materials that affect the general energetic balance of pavement surfaces. High-albedo paving solutions are described, giving some details on constituent materials, chromatic characteristics, and surface properties. Some general issues regarding the overall benefits and drawbacks involved with the utilization of high-albedo pavement materials are debated.

Chapter 3 introduces three-component organic reversible thermochromic microcapsules, including their classification, merits, components, structure, thermochromic mechanism, and thermal and optical properties. The performance of thermochromic asphalt binders is illustrated, covering physical, optical, thermal, rheological, and antiaging properties, and the adjustment of thermochromic asphalt temperature. Finally, some proposals for future research on thermochromic asphalt are given.

Chapter 4 reviews pavements developed to mitigate urban heat islands. This includes information on methods to quantify surface temperature and heat transfer from pavement to urban temperature. Furthermore, the impacts of pavement temperature on mechanical performances are presented. Special attention is given to porous pavement, PCM pavement, and hydronic pavement.

Façade materials for reducing building cooling needs are the subject of Part Two (Chapters 5–9).

Chapter 5 presents a revised radiation apportionment model for estimating the benefits of shading against short-wave radiation as cooling-load reduction. Adhering to the principles of an improved radiative transfer model, field data harvested from net radiometers were input into a Microsoft Excel spreadsheet. The Solver function determined the radiative properties of various layers of a windowed building envelope, featuring a climber green wall.

Chapter 6 investigates the potentials of different geometrical brick patterns and their behavior on self-shading potential to reduce mean surface temperature of solar exposed brick walls. The study was shaped in two layers, including field measurements for geometric behavior and evaporative cooling potential. The results are discussed and compared for three configurations of solid, extruded, and perforated under varying boundary conditions over a day.

Chapter 7 presents an innovative low-energy, low-tech, and low-cost cooling system for buildings. This cooling system simultaneously makes use of three available heat sinks: the ground, evaporation of water, and radiation to the sky. A terra-cotta tank is placed along a northern wall of the building to achieve the two last phenomena. The chapter includes a case study simulation on a 100-m<sup>2</sup> house in Bordeaux climatic conditions.

Chapter 8 refers to a retrofitting case study of an office building using hemp-based plaster and passive cooling techniques. An economic simulation is also included.

**Chapter 9** concerns the evaluation of thermal response of advanced glass façade structures with improved energy performance during the cooling period of the buildings. Two types of glazed façade structures were analyzed: 6-pane glazing structure upgraded in a BIPV system with and without PCM inserts, and BIPV double glazed façade with a transparent triple-glazed interior structure. The diurnal transient thermal response of constructions under investigation was evaluated using a CFD technique for extreme daily summer climate conditions for Athens, Ljubljana, and Stockholm.

Part Three (**Chapters 10–12**) deals with roofing materials for reducing building cooling needs.

**Chapter 10** reviews the importance of green roofs for UHI mitigation. It includes design options and green roof modeling. The chapter also includes a description of an experimental set-up with extensive green roofs, including its cooling energy savings.

**Chapter 11** discusses the thermal performance of building roofs with conventional and reflective coatings. A numerical model of a building roof validated with experimental data is included.

**Chapter 12** focuses on utilization of active and passive cool roof systems to enhance the comfort of building occupants with attic temperature reduction. A case study including a thermal reflective coating, MAC-solar powered fan, and a rainwater harvesting system is analyzed.

Part Four concerns PCMs and switchable glazing-based materials for reducing cooling needs (**Chapters 13–18**).

**Chapter 13** contains a short review of recent developments concerning biobased phase change materials for cooling in buildings.

**Chapter 14** deals with PCM selection (mapping), based on its thermophysical properties and climatic parameters, which are location specific, followed by technology for PCM incorporation within building components. It also provides a comprehensive review of studies carried out so far in terms of energy savings through PCM incorporation within buildings.

**Chapter 15** provides a state-of-the-art review of novel PCM-based strategies for building cooling performance enhancement. The investigated strategies include PCM integrated forms (such as distributed and coupled systems) and combined strategies (such as high-reflective coating, radiative cooling wall, and hybrid ventilations). Solutions for system performance enhancement of novel PCM-based cooling systems are comprehensively presented.

**Chapter 16** reviews optically smart thin materials, such as thermochromic and electrochromic coatings, including all the mechanisms that manage their optical smartness. Classical and new methods used to fabricate these materials are detailed. Applications of these materials, such as smart thermal building insulators, and their impact on cooling and heating energy consumption are discussed.

**Chapter 17** focuses on the most promising innovative solutions, in particular those whose strong dynamic and adaptable behaviors are able to tailor building energy needs and to optimize their performance and indoor-outdoor functionality. In this chapter, thermochromic materials are presented together with their major potentialities and limitations. Finally, their effect on building energy efficiency is assessed, with particular focus on the existing applications at the single building and urban scales.



Chapter 18 closes Part Four with an overview of thermochromic glazing products, considering their thermo-optical properties and technological integration. This chapter also includes a quantitative evaluation of their whole building performance. Total energy use and visual comfort aspects are discussed for a typical sun-oriented office building in three different climates, in order to provide an overview of their potential performance improvements as compared to traditional static glazing technologies.

## References

- Bai, X., Dawson, R.J., Üрге-Vorsatz, D., Delgado, G.C., Salisu Barau, A., Dhakal, S., Dodman, D., et al., 2018. Six research priorities for cities and climate change. *Nature* 555 (7694), 23–25.
- Balaras, C., Grossman, G., Henning, H., Infante-Ferreira, C., Podesser, E., Wang, L., Wiemken, E., 2007. Solar air conditioning in Europe—an overview. *Renew. Sustain. Energy Rev.* 11, 299–314.
- Bamber, J.L., Oppenheimer, M., Kopp, R.E., Aspinall, W.P., Cooke, R.M., 2019. Ice sheet contributions to future sea-level rise from structured expert judgment. *Proc. Natl. Acad. Sci.* 116 (23), 11195–11200.
- Baum, S.D., Armstrong, S., Ekenstedt, T., Häggström, O., Hanson, R., Kuhlemann, K., Maas, M.M., Miller, J.D., Salmela, M., Sandberg, A., Sotala, K., 2019. Long-term trajectories of human civilization. *Foresight* 21 (1), 53–83.
- Bayes, A., 2018. Who takes responsibility for the climate refugees? *Int. J. Clim. Change Strateg. Manage.* 10 (1), 5–26.
- Belkin, L.Y., Kouchaki, M., 2017. Too hot to help! Exploring the impact of ambient temperature on helping. *Eur. J. Soc. Psychol.* 47 (5), 525–538.
- Bendell, J., 2018. Deep Adaptation: A Map for Navigating Climate Tragedy. Institute for Leadership and Sustainability (IFLAS) Occasional Papers Volume 2 University of Cumbria, Ambleside, UK. [http://insight.cumbria.ac.uk/id/eprint/4166/1/Bendell\\_DeepAdaptation.pdf](http://insight.cumbria.ac.uk/id/eprint/4166/1/Bendell_DeepAdaptation.pdf).
- Bendell, J., 2019. Because it's not a drill: technologies for deep adaptation to climate chaos. In: Connect University Conference on Climate Change, 13 May 2019. DG Connect, European Commission, Brussels, Belgium <http://insight.cumbria.ac.uk/id/eprint/4776/>.
- Brundtland, G., 1987. *Our Common Future*. Report of the World Commission on Environment and Development Oxford University Press, Oxford.
- Busato, F., Lazzarin, R., Noro, M., 2014. Three years study of the Urban Heat Island in Padua: experimental results. *Sustain. Cities Soc.* 10, 251–258.
- Carleton, T.A., 2017. Crop-damaging temperatures increase suicide rates in India. *Proc. Natl. Acad. Sci.* 114 (33), 8746–8751.
- Cavicchioli, R., Ripple, W.J., Timmis, K.N., Azam, F., Bakken, L.R., Baylis, M., Behrenfeld, M.J., Boetius, A., Boyd, P.W., Classen, A.T., Crowther, T.W., 2019. Scientists' warning to humanity: microorganisms and climate change. *Nat. Rev. Microbiol.* 1.
- Chen, Y., Kelly, R., Genet, H., McGuire, A.D., Hu, F., 2016. Resilience and sensitivity of carbon stocks to increased fire frequency in Arctic tundra. In: AGU Fall Meeting Abstracts.
- Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., Takeuchi, K., Folke, C., 2019. Sustainability and resilience for transformation in the urban century. *Nat. Sustain.* 2 (4), 267.
- Fernandes, N., 2020. Economic effects of coronavirus outbreak (COVID-19) on the world economy. Available at SSRN 3557504.

- FT, 2019. Attack on Saudi facility exposes world economy's 'Achilles heel'. <https://www.ft.com/content/0b89f8e2-d885-11e9-8f9b-77216ebe1f17>.
- Gasser, T., Kechiar, M., Ciais, P., Burke, E.J., Kleinen, T., Zhu, D., Huang, Y., Ekici, A., Obersteiner, M., 2018. Path-dependent reductions in CO<sub>2</sub> emission budgets caused by permafrost carbon release. *Nat. Geosci.* 11 (11), 830.
- Guerreiro, S.B., Dawson, R.J., Kilsby, C., Lewis, E., Ford, A., 2018. Future heat-waves, droughts and floods in 571 European cities. *Environ. Res. Lett.* 13 (3), 034009.
- Huang, Q., Lu, Y., 2018. Urban heat island research from 1991 to 2015: a bibliometric analysis. *Theor. Appl. Climatol.* 131 (3–4), 1055–1067.
- Ivanov, V., Alexeev, V., Koldunov, N.V., Repina, I., Sandø, A.B., Smedsrud, L.H., Smirnov, A., 2016. Arctic Ocean heat impact on regional ice decay: a suggested positive feedback. *J. Phys. Oceanogr.* 46 (5), 1437–1456.
- Kareiva, P., Carranza, V., 2018. Existential risk due to ecosystem collapse: nature strikes back. *Futures* 102, 39–50.
- Kew, S.F., Philip, S.Y., Jan van Oldenborgh, G., van der Schrier, G., Otto, F.E., Vautard, R., 2019. The exceptional summer heat wave in southern Europe 2017. *Bull. Am. Meteorol. Soc.* 100 (1), S49–S53.
- Kolokotroni, M., Giridharan, R., 2008. Urban heat island intensity in London: an investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. *Sol Energy* 82, 986–998.
- Leiva-Leon, D., Perez-Quiros, G., Rots, E., 2020. Real-time weakness of the global economy: a first assessment of the coronavirus crisis. ECB Working Paper No. 2381, March. Available at SSRN: <https://ssrn.com/abstract=3560170>.
- Levermore, G., Parkinson, J., Lee, K., Laycock, P., Lindley, S., 2018. The increasing trend of the urban heat island intensity. *Urban Clim.* 24, 360–368.
- Li, C., Zhou, J., Cao, Y., Zhong, J., Liu, Y., Kang, C., Tana, Y., 2014. Interaction between urban microclimate and electric air-conditioning energy consumption during high temperature season. *Appl. Energy* 117, 149–156.
- Macintyre, H.L., Heaviside, C., 2019. Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city. *Environ. Int.* 127, 430–441.
- Manoli, G., Fatichi, S., Schläpfer, M., Yu, K., Crowther, T.W., Meili, N., Burlando, P., Katul, G.G., Bou-Zeid, E., 2019. Magnitude of urban heat islands largely explained by climate and population. *Nature* 573 (7772), 55–60.
- Meehl, G.A., Tebaldi, C., Tilmes, S., Lamarque, J.F., Bates, S., Pendergrass, A., Lombardozzi, D., 2018. Future heat waves and surface ozone. *Environ. Res. Lett.* 13 (6), 064004.
- Michelsen, C., Clemens, M., Hanisch, M., Junker, S., Kholodilin, K.A., Schlaak, T., 2020. Coronavirus plunges the German economy into recession: DIW economic outlook. *DIW Weekly Report* 10 (12), 184–190.
- Mirzaei, P.A., Haghighat, F., 2010. Approaches to study urban heat island – abilities and limitations. *Build. Environ.* 45 (10), 2192–2201.
- Pacheco-Torgal, F., Labrincha, J., Cabeza, L., Granqvist, C.G. (Eds.), 2015. *Eco-efficient Materials for Mitigating Building Cooling Needs: Design, Properties and Applications* (No. 56). Woodhead Publishing.
- Padma, T., 2019. African nations push UN to improve drought research. <https://www.nature.com/articles/d41586-019-02760-9>.
- Pierrehumbert, R., 2019. There is no Plan B for dealing with the climate crisis. *Bull. At. Sci.* 1–7.
- Read, R., 2018. This civilisation is finished: so what is to be done? [https://ueaeprints.uea.ac.uk/69557/1/Read\\_Rupert\\_This\\_Civilisation\\_is\\_finished\\_so\\_what\\_is\\_to\\_be\\_done.pdf](https://ueaeprints.uea.ac.uk/69557/1/Read_Rupert_This_Civilisation_is_finished_so_what_is_to_be_done.pdf).

- Riley, K.L., Williams, A.P., Urbanski, S.P., Calkin, D.E., Short, K.C., O'Connor, C.D., 2019. Will landscape fire increase in the future? A systems approach to climate, fire, fuel, and human drivers. *Curr. Pollut. Rep.* 5 (2), 9–24.
- Ripple, W.J., Wolf, C., Newsome, T.M., 2019. World scientists' warning of a climate emergency. *Bioscience*. <https://doi.org/10.1093/biosci/biz088>.
- Sailor, D.J., Baniassadi, A., O'Lenick, C.R., Wilhelmi, O.V., 2019. The growing threat of heat disasters. *Environ. Res. Lett.* 14 (5), 054006.
- Santamouris, M. (Ed.), 2019. *Cooling Energy Solutions for Buildings and Cities*. World Scientific.
- Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., Assimakopoulos, D., 2001. On the impact of urban climate on the energy consumption of buildings. *Sol. Energy* 70, 201–216.
- Schirmeier, Q., 2019. Climate change made Europe's mega-heatwave five times more likely. <https://www.nature.com/articles/d41586-019-02071-z>.
- Schuur, E.A., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M., Natali, S.M., 2015. Climate change and the permafrost carbon feedback. *Nature* 520 (7546), 171.
- Screen, J.A., Deser, C., 2019. Pacific Ocean variability influences the time of emergence of a seasonally ice-free Arctic Ocean. *Geophys. Res. Lett.* 46, 2222–2231.
- Shandas, V., Voelkel, J., Williams, J., Hoffman, J., 2019. Integrating satellite and ground measurements for predicting locations of extreme urban heat. *Climate* 7 (1), 5.
- Sharma, R., Hooyberghs, H., Lauwaet, D., De Ridder, K., 2019. Urban heat island and future climate change—implications for Delhi's heat. *J. Urban Health* 96 (2), 235–251.
- Smid, M., Russo, S., Costa, A.C., Granell, C., Pebesma, E., 2019. Ranking European capitals by exposure to heat waves and cold waves. *Urban Clim.* 27, 388–402.
- Spinoni, J., Vogt, J.V., Barbosa, P., Dosio, A., McCormick, N., Bigano, A., Füssel, H.M., 2018. Changes of heating and cooling degree-days in Europe from 1981 to 2100. *Int. J. Climatol.* 38, e191–e208.
- Spratt, D., Dunlop, I., 2018. *What Lies Beneath: The Understatement of Existential Climate Risk*. Breakthrough (National Centre for Climate Restoration). <https://climateextremes.org.au/wp-content/uploads/2018/08/What-Lies-Beneath-V3-LR-Blank5b15d.pdf>.
- Sraders, A., 2020. How much will coronavirus hurt the economy? These new estimates are terrifying. <https://fortune.com/2020/03/17/how-much-will-coronavirus-hurt-the-economy-these-new-estimates-are-terrifying/>. (Accessed 2 April 2020).
- Tabone, I., Robinson, A., Alvarez-Solas, J., Montoya, M., 2019. Submarine melt as a potential trigger of the North East Greenland Ice Stream margin retreat during Marine Isotope Stage 3. *Cryosphere* 13 (7), 1911–1923.
- Tanski, G., Wagner, D., Fritz, M., Sachs, T., Lantuit, H., 2018. Impetuous CO<sub>2</sub> release from eroding permafrost coasts. In: 5th European Conference on Permafrost, 23 June–1 July, Chamonix, France.
- Torres, P., 2019. Facing disaster: the great challenges framework. *Foresight* 21 (1), 4–34.
- Wadhams, P., 2017. *A Farewell to Ice*. Oxford University Press, Oxford.
- Wallace-Wells, D., 2017. The Uninhabitable Earth: famine, economic collapse, a sun that cooks us: what climate change could wreak—sooner than you think. *New York Magazine*.
- Watts, J., 2018. Arctic warming: scientists alarmed by 'crazy' temperature rises. *The Guardian*. 27.
- Xu, Y., Ramanathan, V., Victor, D.G., 2018. Global warming will happen faster than we think. *Nature* 564 (7734), 30–32. <https://doi.org/10.1038/d41586-018-07586-5>.