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Heat in Germany: Health risks and preventive measures

Abstract

**Background:** Climate change has already led to a significant temperature increase in Germany. The average temperature in the past decade was approximately 2°C above the pre-industrial level and eight of the ten hottest summers since the beginning of systematic weather records in 1881 were recorded in the last 30 years.

**Methods:** Based on a selective literature search and authors’ own results, the article summarises the current state of knowledge on heat and its health impacts for Germany, addresses adaptation measures, and gives an outlook on implementation and research questions.

**Results:** Heat can aggravate pre-existing conditions such as diseases of the cardiovascular system, the respiratory tract, or the kidneys and trigger potentially harmful side effects for numerous medications. A significant increase in mortality is regularly observed during heat events. Previous approaches to mitigate the health impact of high temperatures include, for example, the heat alerts of the German Meteorological Service and recommendations for the preparation of heat-health action plans.

**Conclusions:** Evidence on health impacts of heat and awareness of the need for heat-related health protection have grown in recent years, but there is still a need for further action and research.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.

1. Impact of heat on health in Germany

Rising temperatures and an increase in the frequency and intensity of heat events are among the most directly perceivable consequences of anthropogenic climate change. Other extreme weather events are discussed elsewhere in this progress report by Butsch et al. [1]. The health effects of high temperatures, including heat-related mortality, are increasingly becoming the focus of scientific and political initiatives, in Germany and internationally [2]. In the first part of this article we summarise the current state of knowledge on heat and its health impacts for Germany, in the main part we go into detail on adaptation measures that are being implemented and recommended, and in the third part we give an outlook on implementation and research questions that may arise. This compilation was completed at the end of May 2023 and reflects the status of the implementation of measures and recommendations at that time. As awareness of the health effects of heat and the need for countermeasures are constantly increasing, it is possible that further measures will have been decided upon by the time of publication and
that individual recommendations have therefore already been followed.

1.1 Temperature changes in Germany

Climate change has led to temperature changes in Germany in recent decades. While the global mean temperature over land in the last decade (2011–2020) was 1.59°C (90% confidence interval (CI) 1.34–1.83°C) higher than the average temperature in the period from 1850 to 1900 [3], the temperature increase in Germany was 2.0°C (2011–2020 compared to 1881–1910, Figure 1a). The temperature increase has intensified significantly in the decades since 1990. Eight of the ten warmest summers since the beginning of systematic weather records in Germany (1881) were registered in the last 30 years.

This development is also reflected in the number of hot days (days on which the maximum temperature reaches 30°C: Tmax≥30°C). This indicator can be evaluated with reliable accuracy across Germany from the mid-20th century. Here, too, the strongest increase has occurred in the last three decades (Figure 1b). The increase in hot days affects almost all regions of Germany (Figure 1c). The highest absolute values occur in the south-west (Rhine Rift Valley and Rhine-Main region) and in the east (Berlin/southern Brandenburg). In the south-west, over 20 hot days per year were recorded regionally in the last decade, in the east, records show 16 hot days per year over a large area.

An identification of exceptional historical periods of heat, so-called heatwaves, is very much dependent on how a heatwave is defined and which region is considered. A uniform definition of the term heatwave does not yet exist (Info box 1). Since heatwaves are large-scale events, scientific analyses are generally not limited to Germany. An internal evaluation of the German Meteorological Service (Deutscher Wetterdienst, DWD) for the region of Central Europe (2–24°E and 45–55°N), in which heatwaves were defined as periods of at least three days during which the maximum temperature was above the 98th percentile of a reference period, allows a ranking of heatwaves with regard to the affected area, the temperature anomalies that occurred and the duration. If the cumulative temperature anomalies are used as a measure of intensity, the heatwave of August 2003 ranks first among all heatwaves since 1950, followed by the heatwave of July/August 1994. The 2003 heatwave was also one with the longest duration to date, with up to 53 hot days recorded in the Upper Rhine area over the entire summer. The hottest heatwaves (in terms of cumulative temperature anomalies) occurred in 1994 and 2015.

Comparative studies across Europe also identify 1994 and 2003 as the years with the most pronounced heatwaves in Germany in terms of intensity and duration. In third place (depending on the criterion) are the years 2006, 2018, or 2019 [4, 5].

1.2 Future development according to different climate scenarios

As a result of climate change, the number of hot days and the duration and intensity of heat events will continue to increase in Germany. The extent of the increase depends, among other things, on the future development of greenhouse gas concentrations. With the help of regional climate
Heat in Germany: Health risks and preventive measures

Figure 1
Source: German Meteorological Service (DWD)

Figure 1a (top)
Change in the decadal means of the annual mean temperature over Germany between 1881 and 2020. Shown are anomalies of the decadal means relative to the mean of the period 1881 to 1910.

Figure 1b (middle)
Area means of hot days in Germany since 1951. Shown are decadal means, no area means for the number of hot days are available before 1951.

Figure 1c (bottom)
Regional distribution of the number of hot days per decade since 1951. Days in legend are rounded down to next integer.
models and under the assumption of concrete emission scenarios, it is possible to estimate the future development and the existing uncertainties for Germany (see also [10]). Brienen et al. [11] have carried out such an estimation for the emission scenarios RCP2.6 (climate protection scenario), RCP4.5 (moderate scenario) and RCP8.5 (business-as-usual scenario) during the periods 2031 to 2060 (near future) and 2071 to 2100 (distant future), using an ensemble of regional climate models for different regions in Germany. Under RCP8.5, the temperature will rise by 3.0 to 4.2°C by the end of the century compared to the reference period 1971 to 2000, depending on region and season (ensemble median). Hot days will increase significantly in most regions as a result of climate change (Figure 2). In Germany, the average number of hot days under RCP8.5 will increase by about 18 days by the end of the 21st century, with uncertainties between +13 and +28 days (Figure 2). Regionally, the increases vary, and in some regions the average number of hot days could rise to over 40 days per year. The coasts and regions of higher elevations also show significant increases.

In addition to the thermal stress during daytime, conditions at night also play a role during a heat event. Tropical nights, i.e. nights during which the air temperature does not fall below 20°C, are comparatively rare in Germany so far. Only very few, particularly warm stations record two or three tropical nights annually on average. In years with very hot summers, like 2003, however, more than ten tropical nights were observed at some stations. In Kehl near Strasbourg, for example, there were 21 tropical nights recorded in 2003. As a result of advancing climate change, tropical nights will occur more frequently in Germany. On average, Germany could experience up to 16 additional tropical nights per year by the end of the century (Figure 2), and in particularly warm regions even up to 30 additional nights.

Heat events will also continue to increase as a result of climate change, both in terms of duration, frequency, and intensity [12]. Defining heatwaves as periods of at least three days on which the daily mean air temperature is above the 95th percentile of a reference period, Schlegel et al. [12]
were able to calculate an increase in heatwave days of up to 22 to 23 days per year for the period 2021 to 2050 (RCP4.5 and RCP8.5) compared to 13 days in the reference period (1981–2010) (Figure 3). For the distant future (defined here as 2068 to 2097), there are greater differences between the emission scenarios. For RCP4.5, heatwave days increase to 31 days per year, for RCP8.5 there is an increase to 54 days per year. Compared to the reference period, this is a more than fourfold increase in heatwave days.

1.3 Heat-related mortality

Mortality statistics show the drastic effects of high temperatures on human health. A significant increase in overall mortality can regularly be observed during hot weeks (Figure 4). However, only for a very small proportion of deaths occurring during heat events high temperature is explicitly identified as the cause of death (e.g. between 7 and 60 deaths in the category ‘Damage due to heat and sunlight’ as classified by the causes-of-death-statistic by the German Federal Statistical Office [13]). Therefore, statistical methods must be used to quantify the relationship between heat and mortality.

Methods for estimating heat-related mortality

There are different approaches to quantifying heat-related mortality. First, there are methods that estimate the expected course of mortality without heat (background mortality): for this purpose, the average mortality of the previous years can be used [15,16] or the seasonal course of mortality can be replicated using a periodic function, such as a sinusoid with an annual period [17,18]. Both methods re-
quire a time series of mortality over several years and must ensure that excess mortalities that occurred in previous years do not distort the expected number of deaths. The number of heat-related deaths is then calculated as the difference between the observed mortality (during a heat event) and the expected background mortality.

Another frequently used approach describes the influence of ambient temperature on total mortality by means of exposure-response curves \([19, 20]\) (Figure 5). Such curves can quantify percentage changes in mortality as a function of temperature and allow us to investigate the systematic relationship between high outdoor temperatures and increased mortality. In particular, it is also possible to represent differences between geographical regions or demographic groups, or to analyse changes in exposure-response curves over time, which may provide evidence of successful adaptation. For example, the exposure-response curves shown in Figure 5 indicate that, on average, people aged 85 or over experience a significantly greater increase in...
During heat events, a significant increase in mortality is regularly observed, especially in older age groups.

Heat-related mortality in Germany

A nationwide estimation of the heat-related mortality in Germany was first published in 2019 [21]. In the subsequent years, the methodology was further refined and the estimations were continued until the year 2022 [14, 22]. Additionally, some federal states also report regular heat-related mortality estimates [15, 23].

From 2018 to 2020, statistically significant numbers of heat-related deaths were estimated for the first time in three consecutive years. A total of 8,300 heat-related deaths were estimated for 2018, around 6,900 for 2019, and around 3,600 for 2020. In 2021, the number of heat-related deaths in Germany was not statistically significant. In 2022, the number of heat-related deaths was estimated at around 4,500 [22]. Although the increasing frequency of years with significant heat-related deaths is striking, heat-related mortality is not a completely new phenomenon: in the historically hot summers of 1994 and 2003, about 10,000 heat-related deaths per year were estimated, respectively [14].

The number of heat-related deaths in a population depends on a combination of several factors: the intensity and duration of heat events (heat exposure), the size of particularly vulnerable population groups, and also on how successfully adaptation measures have been implemented. The largest share of heat-related deaths occurs in the age group 75 years and older (about 75% of heat-related deaths). As a result of demographic change, a strong increase of the oldest population groups is to be expected in the near future [24], which may also increase the number of people potentially affected by heat-related mortality.

Due to their higher life expectancy, women make up about 60% of the age group 75 years and older, and are thus numerically more affected by heat-related mortalit-
ty [23]. Per 100,000 inhabitants of the same age group, heat-related deaths occur to a comparable extent in women and men. However, the risk factors appear to differ between women and men [25].

The intensity of a heat event depends not only on the air temperature but can also be intensified by other meteorological parameters. For example, Muthers et al. [26] showed that mortality increased significantly more during the 2015 heatwave in Baden-Württemberg than during the 2003 heatwave, which can be explained by the significantly higher humidity in 2015. In addition, regional differences, for example with regard to building structures, healthcare, or age composition of the population, may also lead to differences in the number of heat-related deaths at comparable heat exposure.

Furthermore, in cities, the urban heat island effect also needs to be considered. On average, higher air temperatures can be observed near the ground in urban areas rather than in rural areas. The urban heat island effect is particularly important in the summer months and is more noticeable at night. The intensity of the urban heat island in a city depends, among other things, on the size of the city or the urban agglomeration, as well as on the building density. On clear summer evenings, maximum temperature differences of 10°C and higher have been observed between city centres and rural areas [27].

In the Berlin-Brandenburg region, a correlation between excess mortality during heat events and building density or the proportion of sealed surfaces, was found between 1994 and 2006 [28]. Increased soil sealing was accompanied by increased mortality, with the highest mortality rates being observed in the city centre. However, heat-related mortality is a significant problem in both urban and rural areas.

Heat-related mortality in other European countries

An increase of heat stress up to 1°C has been observed during the summer months of the last decades (1979–2016) [29]. Heat stress was determined using the universal thermal climate index (UTCI), a temperature equivalent, providing a measure of the average subjective human thermal sensation. It takes into consideration several meteorological variables relevant to the human thermal balance, such as air temperature, relative humidity, and wind speed, as well as the mean radiation temperature. A correlation with mortality data from 17 European countries showed that the relationship between the UTCI and the number of heat-related deaths depends on the thermal bioclimate of the observed country. Moreover, the study showed that the number of heat-related deaths increased with moderate (26–32°C UTCI) and severe heat stress (>32°C UTCI). In addition, mortality patterns may also differ depending on the thermal stress. In some countries, higher mortality rates appear to be associated to both high and low UTCI-values. In other countries, mortality increase was only observed under the influence of heat stress, while for some countries, a correlation between heat mortality and the UTCI could not be found [29].

1.4 Heat-related morbidity

The human body responds to heat stress with two key protective physiological mechanisms: (a) the redistribution of blood flow towards the skin (vasodilation) to remove heat
from the muscles to the environment and (b) the secretion of sweat, which cools the body via evaporation [30]. These mechanisms in turn have an effect on other organs of the body: vasodilation requires increased contractility under the condition of reduced filling pressure. As a result, the heart has to beat stronger and faster, which requires a higher oxygen supply. In people with pre-existing heart conditions, this can lead to an imbalance between oxygen supply and demand, which can cause circulatory disorders (ischaemia), infarction, or circulatory collapse.

High temperatures and heat events can trigger heat-related illnesses as direct effects or aggravate pre-existing illnesses (heat-sensitive illnesses) and even lead to death (Figure 6). Mild and moderate heat-related illnesses include heat rash, heat oedema, heat-induced unconsciousness (heat syncope), heat cramps, and heat exhaustion, while heat stroke is a life-threatening consequence of heat [31,32]. On hot days and during heat events, the risk of accidents increases, e.g. during manual labour or during leisure time (drowning while swimming). In addition, according to evaluations by the statutory health insurance, there is a demonstrable decrease in performance during heat events and an increase in heat-related sick leave [33].

The healthcare system is additionally burdened by hospital admissions and heat-related emergencies [30]. At the same time, healthcare structures can be affected by interruptions in their supply (e.g. power outages). Medical staff are also exposed to particular heat stress in the workplace, not least through protective clothing such as during the COVID-19 pandemic [34].

Cardiovascular diseases
In Germany, as in many other western countries, cardiovascular diseases are the most common cause of death. Based on data from 1993 to 2015 for major German cities, it was estimated that just under one percent of annual deaths from cardiovascular disease are attributable to heat [36]. In one study, it was calculated that the morbidity from cardiovascular diseases increases by 2.2% per 1°C increase in air temperature during a heat event [37].

Data from the Augsburg myocardial infarction registry show that severe temperature spikes can increase the risk of myocardial infarction [38]. Sun et al. [39] showed that there was an increase in hospital admissions with a diagnosis of myocardial infarction on days with high temperatures and on days immediately following these. Heat is also associated with increased rates of mortality from heart failure and stroke. People at high risk are the very old and those with pre-existing conditions (especially cardiovascular disease).

Respiratory diseases
Heat-related lung problems (e.g. pulmonary oedema, acute respiratory distress syndrome, increased pulmonary stress due to heat-induced hyperventilation and increased air pollution at high ambient temperatures) are the second most common cause of mortality and morbidity during heat events after cardiovascular diseases [30]. In addition to heat, traffic-related air pollution, especially in large cities, has an indirect effect on the morbidity and mortality risk for patients with chronic respiratory diseases [40] (see also the article in this status report on air pollutants by Breitner-Busch et al. [41]). In the summer
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months, on hot days in large cities, patients with chronic obstructive pulmonary disease (COPD) experience more frequent and sometimes life-threatening exacerbations. During heat, the body releases warmth not only through the skin, but also through the lungs, with a slight increase in respiratory frequency. However, this heat transport is restricted in people with pre-existing lung disease, so that efficient exhalation of heat is only possible to a limited extent. In addition, the muscle work required for the increased breathing movements in turn leads to an increase in body temperature. Finally, dehydration-induced reduced blood flow to the lungs makes the patient more susceptible to infections [42].

Metabolic diseases
People with diabetes are also at increased risk of being hospitalised during heat events. Similar to lung disease, these patients have impaired thermoregulatory responsiveness in the lungs at the vascular level, as heat exposure affects the self-regulation of blood vessels, leading to an increased tendency to form clots [43].

Kidney disease
Reduced blood volume due to dehydration can cause damage to the kidneys. As has been observed, especially in hot regions of the world, in people who work outdoors, chronic dehydration can cause renal fibrosis (scarring of the kidney) and chronic kidney disease [30].

Effects on pregnant women
There is increasing evidence that high temperatures can affect pregnant women and the course of pregnancy, e.g.
through reduced blood supply via the placenta, dehydration, or inflammatory processes that can trigger pre-term birth [44, 45]. For example, a meta-analysis estimated that the probability of pre-term birth is 1.05 (95% confidence interval (CI): 1.03–1.07) times higher for every 10°C increase in temperature and 1.16 (95% CI: 1.10–1.23) times higher during heatwaves (defined as two or more days with temperatures above the 90th percentile). Heat exposure of pregnant women over the course of pregnancy can also lead to low birth weight (<2,500 grams) of the newborn [46].

Interactions with medication

In addition to the factors mentioned above, the intake of medication also plays an essential role in the effects of heat on the individual [47, 48]. Table 1 lists a number of medications and groups of active substances that can have dangerous side effects during heat (Table 1 supplements the table in [48]).

Heat-induced vasodilation can significantly increase the antihypertensive effect of many cardiovascular drugs, with the consequence of syncope with possible serious injury (for example due to falls), critical organ ischaemia (organ circulatory disorders), or even myocardial infarction. People with systolic heart failure (cardiac insufficiency) and patients with high blood pressure are particularly at risk.

In hot temperatures, antihypertensive drugs, which are often prescribed to treat cardiac insufficiency, can lower blood pressure too much. The combination with diuretic drugs is particularly problematic: these are used (alone or in combination with other antihypertensives) to lower blood pressure, but also for drainage in people with cardiac insufficiency [48].

Drugs that inhibit the effect of the neurotransmitter acetylcholine (anticholinergics) can also lead to complications during heat, as they influence central temperature regulation and prevent sweating. This anticholinergic effect is contained in many medicines that are used for a wide range of complaints (bronchial asthma to urinary incontinence) [49].

Other large groups of medications that can develop adverse effects in heat include agents used to treat cardiac arrhythmias (antiarrhythmics), agents used to treat coronary artery disease (antianginosa), and antidiabetics. Various painkillers also carry a high interaction potential, especially opiates that are administered for absorption through the skin [50].

Even in younger persons, who suffer from pre-existing conditions less frequently, certain medicines show potentially dangerous side effects when exposed to heat. For example, an analysis of the Augsburg MONICA/KORA myocardial infarction registry recently showed that patients taking antiplatelet drugs or beta-blockers are more vulnerable to non-fatal myocardial infarctions due to heat exposure than people not taking these drugs [51].

The comparatively new group of active substances called SGLT2 inhibitors, which are used in the treatment of diabetes patients, can also lead to undesirable effects in heat. In this case, there is an increased excretion of glucose and thus volume via the urine. This group of drugs is important to observe, because it will be used in a large number of patients due to its significant expansion of indications (in addition to diabetes all forms of heart failure and prospectively also renal failure) [52, 53].
Furthermore, the shelf life of medicinal products is generally impaired by heat, which can reduce their effectiveness [54]. Many medicines have an extensive interaction potential, which can be massively increased by the effects of heat.

1.5 Vulnerable population groups

Population groups that are vulnerable to heat-related morbidity and mortality due to their risk factors include older persons (especially those living alone), people with pre-ex-
The perceived temperature describes the temperature perception of a ‘reference person’ and translates the current thermal conditions into the air temperature of a standard environment. For the perceived temperature, there are categories of heat stress that enable a thermally relevant evaluation of the current conditions [6].

Heat alerts are issued by the DWD at the municipal level for the current and following day. The alerts consider the respective altitudes, so that an alert may only be valid for parts of the municipality (e.g. areas below 800m altitude). Two warning levels are distinguished for heat warnings: a ‘strong heat stress warning’ is issued when the perceived temperature exceeds a threshold of 32±2°C; an ‘extreme heat stress warning’, on the other hand, is issued when the perceived temperature is expected to exceed the threshold of 38°C in the early afternoon (2pm). The threshold for severe heat stress varies over the course of the summer depending on the meteorological history. If the preceding weeks were cooler (warmer), the threshold is somewhat lower (higher) [18]. This approach accounts for the short-term adaptation to heat that takes place over the course of each summer.

In addition to the conditions during the day, warnings of strong heat stress also take the conditions during the night under consideration. Since most people stay indoors at night, a building simulation model is used to determine the indoor temperature of a standard building [61]. This temperature must be above certain, regionally adapted threshold values before a warning of strong heat stress can be issued. The warnings are supplemented by additional modules that deal more precisely with the burden on older persons and people in need of care, and take into account the effect of the urban heat island.

The following table provides an overview of the affected population groups.

### Table 2: Affected Population Groups

<table>
<thead>
<tr>
<th>Population Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing conditions (especially cardiovascular disease, respiratory disease, kidney disease, obesity, diabetes), pregnant women, infants and young children, people who do manual labour outdoors or engage in intensive sports, people with physical and mental impairments, people with low socioeconomic status, and the homeless [31]. The issue of health equity in climate change is also addressed in an article by Bolte et al. [57] in this status report.</td>
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<tr>
<td>To implement adaptation measures, it is first necessary to predict upcoming heat events and to swiftly inform the population and the healthcare system. In Germany, this task is performed by the heat-health warning system of the DWD [59], which was put into operation nationwide in the summer of 2005, in response to the numerous additional deaths throughout Europe (e.g. [60]) in the summer of 2003. A physiologically relevant assessment of heat events must take into account not only the air temperature but also the water content of the air (humidity), as well as the wind and radiation conditions. In the DWD heat-health warning system, this is done using the perceived temperature [6].</td>
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### 2. Adaptation measures for heat-health protection

#### 2.1 The heat-health warning system of the German Meteorological Service (DWD)

To implement adaptation measures, it is first necessary to predict upcoming heat events and to swiftly inform the population and the healthcare system. In Germany, this task is performed by the heat-health warning system of the DWD [59], which was put into operation nationwide in the summer of 2005, in response to the numerous additional deaths throughout Europe (e.g. [60]) in the summer of 2003.
Table 2
Population groups at greater health risk during heat events
Source: Updated and expanded based on World Health Organization [31]

<table>
<thead>
<tr>
<th>Category</th>
<th>Risk group</th>
</tr>
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</table>
| Physiological adaptive capacity | ▶ Older persons (>65 years)  
▶ Infants and young children  
▶ Pregnant women                                                               |
| Pre-existing conditions         | ▶ Cardiovascular diseases (e.g. arterial hypertension, coronary heart disease, cardiac insufficiency)  
▶ Cerebrovascular diseases (e.g. stroke)  
▶ Respiratory diseases (e.g. COPD, bronchial asthma)  
▶ Metabolic diseases (e.g. diabetes mellitus)  
▶ Neurological diseases (e.g. Parkinson’s disease due to impaired thermoregulation)  
▶ Mental health conditions (e.g. depression, schizophrenia, drug addiction)  
▶ Kidney diseases (e.g. renal insufficiency)  
▶ Obesity  
▶ Those taking certain medicines to treat the diseases mentioned (see Table 1) |
| People with disabilities       | ▶ Physical disabilities (e.g. spinal cord injuries [58])  
▶ Mental disabilities, as people with severe cognitive impairments are less able to protect themselves from heat |
| Functional limitations          | ▶ Being confined to bed  
▶ Residing in care facility                                                   |
| Socioeconomic factors           | ▶ Social isolation, especially in old age  
▶ Homelessness  
▶ Unfavourable housing situation                                               |
| Physical exertion in high outdoor temperatures | ▶ People working outdoors (e.g. in agriculture, construction)  
▶ Outdoor sports  
▶ Health workers, especially in combination with personal protective equipment |
| Workers who cannot leave their workplace during heat events despite high indoor temperatures | ▶ Personnel in medical and care facilities, especially in combination with personal protective equipment |

COPD=chronic obstructive pulmonary disease

In Germany, current heat alerts are distributed via e-mail newsletter, the DWD alert page or various smartphone apps. In addition, heat alerts are disseminated via civil protection warning systems. The e-mail newsletter also includes situation-specific behavioural recommendations. Nursing homes and other healthcare providers are encouraged by the state health offices to subscribe to the DWD newsletter.

Once a heat alert has been issued, the health authorities of the federal states are called upon to initiate intervention measures. In addition to the heat alerts for the next 48
2.2 Heat-health action plans for health protection

Until the extremely hot summer of 2003 with its catastrophic health effects across Western Europe, most European countries lacked appropriate precautionary planning to protect the population from the health effects of extreme heat. Based on initial studies, findings, and experiences, the World Health Organization’s (WHO) Regional Office for Europe published guidelines for heat-health action plans (HHAPs) for health protection in 2008 [63]. HHAPs serve as an instrument for establishing targeted measures for preventive health protection, and have since been established in several European countries, such as France, Italy, and Switzerland.

The overall goal is to reduce the health risk of extreme heat events and to strengthen individual resilience to adverse developments. In order to be better prepared for the environmental changes caused by climate change (some of which have already occurred) targeted adaptation measures are necessary in addition to climate protection. In 2017 in Germany, a working group comprised of federal and state actors, commissioned by the Federal Ministries for the Environment and of Health, drew up recommendations for the development of HHAPs for the protection of human health on the basis of the WHO guidelines [63], which should enable federal states and municipalities to develop concrete plans of action and put them into implementation [64]. They outline short-, medium-, and long-term options for health adaptation measures for a timely and gradual implementation of regionally adapted HHAPs. These recommendations are based on eight core elements and set a framework for the development of individual immediate measures, which are to be implemented during an acute heat event, preparatory, preventive and treatment measures in healthcare and nursing facilities with special consideration of vulnerable population groups, and adjustments in building and urban/spatial planning, which can only yield results in the longer term (Figure 7).

While the federal level provides the framework for climate change adaptation, as with the ‘German Strategy for Adaptation to Climate Change’ [65] and the HHAP recommendations [64], the responsibility for implementing concrete adaptation measures lies predominantly at the municipal level [66]. However, as extreme heat events and their consequences do not occur evenly across Germany, regionally and locally specific conditions must be considered. Therefore, adaptation measures follow the subsidiarity principle, i.e. concrete measures should be implemented competently and responsibly at the most appropriate level. The implementation of HHAPs at the municipal level is strongly recommended [34, 67], but is not yet legally required. Adaptation to the consequences of climate change, including heat, is supported by the federal government through various funding initiatives, which municipalities can apply for to support the implementation of relevant projects.

Several studies in recent years have investigated whether and how the HHAP recommendations have been taken up by federal states and municipalities and which plans and adaptation measures to prevent heat-related health impacts have already been implemented [68–71].
The results of an online survey conducted in Germany in spring of 2020 show that the health relevance of heat is recognised as an interdisciplinary issue at the federal, state, and municipal levels and is addressed by both the environment and health agencies at each level [70, 72]. In some municipalities and recently also at the state level, HHAPs are being implemented [15, 70, 73]. The federal states and municipalities are particularly active in communicating information and educational materials, thus contributing to behavioural prevention by allowing individuals to protect themselves against extreme heat, often through low-threshold, easy-to-implement adaptation measures. For example, many cities list tips for their citizens on their websites or in printed guidelines on how to correctly behave in hot weather. Overall, the number of heat prevention measures and projects in Germany has been steadily increasing since the introduction, dissemination, and promotion of the HHAP recommendations in 2017 [64], and HHAPs have recently been developed at the level of municipalities and federal states (Section 2.4 Positive examples of heat-related health protection). However, it remains unclear whether this fulfils the criteria for effective short- and medium-term protection, as individual projects only include some of the eight core elements of the recommendations [68].
2.3 Further recommendations for heat prevention and heat-related health protection

The evidence for effective heat-related health protection is well known among decision makers and a wide range of information materials is available. Recently, the number of concrete interventions and action plans in the health and nursing sectors has been increasing, and the range of educational modules on the topic has been growing steadily for several years. This is shown by a working document related to the development and implementation of a HHAP for cities and municipalities [75]. A collection of concrete implementation examples from municipal practice is provided in Info box 2 [75]. Some information materials and recommendations for measures in the health sector were adapted to consider the COVID-19 pandemic (e.g. [34, 76]).

In summer 2021, key players from the German health sector were surveyed in semi-structured interviews on the implementation of integrated HHAPs in order to review the recommendations of the 2019 Lancet Countdown on Health and Climate Change Policy Brief for Germany [67]. In line with nationwide studies [68, 70, 75], the experts estimated that so far only a few municipalities have implemented comprehensive and integrated HHAPs in which stakeholders from the health sector, such as the medical and nursing professions, emergency services, and clinics, have been successfully involved in the development of the plans. It is crucial for authorities and actors in the health sector to consider heat-related health protection their responsibility in order to develop initiative and active participation. Kaiser et al. [70] show, however, that the mere existence and awareness of the recommendations is not sufficient for municipalities to successfully develop HHAP. For example, some municipalities lack the financial and

Info box 2
Selection of proposals and recommendations for heat protection for use in the health sector

Health effects due to heat and periods of extreme heat can largely be avoided. Prevention requires a range of measures at different levels: from public health precautions coordinated with meteorological early warning systems, to timely official and medical advice, to improvements in housing and urban planning. The following selected current materials (some in German) serve this purpose:

- **WHO public health advice on preventing health effects of heat – new and updated information for different audiences (2011)**

- **Climate change and education.** Different educational modules for various professional groups (including paediatricians, medical assistants and nursing staff, youth work) in the health sector provided by the Ludwig-Maximilians-Universität München (2020–2022)

- **Heat as a field of action at the German Alliance on Climate Change and Health (2022)**

- **Climate-Human-Health.** Website of the Federal Centre for Health Education on heat and heat protection (2022)

- **Climate change and health: Tips on coping with hot weather and heatwaves.** Advisory brochure of German Meteorological Service and German Environment Agency (2019)

- **The heat etiquette booklet: Tips on how to act in hot weather.** Brochure of the German Environment Agency on heat protection (2021)

- **Working aid for the development and implementation of a heat-health action plan for municipalities from Fulda University of Applied Sciences (2023)**

- **Governmental recommendations for action for the preparation of heat action plans to protect human health (2017)**

This compilation is a selection and makes no claim to completeness.
Heat in Germany: Health risks and preventive measures

human resources to develop and implement HHAPs. The lack of a legal basis enabling binding action with planned resources is also pointed out [70].

In June 2022, the conference of German federal health ministers, in cooperation with federal states’ working groups, decided on an implementation concept to accompany the decision from 2020 [77]. In the meantime, the first federal states, such as Hesse and North Rhine-Westphalia, have issued declarations or resolutions for the implementation of HHAPs. In autumn 2021, the 125th German Medical Assembly also passed several resolutions under the slogan ‘climate protection is health protection’ [78], to reduce the high proportion of between 5 and 6.7% of Germany’s overall greenhouse gas emissions caused by the health sector and to move towards climate neutrality [41, 79].

2.4 Positive examples of heat-related health protection

There are a number of positive examples of heat-related health protection in Germany that have already been implemented in practice. They range from the development of information materials for vulnerable population groups and institutions to HHAPs and alliances for action in the health sector. Training and qualification tools on heat and health, such as the educational materials of the Ludwig-Maximilians-Universität Munich (LMU) or the German Alliance on Climate Change and Health (KLUG), are also available. In the following, a selection will be presented.

First heat-health action plans
Since their publication in 2017, the HHAP recommendations [64] have been continuously and widely disseminated through various communication channels, presented at different events to expert audiences from science and public administration as well as to a broader expert public and stakeholders (e.g. at national symposia, conferences, and further education events of the public health service) and published in various journals. In addition, in 2021/2022, some municipalities and federal states received initial consulting advice for concrete HHAP implementation from Fulda University of Applied Sciences, from state institutions such as the Centre for Health of North-Rhine Westphalia, from the Centre for Climate Adaptation serving for the German Adaptation Strategy on Climate Change and other research, advisory, and non-governmental organisations.

The 2020 online survey described above showed that the respondents consider the HHAP recommendations a predominantly positive helpful basis for their work and an easily understandable and practicable guideline for a HHAP. In some federal states and municipalities, a number of impulses and developments have already been triggered and some health-related adaptation measures for heat prevention have been initiated [70]. Since then, the first concepts for HHAPs at the municipal level have been developed on the basis of these recommendations, as compiled in Info box 3.

The Swiss-style heat toolbox
Based on the original template from Switzerland from 2017 [80], the Bavarian Health and Food Safety Authority developed the Bavarian ‘heat toolbox’ [81]. On coherently presented fact sheets, it provides support for the design, planning, and preparation of HHAPs. In addition, examples of successful implementation are presented [81].
Experiences of heat-health action planning from Switzerland show that successful prevention is based on a variety of measures (before, during, and after the summer) and strengthens individual health competence, thus promoting health.

**Info box 3**

**Selection of first heat-health action plans**

Since the publication of the governmental recommendations for action for the preparation of heat-health action plans (HHAPs) in 2017, first HHAPs had been developed at the municipal level by the end of 2022, mainly supported by various federal funding initiatives. They include (in German):

- Offenbach am Main 2020
- Mannheim 2021
- Cologne 2022: HHAPs specifically for the elderly
- Worms 2022
- Federal state of Brandenburg 2022: Expert review of a HHAP
- Federal state of Berlin 2022: Aktionsbündnis Hitzeschutz Berlin (first model HHAP for outpatient and inpatient care, medical practices and the public health service)
- Federal state of Hesse 2023: Hessian HHAP

Especially in the warmer regions of western Switzerland, a reduction in heat-related mortality risk has been observed in recent years. There are indications that the cantonal HHAPs and thus the coordinated activities for the prevention of negative heat effects on the population have contributed to this reduction. In general, the targeted education of the population about heat-health risks appears to be important. Various projects investigating the effects of heat on health in Switzerland have led to an improvement in the knowledge and action basis in recent years. The presentation and dissemination of the results at stakeholder meetings and to the general public via the media has contributed significantly to raising awareness of this issue [80].

First evaluations report successes for regions with HHAPs compared to those with isolated measures [80]. This corresponds to international reports, although only a few studies on HHAP evaluation are available so far [82]. In Rome, Italy, there are reports of successes of the ‘Long Live the Elderly’-programme [68], which is based on the involvement of neighbours as volunteers, the so-called buddy system. This has yet to be developed for Germany.

**Experience from the care sector**

As a reaction to heat-related deaths in the summer of 2003, a heat-health warning system and a set of measures for care facilities were developed in Hesse to protect vulnerable persons during heat events, driven by an interdisciplinary group of decision-makers and actors involved in care [83]. The practical recommendations, which were first published in 2009 and updated in 2017, cover topics ranging from the identification of residents who are particularly at risk to heat-related health protection measures in care and nursing. Options for regulating room temperature and indoor climate are also presented. Since 2004, the Hessian care and nursing administration has been inspecting and advising inpatient facilities on heat alert days regarding immediate measures, legitimised by a decree of the Hessian Ministry for Social Affairs, with the results being documented. It has been reported that heat-related health protection has become established in the care and nursing facilities in Hesse since the introduction of this system [83].
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An alliance for heat-related health protection in Berlin
The pilot project ‘Aktionsbündnis Hitzeschutz Berlin’ (Action Alliance for Heat-Related Health Protection Berlin), which was launched in March 2022, prioritises those heat protection measures in the health and care sector that increase the protection of vulnerable population groups during an acute heat event [73]. This formation of an essential, interdisciplinary network of actors for heat-related prevention and adaptation in the medical sector at its core was achieved through the responsibility, insight, and initiative of healthcare actors. The network developed a heat alert cascade for the healthcare sector (Figure 8) and concrete interventions, recorded in sector-specific action plans [73, 84]. The ‘Aktionsbündnis Hitzeschutz Berlin’ and its experience can serve as a helpful example for other cities, municipalities, and federal states, specifically the model heat protection plans for various facilities, which were designed as low-threshold checklists.

3. Outlook: Need for action and research
Current climate projections suggest that the probability of heat events in Central Europe will more than double by the end of the century and that they could last 30 percent longer. As a result, heat stress in an ageing German society is expected to increase and therefore heat-related illnesses and mortality rates could continue to rise if no effective countermeasures are taken [85].

An increase in frequency and intensity of heat events could lead to healthcare facilities being temporarily unable to fulfil their function because of overburdening or because of infrastructure failures. It is undisputed that climate change and the growing challenges posed by extreme heat are likely to cause considerable additional costs for the healthcare sector in the medium term, on the one hand due to the care of patients, but also due to awareness campaigns, the adaptation of infrastructure, and the training of staff. In the long term, however, the costs for the healthcare system could again decrease, provided that preventive measures are successfully implemented [85].

Measures of structural prevention for adapting to high temperatures and heat events such as the creation of green spaces and parks, on the one hand benefit the local or urban climate, and on the other hand contribute to the health of the population, e.g. by improving air quality and by providing recreational spaces. Furthermore, climate-friendly individual behaviour (behavioural prevention) usually also results in substantial health benefits, so-called health co-benefits, in addition to climate protection (see also [10]). Recommendations for behavioural prevention that are also climate-friendly thus contain health promotion potential. The open-mindedness and the agreement on the necessity of HHAPs has clearly grown in recent times among health professionals, associations in the health and care sector, in the public health service, and the municipalities.

3.1 Recommendations
There is still a need to improve heat-related health protection and heat prevention in Germany. This requires (a) addressing the overarching structural deficit of the public health service, (b) systematic and nationwide implementation of HHAPs that integrate acute and medium-to long-term measures relating to the eight core elements, and (c) anchoring...
heat prevention and heat-related health protection in the health sector and among the general public. Specific recommendations on measures in the fields of action that contribute to these three goals (structural prevention, health promotion/healthcare/health protection, civil protection, education and training, health awareness and communication, surveillance, urban and spatial planning, and occupational health and safety) are summarised in Table 3. They range from setting policy frameworks for the implementation of HHAPs to the active involvement of healthcare actors and the review of building and occupational health and safety legislation.

Implementation and accompanying research on concrete projects help determine which factors promote the implementation of HHAPs and heat-related health protection measures in relevant institutions, municipalities, districts, and federal states, and which make it more difficult. The results can be used to tailor the implementation process in new projects. Continuous monitoring and evaluation of HHAPs (both of the process and the effectiveness) are needed to determine the effectiveness of HHAPs and integrated measures (Table 3). This can provide information on which factors influence the population’s capacity and ability to adapt to high temperatures and heat, and which measures are helpful in supporting the population to adapt and make them more resilient.

3.2 Research needed in medicine, epidemiology, and health services research

Even though evidence regarding adverse health effects of high temperatures has increased in recent years, there are
Table 3
Recommendations for strengthening heat-related health protection in Germany (As at end of May 2023)

<table>
<thead>
<tr>
<th>Goal</th>
<th>Measure</th>
<th>Starting point</th>
<th>Actors</th>
<th>Feasibility issues</th>
<th>Field of action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic and nationwide preparation and implementation of HHAPs</td>
<td>Establish a central coordination office, enable, facilitate, and broaden financial support for municipalities by the federal and state governments</td>
<td>Individual municipalities have already drawn up HHAPs and are starting to implement them; there are good-practice examples for the preparation</td>
<td>Federal, state, and municipal administrations</td>
<td>Dependent on municipalities’ human and financial resources; regulatory requirements such as state public health laws and federal legislation</td>
<td>Structural prevention, health promotion, health and civil protection</td>
</tr>
<tr>
<td>Strengthening the healthcare sector in its central role in heat-related health protection and the corresponding precautionary measures</td>
<td>Activation of healthcare actors as a central pillar of HHAPs, especially for the implementation of acute preventive adaptation measures</td>
<td>First action alliances in the health sector [84]</td>
<td>Healthcare facilities, nursing homes and care services, general practitioners, public health service, fire brigade and emergency services, associations and federations, volunteers</td>
<td>Sense of medical responsibility; initiative of actors and protagonists</td>
<td>Healthcare</td>
</tr>
<tr>
<td>Raising awareness and competence in dealing with heat in the population</td>
<td>Communication strategy</td>
<td>A wide range of information material is already available</td>
<td>Federal, state, and municipal administrations</td>
<td>Coordination of federal, state, and local governments, different channels required</td>
<td>Health awareness, health promotion, health protection</td>
</tr>
<tr>
<td>Promptly assess health effects due to heat stress on a small scale and in hospitals and care facilities</td>
<td>Expand realtime monitoring of heat mortality, establish monitoring of morbidity and labour situation in hospitals and care facilities during heat events</td>
<td>Realtime mortality surveillance at the Robert Koch Institute, HEAT projects in Hesse [15]</td>
<td>Municipalities, federal states, federal administration</td>
<td>Effort for collection, analysis, and storage of the data</td>
<td>Surveillance</td>
</tr>
<tr>
<td>Heat-resilient health system</td>
<td>Investing in the healthcare system to strengthen the reliability of infrastructures in the event of heat</td>
<td>Existing hospital alert and emergency plan</td>
<td>Federal administration, federal states</td>
<td>Funding opportunities limited so far</td>
<td>Funding and resources</td>
</tr>
<tr>
<td>Heat-literate healthcare personnel</td>
<td>Education and further training of healthcare personnel in heat protection/provision, prevention campaigns [71, 77, 78, 85]</td>
<td>Existing training offers and materials, e.g. projects at LMU on heat-health protection in care</td>
<td>Federal administration, federal states</td>
<td>Existing training courses so far do not extensively cover the topic of heat-health protection</td>
<td>Education</td>
</tr>
<tr>
<td>Heat-resilient building structure with special attention to hospitals and nursing homes</td>
<td>Review and, if necessary, adapt building and occupational health and safety legislation [71] with regard to their effectiveness for heat-related health protection</td>
<td>Special protection of healthcare personnel required; uphold existing legislation on passive cooling of buildings</td>
<td>Federal administration, federal states</td>
<td>Implementation based on the recommendations of the European Network Architecture for Health [86]</td>
<td>Urban and spatial planning, occupational health and safety</td>
</tr>
</tbody>
</table>

Table 3 Continued on next page
still a number of open research questions on the various relevant topics and fields of action. In accordance with the research questions listed here and those that will arise in the future, it is important that funding programmes of the respective authorities are appropriately equipped and directed.

### Medical/epidemiological issues

Above all, more detailed knowledge is required on the effects of high temperatures or heat on morbidity: there are open questions about the role of pre-existing conditions (e.g. cardiac insufficiency, heart attacks, strokes, diabetes, kidney disease, COPD, asthma) and an estimate of the number of people affected, e.g. by calculating the number of years of life lost (YLLs) and the number of years lived with disability or disease (YLDs). Possible long-term effects of high temperatures and heat have hardly been studied so far. The question of how exactly pregnancy complications relate to temperature, and through which pathophysiological mechanisms, has also not yet been answered in detail. Interactions in the combined use of different heat-sensitive drugs require further investigation, along with the development of appropriate preventive measures. The question of the impact of additional environmental factors that strongly influence the effects of heat events on morbidity and mortality (interactions and synergies) should also be further investigated.

### Health services research

According to the Climate Impact and Risk Assessment for Germany 2021 [85], only a few studies examine the consequences of climate change on the healthcare system or the health economy – there is a need for further research in this area.

In the context of health services research, the question arises as to what role heat-related deaths play in hospitals, in care facilities, and in private residences [85]. In order to prepare health services for the effects of heat events, it is important to investigate how many additional patients attend doctors' offices and emergency rooms during heat
events and what costs are associated with this. More precise knowledge about the extent to which employees in health and care facilities are affected in their work in high temperatures (especially indoors) is necessary to protect them and to ensure necessary medical care and nursing during heat events.

4. Conclusion

As climate change progresses, a further increase with respect to the frequency, duration, and intensity of heat events is to be expected in Germany. The population, the healthcare system, and the municipalities are not currently sufficiently prepared for particularly extreme events. Heat events must be taken seriously as an increasing health risk and the federal, state, and local governments, as well as the health and care institutions, have a duty to strengthen existing measures or take new steps to minimise risks, taking into account new findings, and to support the development of resilient structures [84]. The healthcare sector should play a central role in this.

The German version of the article is available at: www.rki.de/jhealthmonit

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Health impacts of extreme weather events – Cascading risks in a changing climate

Abstract

Background: Extreme weather events represent one of the most tangible impacts of anthropogenic climate change. They have increased in number and severity and a further increase is expected. This is accompanied by direct and indirect negative consequences for human health.

Methods: Flooding events, storms and droughts are analysed here for Germany from a systemic perspective on the basis of a comprehensive literature review. Cascading risks beyond the initial event are also taken into account in order to depict downstream consequences.

Results: In addition to the immediate health burdens caused by extreme weather events such as injuries, long-term consequences such as stress-related mental disorders occur. These stresses particularly affect certain vulnerable groups, e.g. older persons, children, pregnant women or first responders.

Conclusions: A look at the cascading risks described in the international literature allows us to develop precautionary measures for adaptation to the consequences of climate change. Many adaptation measures protect against different risks at the same time. In addition to planning measures, these include, above all, increasing the population’s ability to protect itself through knowledge and strengthening of social networks.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.
Health impacts of extreme weather events – Cascading risks in a changing climate

years or more. For the second, the consequences of the event for human society (i.e. health) are important, where these events disrupt social, technical or environmental systems [2, 3]. Below, both points of view are linked.

First, the climate change-induced change in frequency of potentially health-threatening events such as floods, storms, droughts, and fires is presented. Heatwaves are excluded here, as they are the subject of a separate article in this status report by Winklmayr et al. [4]. Based on this, the consequences of these events are analysed along risk cascades and direct and indirect impacts are systematically presented.

Extreme weather events are defined here as a ‘dynamic occurrence within a limited timeframe that impedes the normal functioning of a system’ [2, P. 4]. They trigger disasters when they encounter vulnerable social conditions and

Info box
Evidence: The increase in extreme weather events as a result of climate change

The sixth report of the Intergovernmental Panel on Climate Change (IPCC) asserts in its central statements that anthropogenic climate change is already having an impact on many weather and climate extremes in all regions of the world and that the evidence for attribution to human influence has strengthened in recent years [8].

However, not every extreme weather or hydrological phenomenon can be attributed to climate change. According to the conventions of the World Meteorological Organization (WMO), this attribution is only possible when system variables (e.g. temperature, precipitation or flood parameters, here: extreme values) shift noticeably in the multi-year mean [9]. This proof is difficult to provide due to the high natural variability in the climate system, usually quite short observation series and the rarity of extreme weather events. Since the climate fluctuates on multi-decadal time scales even under natural conditions, it is particularly difficult to clearly detect the share of anthropogenically enhanced climate change. For Germany, a change can be detected in relation to the event types heat, drought, storm surge and river flood (past analysis, data mostly since 1950), although the robustness – i.e. the unambiguity with which climate change can be identified as the reason for the changes – of the detected changes decreases in the aforementioned order. Almost all common heat indicators show significant changes with ever new extreme values [4, 10], which can partly be attributed to the anthropogenic contribution to climate change [11]. Established trends for droughts are more or less pronounced depending on the drought indicator. While meteorological indicators such as the climatic water balance or the forest fire index show comparatively clear changes all over Germany [12, 13], significant trends in hydrological indicators only emerge regionally [14]. This is partly due to compensating effects within the hydrological system, e.g. through water management or glacial melt. With regard to river floods, increases in annual maximum discharges can be observed at many gauges. In the case of extreme floods with a 100-year return probability, corresponding evidence is often not available (e.g. [15]). A similar picture emerges for North Sea gauges with regard to storm surges: while annual storm surges are increasing in magnitude, no trend can be discerned for ‘very severe storm surges’ due to a lack of past events and data [16].

In general, the more extreme and thus rarer an event under consideration, the more the limited length of observation series influences the possibilities for detecting changes. Therefore, it is difficult to reliably prove changes in the occurrence of extreme and destructive heavy rain or flash flood events and storms [17]. The required spatiotemporally high-resolution data series are only available for recent decades. However, this does not mean that climate change does not cause changes in these variables. By applying climate models, it could be shown, for example, that precipitation events such as the one that triggered the flood disaster in western Germany and Belgium in July 2021 have become more likely due to anthropogenic climate change [18].
health impacts of extreme weather events – cascading risks in a changing climate

2. Health impacts of selected extreme weather events

In this section, first the theoretical perspective on cascading risks is outlined. It is then applied to the extreme weather events under consideration – floods, storms, droughts and fires – in order to systematically illustrate the health impacts of these events. Finally, the extent to which vulnerable groups are particularly affected by the consequences of different extreme weather events is considered.

2.1 Cascading risks – conceptual foundations

The International Decade for Natural Disaster Reduction (1990–1999) led to intensive conceptual and theoretical works on risks. The United Nations Office for Disaster Risk Reduction was established as the leading institution; the Hyogo Framework and the Sendai Framework were adopted as internationally binding policy documents for risk reduction within the United Nations [19]. In parallel, new theoretical approaches emerged in the scientific discourse. Disasters are conceptualised as complex events in which the exposure of groups and systems and their vulnerability are analysed [19]. Accordingly, they are not the result of individual events, but arise from the interaction of different processes and circumstances [20]. Compound risks, which can trigger disasters that go beyond the impact of individual events, arise when (1) several extreme events occur simultaneously, (2) they encounter amplifying factors or (3) they are triggered by the unfavourable combination of several individually non-critical occurrences [20]. A special form are natural events that trigger technological failures and, as a consequence,
disasters (NaTech events), e.g. the reactor disaster in Fukushima triggered by a tsunami.

Most recently, concepts of cascading risks have emerged that address the indirect effects of disasters. Through the interconnectedness of systems at local, regional and global scales, disturbances propagate and can be amplified, creating entirely new risks [20, 21]. This concept is based on the assumption of Complex Adaptive Systems (CAS). Complexity means that processes do not necessarily run in a linear fashion. Thus, unpredictable dynamics arise, because the number of connections between subsystems is very large and interactions are difficult to predict. As a result, small changes can have very large effects. When tipping points are crossed, CAS can reach new states of equilibrium. CAS are mostly dynamic and co-evolutions can occur when developments in individual subsystems influence developments in others [22].

The CAS perspective provides a framework for analysing the circumstances that lead to a disaster. Reducing vulnerability through adaptation measures can ideally prevent disasters or at least reduce their consequences, while active disaster management can prevent or at least limit the emergence of cascading risks.

This shows that to assess the health impact of extreme weather events, one must not only consider the immediate consequences of these events. A comprehensive analysis must also systematically examine the indirect and downstream consequences.

2.2 Deaths, injuries and monetary losses due to extreme weather events

Due to the complex interactions, it is not possible to fully assess the health impact of extreme weather events. Official statistics show causes of death according to the International Classification of Diseases (ICD); more detailed information is not collected. For example, if a person is killed by a falling tree, the cause of death statistics do not distinguish whether the tree fell due to a storm or due to another trigger. An alternative source of information is the Emergency Events Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters (CRED) [23]. Data from various sources on the health impact of worldwide disaster events since 1900 (including the extreme weather events considered here) have been collected and evaluated in this database. On the cut-off date of November 11, 2022, it contained 89 events for Germany, starting with a flooding event in the Danube region in 1920. A total of 63 storm events with 718 fatalities, 25 floods with 271 fatalities and one forest fire without any fatalities are documented. The database does not explicitly differentiate between storms and storm surges. The advantage of the EM-DAT database is the worldwide overview, but regional databases sometimes come to different results. The European Environment Agency recorded more than 4,700 deaths and damages amounting to 150 billion euros in 1,500 events between 1980 and 2013 [24]. Floods were the most frequent catastrophic events.

Table 1 shows the ten most serious events in Germany, based on the number of directly affected persons (fatalities and injured persons) registered in EM-DAT. Most injured
persons were recorded for the heavy rain event that led to widespread flooding in mid-July 2021, mainly in Rhine-land-Palatinate (RP) and North Rhine-Westphalia (NW), and the event claimed the second most lives in Germany with 197 fatalities. Most deaths occurred as a result of the storm surge of 1962 (347).

In a global comparison, Germany’s exposure to natural hazards is relatively low and the risk profile differs, so that some globally relevant event types have not yet triggered any disasters here. Globally, 25,722 loss events with 38.4 million fatalities and 10.8 million injuries have been recorded in the EM-DAT database. The five events that have caused the most deaths globally in the last 122 years are (1) droughts, (2) epidemics and pandemics, with the COVID-19 pandemic not (yet) recorded in the database, (3) floods and inundations, (4) NaTech events and (5) earthquakes. At the same time, a decline in the number of fatalities can be observed from the 1930s onwards (Figure 1).

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Region/Place</th>
<th>Registered deaths</th>
<th>Registered injured persons</th>
<th>Number of affected persons recorded</th>
<th>Damages(^1)</th>
<th>Insured losses(^1)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>Flooding</td>
<td>BW, BY, HE, NW, RP, SN, ST, TH</td>
<td>197</td>
<td>1,000</td>
<td>1,197</td>
<td>40.0 bn</td>
<td>9.7 bn</td>
<td></td>
</tr>
<tr>
<td>1962</td>
<td>Storm</td>
<td>HH, North Sea</td>
<td>347</td>
<td>Not specified</td>
<td>347</td>
<td>5.4 bn</td>
<td>Not specified</td>
<td>Storm surge</td>
</tr>
<tr>
<td>1984</td>
<td>Storm</td>
<td>Munich</td>
<td>3</td>
<td>250</td>
<td>253</td>
<td>2.5 bn</td>
<td>1.3 bn</td>
<td>Hailstorm</td>
</tr>
<tr>
<td>2006</td>
<td>Storm</td>
<td>BW, BY, HE</td>
<td>10</td>
<td>200</td>
<td>210</td>
<td>Not specified</td>
<td>Not specified</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>Storm</td>
<td>BB, BE, BW, BY, HB, HE, HH, MV, NI, NW, RP, SH, SL, SN, ST, TH</td>
<td>11</td>
<td>130</td>
<td>141</td>
<td>7.2 bn</td>
<td>4.1 bn</td>
<td>Cyclone (Kyrill)</td>
</tr>
<tr>
<td>2002</td>
<td>Flooding</td>
<td>BB, BW, BY, NI, SN, ST, TH</td>
<td>27</td>
<td>108</td>
<td>135</td>
<td>17.5 bn</td>
<td>2.7 bn</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>Storm</td>
<td>BW</td>
<td>1</td>
<td>100</td>
<td>101</td>
<td>Not specified</td>
<td>Not specified</td>
<td>Hail</td>
</tr>
<tr>
<td>1972</td>
<td>Storm</td>
<td>NI, GDR</td>
<td>54</td>
<td>Not specified</td>
<td>54</td>
<td>2.7 bn</td>
<td>Not specified</td>
<td>Cyclone (Quimburga)</td>
</tr>
<tr>
<td>2017</td>
<td>Storm</td>
<td>Almtötting, Freyung-Grafenau, Passau</td>
<td>3</td>
<td>24</td>
<td>27</td>
<td>0.2 bn</td>
<td>Not specified</td>
<td>Hail</td>
</tr>
</tbody>
</table>

\(^1\) in US dollars, 2020 prices

Table 1: Compilation of the ten most serious events in Germany (direct health consequences) sorted by the number of affected persons recorded
Source: Own representation based on EM-DAT [23]
Considering the growing world population and the increasing number of damaging events, this means a decreasing individual mortality risk, which is related to more effective risk management and improved international cooperation.

For the extreme weather events considered below, the database shows 12,341 events worldwide with 20.2 million deaths (Figure 2). The largest single events are famines, which are triggered by floods or droughts. This represents a reduction in complexity that obscures interdependencies. The famine in Bengal in 1943, for example, is primarily recorded here as a drought, although Sen [25] showed that there was not a lack of food in Bengal, but that the poor population had no access to it. In Germany, storms and floods are the most common extreme weather events with the highest numbers of fatalities and persons affected (Figure 2).

With regard to extreme weather events, opposing trends can be observed globally: the number of events, persons affected and damage is increasing, while the number of fatalities is decreasing (Figure 1) [26]. For Germany, these trends are not equally clear. Due to the floods in July 2021, more deaths have already been recorded in the current decade than in the previous five decades. The highest insured losses were recorded in Germany for the decade 2000–2009.

2.3 Cascading risks due to floods, heavy rainfall and storm surges

Flood events can be triggered by various phenomena. Storm surges can occur in Germany when strong winds from northerly/north-westerly directions push water towards the coast (North Sea and Baltic Sea) and this situation coincides with tidal flooding (mainly North Sea). River floods occur as a result of long-lasting and large-scale precipitation and possibly in conjunction with snow melting in the river catchment areas. Flash floods are the result of local heavy precipitation with high magnitudes, often within hours and in connection with a pronounced relief of the terrain (e.g. narrow valleys, large differences in altitude in

---

**Figure 1**
Global trends of documented loss events (event types considered in this review) since 1900
Source: Own representation based on EM-DAT [23]

Figure 1a (left)
Persons affected and monetary losses

Figure 1b (right)
Fatalities

**Figure 2**
Number of affected persons/damages in billion USD $ Number of events

- Recorded events
- Affected persons
- Damages (2020 prices)
Health impacts of extreme weather events – Cascading risks in a changing climate

Figure 2
Persons affected by different types of events. Number of different event types worldwide and in Germany, recorded fatalities and injured persons from different types of events worldwide and in Germany. Source: Own representation based on EM-DAT [23]

A small area). Current knowledge suggests that all three event types (storm surges, river floods and flash floods) could increase in frequency and magnitude in the future (Info box, [6]). By the end of 2100, 3.7 million people could be affected by coastal flooding in Europe each year [27].

These events can cause great damage if they hit vulnerable groups or structures. Besides magnitude and duration of the events, local hydrodynamic conditions such as flow velocity in a cross-section or built-up areas in the channel determine the outcome [28]. The presence of risk management measures [27] and sources of hazard (e.g. industrial plants, landfills, sewage treatment plants, petrol stations [29,30]) in the potential floodplains determines whether extreme events lead to damage.

Immediate consequences for human health caused by the event may include deaths due to drowning, e.g. due to entrapment in buildings and vehicles, and (fatal) injuries. As a result of large-scale damage or flooding, there may be further deaths and other physical health consequences, e.g. from heart attacks, electrocution, fires, petrol and gas leaks (especially CO, CO₂) due to technical defects and collapsing building components [28,31,32] (Figure 3, which also shows the cascading risks of extreme weather event ‘storms’, considered in Section 2.4 Cascading risks due to storms).

Indirectly, the disruption of critical infrastructures (including energy supply, water supply and disposal, transport and traffic, healthcare facilities) can lead to bottlenecks in medical care (such as through the cancellation of planned treatments, lack of medicines) and delays in disaster response and provision of essential goods (e.g. water, food, emergency shelters) [27,31–33]. The relevant literature also describes an increase in cardiovascular complaints after flooding events [31,34,35]. However, it is not documented whether this is due to psychological distress during the event itself or to the failure of basic medical care. Other indirect health consequences due to increased exposure to heat, cold or damp rooms due to inadequate accommo-
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Existing data are insufficient for the detailed analysis of cascading risks.

Heavy rainfall and flooding can lead to the discharge of pollutants and germs into water bodies via surface runoff, combined sewer overflows [42–44] and the destruction of wastewater infrastructure [41, 45]. In addition, pollutants, including persistent organic pollutants (POPs), heavy metals, pesticides, radionuclides and germs can be mobilised from sediments and polluted soils [29, 45]. Contact with contaminated water carries an increased risk of infections [29, 32], e.g. through the ingestion of antibiotic-resistant bacteria [46]. In Halle (Saale) in 2013, an increased number of infections with the parasite Cryptosporidium hominis was found in children who spent time in floodplains and flooded meadows after a flooding event [47].

Medium-term health damage can be caused by exposure to pollutants via the air, e.g. in contaminated buildings, via water and via food intake. The latter are a consequence of the accumulation of heavy metals and POPs e.g. in arable soils and fish [28, 29]. However, directly observed effects after floods, such as headaches, dizziness, nausea, respiratory and skin irritation, could not yet be clearly attributed to a recorded increased exposure to halogenated pesticides (i.e. organic compounds in which at least one hydrogen atom has been replaced by chlorine, fluorine, bromine or iodine), volatile organic compounds, or heavy metals after flooding events [45]. When estimating the consequences, the limited data available is problematic, especially with regard to exposure before and after the event and the simultaneous recording of symptoms. In addition to the acute health consequences of event-related chemical exposure, it is particularly challenging to relate back to the potential chronic effects that only become noticeable several months after the event [45]. Many inorganic and organic pollutants are suspected of having carcinogenic, cardiovascular, neurotoxic, hepatotoxic, immunotoxic or reproductive effects [29, 48]. Due to the large number of pollutants, however, there are several research deficits.

A significant consequence of flooding events is the impairment of mental health [49, 50]. In Europe, increases in post-traumatic stress disorder (PTSD), anxiety disorders, depression and even suicides have been reported compared to the time before an event [32, 50]. These effects can be observed long after the event [50]. In addition to the direct traumatic experience of the event, the mental health consequences are also due to material losses and the often protracted reconstruction [51]. In a study on the consequences of the 2013 Elbe and Danube floods, the success of recovery correlated negatively with the length of time until the receipt of compensation payments, health status,
Figure 3
Cascading risks triggered by floods, heavy rainfall and storms. Arrows indicate possible causal relationships between risks, amplifying factors and health consequences.
Source: Own representation

- **Flood, heavy rainfall, storm**
  - Disruption of critical infrastructure
  - Disruption of electricity/water supply
  - (Fatal) injuries/drowning
  - Disruption of healthcare system
  - CO poisoning
  - Crises for patients with pre-existing conditions
- Disruption of electricity/water supply
  - Infections, injuries, poisonings, vector-borne diseases
  - Contact with animals/pathogens/toxins
  - Contaminated soil and water
  - Infections
  - (Sexualised) violence

- **Evacuation**
  - Crowding in shelters
  - Infections

- **Loss of public order**
  - Loss of public order

- **Disruption of habitats**
  - Disruption of habitats

**Time**
- CO=carbon monoxide
- NCDs=non-communicable diseases
- PTSD=post-traumatic stress disorder
- NCDs=non-communicable diseases
- PTSD=post-traumatic stress disorder
- **Primary risk**
- **Secondary risk**
- **Amplifying factor**
- **Health impact**

- Distressed in those affected/first responders
  - Distress in those affected/first responders
  - Distress in those affected/first responders

- Injuries first responders
  - Injuries first responders

- Lack of protective equipment first responders
  - Lack of protective equipment first responders

- Allergies, respiratory diseases
  - Allergies, respiratory diseases

- Distress in those affected/first responders
  - Distress in those affected/first responders

- Injuries first responders
  - Injuries first responders

- (Fatal) injuries/drowning
  - (Fatal) injuries/drowning

- Lack of protective equipment first responders
  - Lack of protective equipment first responders

- Living in damaged/destroyed buildings
  - Living in damaged/destroyed buildings

- Disruption of critical infrastructure
  - Disruption of critical infrastructure

- Disruption of electricity/water supply
  - Disruption of electricity/water supply

- CO poisoning
  - CO poisoning

- Crises for patients with pre-existing conditions
  - Crises for patients with pre-existing conditions

- Infections, injuries, poisonings, vector-borne diseases
  - Infections, injuries, poisonings, vector-borne diseases

- Contact with animals/pathogens/toxins
  - Contact with animals/pathogens/toxins

- Contaminated soil and water
  - Contaminated soil and water

- Infections
  - Infections

- (Sexualised) violence
  - (Sexualised) violence

- **PTSD**
  - PTSD

- **Amplification of pre-existing conditions**
  - Amplification of pre-existing conditions

- **Long-term risk for children**
  - Long-term risk for children

- **Rise of NCDs**
  - Rise of NCDs

- **Chronic poisoning**
  - Chronic poisoning

- **Amplification of pre-existing conditions**
  - Amplification of pre-existing conditions

- **CO poisoning**
  - CO poisoning

- **Infections**
  - Infections

- **Infections**
  - Infections

- **(Sexualised) violence**
  - (Sexualised) violence

- **PTSD**
  - PTSD

- **Amplification of pre-existing conditions**
  - Amplification of pre-existing conditions

- **Long-term risk for children**
  - Long-term risk for children
The greatest damage in the last two decades was caused by cyclone Kyrill in 2007. No clear trend in the development of storm events can be determined from past data. Although no reliable statements can be made, an increase in the frequency and magnitude of storm events must be expected in the future [54, 55]. In addition to large-scale storm events, approximately 20 to 60 tornadoes occur annually in Germany, which can cause severe damage on a small scale [56].

In a global comparison, Germany is less affected by severe storm events than countries in the tropics and subtropics, where tropical cyclones regularly trigger severe damage with high wind speeds and precipitation. This is also reflected in the literature on the health consequences of storms. A total of 22 review articles on health consequences of storms were identified, of which 14 were accessible and evaluated for this section. It becomes clear that there are large differences globally in terms of knowledge about the health consequences of extreme weather [34, 57]. The storm event whose consequences were analysed most thoroughly is Hurricane Katrina (2005, south-eastern USA).

In the last 20 years, twelve flooding events in Germany have been registered in the EM-DAT database [23]. The floods in western Germany in July 2021 and the Elbe floods in 2002 and 2013 were particularly devastating.

On the German North Sea and Baltic Sea coasts, storm surges occur regularly, especially in the winter months. On the North Sea there have been 64 severe storm surges (>2.50 m above mean high water, mhw) since 1967, including 13 very severe storm surges (>3.50 m above mhw) [52]. However, effective coastal protection has been erected in many places. In particular, the experience of the storm surge in February 1962 (‘Hamburg storm surge’) led to increased coastal protection measures in Germany [53], so that the damage and health impacts of subsequent, more extreme events (e.g. 1976, 1990, 1994 and 2013 on the North Sea and 1995 and 2006 on the Baltic Sea) were greatly reduced [53].

2.4 Cascading risks due to storms

Large-scale storm events occur in Germany when large low-pressure vortices – cyclones – coming from the Atlantic pass over Central Europe. They can trigger winds of up to 200 km/h [54]. Among the most severe events observed in recent decades were cyclones Lothar (1999), Jeanett (2002), Kyrill (2007) and Zeynep (2022). In the EM-DAT database, a total of 63 storm events have been documented for Germany since 1900, 33 of which occurred since the year 2000 [23]. The greatest damage in the last two decades was caused by cyclone Kyrill in 2007. No clear trend in the development of storm events can be determined from past data. Although no reliable statements can be made, an increase in the frequency and magnitude of storm events must be expected in the future [54, 55]. In addition to large-scale storm events, approximately 20 to 60 tornadoes occur annually in Germany, which can cause severe damage on a small scale [56].

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The effects of storm on human health can be grouped into indirect and direct consequences at different levels (Figure 3). The direct health consequences of storms include injuries, for which comprehensive data are available in numerous studies [34, 58]. However, injuries also occur indirectly when first responders are injured during clean-up operations, during which they may also suffer poisoning [58, 59]. The stress to which storm victims are exposed during the event, but also the change in living conditions triggered by the event (e.g. homelessness, unemployment) manifest themselves in the medium term in an increase in...
non-communicable diseases (NCDs) [60]. The experience of stress also leads to long-term observable developmental delays in children whose mothers experienced a severe storm event during pregnancy. These delays also manifest as direct consequences through postnatal complications and are exacerbated – especially in the developmental context – by temporarily restricted access to food [61–63].

Indirectly, the failure of critical infrastructure causes negative health consequences, e.g. an increase in carbon monoxide poisoning when cooking indoors with wood, coal or gas during power outages [34, 58, 64]. Failures of water supply and sanitation can promote infections, and there is often an increase in unprotected contact with animals, whose faeces can carry pathogens, but which can also injure people through biting [34, 65]. As healthcare facilities are often inaccessible during storm events, critical situations can arise for people with pre-existing conditions, for example patients with chronic obstructive pulmonary disease (COPD), who are dependent on permanent oxygen supply, or patients requiring dialysis [60, 64]. Acutely insufficient healthcare for chronically ill patients can also manifest itself in a permanent deterioration of health [34, 60].

Severe storm events, such as tropical storms, force people to evacuate. Living together in crowded emergency shelters can encourage the spread of infectious diseases [62]. Flight, but also other traumatic events during the storm, can have long-term consequences for mental health, such as PTSD [62, 64, 66].

The loss of public order affects vulnerable groups in particular; in addition to children and older persons [67], women are often exposed to particular dangers (Section 2.6 Vulnerable groups and pathways of impact). There is evidence in the literature that women experience sexualised violence, which leads to further distress [61].

2.5 Cascading risks due to droughts and fires

For droughts, a distinction is made between three different types according to cause and consequence:

1. Meteorological drought occurs when there is a combination of low precipitation and high temperatures. A high potential evaporation results in a negative climatic water balance (typical indicator).

2. Agricultural drought describes the drought stress in agricultural crops due to a lack of water in the rooted soil. In north-western Europe, this only occurs after dry phases lasting several weeks. In extreme cases, this can lead to yield losses or even crop failures.

3. Hydrological drought is recorded on the basis of water level data and is the result of a strained landscape water balance. Long and large-scale dry periods are the root cause for this type of drought as well.

Apart from the immediate effects of low water levels and water volumes, e.g. on drinking water availability, there are impacts on water quality and the risk of fires. Projections show that droughts in Central Europe could increase in frequency, magnitude and duration during the 21st century [6]. Low precipitation, high temperatures and multiple demands could lead to increasing water stress, especially in summer and the transitional seasons.

Cascading risks due to droughts can cause different health impacts (Figure 4). In extreme cases, they lead to malnutrition with increased mortality among vulnerable groups. This is mainly observed in the Global South [68].
People working in agriculture are particularly exposed to the increasing agricultural droughts, often associated with heatwaves and strong sunlight, which is why potential health hazards such as heat stroke, cardiovascular failure and skin cancer especially affect this group of people [4, 71]. The economic uncertainties caused by droughts can also affect the mental health of people working in agriculture and forestry and increase the risk of suicide [72–75] (see also the scoping review by Gebhardt et al. [76] on the effects of climate change on mental health in this status report).

In the Global North, a lack of food and drinking water supply currently poses little risk and the economic consequences dominate.

Droughts are usually accompanied by stable weather conditions and thus a reduced exchange of air masses. This leads to an accumulation of pollutants in the atmosphere and thus a deterioration of air quality with corresponding health consequences [69]. Elsewhere in this status report, the health impacts of climate change due to increased air pollutant loads are considered in more detail by Breitner-Busch et al. [70].

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Low water levels can have a detrimental effect on water quality. Due to the reduced water volume and higher residence times of the water, it gets warmer and pollutants become less diluted [77]. High water temperatures and lower flow velocities during low water in summer are associated with the mass occurrence of potentially toxic phytoplankton (algal blooms), see also an article on water-borne infections and intoxications in this status report [78]. Direct contact with contaminated water occurs through occupational activities in and around water or recreational activities, e.g. water sports. For drinking water supplies in Germany, reduced water quality is a potential risk only in special cases. A possible increase in guideline value exceedances may require more intensive drinking water treatment processes, e.g. in bank filtrates where enriched pollutants or toxins may not be sufficiently filtered out of the water. In drinking water reservoirs, toxin-producing cyanobacterial blooms can complicate water treatment. Contact with the contaminated water can lead to gastrointestinal infections and illnesses as well as zoonotic and vector-associated diseases [69, 78]. For contact with cyanotoxins, additional skin irritations and respiratory diseases have been reported, but are often not clearly attributable to cyanobacterial exposure [79].

Indirectly, droughts can lead to the spread of vector-associated diseases if, for example, in the absence of predators, mosquitoes multiply heavily in pools of water or in vessels for water storage [40, 80].

Droughts can also trigger health impacts as part of compound risks, e.g. when heavy rainfall events occur during a drought. On the one hand, infiltration of dry soils is inhibited, so there may be increased surface runoff and an increase in flash flood hazards and associated health impacts (Section 2.3 Cascading risks due to floods, heavy rainfall and storm surges). On the other hand, entry of pollutants or germs can lead to a deterioration of water quality.

Summer droughts are often accompanied by heatwaves. This provides ideal conditions for the occurrence of fires, which can be triggered by the slightest influences (e.g. by lightning or careless behaviour), thus increasing the risk of forest fires [81, 82]. In addition to climatic changes, other factors such as tree species composition (e.g. a high proportion of conifers) also play a role [6]. Forest and bush fires endanger the physical health of those affected as well as rescue workers directly through burns, through smoke development and the associated consequences for the respiratory tract, but also through effects on mental health or indirectly through disruption of infrastructure [83–85].

After 1959, which was an extremely dry year, the years 2003, 2018, 2019, 2022 had a particularly high precipitation deficit and drought periods, with additional regionally effective drought events [12, 14, 86]. The multi-year drought of 2018 to 2020 represents the most severe drought in Europe in the last 250 years [87].

No drought event is listed for Germany in the EM-DAT database [23] and in the recent past there have been no direct health effects of droughts in Germany documented in the literature. However, the hydrological droughts of recent years have led to pronounced low-water situations with observable deteriorations in water quality, e.g. due to massive phytoplankton blooms such as those observed recurrently in the Moselle since 2017 and in the Oder in 2022.

In the period between 1991 and 2021, the years 1991, 1992 and 2003 are those with the greatest number of for-
Four population groups are particularly affected by the health consequences of extreme weather events for different reasons:

1. children, older people and people with physical limitations – they may not be able to care for themselves or get to safety and the physical stresses that occur may push them to their limits;
2. people with low socioeconomic status – they are often directly exposed to extreme weather events and may have lower coping capacity;
3. men are more often affected by the immediate consequences (e.g. higher risk tolerance);
4. specific long-term consequences can occur for women (e.g. pregnancy complications).

The numbers of victims of the floods in western Germany and Belgium in July 2021 illustrate these overlapping vulnerabilities: among the immediate fatalities (184) in RP and NW, 138 persons (75%) were older than 60 years (population share in NW: 27%) and 3 (1.6%) were children under 14 years (population share in NW: 13%) [32, 90]. The ratio of men (65) to women (70) among fatalities was balanced in RP, while in NW about twice as many men (31) as women (18) died [32]. This is consistent with sources suggesting that men are less likely to take protective measures, such as evacuations [91]. The gender ratio in RP is consistent with patterns in storm surges (1953, 1962). The ratio in NW corresponds to the pattern of flood victims in Europe, the United States, and Australia [32]. People with physical or mental disabilities were particularly affected: twelve residents of a care facility died in their flooded living quarters [32].

The impact of extreme weather events differs regionally and for different population groups. Natural circumstances predispose a region for the occurrence of individual event types. Storm surges are a phenomenon of coasts and estuaries. Particularly strong winds can also occur there, as well as in exposed inland mountainous areas. Storm damage can also occur on a small scale where vulnerability is increased (e.g. forests, cities, vulnerable transport infrastructures such as overhead railway lines). River floods affect areas along waterways, flash floods can cause particular damage in areas with high relief. Extreme heavy rainfall events, however, can affect any place in Germany.

An increased risk of droughts and their potential consequences cannot be directly located, but there are different levels of impact depending on the type of drought (agricultural, hydrological). In regions and seasons with an already strained water balance, the consequences are more pronounced (e.g. eastern Germany) than in regions with some reserves in the system (e.g. Rhineland).
Another vulnerable group are first responders. They are exposed to great physical dangers — through injuries, poisoning and great psychological strain. Disaster preparedness and post-disaster care can reduce the vulnerability of this group. An American study on the health risks associated with clean-up work after extreme events found that occupational fatalities occurred a median of 36.5 days after a storm (surge) event and were most common in clean-up (44%), restorative construction (26%), public utility restoration (8%) and preservation of law and order (6%) [92]. Animal bites are also described among rescue workers and animal owners [65].

3. Adaptation measures to increase resilience to extreme weather events

In order to increase resilience to extreme weather events, preventive precautionary and adaptation measures can be taken. These include measures that address different types of events as well as event-specific measures.

Self-protection is an important element of security provision for society as a whole. Since rescue forces cannot be everywhere at once during large-scale catastrophic events and may also be affected themselves, it may take some time until state assistance arrives. A population that has prepared for emergency situations in advance makes a significant contribution to coping with emergency situations collectively [93–95]. Social networks are an important asset for the emergence of spontaneous civil disaster relief, which is often of high importance in the first hours after a disaster [96]. Strengthening social networks in associations, faith-based institutions and through various forms of voluntary work is an abstract and difficult goal to achieve, but nevertheless an important building block of social resilience. As a first step, politics and society must recognise the importance of such networks for societal resilience in order to promote these institutions.

The Federal Office of Civil Protection and Disaster Assistance (Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, BBK) offers various pages with recommendations for action responding to different types of hazards (e.g. heavy rain, storms, heatwaves) on its website [94, 97]. Likewise, timely risk communication and warning of the population is essential to minimise health impacts of extreme weather events. For this purpose, a mix of warning systems (e.g. sirens, mobile phone apps, cell broadcast — messages to all mobile phone users of selected radio cells) is used in Germany and is being further developed. The earlier the population is warned, the sooner they can prepare for the event and take precautionary measures or evacuate from an affected area [95, 98, 99].

Securing the water supply during and after extreme weather events is particularly important. Three areas of responsibility can be named for this: Water supply companies draw up action plans to maintain the supply. If the supply can no longer be maintained in the event of an incident, municipalities, through local disaster relief authorities among others, can (with the support of the district or the federal state) help with replacement supply measures (e.g. through self-sufficient wells, transport containers, mobile treatment plants) in accordance with §12 of the German Civil Protection and
Disaster Relief Act. After flooding or during drought events, municipalities can issue orders to boil all drinking water to kill germs and thus ensure a safe drinking water quality [100].

In order to describe flood risks and damage potentials in Germany and Europe and to focus related measures, the EU directive on the assessment and management of flood risks [101] came into force on November 26, 2007 and was transposed into national law on March 01, 2010. Furthermore, a national spatial development plan for flood protection came into force on September 01, 2021 [102]. Likewise, heavy rain hazard maps can help to raise awareness among the population or help those responsible to take necessary structural measures [103].

In order to protect the particularly vulnerable group of emergency personnel in forest fires and to prepare them for operations, the German fire brigade association has published a recommendation on safety and tactics during vegetation fires [104]. The population can be informed about forest fire hazards and correct behaviour by means of information boards, flyers [81, 105] and other services such as the forest fire hazard index [106] and grassland fire index [107] of the German Meteorological Service (both currently available from March to October each year). In addition, silvicultural measures can be implemented to prevent forest fires, such as creating firebreaks or increasing the proportion of hardwoods in coniferous forests and reforesting with deciduous trees instead of conifers [105]. For early detection and suppression of forest fires, an automated early wildfire detection system is used in Lower Saxony, Brandenburg, Berlin, Mecklenburg-Western Pomerania, Saxony and Saxony-Anhalt [105, 108].

A political framework for strengthening Germany’s resilience to extreme weather events is provided by strategies that can be used to define and implement measures, e.g. the German Strategy for Adaptation to Climate Change, the German Strategy for Strengthening Resilience to Disasters and the National Water Strategy for Germany [109–111].

4. Discussion and conclusion

Extreme weather events, which already posed substantial health risks for Germany in the past, are expected to occur more frequently in the future due to climate change. The evidence is clearest for heatwaves, but hydrological events (heavy rain, floods, droughts) are also likely to increase. For storms, however, the evidence is less clear.

A key message at this point is that extreme weather events can only trigger disasters if they hit a vulnerable population and/or a vulnerable infrastructure. Although the complexity of human-environment systems makes it impossible to predict all interactions, adaptation measures can significantly reduce the risk. Many adaptation measures protect against different risks at the same time. In addition to planning measures, these include increasing the population’s ability to protect itself through knowledge and strengthening of social networks.

The healthcare system must be able to respond to extreme weather events on different time scales. In disaster situations, injuries and poisonings must be treated on site and it is necessary to ensure continuous care for those pregnant or with pre-existing conditions in order to minimise long-term consequences. When organising relief efforts, it is important to consider vulnerable groups and
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their needs. For this purpose, it would be important, for example, to know the residence of those people who cannot independently evacuate in the event of a disaster. In the medium and long term, the restoration of mental health is important, and healthcare resources must be earmarked for this. This also means that capacity building to respond to the challenges outlined here in the short, medium and long term must be part of climate change adaptation. In addition to disaster management, this also applies to the healthcare system, where necessary backup capacities must be created and permanently maintained.

One difficulty in recording the health impacts of extreme weather events is often inadequate data – both with regard to the events themselves and the health consequences. Especially the indirect consequences that unfold via cascading risks are not systematically recorded. For improved risk management, the creation of a database with comparable case studies would be an important knowledge base. This should integrate the different types of data and knowledge mentioned – from meteorological observations to descriptions of the event by the population – and thus enable the measuring of cascading effects.

In view of the available knowledge on future developments, it is advisable for all actors to review existing levels of protection. Authorities, the healthcare system, civil society and citizens must be aware of the shift in risks and actively adapt within their scope of action. Particular attention must be paid to vulnerable groups who cannot help themselves. How society deals with changing risks will pose major challenges in the coming decades. This includes negotiating responsibilities for preparedness and loss management. One important key to promoting social resilience in this context is empowering people to protect themselves – individually and in social networks.

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Impact of climate change on non-communicable diseases caused by altered UV radiation

Abstract

Background: UV radiation can cause serious skin and eye diseases, especially cancers. UV-related skin cancer incidences have been increasing for decades. The determining factor for this development is the individual UV exposure. Climate change-induced changes in atmospheric factors can influence individual UV exposure.

Methods: On the basis of a topic-specific literature research, a review paper was prepared and supplemented by as yet unpublished results of the authors’ own studies. The need for scientific research and development is formulated as well as primary prevention recommendations.

Results: Climate change alters the factors influencing UV irradiance and annual UV dose in Germany. First evaluations of satellite data for Germany show an increase in mean peak UV irradiance and annual UV dose for the last decade compared to the last three decades.

Conclusions: The climate change-related influences on individual UV exposure and the associated individual disease incidence cannot yet be reliably predicted due to considerable uncertainties. However, the current UV-related burden of disease already requires primary preventive measures to prevent UV-related diseases.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.

1. Introduction

Climate change has serious consequences for humans and the environment. Catastrophes such as floods, storms, droughts, or heatwaves clearly demonstrate this. Less obvious, but no less problematic, are the effects of climate change that can have negative consequences for humans and nature, but go unnoticed and thus insidiously worsen the situation. One of these is the climate change-induced modification in the factors influencing ultraviolet (UV) radiation exposure (in this article, UV is often used in compounds as an abbreviation for ultraviolet radiation).

UV radiation is the initiator of the body’s own vitamin D formation. At the same time, UV radiation is the main cause of skin cancer and can lead to other negative health consequences for the eyes and skin [1, 2]. UV radiation damages the genetic material and, like asbestos and ionising radiation, is classified in the highest risk group 1 as ‘carcinogenic to humans’ [3]. Especially UV-related cancers are a burden on the general welfare and cause high costs for...
the healthcare system [2, 4]. UV-related health damage to the eyes and skin can basically affect everyone. Children are particularly at risk [1].

According to the current state of scientific knowledge, climate change is altering the factors influencing ambient UV radiation worldwide and also in Germany and thus the UV-related human disease risk. In addition to individual UV exposure behaviour, the structures in people’s living environments that offer UV relief – such as shaded areas – play a decisive role for individual UV exposure and thus for the UV-related disease risk [2].

In this paper, the changes in ground-level UV radiation, the resulting consequences for individual UV exposure, and the associated health risk are considered and recommendations for adaptation are given. The literature search for this article was based on international reviews on the topics ‘stratospheric ozone’, ‘climate change’, ‘interactions between ozone and climate and effects on solar UV radiation’ and ‘climate change, UV exposure, human health’, among others, in the free full-text archive of biomedical and life science journal literature PubMed. In addition, reports and data services of national and international authorities and their bibliographies were used, as well as the authors’ own studies that have not yet been published. These are marked with the note ‘Author et al.; data not published’.

2. Development of ground-level UV radiation

2.1 Retrospective development of ambient UV radiation

UV radiation in the human habitat is characterised by a very strong spatial and temporal variability, which is mainly determined by the position of the sun, the thickness of the ozone layer, and cloud cover. Further influences result from the aerosol content of the air, the reflectivity of the ground, and the altitude of the location. Changes in the position of the sun are reflected in changes in UV radiation both with latitude and over the course of the day and year. The strongest absorber of UV radiation, atmospheric ozone, usually has higher concentrations at northern latitudes and in turn has an annual cycle with the highest values in March and April and the lowest values in October and November. Anthropogenic emissions of chlorofluorocarbons (CFCs) not only caused the Antarctic ozone hole, but also reduced the thickness of the ozone layer in varying degrees globally. Due to international agreements such as the Montreal Protocol in 1987 and subsequent agreements, CFC emissions have been reduced almost completely to zero compared to the 1970s and 1980s, so that chlorine pollution in the atmosphere has been declining since around the year 2000 and the thickness of the ozone layer is slowly recovering. In the case of Arctic ozone, this has not yet been verified due to the high variability [5].

Effects of the above-mentioned influencing factors on UV irradiance

How the above-mentioned influences affect ambient UV irradiance can be seen, for example, in the average frequency of occurrence of certain UV Index categories (no to low, moderate, high, very high, and extreme [6]). The UV Index (UVI) is a measure of the daily maximum of sunburn-effective (erythema-effective) UV irradiance occurring on a horizontal surface [6]. Figure 1 shows the results of the analysis of satellite data for thirds of month (periods of 10 ± 1 days) at four sites of different latitude in Germany (Sylt, Berlin,
Frankfurt/Main, Munich). In the long-term average (data basis here: 1983–2019), high UV indices (UVI ≥6) occur everywhere in Germany in summer, but there are differences in how many days and which further periods are affected in spring and autumn. The affected period as well as the average proportion and the maximum number of days with high UV indices within one third of month are larger in the south than in the north of Germany. With the time division made here, high UV indices additionally occur in three thirds of month in Munich compared to Sylt. If we...
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Look at the third of month with the highest UV indices, 37% more high UV indices are recorded in Munich than in Sylt. A similar pattern can be seen with the very high UV indices (UVI ≥8), with the particularity that they typically occur extremely rarely in the very north in Sylt and therefore do not play a role in the representation of the long-term average. In Munich, ten thirds of month are affected by very high UV indices, five times as many as in Berlin, and the maximum proportion of such days within a third of month is 15% higher compared to Berlin. Low ozone events that can lead to exceptional values of the UVI are discussed later in this section.

Change in ambient UV radiation
Ambient UV radiation in Germany in the recent past differs from the long-term mean conditions. This is illustrated by a mean of the UVI anomalies of the four sites shown in Figure 1, which for each site is based on the deviations of the thirds of month during the period 2010–2019 from the respective thirds of month during the overall period 1983–2019 (Figure 2). The four-site mean in Germany shows a statistically significant increase in the values of the UVI during the period 2010–2019 compared to the long-term average 1983–2019. During the months February to July, on average, exclusively positive UVI anomalies are recorded, i.e. here the UVI had higher values on average during the last decade. The magnitude of the anomalies varies, reaching the highest values around 0.5 UVI (difference around 12.5 milliwatt per square meter (mW/m²) sunburn-effective UV irradiance) in early July and early June. The mean UVI anomaly in the month of June is 0.35 UVI (8.75 mW/m² sunburn-effective UV irradiance). The positive UVI anomalies also occur at times of the year that are particularly significant with regard to the health consequences of UV exposure: as a rule, in spring the skin of most people in Germany is still unaccustomed to the sun and thus particularly at risk.

The period around the solar maximum in June is characterised by the highest absolute values of the UVI over the course of the year, as shown above. These results, based on satellite data, mainly reflect the effects of changes in cloud cover and ozone layer thickness. The anomalies of the UVI at clear sky conditions are, on this data basis, the result of changes in the ozone layer thickness. On average over the entire year, there is a slight (but statistically not significant) decrease in the UVI anomaly at clear sky conditions, which can be interpreted as an expression of the improving situation of the ozone layer due to the implementation of the Montreal Protocol.

Overall, the evaluations of the satellite data give first indications that ambient UV irradiance in Germany during the last decade (2010–2019) is mainly shaped by decreases in cloud cover in spring and summer. The development of the thickness of the ozone layer plays a much smaller role in comparison ([7], Laschewski et al.; data not published). The influence of longer-term aerosol changes is not represented in this data basis.

In addition to the daily maxima of the erythema-effective UV irradiance in the form of the UVI, the values summed up for all hours of the days of a year in the form of the annual UV dose are also significant, which were evaluated in analogy to the UVI for the period 1983–2019 (Laschewski et al.; data not published). The four-site mean in Germany indicates a 2% higher annual UV dose per dec-
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ade when comparing the mean value of the period 2010–2019 with the long-term mean value of 1983–2019. The annual UV dose is characterised by strong variability from year to year. In 2018, a year with particularly high levels of sunshine, the mean annual UV dose of the four sites in Germany was about 13% above the long-term mean, while in 1987, a year with particularly little sunshine, it was about 16% below the long-term mean. Evaluations of the UV monitoring network data measured at ground level confirm this correlation ([8], Lorenz et al.; data not published).

The regional differences in ambient UV radiation between northern and southern Germany are considerable. The percentage changes in the UVI and the annual UV dose therefore have different regional effects. For example, based on satellite data, the annual UV dose in Munich is 29% higher than that of Sylt in the long-term average, which is primarily due to the latitude (i.e. the position of the sun) ([7], Laschewski et al.; data not published). The extent to which long-term changes in the aerosol content of the air in Germany correspond to changes in ambient UV radiation is currently unclear. For such an evaluation, quality-assured data series of ground-based measurements are necessary.

The presented findings from the analysis of satellite data for Germany ([7], Laschewski et al.; data not published), which show a 3%-per-decade higher mean value of the UVI and a 2%-per-decade higher mean annual UV dose for the period 2010–2019 compared to the overall period (1983–2019), are within the value range of the changes in UV radiation determined on the basis of ground-based measurements for several European stations [9]. In this study, measured data from stations at latitudes of Germany show changes in UV radiation ranging from -7% to +5% per decade over the last 22 years (1996–2017).
Changes in cloud cover, aerosol content of the air, and reflectivity of the ground can be identified as the main causes of long-term changes in UV radiation in most locations outside the polar regions, while changes in ozone layer thickness are less important [10]. The successful implementation of air pollution-reducing measures caused a general decrease of the aerosol content since about the mid-1980s and led to a higher radiation transmittance of the atmosphere, also in Germany [11]. As a result, an increase in ground-level UV radiation can also be assumed due to the reduction in the aerosol content of the air, which is particularly pronounced in urban areas and cannot be attributed to climate change.

Low ozone events
As shown above, the development of the ozone layer also plays a much smaller role in Germany in the development of ambient UV radiation than changes in cloud cover. Nevertheless, so-called low ozone events (LOEs) require special consideration, as they can lead to unexpectedly high UV exposures for a few days. There are various reasons why LOEs can occur. Firstly, weather conditions can lead to an increase in the height of the tropopause, which marks the transition from the troposphere to the stratosphere, and thus to a (reversible) displacement of part of the stratospheric ozone. This is called LOE of dynamic origin. On the other hand, it is possible that air masses from the Arctic polar vortex, in which ozone has been irreversibly depleted by chlorine chemistry, are transported to lower latitudes in spring. These LOEs of chemical origin can occur between March and mid-April.

Not all LOEs lead directly to increased ground-level UV exposure, as UV radiation can be greatly reduced by clouds or aerosols as it passes through the atmosphere. A recent study based on satellite data from 1983–2019 evaluates the occurrence of all LOEs with associated UV anomaly, i.e. on these days there is stronger ground-level UV radiation than would be recorded in cloudless conditions with normal ozone layer thickness [12]. This study shows that the annual number of LOEs of different origin is characterised by a high variability. They occur relatively rarely and not every year. LOEs of dynamic origin can occur at all months of the year. The period of greatest global ozone depletion in the 1990s is characterised by a greater frequency of LOEs. During the last two decades (1998–2019), a decreasing average number of all LOEs in a year was evident, although the annual sums of LOE-associated UV dose anomalies were unchanged on average during this period. Overall, the mean value of the annual sums of the LOE-associated anomalies of the UV dose provides a rather small contribution with less than 1/1000 of the annual UV dose. Looking at the peak loads (LOE-associated UVI anomalies), spring is the season most affected by LOEs, accounting for more than half of the cumulative peak UV loads. The skin of most people in Germany is unaccustomed to the sun at this time of year and thus particularly at risk. This results in the health relevance of LOEs occurring in spring, which do not take place every year. Within the last two decades, summer (and thus the most radiation-intensive time of the year) provides an increasing share of all LOE-associated peak loads. During the study period (1983–2019), the strongest LOE-associated increase in erythema-effective UV irradiation is achieved
when LOEs occur near the annual solar peak in June or early July; with respect to the four sites in Germany considered, the maximum anomaly values for Berlin, Frankfurt, and Munich are about 45 mW/m² (corresponding to 1.8 UVI). Primarily due to the different latitude (i.e. the different position of the sun), different absolute values of the UVI are associated with these anomaly maximum values in the evaluated period, ranging from UVI 8 in Berlin to UVI 9 in Munich.

### 2.2 Expected development of ambient UV radiation until the middle and end of the century

The possible future climate change developments are modelled with a number of different scenarios. An introduction to the scenarios can be found, for example, in the introductory article of this status report [13]. Assuming scenario SSP2-4.5 (radiative forcing of 4.5 W/m², the so-called middle-of-the-road scenario, in which the previous development is continued and environmental systems experience some deterioration [14]), a return to 1980 ozone column values is expected outside polar latitudes around 2035 for mid-northern latitudes (35°N–60°N) and around 2045 for the Arctic [5]. However, simulations with chemical climate models for the period 1960–2100 suggest that changes in UVB radiation at mid-latitudes in the second half of the 21st century may be dominated by factors other than changes in global stratospheric ozone [15], namely a statistically significant decrease in cloud cover of 1.4% per decade. According to these calculations, UVB radiation would be projected to increase by 1.3% per decade between 2050 and 2100, although at the same time no trend in ozone layer thickness is detectable. These projections depend critically on the accurate description of clouds by the climate models, and the uncertainties in their modelling cause considerable uncertainties also for the projected changes in UV radiation.

In terms of changes in stratospheric ozone (and subsequently indirectly in terms of LOEs due to polar chemical ozone depletion), the influence of climate change leading to stratospheric cooling and an increase in stratospheric water content favours springtime ozone depletion in the Arctic polar vortex and could thus counteract recovery due to decreasing chlorine levels [5, 16]. There is a very large variability in Arctic ozone depletion from year to year. Based on modelling to date, the extent of Arctic ozone depletion is currently expected to decline in the spring until mid-century [5], with other estimates inferring a time horizon to the end of the century [16]. LOEs over Germany due to polar chemical ozone depletion, which do not occur every year, may become less frequent over the course of the century, but may continue to occur. In addition to these LOEs of chemical origin, the predominant type are LOEs of dynamic origin. It is currently unclear how the frequency of their occurrence and the associated ambient UV radiation will develop. So far, there are no known indications that would point to their fundamental absence in the coming decades. Simple extrapolations of retrospective trends would, on the one hand, suggest a decrease in ambient UV radiation due to the declining number of LOEs. On the other hand, a further decrease in cloud cover and a more frequent occurrence of LOEs in summer could make an increase in UV exposure more likely. Neither the net effect of the opposing trends nor the admissibility of the ex-
trapolations can be reliably estimated at present. There is a need for further research.

Due to considerable uncertainties, the development of ambient UV radiation in Germany up to the middle and end of the century cannot be reliably predicted at present.

3. Changes in individual UV exposure and effects on UV-related diseases

The previously described climate change-related changes in the factors influencing the ground-level UV irradiance and the annual UV dose can change the individual UV exposure and thus have an effect on the risk of disease caused directly by UV radiation [1, 2, 17, 18]. Indirect health effects caused by UV radiation are, for example, the effects of increased ground-level ozone (see Breitner-Busch et al. [19] in this status report) or the negative influence of UV radiation on atopic dermatitis (see Bergmann et al. [20] in this status report), which will not be discussed in detail here.

When considering the health risks from UV radiation, both the individual UV radiation moments and the UV dose accumulated over a lifetime, the lifetime dose, must be considered due to the fact that UV radiation can immediately cause health-relevant damage and that these can accumulate over a lifetime [1, 2]. With regard to the health consequences of altered near-ground UV exposure, the increase in ground-level UV irradiance observed over the past decades [7], longer-term increased annual UV dose [8], and LOEs [21–24] must be considered individually accordingly.

UV-related skin cancer (Info box 1) is used to describe UV-related disease incidence, as there are data available that allow quantification of the disease incidence.

Info box 1
Skin cancer

A distinction is made between non-melanoma skin cancer and (malignant) melanoma skin cancer. Non-melanoma skin cancer includes basal cell carcinoma (basalioma) and squamous cell carcinoma (spinaloma). In the case of non-melanoma skin cancer, melanin-less skin cells (melanin = colour-giving pigment of the skin and hair) multiply uncontrollably. Non-melanoma skin cancer may be preceded by skin changes, the so-called precancerous lesions, such as actinic keratosis or Bowen’s disease. In (malignant) melanoma, melanin-containing skin cells degenerate. Both squamous cell carcinoma and melanoma can spread and metastasise.

Worldwide, an increasing incidence of skin cancer has been recorded for decades. In Germany, the incidence of non-melanoma skin cancer has quadrupled (men) to quintupled (women) in the last 30 years [2, 25]. For malignant melanoma, the incidence has approximately quadrupled since the 1970s [2, 25]. Since 2012, the incidence of malignant melanoma has declined slightly in women and remained roughly constant in men [26]. According to the extrapolations from the data of the Skin Cancer Registry Schleswig-Holstein, which in contrast to the data of the Robert Koch Institute also include in-situ melanoma and in-situ squamous cell carcinoma, about 300,000 people per year are currently newly diagnosed with skin cancer [27]. Hospital treatments of UV-related skin cancers increased by 75% between 2001 and 2021, and deaths increased by 55% with about 4,100 deaths in 2021 during the same period [28]. Between 2001 and 2021, approximately 72,000 people died in Germany due to skin cancer (melanoma and other malignant neoplasms of the skin) [29].
According to model calculations, a 1% reduction in stratospheric ozone could mean an increase in the incidence of malignant melanoma of 1 to 2% [30, 31], a 3 to 4.6% increase of squamous cell carcinoma, and a 2.7% increase for basal cell carcinoma [32-34]. Given the 3% ozone reduction that has occurred over Germany, this would theoretically mean an estimated increase of 3 to 6% for malignant melanoma, 9 to 15% for squamous cell carcinoma, and 9% for basal cell carcinoma. Assuming full compliance with the Montreal Protocol and taking skin type into account, modelling showed that three to four additional skin cancer cases per 100,000 inhabitants per year can be expected for Western Europe by the end of the 21st century due to stratospheric ozone loss [35]. In Germany, with a population of about 83 million, this would result in approximately 2,500 to 3,300 additional skin cancer cases per year.

The LOEs observed in Germany lead to unexpectedly high UV irradiances, which are especially unexpected in spring, and sun protection measures are not considered accordingly. An associated higher sunburn risk and subsequently skin cancers can be assumed. However, quantification is currently not possible due to the lack of a description of a dose-effect relationship between individual UV dose and skin cancer incidence. The same applies to the quantification of the health impacts of an increased annual UV dose in years with plenty of sunshine.

The temperature increase associated with climate change is also discussed as a factor influencing skin cancer incidence. Studies show that heat stress can inhibit the programmed cell death of UV-damaged cells and that a temperature increase of 2°C could increase the incidence of non-melanoma skin cancer by about 11% [36–38]. The studies to date on the effect of higher temperatures on the development of UV-related skin cancer leave questions unanswered, so further research is needed to clarify and consolidate the findings [2].

The estimates of the increase in incidence found in the literature do not consider the behavior of the population with regard to spending time outdoors – i.e. how long they expose themselves to which UV irradiances under which UV protection measures. This so-called UV exposure pattern is, however, a significant risk factor for skin cancer [2]. Sunburns as a consequence of intensive UV exposure, for example, double the risk of developing malignant melanoma – in children, the risk is reported to triple [2, 4].

Climate change-induced alterations in human sun exposure behaviour may have an important impact on future health risks from UV radiation. Previously published scientific studies support the theory that people spend more time outdoors in pleasant weather conditions and temperatures, wearing light clothing, and thus increase their individual UV exposure, especially under low cloud cover (radiant weather). A recent review summarises the scientific findings to date on climate-related changes in human sun exposure behaviour [39]. Accordingly, there are more opportunities for weather-dependent behaviour, especially in leisure activities and active leisure mobility, than in routine activities, even if the direction and extent of the effects vary. It also shows that it is not justified to transfer results and conclusions between different climatic zones and seasons and to generalise between different leisure activities and forms of active mobility. It should also be noted that behavioural changes may develop differently depending on individual human characteristics such as affinity for heat, leisure type,
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For a temperate climate, as prevails in Germany, the available studies provide indications that a possible increase in UV exposure would result primarily from a reduction in clothing and only secondarily from a change in the length of time spent outdoors. In the case of strong heat stress, there is a tendency to avoid spending time outdoors or in the sun. For Germany, the records of the Deutscher Wetterdienst (DWD; German Meteorological Service) show a clear increase in temperature, the number of so-called ‘summer days’ (temperature maximum at least 25°C) and ‘hot days’ (temperature maximum at least 30°C) compared to the reference period 1961 to 1990. Another article in this status report by Winklmayr et al. provides detailed information on temperature development and heat in Germany. Ultimately, however, no quantitative statements about the individual UV exposure resulting from weather-dependent behaviour are possible at this time.

4. Recommendations for reducing the risk of UV-related health damage

A nationwide, target group-oriented and sustainable establishment of suitable measures is urgently required due to the given situation with a high and currently increasing number of UV-related diseases in Germany and with the associated burden on the healthcare system and general welfare. On top of that, there is the influence of climate change. Within the context of the ‘Climate Impact and Risk Assessment 2021 for Germany’, a medium to high climate risk with medium certainty for the period up to 2060 was determined for the climate impact of UV-related health damage and a very urgent need for action, in particular due to the long lead time. Adaptation strategies to the health consequences of climate change should accordingly focus on preventive measures to prevent UV-related diseases. Here it has to be emphasised that these measures do not mean avoiding UV radiation and thus the sun completely. Rather, it is a matter of establishing the conditions for a conscious approach to the sun and UV radiation, and of making liveable UV protection possible.

Suitable measures are primary prevention measures to prevent UV-related diseases. Primary prevention comprises measures that, on the one hand, promote risk-conscious and health-oriented behaviour (behavioural prevention) and, on the other hand, shape people’s living, working, and environmental conditions in such a way that high UV exposures can be avoided to a large extent (structural prevention). In doing so, behavioural and structural prevention measures have to be meaningfully intertwined.

Effectively reducing the risk of UV-related diseases is a sociopolitical task and includes preventive measures from birth. In particular, an effective protection of children is required, as children have a significantly higher sensitivity of the eyes and the skin to UV radiation than adults. Some measures, such as creating effective shaded areas, can simultaneously serve to prevent outdoor heat stress hazardous to health. However, it must be considered that health-relevant UV irradiance levels can be present even when seeking shade is unnecessary, e.g. when it is cool or the sky is cloudy. Therefore, in places that are generally rather cool and where children as well as adults spend longer periods of time (outdoor areas in kindergartens and schools, public transport stops, etc.), it might be appropriate to install canopies from materials such as polycar-
bonate that block UV radiation but not heat. For shading measures, it should be noted that the sun-protective effect is influenced by the size, shape, and position of the shading structure, as well as by the surrounding environment and weather conditions [46]. Research suggests that shading of outdoor areas can increase the use of shade [2]. When using plants to generate shade, allergenic greenery should be avoided [43].

An important measure, in addition to creating shaded areas and ensuring UV protection for children, is to publicly display the prevailing UV irradiance, because UV radiation is not perceptible to humans and corresponding misconceptions of the UV-related health risk are ubiquitous. The sunburn-effective UV irradiance is measured by the Federal Office for Radiation Protection or modelled by the DWD and published as the UV Index, a globally uniform measure [47, 48]. The UVI values are divided into ranges for which different protection recommendations apply. The UVI is thus not only a guide for the expected sunburn-effective UV irradiance, but also provides recommendations as to the UVI values above which sun protection measures should be taken.

Recommendations with regard to surveillance and implications for a resilient public health system are addressed to science and politics (federal and state levels). With regard to their effective establishment and implementation, other actors are to be involved [42]. The recommendations listed in Table 1 are formulated in accordance with the recommendations of the oncological S3 guideline ‘Prevention of skin cancer’ [2] and the Climate Impact and Risk Assessment 2021 for Germany, sub-report 5 [43], and supplemented with further information and concrete measures for local authorities. Their order does not represent a weighting in terms of effectiveness or urgency. Unless otherwise stated, detailed information on the recommended measures can be found in the S3 guideline.

Effective implementation of the recommended measures also requires acceptance and motivation. The basis for this is, on the one hand, that medical, scientific, and official institutions provide comprehensive information regarding UV radiation, the effects of UV radiation, protection against UV radiation, preventive measures, and UV protection as a climate adaptation measure. On the other hand, funding is provided (see Info box 2).

5. Discussion and conclusion

The scientific measures considered necessary are very challenging – especially the description of a dose-response relationship for UV radiation/skin cancer and the projection of future ground-level UV exposure. Both the dose-response relationship and the UV projection are of great importance for a reliable assessment of the effects of future climate change-induced changes in UV exposure.

The measures recommended with regard to occupational and civil protection to reduce individual UV exposure are already partly being implemented. The driving force here is the fact that in 2015, due to the clear association with occupational UV exposure, the non-melanoma skin cancer entity, squamous cell carcinoma, and its precursors, actinic keratoses, were classified as an occupational disease [58]. Workers with outdoor jobs also have an increased risk of basal cell carcinoma [59]. Employers are accordingly obliged to carry out a risk assessment of outdoor activities, to take
Table 1
Recommended actions for science and politics to reduce UV exposure and to prevent UV-related diseases
Source: Own representation based on S3 guideline ‘Prevention of skin cancer’ [2] and Climate Impact and Risk Assessment [43]

<table>
<thead>
<tr>
<th>Field of action</th>
<th>Recommendations</th>
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<tr>
<td><strong>Science</strong></td>
<td>▶ Quantification of the effects of climate change (greenhouse gases – ozone layer – low ozone events, cloud cover, and aerosols) on UV exposure</td>
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<td>▶ Scientific evaluations and analyses of the current UV irradiance in Germany and the UV irradiance measured over the last decades.</td>
</tr>
<tr>
<td></td>
<td>▶ Development of suitable indicators for UV monitoring.</td>
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<td></td>
<td>▶ Development of projections of the UV radiation situation for Germany/Europe in relation to the scenarios modelled for possible future climate change developments, considering cloud cover, aerosol concentration, and reflectivity (albedo)</td>
</tr>
<tr>
<td></td>
<td>▶ Further research on the long-term effects of UV radiation on the eyes.</td>
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<td></td>
<td>▶ Establishment of registration procedures for UV-related diseases other than skin cancer and optimisation of existing registration procedures for all skin cancer entities</td>
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<td></td>
<td>▶ Description of a dose-response relationship UV radiation/skin cancer.</td>
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<td>▶ Investigation of the influence of temperature on the effects of UV radiation.</td>
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<td>▶ Investigation of a possibly combined health effect of UV radiation, air pollutants, and meteorological factors</td>
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<td>▶ Quantification of weather-dependent behavioural habits and clarification of the influence of climate change-induced weather and temperature changes on behavioural habits and individual UV exposure</td>
</tr>
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<td>▶ Evaluation of the implementation and effectiveness of recommended actions and preventive measures</td>
</tr>
<tr>
<td></td>
<td>▶ Development of geographic information system (GIS)-based modelling programmes to visualise UV exposure for urban and building planning as well as landscape architecture to create reasonably UV-reduced outdoor areas</td>
</tr>
<tr>
<td><strong>Occupational safety and health</strong></td>
<td>▶ Testing, evaluation, and optimisation of existing regulations and state rules on occupational health and safety (protection against work-related UV radiation hazards [49]) and on occupational medicine (precautionary examination for occupational disease BK 5103) in accordance with the Ordinance on Preventive Occupational Health Care (ArbMedVV) [50].</td>
</tr>
<tr>
<td><strong>Civil protection</strong></td>
<td></td>
</tr>
<tr>
<td>Behavioural prevention measures</td>
<td>▶ Financial support for the nationwide establishment of behavioural prevention measures</td>
</tr>
<tr>
<td></td>
<td>▶ Pedagogically evaluated information and education about UV protection measures (e.g. [51]) and their necessity for children and adolescents in day care centres and schools, with the involvement of parents. Examples: ‘Clever in Sonne und Schatten’ (Clever in Sun and Shade) [52], SunPass program [53]</td>
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<td></td>
<td>▶ Iterative, multi-media, interactive, multi-component, and multi-channel interventions for young people.</td>
</tr>
<tr>
<td></td>
<td>▶ Individualised interventions such as in the context of medical counselling sessions for adolescents and adults.</td>
</tr>
<tr>
<td></td>
<td>▶ Integration of the topic ‘protection from UV radiation’ into teaching, educational, and training curricula for early childhood education and school teaching on the basis of a catalogue of basic principles, as well as into teaching, study, and training curricula and further and advanced training for the occupational profiles to be addressed</td>
</tr>
<tr>
<td></td>
<td>▶ Development, evaluation, and optimisation of information and training offers</td>
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<tr>
<td></td>
<td>▶ Creation and demand-driven dissemination of target group-oriented information materials for vulnerable population groups</td>
</tr>
<tr>
<td></td>
<td>▶ Support for the activities of education institutions regarding the conception of further education measures in the social, health, and care sector</td>
</tr>
</tbody>
</table>

Table 1 Continued on next page
### Field of action | Recommendations
--- | ---
Civil protection  Structural prevention measures  Federal / state levels  | - Political and programmatic anchoring of behavioural and structural prevention measures for the prevention of UV-related diseases. The legal prerequisites for this are provided, in Germany, by the Prevention Act, the Early Cancer Detection and Registry Act, the ‘Patientenrechtsgesetz’ (Act on Patients’ Rights), supplemented by a legal obligation arising from the Building Code (§ 1, par. 6, nos. 1 and 7c; consideration of the general requirements for healthy living and working conditions as well as the environmental impact on people and their health)
- Inclusion of measures for the prevention of UV-related diseases in people’s living environments in funding programmes for adaptation measures to the impact of climate change and urban development funding
- Consideration of UV radiation as a health-relevant environmental factor in the establishment of an integrated environmental health monitoring system at federal level
- Establishment of preventive measures for the prevention of UV-related diseases within the framework of heat-health action plans [54]
- Integration of UV exposure into early warning systems (e.g. heat alert system)
- Information on characteristics of different tree species and on-site factors with regard to shade and transpiration processes for the effective reduction of heat and UV exposure
- Promoting the nationwide establishment of structural prevention measures at the municipal level

Civil protection  Structural prevention measures  Municipalities  | - Identifying and establishing interfaces and docking points for structural prevention measures to reduce outdoor UV exposure in (planning) processes for urban development, town planning, and building planning. Embedding area-related activities to reduce health-relevant UV exposures in a cross-area development policy
- Inclusion of structural prevention measures, including the demand for their implementation in municipal tenders for urban development, urban and building planning as well as landscaping (new buildings, renovation measures of existing open spaces and buildings)
- Funding and municipal implementation of the following measures are recommended:
  - Display of the UV Index in public spaces (outdoor swimming pools, bathing areas, city squares, etc.)
  - Creation of shaded areas by means of structural-technical measures (roofing, sun sails, parasols, awnings, etc.) [55] as well as tree planting (see the road-side tree list of the German Conference of Garden Authorities [56]) in municipalities, in public transport waiting areas, and in day care centres and schools
  - Use of non-reflective surfaces for building walls to reduce albedo (surface reflectivity)
  - Construction of facade greening (see publication of the Federal Agency for Nature Conservation [57])
  - Desealing and greening of open spaces

---

**Table 1 Continued**

**Recommended actions for science and politics to reduce UV exposure and to prevent UV-related diseases**

Source: Own representation based on S3 guideline ‘Prevention of skin cancer’ [2] and Climate Impact and Risk Assessment [43]

Suitable protective measures [60] if necessary, and to document them. This applies to the approximately two to three million employees in Germany who work mainly or exclusively outdoors [61] as well as to children in day care centres and schools who are insured through accident insurances.

For an effective reduction of UV exposure for all, the measures recommended at the local level are crucial, which can also be seen in the context of recommendations in other articles of this status report, especially those on heat, as summarised by Winklmayr et al. [41]. At best, the recommended measures correspond or complement each other. However, with regard to the recommendations for adaptation to heat, one contradiction becomes apparent: for protection against UV radiation, surfaces of buildings should have low to no albedo (surface reflectivity) [2], but for heat reduction indoors, it is recommended to increase the albedo of building exteriors [43]. The recommendation for a low albedo is based on the fact that due to reflected heat.
The steady increase in incidence of UV-related skin cancer alone requires action be taken now, especially since it takes years to establish effective prevention measures.

### Info box 2

**Information, recommendations, and funding for effective UV protection in Germany**

- German Commission on Radiological Protection
- German Guideline Program in Oncology (German Cancer Society, German Cancer Aid, Association of the Scientific Medical Societies in Germany (AWMF)): S3 guideline ‘Prevention of skin cancer’
- German Federal Office for Radiation Protection: Background information and teaching materials on UV radiation, UV radiation and climate change, UV Index, effects of and protection against UV radiation, and on the UV campaign ‘UV safe’ with packages of measures for local authorities, kindergartens, schools, and sports clubs
- Federal Centre for Health Education (Bundeszentrale für gesundheitliche Aufklärung, BZgA): child health – sun protection for children and Klima-Mensch-Gesundheit (BZgA website, including the topics UV radiation and UV protection (2022))
- Climate Impact and Risk Assessment 2021 for Germany, sub-report 5, cluster ‘Health’, climate impact ‘UV-related health damage’
- Recommendations for the preparation of heat-health action plans including UV radiation
- German Cancer Aid (Stiftung Deutsche Krebshilfe) provides detailed information on its website about UV radiation and skin cancer
- Federal Institute for Occupational Safety and Health, German Social Accident Insurance and Federal State Accident Funds
- Funding by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection especially for municipalities and municipal institutions as well as social institutions

This compilation is a selection and makes no claim to completeness.

radiation, UV exposure can be intensified in the vicinity of such buildings. A reduced surface albedo would also be positive in terms of heat protection, as the temperature near these buildings may increase due to a high reflectivity of building exteriors. One solution to this contradiction would be to achieve effective heat reduction indoors by means of appropriate building insulation and ventilation.

Behavioural and structural prevention measures to minimise UV-related disease risk are easy to implement, but can be cost-intensive. Internationally, such measures are evaluated positively from a health economic perspective, as corresponding analyses clearly showed a high economic and health-related benefit.

The investment can significantly reduce skin cancer cases and deaths, which are a particularly heavy burden on the health system, and save the health sector and the economy (due to prevented productivity losses) double to four times the costs invested in prevention measures [2].

The integration of preventive measures in municipalities including day care centres, schools, clubs, and societies requires a multidisciplinary approach. A shading policy established at the municipal level is recommended [46].

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Impact of climate change on allergic diseases in Germany

Abstract

Background: Allergic diseases, especially inhalation allergies, have reached epidemic levels and environmental factors play an important role in their development. Climate change influences the occurrence, frequency, and severity of allergic diseases.

Methods: The contents of this article were selected by the authors and developed section by section according to their expertise and the current state of knowledge. The sections were then discussed and agreed upon amongst all authors.

Results: The article highlights direct and indirect effects of climate change on allergies. It goes into detail about the connections between climate change and (new) pollen allergens as well as (new) occupational inhalation allergens, explains the effects of climate change on the clinical picture of atopic dermatitis, discusses the connections between air pollutants and allergies, and provides information about the phenomenon of thunderstorm asthma.

Conclusions: There is a need for action in the field of pollen and fungal spore monitoring, allergy and sensitisation monitoring, urban planning from an allergological perspective, and changes in the working environment, among others.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.
Impact of climate change on allergic diseases in Germany

Recommendations on the topics of pollen and fungal spore monitoring, allergy and sensitisation monitoring, urban planning under allergological aspects, and changes in the working environment conclude the article.

1.1 Definitions of terms: Allergy, sensitisation, atopy

An allergy is an exaggerated response of the immune system to a normally harmless substance from the environment. Depending on the way the immune system reacts to this substance, the allergen, four types of allergy are distinguished, of which type I, also known as immediate-type, and type IV (contact hypersensitivity) are the most common (Table 1). Classic type I allergies are allergic rhinitis/rhinoconjunctivitis, also known as hay fever, and allergic bronchial asthma. The classic representative of a type IV allergy is allergic contact dermatitis. Why the immune system reacts allergically, i.e. in an exaggerated manner, to some substances from the environment has not been conclusively clarified.

In the context of allergies, we speak of type I sensitisation if allergen-specific immunoglobulin E (IgE) antibodies can be detected in the blood and/or if the skin test (prick or intradermal test) is positive. After sensitisation, renewed exposure to the allergen in allergic people leads to the release of mediators eliciting the allergic symptoms.

Atopy (atopía, Greek = placelessness) is a familial predisposition to develop allergic diseases (especially of the immediate-type/type I) based on an immunological hypersensitivity of the skin and mucous membranes to allergens, which is accompanied by an increased production of IgE antibodies and the formation of allergen-specific IgE antibodies. Atopics are thus a subgroup of people with allergies and often show some typical clinical manifestations. These include a double fold on the lower eyelid (Dennie-Morgan fold), dark skin around the eyes, thinning of the lateral eyebrows (Hertoghe’s sign), predominantly dry and itchy skin, and a dry scalp.

1.2 Frequencies of allergic diseases and sensitisations

Worldwide, the prevalence of allergic diseases has increased strongly over recent decades and is currently stagnating at a high level. It is estimated that a total of 20 to 30 million people in Germany are affected by allergies [2], and the age of onset tends to decrease [3]. The increase in allergic diseases has been accompanied by concurrent changes in lifestyle and environment. Many factors associated with these changes were linked to the increased occurrence of allergic diseases, as illustrated, for example, by comparisons between East Germany and West Germany [4].

Cross-sectional population data

Population-representative data on the epidemiology of allergic diseases in Germany are provided by the ongoing health monitoring at the Robert Koch Institute [5]. For adults, the most recent data are from the nationwide survey ‘German Health Update’ (GEDA 2019/2020-EHIS), which was conducted between April 2019 and September 2020. This survey includes the questionnaire of the European Health Interview Survey (EHIS), which takes place every five years. Based on respondents’ self-reports, 8% of adults currently suffer from bronchial asthma (including...
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Allergic asthma), i.e. in the last 12 months before the survey. Almost one third of adults (31%) reported that they were currently affected by an allergy. Allergies asked about in the GEDA 2019/2020-EHIS were hay fever, allergic reactions of the eyes or skin, food allergies, or other allergies (except allergic asthma). Overall, women reported being affected by allergic diseases more frequently than men [6].

A detailed survey of the frequency of physician-diagnosed allergic diseases was last carried out in the nationwide study ‘German Health Interview and Examination Survey for Adults’ (DEGS) from 2008 to 2011. At that time, around 16% of adults stated that they had received a medical diagnosis of hay fever (allergic rhinitis). Allergic rhinitis is thus the most common allergic disease. The lifetime prevalence of bronchial asthma was around 9% (however, not all types of asthma have an allergic genesis). Allergic contact dermatitis, which had been diagnosed by a doctor in about one in eleven adults (9%) at some time in their lives, was similarly frequent to bronchial asthma. Less prevalent were food allergies (5%), atopic dermatitis (4%), and insect venom allergy (3%). With the exception of atopic dermatitis, women were more often affected by allergic diseases than men [7].

Sensitisation is even more common than allergic diseases. The DEGS study showed that allergen-specific IgE antibodies against environmental allergens were detectable in the serum of 50% of adults in Germany. For example, 34% of adults were sensitised to a mixture of timothy, rye, birch, mugwort, cat, dog, dust mite, and Cladosporium herbarum (sx1 allergen mixture), 26% to food allergens (with only 2% being sensitised exclusively to food allergens), and 19% each to grass and tree pollen. 11% were sensitised to herb pollen [8].

For children and adolescents, population-based prevalence of allergic diseases and sensitisation were most recently derived on the basis of the second follow-up survey of the ‘German Health Interview and Examination Survey for Children and Adolescents’ (KiGGS Wave 2; data collection 2014 to 2017). According to this study, 11% of all children and adolescents aged 0 to 17 years had received a

### Table 1: Overview of allergic reaction types

<table>
<thead>
<tr>
<th>Name (type)</th>
<th>Reaction process</th>
<th>Duration from contact to reaction</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I, immediate-type</td>
<td>Mediation through allergen-specific IgE-antibodies, release of mediators (especially histamine)</td>
<td>Seconds to minutes (potential late-phase reaction after 4–6 hours)</td>
<td>Allergic rhinitis/conjunctivitis, allergic asthma, urticaria, insect venom allergy, anaphylaxis</td>
</tr>
<tr>
<td>Type II, cytotoxic type</td>
<td>Formation of antigen-antibody-complexes, destruction of the body’s own cells</td>
<td>6–12 hours</td>
<td>Transfusion reactions, some drug reactions and autoimmune diseases</td>
</tr>
<tr>
<td>Type III, immune complex type</td>
<td>Formation of antigen-antibody-complexes, release of tissue-damaging substances</td>
<td>6–12 hours</td>
<td>Allergic vasculitis, serum sickness, exogenous allergic alveolitis (e.g. farmer’s lung)</td>
</tr>
<tr>
<td>Type IV, contact/delayed-type</td>
<td>Mediation through cells (allergen-specific T lymphocytes)</td>
<td>12–72 hours</td>
<td>Allergic contact dermatitis, drug reactions, transplant rejection reaction</td>
</tr>
</tbody>
</table>

Source: Allergieinformationsdienst [1] (original language German)
Impact of climate change on allergic diseases in Germany

Allergic diseases, especially inhalation allergies, have reached epidemic levels. One of the most common triggers of inhalation allergies are the allergens contained in pollen.

Medical diagnosis of hay fever at some point in their lives, and the figure for bronchial asthma was 6%. Boys were affected more often than girls. The lifetime prevalence of atopic dermatitis was 13%, with girls being affected more frequently than boys. In both girls and boys, 3% had already been diagnosed with allergic contact dermatitis by a doctor at some point in their lives [9].

37% of children and adolescents in Germany were sensitised to the sx1 allergen mixture consisting of the above-mentioned eight inhalation allergens. The prevalence of sensitisation to timothy and rye pollen, birch pollen, and dust mites was between 14 and 23%, and the prevalence of sensitisation to most of the animal and food allergens tested was between 5 and 11%. Boys were generally more frequently sensitised than girls.

A factor analysis regarding sensitisation patterns identified seven sensitisation groups for girls and boys alike, namely timothy/rye pollen, birch pollen/apple, food/mugwort pollen, dust mites, animals, cow’s milk/egg white and mould [9,10].

Population-based longitudinal data
Studies on the development on an individual level (longitudinal) within the KiGGS cohort showed that every fifth girl (21%) and every third boy (29%) newly developed a sensitisation to at least one of the sx1 allergens in the course of ten years of life (cumulative 10-year incidence). Additionally, it was shown that once sensitisation had been detected, it persisted for the most part. Only in 11% of the affected girls and 6% of the affected boys was sx1 sensitisation no longer detectable (remission) ten years later [11]. Longitudinal results in adults indicate that the observed increase in the prevalence of sx1 sensitisation is most likely a cohort effect, due to a higher prevalence in younger cohorts [12].

1.3 Pollen as an allergy trigger

The most common trigger of allergic respiratory diseases are pollen or, more specifically, the allergens they contain.

Pollen consists of pollen grains, which can range in diameter from less than 10 μm (e.g. woodland forget-me-not pollen) to more than 100 μm (e.g. white fir pollen) [13].

Pollen is part of plant reproduction. The transfer of pollen grains from the male anther to the female stigma is called pollination. There are two basic types of pollination: in autogamy (self-pollination), the pollen is transferred to the stigma of the same flower or to the stigma of another flower of the same plant (geitonogamy). In allogamy (cross-pollination), the pollen from one plant is transferred to the flower of another plant. Pollination occurs through transport vectors such as water (hydrogamy), animals (zoogamy) or wind (anemogamy). The most common way of pollen transfer is zoogamy, in Germany specifically insect pollination (entomogamy, e.g. in dandelions or apple trees).

However, from an allergological point of view, anemophilous plants, i.e. plants with characteristics that favour the transmissibility of pollen by wind, play the most important role in Germany; most allergy-relevant pollen taxa belong to this group. The usually large amount of pollen of anemophilous plants in the air leads to an increased human exposure to the pollen of these plants, which also increases the possibility of developing sensitisation and allergic symptoms. Typical representatives of anemophilous
additional, if precipitation changes only slightly, soils can be expected to dry out more quickly during the vegetation period if land use does not change. The number of days with low soil moisture has already increased significantly since 1961 and will continue to increase [17, 18]. Consequently, the water availability for plants within the vegetation period decreases and dryness and drought can be expected to increase. From 1971 to 2000, the average number of months of drought in Germany was about two months per year. A warming of 3°C would double the drought duration [19]. At the same time, a rise in temperature leads to an increase in the potential for extreme precipitation events, which in turn can lead to increased flooding [20]. With the increase in extreme events, the potential for so-called thunderstorm asthma also increases (Info box).

2. Climate change and allergies: Direct and indirect effects

As mentioned in the introductory article of this status report [15], the mean air temperature in Germany has increased by about 1.6°C since the beginning of nationwide weather records in 1881. By the end of the century (2071–2100), an increase in the annual mean temperature of at least 1°C to more than 4°C is expected in Germany, depending on the emissions scenario, with the strongest warming in the Alps and the Alpine foothills. Overall, the warming is expected to be similar in the different seasons, with the exception of spring, where model calculations show a slightly lower warming [16, 17]. Precipitation in Germany has increased by 8% in the annual sum since 1881. While the greatest increase is in winter, followed by spring and autumn, summer precipitation has decreased slightly. By the end of this century, a further 8% increase in annual precipitation is expected compared to the period 1971 to 2000. The largest increases of up to 17% will occur in winter, while a decrease in precipitation is expected in summer. It should be noted that modelled changes below 10% cannot be distinguished from natural climate variability [17].

In addition to temperature and precipitation, evaporation and soil moisture also play a role in plant development. Evaporation usually increases with higher temperatures. In plants with allergy-relevant pollen are hazel, alder, birch, oak, grasses, and mugwort. However, pollen of entomophilous plants can also become airborne in quantities sufficient to trigger sensitisation or allergy in Germany (e.g. tree of heaven pollen [14]).

2.1 Climate change and (new) pollen allergens

Changes in the phenological development of pollen-producing plants

Plant development and thus the pollen season depend significantly on the interaction of temperature and precipitation. The last decades of the 20th century saw a significant shift in the phenological seasons, i.e. the onset of different developmental stages of plants (from flowering to leaf fall) [17], which also resulted in a shift of the pollen season. In hazel, for example, the onset of flowering has shifted forward by about one month since 1951, while the beginning of leaf discolouration of English oak (late autumn), which is used here as an indicator for the end of the vegetation period, has occurred only slightly later (Figure 1). The end of the growing season is generally controlled less by temperature than by
The flowering and therefore the timing of pollen occurrence is changing. Changes in pollen concentration and in the spectrum of allergenic pollen are also to be expected.

### Info box

**Extreme weather and asthma**

In the course of climate change and increasing extreme weather events, the phenomenon of thunderstorm asthma could become more significant in Germany. Severe asthma attacks can occur during thunderstorms, especially in people with hay fever and allergic asthma. Asthma has also been observed during thunderstorms in people who only suffer from hay fever. The phenomenon of thunderstorm asthma has occurred relatively rarely so far: worldwide, about 30 such events have been recorded since 1983, mainly in Australia and England. The exact mechanisms of thunderstorm asthma are not yet fully understood [21–23]. Essential features of thunderstorm asthma are:

- Occurrence mainly in late spring and summer during special weather events such as thunderstorms or convergence lines
- (Unusually) high concentration of aeroallergens in the air, sometimes even several days before the weather event (aeroallergens in connection with thunderstorm asthma are mainly grass pollen, but also tree and herb pollen as well as fungal spores; weather changes such as precipitation, increase in humidity and lightning activity can fragment pollen, creating smaller, easily respirable particles to which allergens are bound and which are transported to the ground by strong downdrafts)
- Onset of symptoms often during the first 20 to 30 minutes of the weather event (increased risk of severe symptoms such as acute asthma attacks, increased risk of emergency room visits)

Even if the pollen of beech and oak (beech family) has low allergy potential, allergen exposure can be increased by cross-reactivity to pollen of botanically related species like birch, alder, hazel (birch family). In addition, mast years

Influence of climate change on plant productivity

Due to increasing CO₂ concentrations, an increase in the amount of pollen is to be expected, as shown, for example, by experiments on ragweed [28, 29] and timothy [30]. High pollen concentrations also occur in so-called mast years. In these years, increased seed production occurs in certain tree species. Mast years are subject to a specific cycle; for beech, for example, mast years occur approximately every three to six years and for oak every six to twelve years [31]. Even if the pollen of beech and oak (beech family) has low allergy potential, allergen exposure can be increased by cross-reactivity to pollen of botanically related species like birch, alder, hazel (birch family). In addition, mast years
Due to the influence of climate change on plant development, there are changes in the exposure of the population to allergenic pollen. These concern: (a) the timing of pollen flight; (b) pollen concentrations; (c) the pollen spectrum; and (d) the allergenicity of pollen, among other things in connection with changes in air quality, for details see Section 2.4 Air pollutants.

Changes in the timing of pollen occurrence
Using the symptom-oriented definition of a pollen season by the European Academy of Allergy and Clinical Immunology [38], the strongest changes can be observed in the birch pollen group (e.g., hazel, alder, birch, beech, oak). The seasonal onset of this group has occurred about two to  }
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The earlier start of the birch pollen flight has also been recorded in the national pollen calendars, which have been published for decades by the German Pollen Information Service Foundation (Stiftung Deutscher Polleninformationsdienst, PID) [25]. Similar observations have been made for beech pollen at two PID monitoring sites located several hundred kilometres apart and at different altitudes [42].

The flight of grass pollen has changed less, tending to start earlier. In some countries (United Kingdom, Spain, Portugal) a prolongation of the flight of grass pollen has been observed [43]. As a result of warmer autumn months, a prolonged flight of mugwort and ragweed pollen can also be expected; based on measurements between 2011 and 2016, the pollen calendar 4.0 indicates a possible occurrence of mugwort and ragweed pollen from June to the end of October/beginning of November [25].

Overall, the earlier start of the tree pollen season and the extension of the herb pollen season into autumn results in a spread of the pollen season for allergenic plant species. This prolongs the symptom period for those who are allergic to tree pollen as well as grass and herb pollen. Since polysensitised people generally have a higher risk of developing more severe symptoms and bronchial asthma [44], the extended exposure period poses a particular risk for this group of people.

Changes in pollen concentrations

The annual sums of the allergenic pollen relevant in Germany have been subject to constant changes over the last two or three decades. For example, in the case of birch, a year with a high pollen release was often followed by a year with a lower release. However, the average annual pollen sum for birch has tended to increase (Figure 2). For the PID monitoring site in Munich, the number of days with high birch pollen concentrations (≥100 pollen/m³) has also increased significantly [45].

The only previously published data on the course of the annual pollen sum of 23 pollen types from 97 measurement sites in Europe over recent decades showed significant increases for ten of them, including alder, birch, hazel, ash, plane, oak, and cypress. In contrast, the annual pollen sum of mugwort showed a significant decrease [47].

However, the severity of allergic symptoms does not depend solely on the pollen concentration as the allergen content of the pollen is also important. A grass pollen grain contains <1 to 9 picograms (pg) Phl p 5 (major allergen of grass pollen), the average value is 2.3 pg Phl p 5. However, grass pollen does not release Phl p 5 continuously, so that patients can be symptom-free despite pollen flight depending on climatic conditions. The concentration of free allergens increases with humidity [48]. The symptoms of people with allergies thus depend not only on the extent of the pollen count, but also on climatic conditions [49].

Changes in the spectrum of allergenic pollen

With climate change progressing, the spectrum of allergenic pollen in Germany will very likely continue to change:

(A) The allergological significance of pollen from some free-growing but non-native plant species will increase.
(B) New pollen allergens will occur.
(C) The allergological significance of pollen of some native plant species may change.
Scenario A is discussed in more detail below. Scenario B is exemplified by olive tree pollen [50, 51], scenario C by birch tree pollen [52].

Scenario A, example 1: Ragweed pollen
The common ragweed (*Ambrosia artemisiifolia*) is native to North America and produces large amounts of pollen with high sensitisation and allergy potential [53, 54]. In the United States, as many people are sensitised to ragweed as to grasses [55]. The plant probably reached Europe via cereals or clover seed and is now widespread mainly in Ukraine, Hungary, Italy (Po Valley), and France (Rhone Valley). In Germany, it was found growing wild as early as 1860 and for a long time was considered impermanent and rare. However, for several years it has continued to spread [53, 54]. In addition to human-aided entry, current changes in climate seem to be promoting the growth of the plant and its pollen and allergen production [56].

In 2006 and 2014, considerable amounts of ragweed pollen were detectable in Germany, having probably entered via long-distance transport from Hungary (Figure 3). Due to existing cross-reactivities to the native mugwort, clinical complaints in patients allergic to mugwort could have occurred despite the one-off event. However, there are no data on this. Compared with the long-distance transport events of 2006 and 2014 and with the annual average for Germany as a whole, significantly higher pollen concentrations have been detectable in the region around Drebkau in south-eastern Brandenburg for several years, resulting from the establishment of the plant in this region (Table 2).

![Figure 2](image-url)

**Figure 2** Overview of the mean number of birch pollen measured per year at various monitoring stations in Germany with trend line. Percentages show the respective change compared to the previous year. Source: German Pollen Information Service Foundation [46] (original language German)
ways (RCP) scenarios (RCP4.5 and RCP8.5). Furthermore, pollen concentrations in Germany will be at least twice as high in the main flowering season as in the comparative period 1985 to 2005. Pollen in clinically relevant amounts will also be detectable in the off-season [59]. With regard to population-related sensitisation to ragweed pollen, an increase from 0 to 10% in the period 1985 to 2005 to an increase of 15 to 25% in the period 2041 to 2060 is assumed for Germany [59].

Scenario A, example 2: Wall pellitory pollen

The wall pellitory (Parietaria officinalis) is widespread in central and southern Europe and is considered an archaeophyte in Germany (i.e. plant species permanently established before 1492). In southern European countries, patient-related sensitisation rates against wall pellitory are around 20%. In Germany, the percentage is below 10% (prick test data: [60], allergen-specific IgE data: [61]). With climate change progressing, wall pellitory plants could...
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Outdoors workers in particular are affected by exposures to plant and animal profiteers of climate change.

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Spread in Germany and subsequently lead to an increase in the number of patients with wall pellitory allergy.

Scenario A, example 3: Pollen of the tree of heaven

The tree of heaven (*Ailanthus altissima*) is present on all continents except Antarctica, but is only native to parts of Asia. In Germany, it is currently mainly found within urban heat islands. It is expected to spread beyond these heat islands as warming continues [62]. The tree is predominantly insect-pollinated, but its pollen can also be dispersed by wind and, beyond possible cross-reactivity, could also become allergenic in this country [62–64].

2.2 Climate change and (new) occupational inhalant allergens of animal, plant, and microbial origin

As a result of climate change, the conditions of employees in various workplaces will change in many ways. The agricultural and forestry sector, with more than 4.4 million jobs in the European Union (about 9.2% of the total workforce) and almost one million workers in Germany [65], is highly vulnerable to climate change. Studies point to strong regional differences in the spatial distribution of climate impacts. In the northern regions, for example, this is noticeable in the variability of crop yields and in an increase in pest infestations and diseases, which in turn can lead to health problems for the exposed employees.

Oak processionary moth

The oak processionary moth (*Thaumetopoea processionea*) belongs to the moth family Notodontidae. The stinging hairs of the caterpillar can cause both dermal (so-called caterpillar dermatitis) and respiratory complaints in humans. The pine processionary moth (*Thaumetopoea pityocampa*) and the northern pine processionary moth (*Thaumetopoea pinivora*) belong to the same subfamily. Their distribution has so far been described mainly in southern Europe, but is expected to also spread to Germany due to progressive climate change.

Processionary moths, mostly the oak processionary moth in Germany so far, are beneficiaries of climate change. They cause forestry damage in infested areas and pose a health hazard to humans, including landscapers and arborists. Fluctuating weather conditions can have a major impact on the development of this moth [66]. Very strong populations have been observed in the spring months during mild weather when conditions were good (little wind and precipitation, lots of sun) especially during moth flight and egg laying in the preceding late summer.

The third larval stage, in particular, poses the health hazard, as the caterpillars form stinging hairs that contain the protein thaumetopoein (nettle poison). The fine hairs break easily, can fly hundreds of metres with the wind and attach themselves to the skin of humans and animals via barbs. Direct contact with the stinging hairs of the oak processionary moth can cause mechanical-irritative, toxic and also allergic reactions, which can lead to skin irritation, eye irritation, fever, dizziness, and in individual cases even allergic shock. Breathing in the fine hairs can also cause respiratory problems such as bronchitis and asthma.

Hard ticks

Other beneficiaries of climate change include hard ticks, which prefer warmer air temperatures and high humidity.
Moulds
Increased humidity combined with higher temperatures and $\text{CO}_2$ levels promotes fungal growth. Workers who carried out renovation work immediately after flood events were exposed to increased levels of mould [70]. In addition to spores, fragments of mycelial filaments (0.2 to 10 mm in length) are airborne allergen carriers that can occur in even greater quantities than spores. One can therefore be exposed to mould allergens through both spores and mycelial fragments. Mould exposures can cause various diseases of the upper and lower respiratory tract and the skin, for example allergic rhinitis or asthma.

Cannabis plants
Cannabis plants are also among the beneficiaries of climate change, as the plant thrives better under increased UV radiation exposure, which can be a result of climate change. In addition, cannabis and hemp plants are becoming increasingly important as raw materials with a growing range of products for fibre products, food and medicines. The increasing range of hemp-based products is leading to more and more employees working in this growing industry. Exposure to components of the cannabis plant in these workplaces is causing an increasing number of health problems, especially allergic complaints [71]. Sussman et al. [72] point out that the increase in cannabis use could lead to a scenario comparable to that caused by natural rubber latex exposure in the health sector in the 1980s and 1990s.

New allergens associated with food and feed production
In addition to the direct influences of climate change on allergen exposure in workplaces and thus often also on the
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Some people with atopic dermatitis also suffer from a pollen allergy, which further aggravates the symptoms during heat, sun, and pollen exposure [76]. The altered pollen flight due to climate change can thus lead to increased symptom severity for this group [77].

Certain diseases may occur together with atopic dermatitis as a result of exposure to harmful environmental factors or lack of protective factors. These include, in particular, allergies, allergic asthma, eosinophilic oesophagitis (allergy-like inflammation of the oesophagus), and urticaria. Atopic dermatitis is a major risk factor for the development of allergies [78]. These diseases are thought to be linked through complex genetic, epigenetic, and immunological mechanisms.

From demographic change and the increasing incidence of atopic diseases in middle and advanced age, it follows that older persons and those with comorbidities are also increasingly becoming vulnerable groups to the consequences of climate change.

2.3 Atopic dermatitis and climate change

Atopic dermatitis (atopic eczema) is a chronic, itchy, inflammatory skin disease that is a considerable burden for patients [75].

It is triggered and exacerbated by environmental changes like those already occurring in Germany and Europe due to climate change, such as longer periods of heat, accumulation of tropical nights, and higher average temperatures. People suffering from atopic dermatitis should take measures to protect themselves from UV radiation and heat. Early warning systems can enable patients to better plan their daily routine and, if necessary, to refrain from outdoor activities in extreme heat or to postpone them until the early morning hours.

2.4 Air pollutants: Influence of air pollution on pollen grains, aeroallergens and allergic reactions

Experimental studies show that the combined effect of pollen and air pollutants is particularly unfavourable for people with allergies. The effects of air pollutants on health, as described by Breitner-Busch et al. [79] in this status report, and on respiratory allergies in particular, depend on a combination of factors including concentrations of environmental pollutants (e.g. nitrogen dioxide (NO₂), carbon monoxide (CO), ozone (O₃)), duration of exposure, ventilation, climatic conditions, and the interaction between pollutants.
and pollen. Air pollution seems to have several effects on pollen grains: changes in biological and reproductive functions, alterations of physico-chemical properties of the pollen surface, alterations of allergenic potential, and an adjuvant effect that increases potential health risks [80].

Pollen wall damage, allergen release and distribution in the environment
The flowering and pollen seasons are sensitive to environmental variability in terms of meteorological parameters, but also in terms of pollutants. Recently, an earlier flowering season has been demonstrated due to the combination of higher temperatures and degree of urbanisation. This is observed most clearly at sites with higher NO₂ concentrations [40]. Additionally, a decrease in viability and/or germination of pollen exposed to very low O₃ or NO₂ concentrations in vitro has been observed in several species [81, 82]. It can be assumed that pollen in nature is exposed to both pollutants simultaneously and thus synergistic effects can be expected, since the presence of O₃ increases NO₂ uptake. This favours the nitration of proteins and thus impairs protein/enzyme functions [83].

According to various studies, pollen grains in areas with high air pollution are smaller and more fragile than in areas with lower air pollution. The interaction between air pollutants and pollen grains could damage the pollen wall and increase the number of allergens released into the environment [84], which eventually penetrate the lower airways and cause asthma-related symptoms.

There is some evidence that climate change and air pollutants as plant stressors change the morphology of antigens and thus the allergenic potential of pollen particles. Pollen from urban areas and from more polluted regions has a higher allergen content per pollen grain [85]. A higher allergen content was detected in extracts from birch pollen exposed to high O₃ concentrations [86].

In addition, some studies show that allergenicity and viability of some pollen species increase when vegetation is increasingly polluted with certain pollutants. NO₂, a major traffic-related air pollutant, was found to increase the allergenicity of the birch pollen allergen Bet v 1 [87].

Finally, several air pollutants act as adjuvants (amplifying agents) by binding to allergens and stimulating IgE synthesis, leading to an exacerbation of asthma symptoms. Several in vitro studies have shown that traffic-related air pollutants can modify pollen, increasing the frequency and intensity of symptoms in allergic individuals [80, 88]. In predisposed individuals, airway sensitisation to aeroallergens may be promoted [89]. By inducing airway inflammation, pollutants can damage the mucosal barrier, triggering an allergenic response [90]. Damage to the airway mucosa can facilitate the access of inhaled allergens to the cells of the immune system.

3. Recommendations
3.1 Pollen and fungal spore monitoring
Clinical and societal significance of pollen and fungal spore monitoring
There are various pharmacological and non-pharmacological measures for the prevention and treatment of allergic respiratory diseases caused by pollen or fungal spores [91]. One of the primarily non-pharmacological approaches is to be able to inform oneself – as the person affected or as the attending physician – about when, where, and in what
quantity allergy-triggering pollen or fungal spores are present in the air in order to (a) avoid these places if possible and (b) be able to take medication before the onset of symptoms if necessary.

Continuous pollen monitoring also makes it possible to observe local, regional or transnational changes in the pollen spectrum and pollen flight. For such observations, which can be used as one of the tools in uncovering the relationships between climate change, nature, and health, it is necessary to ensure high-quality and long-term measurements of a broad spectrum of pollen and fungal spores at the same sites, as provided by the PID since 1983.

Air sampling and analysis of pollen and fungal spores

Air sampling can be passive, by sedimentation or filtering of the air, or active, by aspiration of a defined volume of air using a volumetric pollen and spore trap. The subsequent analysis of the airborne dust samples for pollen and fungal spores is mainly carried out by pollen analysts using light microscopy, less frequently by DNA analysis or by newly developed automated identification of pollen taxa using various methods (e.g. digital microscopy, fluorescence) [92–96].

Status quo of pollen and fungal spore monitoring in Germany

As in most European countries, there is a nationwide pollen monitoring network in Germany, which has been operated by the PID since 1983. The sites of the current monitoring stations are shown in Figure 4.

The PID monitoring network currently operates on the basis of the Hirst-type volumetric spore trap [93] and light microscopic pollen analysis [95]. Part of the measured pollen data is used for the pollen forecast (Pollenflug-Gefahrenindex) for eight allergy-relevant pollen types provided by the Deutscher Wetterdienst (DWD; German Meteorological Service) [98]. As pollen from other plants and fungal spores also trigger sensitisation and allergies, monitoring by the PID covers a wider spectrum of pollen types as well as some allergy-relevant fungal spores, specifically Alternaria, Cladosporium, Epicoccum, and Pleospora at a limited number of monitoring stations. Based on these data, the PID publishes detailed weekly pollen and spore forecasts for Germany [99]. The nationwide pollen monitoring also forms the basis for national and regional pollen calendars, which are reissued every few years [25].

Further development of pollen monitoring

The long-term maintenance and further development of nationwide pollen monitoring as well as the further development and expansion of fungal spore monitoring can only be guaranteed if funding is secured.

To this end, the interdisciplinary Working Group Nationwide Pollen Monitoring was formed in 2017 and developed a position paper on perspectives for nationwide pollen monitoring in Germany [100]. The paper addresses: (a) the health and economic importance of pollen and pollen data; (b) methods for measuring pollen data; (c) the status quo of the nationwide pollen monitoring network in Germany; (d) pollen monitoring networks in other European countries; (e) legal framework conditions in Germany; and (f) possibilities for a reliable nationwide pollen monitoring network. In its conclusion, the working group provides the following recommendation:

Pollen monitoring is an important tool for uncovering the relationships between climate change and health and should be included in services of general interest.
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3.2 Allergy and sensitisation monitoring

Monitoring at population level

Allergies are a highly relevant public health issue due to the large number of people affected in Germany. In order to address the problem of allergies affected by climate change by suitable primary, secondary, and tertiary prevention measures, the description of the current state and the observation of developments over time (trends) need to be continuously provided by indicator-based surveillance. Surveillance is defined by the World Health Organization as ‘the systematic on-going collection, collation and analysis of data […] and the timely dissemination of public health information for assessment and public health response’ [101, P. 14].

Suitable allergy indicators can be found, on the one hand, in the frequency and therapy of manifest diseases essential goods and services (services of general interest)’. It further states: ‘With regard to possible responsibilities within the framework of services of general interest, several approaches were discussed in the working group. These included the possibility of entrusting a federal institution, such as the DWD, with the continuation and further development of the nationwide pollen monitoring network. Another possibility would be to transfer the task to the German Pollen Information Service Foundation or other institutions. Regardless of the future responsibility, the cooperation of metrological, clinical, and scientific institutions is of fundamental importance for adequate preventive health measures’ ([100, P. 659] original language German).
Allergy and sensitisation monitoring should be permanently established at both population and patient levels.

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with clinical symptoms. On the other hand, sensitisation is relevant as a disease-related risk factor, since the immune system classifies an initially harmless environmental substance (allergen) as harmful and reacts with an allergen-specific immune response. After sensitisation, any further contact with the allergen can lead to symptoms. In Germany, existing health monitoring at the Robert Koch Institute with population-representative interview and examination surveys of adults (DEGS) and children/adolescents (KiGGS) provides a sound basis for the establishment of public health surveillance that includes allergies as non-communicable diseases [102]. Data should come from surveys and examinations as well as from official statistics and billing and care data. In addition, the courses of the most common allergic diseases (including the type I diseases, allergic rhinitis and allergic bronchial asthma, and the type IV disease, allergic contact dermatitis) should be investigated jointly across several age groups.

Monitoring at patient level
In addition to continuous monitoring at the population level, patient-related monitoring systems can efficiently record the diagnosis, severity, and course of allergic diseases within the healthcare system. The underlying data are usually collected at very close intervals on a centre- or study-specific basis [60, 61].

For adequate care of patients, especially those with inhalation allergies, such a system at the patient level makes sense as a supplement to sensitisation monitoring at the population level. In addition to a registry, sensitisation monitoring at patient level could specifically include allergens that could become clinically relevant but currently play no or only a minor role in everyday clinical practice, such as Amb a 1, the main allergen of ragweed. This requires suitable diagnostic tools to be available for rare and new allergens [61].

The concrete design of such a monitoring system could be developed in an interdisciplinary manner, analogous to the perspectives for a nationwide pollen monitoring system developed by the Working Group Nationwide Pollen Monitoring [100].

3.3 Urban planning from an allergological perspective
Urban green spaces can reduce some of the negative impacts of climate change. Parks, road-side trees, green facades, and roofs create recreational spaces, while cold islands and cool buildings provide shade, improve air quality, and have a positive effect on people’s overall well-being [15].

However, which urban greenery should be planted? This question can be approached from different points of view. For example, the German Conference of Garden Authorities (Deutsche Gartenamtsleiterkonferenz, GALK) has selected ‘future trees for the city’ from its list of road-side trees in 2022, which has been maintained and regularly revised since the 1970s and takes the aspect of climate robustness into account [103].

From an allergological point of view, the aspect of the allergenic potential of urban green spaces must also be considered (e.g. [104]). It would not make sense from either a health or an economic perspective to continue planting trees to whose pollen a large number of people in Germany are allergic [105] or could develop an allergy during
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The allergenic potential of plants must be considered when planning urban green spaces.

Figure 5. Influence of climate change factors on the environment and thus on employees in different workplaces. Only a few allergen sources for which an increase in exposure is to be expected are shown as examples. Source: Own representation based on Rauf, Hut (Institute for Prevention und Occupational Medicine).

their lifetime [106]. It would also be ill-advised to resort to previously non-native trees that are adapted to high air temperatures but have a high allergenic potential, such as the olive tree [60]. In order to address the allergological aspect of urban green spaces, Bergmann et al. [107] recommended in 2012 that cities and municipalities should be considerate of pollen allergy sufferers when planting public spaces. They published a list of tree and shrub species resident in Berlin that are suitable for new plantings from an allergological perspective. This list is currently being revised and should be merged with the GALK list of future trees.

3.4 Responding to changes in the working environment

Although a precise assessment of the health and economic consequences of climate change on the working environment is currently not possible, the risks to occupational safety and health associated with climate change must be increasingly addressed in global occupational legislation (Figure 5). Adapted assessment scales and protective measures need to be provided. This was done, for example, for the effects of increased UV radiation exposure during outdoor employment. Certain UV-related skin cancers were introduced in the official occupational disease list and are now recognised occupational diseases in Germany (BK 5103) [108]. In addition to climate change-related stressors such as heat and UV radiation, another focus should lie on infectious diseases and allergies.

It is also important to adequately inform affected occupational groups about the possible effects of climate change and to implement targeted preventive measures. Prevention, especially of allergic diseases, includes early and targeted diagnostics that are continuously adapted to the changing conditions. Research is required to expand knowledge regarding the type, distribution, and impact of allergens, for example, which can serve as a basis for preventive measures. Climate change reaches all areas of society and does not stop at occupational health and safety.
4. Summary and outlook

Inhalation allergies in particular, amongst other atopic diseases, have increased worldwide and reached epidemic levels. Climatic changes influence flora and fauna and therefore the occurrence of aeroallergens. Polysensitised pollen allergic patients can suffer from allergy symptoms almost all year round due to changes in the flowering period of plants. More detailed information on climate change and (new) pollen allergens can be found in Section 2.1 Climate change and (new) pollen allergens.

The triggering of allergic symptoms is always preceded by the phase of sensitisation through allergen exposure. Environmental factors such as air pollutants and climate influence the allergenicity of pollen through chemical modifications and accumulation of allergens (agglomeration), which can lead to the formation of new allergens (neoallergens) [109, 110]. Environmental pollutants can promote the penetration of allergens into the skin and mucous membranes by damaging the skin and mucous membrane barrier, modulating the immune system, causing inflammation and thereby influencing individual susceptibility to developing allergies [109]. More detailed information on these topics can be found in Section 2.3 Atopic dermatitis and climate change and Section 2.4 Air pollutants.

Symptoms of allergic reactions are triggered by released mediators. The strength of the reaction depends on the allergen concentration and thus, on the one hand, on the pollen concentration and, on the other hand, on the quantity and structure of the allergens released from pollen, which in turn also depend on climatic conditions [49]. This becomes clear in a phenomenon that has gained importance, known as thunderstorm asthma. People with hay fever can suffer severe asthma attacks in such exceptional situations, which they had not experienced before [111]. A more detailed insight into the phenomenon of thunderstorm asthma is given in the Info box above.

Storms and heavy rain lead to flooding; damp flats are predestined for mould and bacterial growth. People who occupy damp apartments or houses are at risk, as well as workers involved in renovation and demolition [112, 113]. Climatic changes lead to changes in flora, fauna, and fungi, i.e. the fungi found in an area. Increasing temperatures favour the growth of plants and fungi as well as the spread of animals, including pests, which are otherwise native to warmer regions. Insect components are considered relevant aeroallergens, especially in warm climates. More detailed information can be found in Section 2.2 Climate change and (new) occupational inhalant allergens.

For targeted allergological diagnostics, all allergens must be available, even those that have not been of high relevance in Germany so far. Currently, allergen immunotherapy is still the only treatment option that aims to induce tolerance to individual allergens in patients. Allergen extracts may have to be adapted to the respective sensitisation profile. Since climatic changes can lead to plants expressing new allergens or to changes in the quantitative composition of allergens; it must be ensured that the relevant allergens are contained in adequate concentrations in extracts. More detailed explanations on the topic of sensitisation monitoring and further recommendations can be found in Section 3 Recommendations.

Climate change is increasingly influencing our health and our lives. Politicians and society, and especially health-
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care workers, are called upon to consider findings from basic scientific research, environmental, working environment and disease monitoring in their actions.

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Impact of climate change on allergic diseases in Germany


Impact of climate change on non-communicable diseases due to increased ambient air pollution

Abstract

Background: The impacts of air pollutants on health range from short-term health impairments to hospital admissions and deaths. Climate change is leading to an increase in air pollution.

Methods: This article addresses, based on selected literature, the relationship between climate change and air pollutants, the health effects of air pollutants and their modification by air temperature, with a focus on Germany.

Results: Poor air quality increases the risk of many diseases. Climate change is causing, among other things, more periods of extreme heat with simultaneously increased concentrations of air pollutants. The interactions between air temperature and air pollutants, as well as their combined effects on human health, have not yet been sufficiently studied. Limit, target, and guideline values are of particular importance for health protection.

Conclusions: Measures to reduce air pollutants and greenhouse gases must be more strictly implemented. An essential step towards improving air quality is setting stricter air quality limit values in Europe. Prevention and adaptation measures should be accelerated in Germany, as they contribute to climate-resilient and sustainable healthcare systems.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.

1. Introduction

In the course of their lives, people are exposed to different risk factors that can have a negative impact on their health. Some of these risk factors, such as smoking and physical inactivity, can be influenced by structural changes (e.g. bans on tobacco advertising, availability of cycle paths), but also by people’s behaviour (their individual lifestyles). Other risk factors, such as air pollution, on the other hand, can mainly be influenced by structural changes, e.g. by legally setting maximum permissible emissions. However, individual behavioural changes can contribute, e.g. by consciously choosing environmentally friendly mobility, energy, and heating systems.

According to the World Health Organization (WHO), about 99% of the world’s population live in areas where air quality standards do not meet recommended guideline values. According to the latest State of the Global Air report [1], which is based on the findings of the Global Burden of Disease (GBD) study [2], it is estimated that air pollution
Impact of climate change on non-communicable diseases due to increased ambient air pollution

was responsible for one in nine deaths worldwide in 2019. Air pollution is thus one of the four most important risk factors for the global burden of disease, surpassed only by high blood pressure, smoking, and poor nutrition. Info box 1 introduces the main air pollutants in Germany and their sources.

When considering exposure in the light of the new WHO guideline value for PM$_{2.5}$ of 5μg/m$^3$ (annual mean value) published in 2021, almost 100% of the German population are exposed to PM$_{2.5}$ fine dust values above the guideline value (Info box 2). Based on the results of the GBD study, the burden of disease due to air pollution is the tenth most

Info box 1
Major air pollutants relevant to human health in ambient air in Germany

Particulate air pollutants: These can be of natural origin or generated by human activities. An important source of particulate air pollutants is motor vehicle traffic. In addition to exhaust emissions, there is also the whirling up of dust, wear of brakes and tyres, and abrasion of road surfaces. Other important sources are chimneys of industrial plants and power stations, heating systems in private households as well as agriculture. Natural sources of particles are emissions from volcanoes and oceans, forest and bushfires, and certain biogenic aerosols such as viruses.

To enable a uniform classification, the particles present in the air are often divided into the following categories based on their aerodynamic diameter:

- Total Suspended Particles (TSP): mass of all particles contained in total suspended particulate matter, this value is no longer routinely measured and regulated
- Inhalable particulate matter: particles whose aerodynamic diameter is smaller than 10 micrometres (<10μm, abbreviated PM$_{10}$)
- Coarse PM: Particles whose aerodynamic diameter is <10μm but larger than 2.5 micrometres (>2.5μm, PM$_{10-2.5}$)
- Respirable particulate matter: particles with an aerodynamic diameter <2.5μm (PM$_{2.5}$)
- Ultrafine particles (UFP): particles whose aerodynamic diameter is <0.1μm or smaller than 100 nanometres (PM$_{0.1}$)

Concentrations of larger particles (PM$_{10}$, PM$_{10-2.5}$, and PM$_{2.5}$) are usually determined as particle mass. UFP, on the other hand, contribute very little to the particle mass, but conversely determine the number of particles in the ambient air. Therefore, the appropriate measurement parameter for UFP is their number per unit volume (e.g. number per cubic centimetre, cm$^3$).

Gaseous air pollutants: O$_3$, ground-level ozone, is not released by a pollutant source, but is formed as a result of complex conversion processes. These mechanisms mainly involve volatile organic compounds and nitrogen oxides; solar radiation provides the energy for the formation of ground-level ozone. Therefore, a particularly large amount of ozone is produced, especially in summer and in anthropogenically polluted air masses.

Nitrogen dioxide (NO$_2$) is a trace gas in the atmosphere and is produced as a by-product of natural and anthropogenic combustion processes. The main sources in ambient air are combustion engines and furnaces (for coal, oil, gas, wood, waste). In addition to its role as a precursor substance for ozone, NO$_2$ is also involved in the formation of particulate matter.

Carbon monoxide (CO) is a gas that is formed during the incomplete combustion of fossil fuels. It forms when too little oxygen is available during combustion processes. Road traffic and combustion plants are the main sources. Carbon monoxide is also present in tobacco smoke in significant quantities.

Polycyclic aromatic hydrocarbons (PAHs) are substances produced by incomplete combustion processes of organic materials (e.g. wood, coal, or oil) or in food (e.g. during grilling or frying). The main sources are industrial processes in mineral oil processing, coal chemistry, metal processing, or energy production.
important risk factor for human health in Germany and is considered the most important environmental risk factor [2].

Air quality is generally subject to weather and shows weather-dependent as well as seasonal and interannual fluctuations. The average concentrations of air pollutants show a clear urban-rural gradient for particulate matter (PM) and nitrogen oxides (nitrogen monoxide and nitrogen dioxide, NOx). The highest pollution levels occur near their point of origin, in urban areas and places with heavy traffic. Low-wind weather conditions and inversion weather types, characterised by a reversal of the usual temperature decrease with altitude, thus preventing vertical air exchange, can lead to a strong accumulation of air pollutants in the lower atmosphere. In contrast, precipitation events usually lead to a reduction of pollution through leaching processes. High ozone concentrations mainly occur in Central Europe in the spring and summer months, often in combination with high air temperature and strong UV radiation, as ozone is formed photochemically under solar irradiation (discussed in more detail in this status report by Baldermann et al. [3]). Therefore, UV-intensive high-pressure weather conditions are usually associated with high ozone levels and high temperatures [4]. Concentrations of ozone generally increase towards suburban and rural areas. The highest pollution levels are caused by chemical reactions of the precursors of ozone, nitrogen oxides and volatile hydrocarbons, usually outside urban areas at some distance from the sources. The precursors of ozone are transported out of the city by wind, where they have time to react to form ozone. In addition, in inner cities, much of the ozone is immediately broken down by reacting with nitrogen monoxide (NO) from car exhausts.

This is why ozone pollution in inner cities, with lots of traffic, is significantly lower than on the outskirts and in neighbouring rural areas.

Air pollutants and greenhouse gases are mostly different substances, but often have the same sources. The emission of greenhouse gases (especially carbon dioxide (CO2), methane, and nitrous oxide) is a major cause of global warming, which has a lasting negative impact on the environment and health [5, 6]. The increase in mean air temperature changes the atmospheric circulation, short-term weather patterns, and long-term climate. Changes in atmospheric transport and mixing processes influence physico-chemical processes and the state of air quality. Since the beginning of this century, it has been shown that extreme weather events, which impact air hygiene, have increased and intensified, especially during the summer months, in Europe and Germany. These include, in particular, periods of extreme heat with simultaneously increased...
concentrations of air pollutants such as ozone, which can trigger health effects [7, 8]. Due to the correlation of ozone formation processes with temperature, ozone concentrations are expected to increase as climate change continues, especially in projections with strong climate change and limited reduction of precursor substances. In addition, exposure to PM\textsubscript{10}, whose emissions may come from both anthropogenic and natural sources, may increase. The anthropogenic share is emitted by combustion processes in industry and traffic. Natural processes such as vegetation fires [9] and the dispersal of dusty and dry soil by wind during prolonged summer droughts, such as the drought summer of 2018 [10], can be a significant additional burden on total PM emissions.

This article provides an overview of the health effects of air pollutants and their interaction with air temperature, as well as an assessment of the relevant limit, target, and guideline values. Finally, recommendations for public health are collected. The analysis is based on the current literature within the framework of a narrative review.

2. Health effects of air pollutants

2.1 Overview

Although air pollutants primarily enter the body via the respiratory tract, which initially suggests a health risk for the respiratory tract and lungs, research over the past decades has shown that the greatest attributable risk of air pollutants lies with the cardiovascular system. The effects range from short-term health impairments to hospital admissions and deaths. These can occur acutely at high concentrations or as a consequence of long-term exposure [11].

Poor air quality increases the risk of heart disease, lung disease and respiratory infections, type 2 diabetes, and other health problems (Figure 1). Exposure to air pollutants during pregnancy can lead to an increased risk of pre-term birth and low birth weight. Air pollutants have also been linked to asthma and lower respiratory tract infections in children. These impacts on health can lead to school and work absenteeism, chronic illness, and death. Overall, exposure to air pollutants shortens life expectancy [12–14]. Air pollution is by far the most important environmental risk factor for human health.

With regard to health impacts, a distinction is usually made between short-term effects of high air pollutant concentrations – effects that occur in the immediate temporal vicinity of exposure, i.e. within a few days – and those effects that result in the long term from increased (chronic) exposure to air pollutants (e.g. annual average exposures at the place of residence or work). Short-term increases in PM\textsubscript{2.5} increase the relative risk of acute cardiovascular events by 1 to 3% within a few days. Longer-term exposures over several years increase this risk to a greater extent (about 10%), partly due to the development and/or exacerbation of cardiometabolic diseases such as hypertension and diabetes mellitus [16]. Reducing air pollution could significantly lower disease burden from strokes, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma.

In particular, short-term elevated exposures may pose little risk to healthy individuals. However, subclinical health effects may well be considered a plausible precursor to serious or fatal events in susceptible individuals. In contrast, repeated exposures or high long-term exposure may con-
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Ambient air pollution is one of the greatest environmental health risks.

Figure 1
Health impacts of air pollutants
Source: Own representation based on European Environment Agency [15] and Thurston et al. [12]

1. Impacts on the central nervous system, e.g. stroke
2. Neurodegenerative diseases, e.g. dementia
3. Mental health, e.g. anxiety
4. Headaches

2. Respiratory problems
1. Irritations of eyes, nose and throat
3. Skin ageing

4. Respiratory diseases, e.g. chronic obstructive pulmonary disease
5. Reduced lung development
6. Lung cancer
7. Irritations, inflammations, and infections

5. Cardiovascular diseases, e.g. myocardial infarction
6. Hypertension
7. Endothelial dysfunction
8. Systemic inflammation
9. Increased blood clotting

7. Respiratory problems, e.g. lung cancer

8. Impacts on liver, spleen, and blood
9. Insulin resistance
10. Type 1 and type 2 diabetes
11. Impacts on the reproductive organs, e.g. sperm quality
12. Impacts on birth outcomes, e.g. premature births

Impacts on the central nervous system, e.g. stroke
Neurodegenerative diseases, e.g. dementia
Mental health, e.g. anxiety
Headaches

Respiratory problems
Irritations of eyes, nose and throat
Skin ageing

Respiratory diseases, e.g. chronic obstructive pulmonary disease
Reduced lung development
Lung cancer
Irritations, inflammations, and infections

Cardiovascular diseases, e.g. myocardial infarction
Hypertension
Endothelial dysfunction
Systemic inflammation
Increased blood clotting
Deep vein thrombosis

Impacts on liver, spleen, and blood

Insulin resistance
Type 1 and type 2 diabetes

Impacts on the reproductive organs, e.g. sperm quality
Impacts on birth outcomes, e.g. premature births

Deep vein thrombosis

Potential mechanisms
Air pollutants are transported into the lungs via the respiratory tract. Particularly PM$_{2.5}$ reaches the smallest airways and alveoli. UFP can also reach other organs via the bloodstream (Info box 3). In summary, the particle effects can be caused by various mechanisms that – alone or together – increase the risk for cardiovascular diseases and cardiovascular events in particular (Table 1) [16,19–22].

Furthermore, exposure to air pollutants can lead to epigenetic changes, e.g. changes in DNA methylation (chemical changes in the basic building blocks of a cell’s genetic material), which are similar to those of epigenetic ageing [16, 21]. Studies have also shown that air pollutants can accelerate the so-called epigenetic ageing clocks and thus increase the difference between chronological age and methylation age, with a larger difference being associated
ttribute to the development of cardiovascular and respiratory diseases. The health impacts associated with air pollution may seem small from a medical point of view compared to other risk factors such as smoking or obesity, but on a population-wide basis the effects are immense. Despite the good state of research, no lower threshold for health effects could be identified thus far. Even at low exposure levels, the health impacts increase with increasing air pollutant concentrations. This was investigated in a large study with several million participants in the United States amongst others. The results showed a linear exposure-response relationship between PM$_{2.5}$ and mortality, even far below the current U.S. limit of 12µg/m$^3$ [17]. This means that every reduction in exposure is associated with a health gain – both in the short and long term [18].
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The pathways and mechanisms shown in Table 1 are partly interdependent and can cross-react (e.g. ‘feed-forward’ or mutual reinforcement). Overall, it is assumed that direct effects of particles can trigger cardiovascular events within a few hours. In addition, there is increasing evidence that particles contribute to the development and progression of atherosclerotic lesions, a possible mechanism for the observed long-term effects [20].

Susceptible population groups

Potential factors for particular susceptibility to air pollutants are age (infants, children, and older persons), smoking and other lifestyle factors. In particular, social status is a factor that plays an important role in the study of health impacts through air pollution. It correlates with other social and personal factors as well as with the environmental conditions at the place of residence. Specific life stages such as pregnancy also contribute to increased susceptibility, affecting both expectant mothers and the unborn. Chronic pre-existing conditions are another important factor: sensitivity is increased especially in children and older persons with chronic respiratory diseases (e.g. bronchial asthma, chronic obstructive pulmonary disease) and with cardiovascular diseases, and is reflected in sudden exacerbation of the underlying diseases on individual days, especially during episodes with high ambient air pollution (e.g. smog situations) [20, 23].

2.2 Health impacts of air pollutants in interaction with high air temperature

As mentioned above, high air temperature combined with intensive solar radiation favours the formation of ground-level ozone concentrations through the reaction of nitrogen oxides and water. In addition, particulate matter pollution can increase due to the formation of so-called secondary aerosols [24]. On hot days, there is also little air circulation, so air pollutants generated in cities, in particular,
cannot be removed and remain in the air in higher concentrations. During hot spells with prolonged drought, forest fires may occur frequently, contributing significantly to high concentrations of pollutants, especially particulate matter [25].

Ozone and particulate matter (PM$_{10}$ and PM$_{2.5}$) are, therefore, of particular relevance to health during dry, hot, high-pressure weather conditions in summer. Health-related studies have indicated the influence of air pollutants when heat co-occurs, mainly affecting people in urban areas [26, 27]. The exposure-dependent nature of health effects (parallel individual effects vs. combination effects on morbidity and mortality) cannot yet be conclusively assessed due to effect modification and the interaction of individual factors and thus requires further research [5, 26].

So far, high air temperatures or heat events and air pollutants have mostly been considered separately. Most studies to date have examined the health effects of different air pollutants by considering air temperature as a potential confounding factor and vice versa. However, the interactions between high air temperatures, heat events, and air pollutants, as well as their combined effects on humans, have not yet been sufficiently explored, especially considering global climate change [28, 29].

**Table 1**
Possible mechanisms that explain the observed relationship between air pollutants and disease
Source: Own representation based on Schulz et al. [23]

<table>
<thead>
<tr>
<th>Primary paths</th>
<th>Mechanisms</th>
<th>Possible consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhaled particles cause persistent oxidative stress and defence processes in the form of weak chronic inflammatory reactions</td>
<td>Release of messenger substances in the lung tissue, which leads to a systemic inflammatory reaction (involving the innate and acquired immune defence)</td>
<td>Disruption of endothelial function; formation of thrombi; progression of atherosclerotic lesions; impaired lung function; exacerbation of asthma and COPD; DNA damage; promotion of carcinogenesis and metastasis</td>
</tr>
<tr>
<td>Respirable particles or secondary mediators stimulate reflex receptors on the surface of the alveoli</td>
<td>Imbalance of the autonomic nervous system and thus influence on the autonomic control of the heart by favouring sympathetic tone via afferent nerve pathways; oxidation; alteration of central signalling pathways of cell differentiation and growth; mitochondrial dysfunction</td>
<td>Influence on cardiac output; cardiac arrhythmias; bronchoconstriction; damage to the mucous membrane of the respiratory tract; restriction of the self-cleansing mechanism of the bronchial tubes</td>
</tr>
<tr>
<td>Direct translocation: UFP or particle components penetrate the alveoli and enter the bloodstream</td>
<td>Direct influence on organs or blood components</td>
<td>Influencing the viscosity of the blood; local inflammatory reactions: increased inflammation levels and increased tendency to clot; central nervous system: effects on metabolism and hypothalamic-pituitary-adrenal axis activation</td>
</tr>
</tbody>
</table>

COPD=chronic obstructive pulmonary disease, DNA=deoxyribonucleic acid, UFP=ultrafine particles
Effects of short-term exposure to air pollutants on mortality – effect modification by heat
Most studies published so far have examined the change in the effects of air pollutants due to temperature. The majority of these studies have shown that high temperatures increase the effects of ozone or particulate matter on (cause-specific) mortality. However, some studies also indicate stronger effects of ozone and particulate matter at lower temperatures, or show no change in the effect of air pollutants corresponding to temperature [30].

Effects of short-term exposure to heat on mortality – effect modification by air pollutants
In contrast, there are only a limited number of studies investigating whether air pollution modifies the effects of temperature [29, 31]. For example, in the aftermath of the hot summer of 2003, the independent and synergistic effects (i.e. a joint effect greater than the sum of the individual effects) of heatwaves and air pollutants on daily mortality in nine European cities were investigated [8] (see also Winklmayr et al. [32] in this progress report). It was shown that the mortality risk from heat was increased by simultaneously elevated concentrations of ozone and PM$_{10}$. Older persons were particularly at risk. A recent systematic review with meta-analysis found similar results: a significant change in the heat effect on all-cause or natural mortality due to ozone and PM$_{10}$ was observed, with stronger heat effects on days with high exposure to air pollutants [31]. These effects were confirmed by a comparative study carried out in eight German cities on temperature-dependent threshold value determination. According to this study, the ozone effect on total mortality appears to be greater at low air temperatures, whereas the temperature effect dominates equally as much as ozone during heat [33].

Another European study also showed that high air temperatures modify the effects of air pollutants on total mortality from natural causes and on mortality from cardiovascular diseases, and that high concentrations of particulate matter, UFP, and ozone amplify the effect of air temperature [6].

Combined effects of short-term exposure to air pollutants and heat on mortality
A U.S. study recently showed that the risk of death in California increased by about 6% on days with extremely high temperatures and by about 5% on days with high PM$_{2.5}$ concentrations from 2014 to 2019 [34]. On days with both extreme heat and high air pollution, the risk increased by 21%, higher than the sum of the individual effects of extreme temperature and PM$_{2.5}$ alone. Katsouyanni et al. [35] also found that high air temperature increased the adverse health impact of PM$_{10}$; in a region with a warm climate, a $10\mu g/m^3$ increase in particulate matter caused a 0.8% increase in all-cause mortality, whereas in a cooler climate, the increase was only 0.3%.

Short-term exposure to air pollutants and heat – effects on morbidity
The vast majority of studies conducted to date have examined the effects of the interaction of air temperature and air pollutants on mortality. In contrast, only a few studies have examined interactive effects or changes in effects on hospital admissions or other morbidity endpoints. For example, studies from Australia, China, and the United
States have shown that high particulate matter concentrations increased the effects of heat on cardiorespiratory hospital admissions and that high temperatures influenced the effects of particulate matter; particle effects were generally stronger in heat [36]. A recent review with meta-analysis on respiratory hospital admissions also showed stronger PM$_{10}$ particulate matter and ozone effects at concurrent high temperatures [37]. However, other studies showed stronger effects of air pollutants at concurrent lower temperatures or no interaction or effect modification [36].

Other studies also found evidence of interactive effects of temperature and particulate matter, soot, or ozone on lung function, heart rate and heart rate variability, blood pressure and markers of endothelial function [29].

Interaction of chronic exposure to air pollutants and air temperature
While an increasing number of papers in recent years have investigated the health effects of the association between short-term exposure to elevated air temperature and air pollutants, there have been very few studies on the interaction of chronic exposure to air pollutants and air temperature. However, given the changing climate, it is important also to understand the longer-term effects, such as annual average temperatures, and their interaction with chronic exposure to air pollutants.

A study of the association between chronic particulate matter pollution and mortality in 207 American cities showed that the PM$_{2.5}$ effects were particularly pronounced in cities where the annual average temperature was higher [38]. Similar effects were described in other U.S. studies [29].

3. Limit, target, and guideline values with regard to the current air quality situation in Germany
Guideline values represent recommendations by experts from the relevant fields and are based on the current state of knowledge on the health effects of air pollutants (see WHO air quality guidelines), while limit values are laid down in ordinances and regulations. In addition, there are target values that should be met within a certain period of time. The legal basis for the protection of human health through air pollution control and air quality assessment is summarised in Info box 4. For PM$_{10}$ the limit value is 50 μg/m$^3$ as a daily mean (35 permissible exceedances per year) and 40 μg/m$^3$ as an annual mean. For PM$_{2.5}$ the annual mean limit value is 25 μg/m$^3$. For ultrafine particles, which are also relevant to health, there are currently neither guideline nor target or limit values. For NO$_2$, the limit values are 200 μg/m$^3$ as an hourly average (18 permissible exceedances per year) and 40 μg/m$^3$ as an annual mean. For ozone, the daily maximum eight-hour mean may exceed 120 μg/m$^3$ on a maximum of 25 days per calendar year, averaged over three years. In the long term, the maximum eight-hour mean should not exceed 120 μg/m$^3$ at all.

Based on numerous new scientific studies, the WHO in 2021 revised its previous air quality guideline from 2005 and published it with new, global recommendations and guideline values [39]. Guideline values of 45 μg/m$^3$ (daily mean) and 15 μg/m$^3$ (annual mean) were derived for PM$_{10}$ and 15 μg/m$^3$ (daily mean) and 5 μg/m$^3$ (annual mean) for PM$_{2.5}$. For NO$_2$, the new WHO guideline recommends a guideline value of 25 μg/m$^3$ for the hourly average and 10 μg/m$^3$ for the annual mean. The guideline values for ozone are 100 μg/m$^3$.
for the daily maximum eight-hour mean and a maximum of 60 μg/m³ as the highest six-month running-average.

Due to the different levels of air pollution control in various countries around the world, interim targets were also recommended, through which a gradual development process should be initiated until the WHO guideline values are reached. It follows from the recommendations of the new WHO air quality guidelines that the concentrations of air pollutants currently measured in Germany and the limit values still in force are set too high to ensure effective health protection for the population. Figure 2 shows the percentage of exceedances of the WHO guideline values and interim targets for particulate matter (PM₁₀ and PM₂.₅), ozone, NO₂, SO₂, and CO at the air quality monitoring stations in Germany in 2020. Various measures have been taken in Germany in the past to reduce air pollutant concentrations. The focus is on the desired reduction and avoidance of harmful effects on human health and the environment caused by air pollutants. Compliance with the prescribed air quality values and emission ceilings is intended to reduce pollution, although compliance with the legal limits does not mean complete health protection. All EU member states are obliged to draw up air pollution control and action plans in accordance with EU law in the event of exceedances of the EU air quality limit values from 2008. The results of the current air quality evaluation 2021 show that, for Germany, air pollution by particulate matter, NO₂, and ozone must be further reduced on a large scale in order to protect public health [3].

4. Significance for public health and recommendations

Climate projections show that climate change is very likely to lead to an increase in extreme weather events and changes in air pollutants with different impacts on human health in the coming years and decades (see Hertig et al. [41] in this status report). Therefore, international agreements, national laws, and ambitious regulations must be increasingly implemented and adhered to, such as the measures to reduce greenhouse gas emissions of the German Climate Change Act as well as the new regulations on air

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**Info box 4**

**Legal basis for air pollution control and air quality assessment**

The legal basis for air pollution control and air quality monitoring has been created by international agreements, directives at European level and their transposition into German law. The member states of the European Union (EU) have developed uniform regulations for the assessment and control of air quality. The basis for this is Directive 2008/50/EC on ambient air quality and cleaner air for Europe of May 2008. The 39th Ordinance (39th BImSchV – Ordinance on Air Quality Standards and Emission Ceilings of August 2010) to the Federal Immission Control Act (BImSchG - Act on the Prevention of Harmful Effects on the Environment caused by Air Pollution, Noise, Vibration and Similar Phenomena) transposed the EU Directive into German law. Binding limit and target values have been set for various air pollutants. To ensure comparability of the measurements carried out in the individual member states, the directive contains binding regulations on the location and minimum number of sampling points, uniform criteria on data quality objectives and calculation rules, and specifications for the report of the air quality assessment to the EU Commission. Reference methods for assessing the various pollutant concentrations are also laid down here. Each member state reports to the EU Commission on September 30 of each year on the air quality of the previous year.

Source: Wichmann-Fiebig et al. [40].
pollution control and the reduction of air pollutant emissions, which are being revised. In addition, in the upcoming Climate Adaptation Act for Germany, which is currently being drafted, nationwide preventive and adaptation measures are prepared in order to enable and ensure effective health protection as well as early and precautionary adaptation of the population.

At the level of individual behavioural prevention, in order to avoid health burdens caused by air pollutants, the population should refrain from prolonged physical exertion at times of day that are associated with increased concentrations of air pollutants. This applies particularly to at-risk individuals with health problems, for example during the midday and afternoon hours when ozone concentrations...
are elevated. From the point of view of preventive health protection, an integrated environmental, economic, transport, climate and air pollution control policy should, in the sense of the ‘Health in All Policies’ approach, ensure sustainable compliance with the upper limits of the concentration values for air pollutants – at least the air quality values stipulated by law, but ideally the scientifically derived guideline values of the new WHO air quality guidelines 2021. Appropriate measures should prevent the uncontrolled increase in industrial and individual energy consumption and the associated rise in \( \text{CO}_2 \) emissions. The release of ozone precursors, which are increasingly emitted in summer due to the use of air conditioning systems, should also be prevented.

### 4.1 Synergies of environmental, climate, and health protection

The use of fossil fuels such as coal, oil, and natural gas not only has a harmful effect on the climate, but also leads to air pollution that is harmful to health. We must systematically and quickly reduce greenhouse gas emissions and implement extensive energy-saving measures, while also switching to renewable energies to cover energy demand, thus reducing health risks from air pollution [42]. Large energy consumers in the health sector, such as inpatient healthcare facilities, run 24/7 and, together with outpatient service provision, cause an annual raw material consumption of about 107 million tonnes (half of which is biomass and fossil fuels), with about one-third coming from domestic raw material extraction and two-thirds from imports [43]. Implementing structural prevention measures for climate protection (mitigation), such as the energy renovation of hospitals and their replacement by new low-energy buildings adapted to climate change, would go a long way towards active mitigation and thus also improve health protection for patients and staff in these facilities. Patient care is the top priority and therefore, in view of increasing extreme heat events, adaptation measures for structural and air-conditioning renovation, shading, passive building cooling and, if medically necessary, individual room air-conditioning powered by renewable energies must be implemented. So far, there are no central and coordinated mitigation measures for a nationwide energy efficiency upgrade of existing hospital buildings.

An integrated environmental, climate and health policy alongside individual health behaviour oriented towards climate protection can have synergistic effects and generate win-win situations or health co-benefits of climate protection and climate adaptation measures. The following are examples of combined structural and behavioural prevention measures that aim to generate such co-benefits:

1. **Mobility:** On separate and secured transport routes, cycling and other forms of active transport through physical activity not only avoid air pollutant emissions from motor vehicle traffic, but also reduce the risk of cardiovascular diseases as a co-benefit and promote fitness and health.

2. **Urban development:** Urban development measures such as the deconstruction of sealed surfaces and the nature-orientated expansion of urban green spaces improve air quality and also reduce the risk of heat-related health problems through cooler air and shade. They serve the ecological needs of a city as well as the individual’s physical and mental health [44].
4.2 Climate-resilient and sustainable health systems

According to current estimates, the German health sector is responsible for 5 to 6.7% of Germany’s overall greenhouse gas emissions [45, 46]. About one-third of these are caused by emissions from heating and energy consumption of healthcare facilities and about two-thirds by upstream and downstream processes, such as the production of medical devices and pharmaceuticals, delivery processes, and waste disposal. Thus, the health sector is called upon to permanently minimise its greenhouse gas emissions as a climate protection and air pollution control measure while maintaining the same quality of basic care and high-quality standard of the services provided. However, Germany has so far lacked a national climate strategy for the health sector. A representative survey on the status of the transformation towards a climate-neutral and climate-resilient healthcare system asked managers and medical specialists about their personal attitudes and the implementation of environmental, climate protection, and sustainability measures, as well as barriers to implementation [47]. The survey showed that many decision-makers in the health sector are aware of the relevance and urgency of the issue. The vast majority of the physicians and managers interviewed agree that measures must be taken to address climate change in healthcare facilities. However, there is a lack of specialised knowledge of climate protection and sustainability, as well as clear accountability at the management level. An important factor for the implementation of the transformation of the healthcare system concerns the avoidance of unnecessary therapies, which will free up personnel and ecological resources. Furthermore, the study identified a lack of knowledge concerning concrete climate adaptation strategies, for example with regard to protection against summer heat in hospitals as part of internal alert planning and increasing resilience against extreme weather events. As part of the critical infrastructure, the health sector is only just beginning to face the enormous challenges in identifying its adaptation needs and strengthening its resilience in the long term [45].

The increased occurrence of climate change-associated physical and mental illnesses, for example triggered by extreme weather events, poses new challenges for those working in the health professions. The importance of climate change as a factor influencing health is not adequately reflected in the education, training, and continuing education of the health professions so far. It is recommended that further training regulations be adapted and supplemented to include appropriate content, enabling those working or planning to work in the healthcare sector to react appropriately to climate-related changes [45].

5. Discussion and conclusion

The air hygiene situation in Germany has improved significantly in recent decades. However, many cities and regions have not yet succeeded in complying with the European limits for air pollutant loads. Current studies predict that, despite air pollution control efforts, health risks from air pollution will continue to increase in the future, especially in conurbations and inner cities [25]. The reason for this is that energy consumption based on fossil combustion processes is still high or even increasing. Furthermore, a warmer climate can indirectly change the emissions of air...
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pollutants and their precursors. In addition to increasing ozone formation potential, more frequent droughts can also increase particulate matter pollution, e.g. when they promote forest fires or through the deflation of parched soils. Besides these air pollutants, changes in the duration and intensity of pollen exposure could cause an additional health burden for people with allergy-related respiratory or lung diseases [48,49]. Interactions with air temperature, specifically during heatwaves, may also influence the health effects of air pollutants.

Tightened limits for air pollution in the EU are essential to improving air quality in Europe. Lowering the values, especially for particulate matter and NO\textsubscript{2}, would be an important contribution to reducing the population’s disease burden due to air pollutants. It is also essential to expand the monitoring of air pollutants, both regulated and non-regulated, such as UFP, soot particles, and ammonia. A commitment to continuous improvement of air quality up to or below the guideline values of the new WHO air quality guidelines (2021) could maximise health benefits for the European population. Air pollution remains one of the leading causes of illness and death, and the burden of disease caused by air pollution in Europe is high. Among other things, this also poses a huge financial burden and puts strain on healthcare systems across the EU. Every single person would benefit from cleaner air, with babies, children, pregnant women, older persons, and people with cardiovascular and respiratory diseases among the most vulnerable groups. Therefore, we need an ambitious air quality regime that promotes and supports action at all levels – EU, national, local – and in all sectors such as transport, energy, industry, agriculture, and residential heating. The proposals initiated by the publication of the new WHO guideline, currently under discussion, to reduce EU limits and targets and to further improve current air quality contain important steps towards achieving cleaner air. However, greater ambition is needed to maximise health benefits for all. In addition, better air quality will help to mitigate the impacts of climate change and the associated health effects. It is, therefore, even more important that the EU values currently under discussion are achieved across the board before 2030.

The interaction of high air temperatures with heat events and air pollutants as well as their combined health effects have not yet been sufficiently researched, especially taking climate change into account. Therefore, in addition to the development of appropriate adaptation measures, further basic research on the combined effects of air pollutants and temperature on health is needed to gain a better understanding of the interrelationships. The effects of other multi-exposures, such as air pollutants and thermal exposure in combination with pollen and UV exposure, have also been insufficiently researched so far. Since atmospheric environmental exposures do not affect humans in isolation, but humans are instead exposed to a mix of environmental factors, a more comprehensive view is essential.

In the area of prevention and adaptation measures, air pollutants, temperature exposure, pollen, and UV should also be considered together in order to design and implement effective action measures. This applies to behavioural prevention measures as well as to the area of structural prevention. For example, heat-health action plans should not only address the thermal burden, but also include protective measures against anthropogenic and biogenic air...
pollutants. When designing urban green spaces, air quality and other factors for maintaining the mental and physical health of the urban population, such as accessibility and quality of stay should also be considered, in addition to the goal of reducing thermal load. In the health sector, a national climate change strategy should be developed that takes into account both the occupational health interests of all staff and the concerns of patients, but also considers changes in air pollutant exposures in the population. This can only succeed within the framework of inter- and transdisciplinary cooperation. Programmes that reduce air pollution lead to large health benefits that are compounded over time. The projected cost savings of health benefits from improved air quality far outweigh the implementation costs of air quality measures [50].

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**Conflicts of interest**

The authors declared no conflicts of interest.

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**References**


Impact of climate change on non-communicable diseases due to increased ambient air pollution


Impact of climate change on non-communicable diseases due to increased ambient air pollution


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Scoping review of climate change and mental health in Germany – Direct and indirect impacts, vulnerable groups, resilience factors

Abstract

Background: Climate change is a major threat to human health and has direct and indirect impacts on the human psyche.

Methods: To assess the state of knowledge on the impact of climate change on mental health in Germany, a scoping review was conducted for the focus topics extreme weather events, temperature increase, intra-psychological processing, sociological aspects, and resilience factors. Ten studies met the inclusion criteria of the searches in the databases Academic Search Complete, CINAHL, PubPsych, PubMed, and PsychInfo. The majority of the studies looked at correlative relationships in a cross-sectional design.

Results: There are indications of an accumulation of psychiatric disorders after extreme weather events; in addition, the risk of suicide increases with higher temperatures and it appears there is an increase in aggressive behaviour. The majority of people surveyed in Germany report concerns about the consequences of climate change, although these currently rarely lead to clinically significant impairments in mental health.

Conclusions: Overall, the evidence for Germany must be classified as insufficient. In addition to the absolute priority of climate protection (mitigation) by reducing emissions, there is a particular need for additional research with a focus on vulnerable groups and possibilities for prevention and adaptation.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.
are additional significant mental stressors [1]. As these factors do not (yet) have a noticeable impact within Germany, they are not considered in more detail in this article with its methodological focus on Germany.

1.1 Extreme weather events and psychological consequences

In the course of climate change, extreme weather events will become more frequent. In Germany, more frequent heavy rainfall events, heatwaves, and storms are expected [2, 3]. A detailed analysis of the psychological effects of extreme weather events in the context of somatic-general health and society can be found in the corresponding article of this status report by Butsch et al. [4]. Previous international studies have found an increase in post-traumatic symptoms, depressive and anxious symptoms, as well as heightened levels of substance use disorders in the aftermath of severe extreme weather events (e.g. heavy rainfall resulting in flooding) [5, 6]. According to international studies, whether and to what extent such extreme weather events contribute to the development and aggravation of psychiatric disorders depends on various factors. These include the type, duration, and severity of the event, the resulting physical harm, the immediate threat to one’s own life or the life of a loved one, the influence of the event on social networks, and any aid received. The subjective significance of the event and the correspondence with other biographical experiences is just as relevant as whether one’s own social existence was affected through the destruction of one’s home or personal infrastructure or the loss of income [6, 7]. In particular, persons of female sex and persons with pre-existing psychiatric disorders are considered vulnerable to the (re)occurrence and development of further psychiatric disorders as a result of an extreme weather event [8].

1.2 Direct effects of temperature increase on the psyche

Heat-related effects on physical health are discussed by Winklmayr et al. [9] in this status report. However, the climate change-related increase in heatwaves and days with extreme heat also has a direct impact on mental health. In international, large-scale epidemiological studies, a correlation was shown between milder temperatures, close to a comfortable 21°C, and more frequent occurrence of socially compatible character traits, such as openness and extraversion [10]. Hot days and heatwaves, on the other hand, lead to more aggressive and hostile behaviour [6, 11], which is also reflected in an increase in delinquencies, e.g. assaults, homicides, rapes, and robberies [12]. Correlations have been reported for the general population, in Germany, and internationally, between isolated rises in temperature and an increased suicide risk on the following day [13, 14]. In addition, the presence of a psychiatric disorder seems to increase vulnerability to the stressful effects of heat: in patients with dementia, bipolar disorder, or schizophrenia, a significant association between an increase in daily mean temperature and an increase in mortality can be observed [15].

1.3 Perception and intra-psychological processing of climate change

Awareness and realisation of the impacts of climate change can cause a variety of negative affects [16], including clinically
significant psychological distress. The emotional reactions to climate information are discussed in research under terms such as climate/eco-anxiety, climate/eco-anger, solastalgia, ecological grief, ecological guilt, eco/climate depression, or climate distress [17]. However, a consistent operationalisation of the terms is still lacking, which makes it difficult to compare the results of studies [17]. The construct of climate anxiety, operationalised by the Climate Anxiety Scale, has been studied most frequently to date [18]. However, there are also questionnaires, among others, on eco-anxiety [19], climate worry [20], solastalgia [21], eco-grief, and eco-guilt [22]. The focus of scientific evaluation to date has been on links between emotional reactions to climate change and risk perception [23], climate protection behaviour [24, 25], repression/denial of climate change [26, 27], as well as protest behaviour [25, 28] and psychological distress [6, 29]. International studies agree that climate-related concern is widespread, but clinically significant symptoms are significantly less common [11, 30, 31].

1.5 Resilience factors for mental stability in the context of climate change

In addition to the risk factors and vulnerabilities that have an influence on the development of psychiatric disorders, there has been little research to date on the protective factors that relate specifically to climate change-related mental distress. According to the differentiation by Clayton [29], protective factors can be found for direct, i.e. acute events such as extreme weather events, and for indirect effects of climate change. With regard to the direct effects of climate change, significant psychological distress. The emotional reactions to climate information are discussed in research under terms such as climate/eco-anxiety, climate/eco-anger, solastalgia, ecological grief, ecological guilt, eco/climate depression, or climate distress [17]. However, a consistent operationalisation of the terms is still lacking, which makes it difficult to compare the results of studies [17]. The construct of climate anxiety, operationalised by the Climate Anxiety Scale, has been studied most frequently to date [18]. However, there are also questionnaires, among others, on eco-anxiety [19], climate worry [20], solastalgia [21], eco-grief, and eco-guilt [22]. The focus of scientific evaluation to date has been on links between emotional reactions to climate change and risk perception [23], climate protection behaviour [24, 25], repression/denial of climate change [26, 27], as well as protest behaviour [25, 28] and psychological distress [6, 29]. International studies agree that climate-related concern is widespread, but clinically significant symptoms are significantly less common [11, 30, 31].

1.4 Sociological aspects of the psychological consequences of climate change

Sociological factors play a central but often neglected role in the assessment of the psychological effects of a challenge to society as a whole, such as climate change. By sociological factors we mean diverse social contexts that influence individual and collective experience, reflection, and decision-making. While many sociological factors correlate with demographic categories such as gender, age, socio-economic status, and ethnicity, our definition also comprises organisational forms, social practices, geographic specifics, physical and ideational infrastructures, cultural norms, and political decision-making structures [32]. This is particularly important for dealing not only individually but also collectively with psychological impairments caused or exacerbated by climate change. Group determinants of mental health and illness are important in climate-related epidemiology, risk assessment, and resilience. Population subgroups that are at higher risk of experiencing negative health effects due to existing structural disadvantages and vulnerabilities are also proportionally more affected by climate change and its mental health effects [33]. International studies show that older population subgroups, for example, are more affected by psychiatric disorders as a result of extreme weather events [34]. Children, on the other hand, show a significantly increased vulnerability to the psychological consequences of extreme weather events such as floods and hurricanes [33]. Girls are a particularly vulnerable group, at increased risk of developing anxiety disorders and substance abuse after experiencing natural disasters [33].

Heat and sharp temperature rises lead to increase in suicide rates and aggressive behaviours.
change, the resilience factors are largely similar to those for post-traumatic stress disorder (PTSD) and include personality traits such as higher self-esteem and a more pronounced sense of coherence (the feeling that the world and oneself are understandable and predictable), individual coping strategies such as meaning-focused coping and successful emotion regulation strategies, as well as environmental factors such as family support and support in the wider social environment [35]. Resilience factors for indirect events, on the other hand, have hardly been researched so far. Initial findings indicate that personal characteristics such as gender or political orientation can, by contributing to psychological resilience, lead to relief or faster recovery from psychological distress [27].

2. Methods

The procedure for preparing the scoping review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [36]. Reviews of international literature on the individual aspects were also identified using systematic searches. Relevant publications without peer review were specifically selected on the basis of the authors’ prior knowledge.

2.1 Scoping review

Between 05.09.2022 and 30.09.2022, the databases Academic Search Complete, CINAHL, PubPsych, PubMed, and PsychInfo were searched for scientific papers that contained one of the possible combinations of search queries in the title or abstract. No restriction was made on the date of publication. All search queries consisted of one climate change or weather-related term, such as ‘climate change’ or ‘heat wave’, the specification ‘German’ or ‘Germany’, and a search term specific to the focus topic. The latter was, for example, ‘post-traumatic stress disorder’ for extreme weather events, ‘aggression’ for temperature increases, ‘climate anxiety’ for intra-psychological processes, ‘resilience’ for resilience factors and ‘social infrastructure’ for sociological aspects. Only studies published in peer-reviewed journals were included. The exact search queries for the databases per focus topic are shown in Annex Table 1. No review protocol was published.

The database searches were carried out by the first author (NG) for all topics. The titles and summaries of the studies found were reviewed by the authors per focus topic.
Scoping review of climate change and mental health in Germany

(Extreme weather events: MB, temperature increase: CN and NG, intra-psychological processing: KB, resilience factors: PN, sociological aspects: TM). Ambiguities were discussed by the whole team until a consensus was reached. Articles were excluded if they were not related to climate change; were not related to the focus topic; used a qualitative research design; were reviews, commentaries, or other articles not presenting new data. The selected studies were transferred into a standardised table by the authors. For this purpose, a table with the relevant variables was created by the research team before data extraction began. The following information was recorded: Data source; (sub-)population; number of study units; region in Germany; time period considered; type of study; phenomena/variables studied; tools; results. If studies reported data from several countries, only the data related to Germany were included in the table.

2.2 Review of international literature

Internationally published reviews on the focus topics of this paper were also compiled between 05.09.2022 and 30.09.2022 without a specification for Germany and using the same search strategy as the scoping review. These were included in the discussion in order to be able to meaningfully contextualise the studies reported for Germany in the results. For this purpose, the search query was appended with ‘systematic review OR meta-analysis OR meta-analysis OR literature review OR scoping review’. These search queries can also be seen in Annex Table 1.

3. Results

In total, the search queries for Germany yielded 486 results across all focus topics, 111 of which were duplicates, so that 375 studies were screened for their relevance. Of these, 365 were excluded, so that ten studies were included in the final evaluation. Various study results from one article [37] were included in the results for both the focus topics intra-psychological processing and resilience factors, so that the presentation of results refers to ten studies from nine articles. Table 1 provides an overview of the results of the included studies; the PRISMA flowcharts [38] of the article selection per topic can be seen in Annex Figure 1.

3.1 Extreme weather events and psychological consequences in Germany

The initial search yielded 99 results, 20 of which were duplicates and one article that was not written in German or English, so that title and abstract were screened for 78 studies. Of these, 73 were excluded because they were not publications related to extreme weather events, three others were excluded because they were not related to the psychological effects of extreme weather events, and one review paper without data from Germany. Ultimately, one study was included and reviewed.

Otto et al. [39] used cross-sectional questionnaire data to examine the effects of the flood disaster in Saxony in 2002 in n=112 persons affected. Of these, 23% screened positive for the presence of PTSD, 13% for depression and 11% for anxiety disorders. Predictive for a higher burden of post-traumatic symptoms was the feeling that one’s life
### Results of the Scoping Review on the impact of climate change on mental health in Germany

#### Focus topic: Extreme weather events and psychological consequences in Germany

<table>
<thead>
<tr>
<th>Authors, publication year</th>
<th>Data source</th>
<th>(Sub-) population</th>
<th>Number (n)</th>
<th>Region, period under consideration</th>
<th>Type of study</th>
<th>Phenomena/variables studied</th>
<th>Tools</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Otto et al. [39], 2006</td>
<td>Questionnaire survey</td>
<td>Victims of the 2002 flood disaster in Saxony</td>
<td>112</td>
<td>Saxony, 2002–2003</td>
<td>Cross-sectional design</td>
<td>PTSD, depression, anxiety disorders, general psychological distress</td>
<td>Validated, psychological questionnaires (IES-R, BDI, BAI, BSI)</td>
<td>Symptoms of PTSD: n=26, symptoms of depression: n=15, marked anxiety: n=12. Those who reported that their lives had been in danger, that they had suffered personal losses and that they expected their future to be affected had significantly more symptoms of PTSD. The likelihood of depression and anxiety also increased when life was in danger and the future was expected to be affected.</td>
</tr>
</tbody>
</table>

PTSD=post-traumatic stress disorder, IES-R=Impact of Event Scale Revised, BDI=Beck Depression Inventory, BAI=Beck Anxiety Inventory, BSI=Brief Symptom Inventory

#### Focus topic: Direct effects of temperature increase on the psyche in Germany

<table>
<thead>
<tr>
<th>Authors, publication year</th>
<th>Data source</th>
<th>(Sub-) population</th>
<th>Number (n)</th>
<th>Region, period under consideration</th>
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<th>Phenomena/variables studied</th>
<th>Tools</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eisele et al. [40], 2021</td>
<td>Electronic health data</td>
<td>Patients in psychiatric institutions</td>
<td>164,435</td>
<td>Baden-Württemberg, 2007–2019</td>
<td>Correlative relationships in a cross-sectional design</td>
<td>Aggressive behaviour</td>
<td>SOAS-R</td>
<td>At daily maximum temperatures &gt;30°C significantly more aggressive incidents, number increases linearly with temperature; no significant correlation of daily maximum temperature with number of coercive measures</td>
</tr>
<tr>
<td>Müller et al. [41], 2011</td>
<td>Official data</td>
<td>(Attempted) suicides in the general population</td>
<td>2,987</td>
<td>Middle Franconia, Bavaria, 1998–2005</td>
<td>Correlative relationships in a cross-sectional design</td>
<td>Attempted suicide, completed suicide</td>
<td>Police protocols</td>
<td>Significant increase in the number of suicide attempts and suicides with rising temperatures and increased sunlight; no significant association with humidity, gender, motive or method of suicide (attempt)</td>
</tr>
<tr>
<td>Schneider et al. [42], 2020</td>
<td>Official data</td>
<td>Suicides in the general population</td>
<td>10,595</td>
<td>Bavaria, 1990–2006</td>
<td>Correlative relationships in a cross-sectional design</td>
<td>Suicide</td>
<td>Not applicable</td>
<td>Significant increase in the number of suicides by 5.7% for temperature rises &gt;5°C the previous day in summer, autumn, and winter, not in spring; 9.0% for persons &gt;65 years of age</td>
</tr>
</tbody>
</table>

SOAS-R=Staff Observation Aggression Scale Revised

Continued on next page
Scoping review of climate change and mental health in Germany

### Focus topic: Perception and intra-psychological processing of climate change in Germany

<table>
<thead>
<tr>
<th>Authors, publication year</th>
<th>Data source</th>
<th>(Sub-)population</th>
<th>Number (n)</th>
<th>Region, period under consideration</th>
<th>Type of study</th>
<th>Phenomena/variables studied</th>
<th>Tools</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klöckner et al. [37], 2010</td>
<td>Questionnaire survey</td>
<td>9- to 14-year-old pupils (representative), years 4–7 at mainstream schools (no special schools)</td>
<td>2,013</td>
<td>Hesse, 2010</td>
<td>Correlative relationships in a cross-sectional design, multithematic panel study</td>
<td>Emotional reactions, environmental behaviour, general well-being</td>
<td>Self-generated questionnaire with 1 item each on feelings, well-being, knowledge of action, possibilities for action</td>
<td>Most children report ethnically motivated, self-referential emotions, e.g. a guilty conscience about climate change. Girls mentioned consequence-based emotions (fear, grief) more often than boys, but coping-centred non-emotional expressions (e.g. disinterest) less often. With regard to climate change, the proportion of coping-centred expressions, as well as other non-emotional expressions, increased with children’s age. Ethically motivated, self-referential emotions became less frequent with increasing age. Well-being is hardly affected by climate-change-related emotions.</td>
</tr>
<tr>
<td>Lippold et al. [43], 2020</td>
<td>Online survey</td>
<td>General population</td>
<td>3,469</td>
<td>Germany, 03/2020</td>
<td>Multivariate linear regression models</td>
<td>Fear of coronavirus, refugees, and climate change</td>
<td>rRST-Q, BFI, and other custom-made items</td>
<td>Compared to international respondents, those in Germany report less fear of climate change than respondents from other countries. Fear of climate change correlates negatively with a conservative political attitude.</td>
</tr>
<tr>
<td>Schwaab et al. [44], 2022</td>
<td>Questionnaire survey</td>
<td>Medical students</td>
<td>203</td>
<td>Heidelberg, 05–12/2021</td>
<td>Correlative relationships in a cross-sectional design</td>
<td>Psychological stress in general and due to climate change, resilience factors</td>
<td>Climate change questions from the European Social Survey, PHQ-9, GAD-7, PTSS-10, PSQ-20, RQ, OPD-SF, SOC-13</td>
<td>60% of participants report being (very) concerned about climate change, but clinical symptoms (trauma, depression, anxiety) when thinking about climate change are hardly reported, although 23% report increased stress levels (PSQ-20). These correlate with a less secure attachment style, less structural integration, and a less pronounced sense of coherence.</td>
</tr>
<tr>
<td>Wullenkord et al. [45], 2021</td>
<td>Online questionnaire survey</td>
<td>General population (stratified sampling)</td>
<td>1,011</td>
<td>Germany, not specified</td>
<td>Correlative relationships in a cross-sectional design</td>
<td>Psychological stress in general and due to climate change, environmental behaviour, political orientation</td>
<td>Climate Anxiety Scale (German translation), PHQ-4, scales on political attitudes and attitudes towards the environment</td>
<td>High levels of climate anxiety are associated with high levels of anxiety and depression, avoidance of the issue in everyday life, and more awareness of the impacts of climate change and one’s own part in its genesis. Women report more climate anxiety than men, with no difference for education and income. Environmentally friendly behaviour is more pronounced for high climate anxiety scores.</td>
</tr>
</tbody>
</table>

1 For each focus topic, the partial results of interest from the study by Klöckner et al. [37] are reported. rRST-Q-revised Reinforcement Sensitivity Theory Questionnaire, BFI=Big Five Inventory, PHQ=Patient Health Questionnaire, GAD=Generalised Anxiety Disorder Scale, PTSS=Posttraumatic Stress Scale, PSQ=Perceived Stress Questionnaire, RQ=Relationship Questionnaire, OPD-SF=Operationalised Psychodynamic Diagnostics Short Form, SOC=Sense of Coherence

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Table 1 Continued on next page
was in danger, that one had suffered personal losses, and that one’s own future had been destroyed. The perceived danger to one’s life as well as the assumption of a destroyed future were also predictive for stronger symptoms of anxiety and depression. A personal belief in a just world may have had a protective effect on the expression of symptoms of anxiety and depression, as pointed out by the authors of the study.

### 3.2 Direct effects of temperature increase on the psyche in Germany

The initial search yielded 73 results, 15 of which were duplicates and one article in a language other than German or English, so that title and abstract were screened for 57 studies. Of these, 48 were excluded because they were not publications related to ambient temperature and its effect on the psyche. Seven more studies were excluded because they were not related to mental health. In addition, one study from the database query for the topic ‘sociological aspects’ met the inclusion criteria and was also included in the final synthesis, so that three studies were included. All included studies looked cross-sectionally at associations between psychological variables and temperatures on the same day or in the preceding days. Müller et al. [46] reported a 0.9% increase in suicide rates for every 1°C increase in temperature in spring and summer, but not in autumn and winter. Schneider et al. [42] calculated a 5.7% increase in suicide rates for every 1°C increase in temperature in spring and summer, but not in autumn and winter.

### Table 1 Continued

Results of the Scoping Review on the impact of climate change on mental health in Germany

<table>
<thead>
<tr>
<th>Authors, publication year</th>
<th>Data source</th>
<th>(Sub-) population</th>
<th>Number (n)</th>
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<td>Klöckner et al. [37], 2010</td>
<td>Questionnaire survey</td>
<td>9- to 14-year-old pupils (representative), years 4–7 at mainstream schools (no special schools)</td>
<td>2,013</td>
<td>Hesse, 2007</td>
<td>Correlative relationships in a cross-sectional design</td>
<td>Reporting of climate change, emotional concern, behavioural change</td>
<td>Custom-made questionnaire</td>
<td>The type of climate change-related emotions is not related to overall well-being. However, children who have emotions such as sadness about climate change and at the same time have ideas on how to mitigate it (e.g. taking the train instead of driving) report lower well-being. Children who report emotional reactions to climate change have more actionable knowledge about climate protection than children who emotionally withdraw from the climate discussion.</td>
</tr>
<tr>
<td>Wullenkord and Reese [27], 2021</td>
<td>Online questionnaire survey</td>
<td>General population (convenience sample)</td>
<td>Study 1: n=354 Study 2: n=453</td>
<td>Germany, not specified</td>
<td>Correlative relationships in a cross-sectional design</td>
<td>Self-protective strategies, PEB, sociodemographic background (age, gender, education, income), political orientation</td>
<td>Climate Self-Protection Scale (CSPS)</td>
<td>Different self-protective strategies exist in coping with the emotions and fears triggered by climate change. A male gender and a right-wing political orientation are related to coping strategies such as avoidance, rationalisation, or denial of the global and personal consequences of climate change, as well as one’s own complicity in causing it.</td>
</tr>
</tbody>
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</tr>
</tbody>
</table>

1 For each focus topic, the partial results of interest from the study by Klöckner et al. [37] are reported. PEB=pro-environmental behaviour
in suicide risk for temperature jumps of 5°C the previous day in summer, autumn, and winter, but not in spring, with the risk being particularly high for older people. One study used electronic health records for patients in mental health facilities to show a significant association between daily maximum temperatures above 30°C and aggressive incidents [40].

3.3 Perception and intra-psychological processing of climate change in Germany

The initial search yielded 79 results, eight of which were duplicates and one article in a language other than German or English, so that title and abstract were screened for 70 studies. One article was not retrievable, 52 were excluded because they were not publications related to climate change. Nine further studies were excluded because they were not related to mental health, two studies did not collect data, and two other studies did not have a German sample. Ultimately, four studies met the inclusion criteria. In all included studies, cross-sectional correlations between psychological variables and subjective well-being were investigated. Lippold et al. [43] compared anxiety due to climate change with anxiety in the context of the COVID-19 pandemic. In the other studies, the focus was on assessing the emotional impact of climate change. Based on questionnaire data, the results agreed that hardly any clinically significant psychological distress currently arises from the emotional confrontation with climate change [37, 44, 45].

However, children and adolescents are considered vulnerable groups for the development of a clinically manifest psychiatric disorder in the event of an increase in climate change impacts [37]. Lippold et al. [43] found a below-average expression of reported anxiety due to climate change in an international comparison. Wullenkord et al. [45] report more pronounced climate change anxiety among women; furthermore, participants reported less pronounced climate anxiety when they perceived the global and personal consequences of climate change, as well as their own complicity in causing it, to be lower. Climate change-related perceived stress correlates positively with a less secure attachment style, a lower availability of regulating self-functions and a less pronounced sense of coherence, i.e. the feeling that the world and oneself are understandable and predictable [44].

3.4 Sociological aspects of the psychological consequences of climate change in Germany

The initial search yielded 140 results, 44 of which were duplicates, so that title and abstract were screened for 96 studies. Of these, 91 were excluded because they were not publications on sociological aspects related to climate change. In addition, two studies were excluded because they were not related to mental health, one because the data were mainly collected outside of Germany, one because the data were qualitative in nature, and one because the references to mental health were not supported by data. Thus, no study could be included as a quantitative research paper on the sociological aspects of the psychological consequences of climate change in Germany.
3.5 Resilience factors for mental stability in the context of climate change in Germany

The initial search yielded 95 hits, 24 of which were duplicates, so that title and abstract were screened for 71 studies. Of these, 47 were excluded because they were not publications related to climate change, twelve were excluded because they were not related to psychological impacts, and ten were excluded because they were not related to resilience or coping mechanisms. Two studies were included and reviewed.

In the two studies included, cross-sectional design identified coping strategies with regard to climate change-related psychopathologies. In a study by Wullenkord and Reese [27], self-protective strategies and their correlations in dealing with the effects of climate change were analysed with a questionnaire newly designed for this purpose. The existence of different coping strategies could be shown, such as avoidance, rationalisation, or the denial of the global and personal consequences of climate change as well as one’s own role in causing it. Furthermore, these strategies were more pronounced in men and in those with a right-wing political orientation; only avoidance was reported to be more pronounced in women than in men. Klöckner et al. [37] studied 9- to 14-year-old pupils and were able to show that emotional reactions to climate change correlated positively with more knowledge about how to mitigate it. The authors interpreted this as an indication that children who are overwhelmed with climate change withdraw emotionally and consequently absorb less information on the topic. There was no correlation between the type of climate change-related emotions and general well-being.

4. Discussion

4.1 Strengths and limitations

The present review provides a comprehensive overview of the literature on the effects of climate change on mental health in Germany, drawing on a total of five systematic literature searches in five databases. This broad search strategy is contrasted by a highly insufficient number of studies, so that the generalisability of the results is limited. In order to derive meaningful recommendations, the results obtained are therefore considered alongside surveys and studies without peer review from Germany, as well as internationally published reviews on the focus topics of this article, compiled by systematic literature research. However, the state of knowledge remains insufficient after considering this set, particularly with regard to successful adaptation [48]. The search terms used were adapted for each focus topic in order to include as many relevant publications as possible, but it cannot be ruled out that additional studies might have been included if other combinations of search terms had been used. The results of qualitative studies were not included in this review due to the methodological approach followed. However, given the many connections between climate change and mental health that remain to be clarified, they provide many complementary results, such as a better understanding of the connections between climate change-related emotions and general well-being or resilience in relation to psychological distress caused by climate change [49–52].
4.2 Evidence and need for knowledge

When evaluating the results on the effects of climate change on mental health in Germany, it becomes apparent that there is a large discrepancy between the data and knowledge available for Germany and international findings. Both nationally and internationally, there is a great need for further scientific knowledge on the psychological effects of the climate crisis and possible adaptation strategies.

Common aspects across the focus topics

The effects of climate change on mental health in Germany have so far been insufficiently studied, both cross-sectionally and longitudinally. Previous international findings on the focus topics investigated for Germany in this article come largely from Australia, Canada, and the USA. Only a small proportion of the studies relate to the European population [48]. In addition, relevant constructs, such as intra-psychological processing and resilience factors, are not distinctly operationalised, and validated assessment tools are often lacking. This makes it difficult to compare the results and derive recommendations. Different methodological approaches and evaluation tools are also used to record psychological distress patterns. Often, mental health burden is recorded by means of questionnaires. However, these are often not clinically validated, i.e. no clinical diagnoses are made by clinical experts, and no validated structured clinical interviews corresponding to manuals of psychiatric disorders are conducted (e.g. the structured clinical interview according to DSM-V, the Diagnostic and Statistical Manual of Mental Disorders [53]). A special focus of future research should be on the mental health burden for vulnerable groups, of which there are hardly any findings for Germany. An increased vulnerability among children and adolescents, older persons, those with pre-existing psychiatric disorders or low socioeconomic status can be assumed in correspondence with international studies [11, 48, 54]. The same applies to people who are increasingly exposed to the consequences of climate change either directly, through extreme weather events, or indirectly, e.g. as activists or health professionals [33, 48].

Extreme weather events and psychological consequences

The data found in a regional sample in Germany [39] are consistent with findings in international literature on post-traumatic stress symptoms, depression, and anxiety in the aftermath of a flooding event [5, 11, 55, 56]. Floods can exacerbate pre-existing psychiatric disorders [57]. This is reflected in a higher prescription rate of psychotropic drugs such as sedatives, hypnotic psychiatric disorders or antidepressants after floods and storm surges [58, 59]. Those individuals who have to be relocated as a result of the flooding have a significantly higher risk of a subsequent psychiatric disorder, which can still be observed a year after the event [60]. Children and adolescents in particular show increased vulnerability to the effects of extreme weather events because they have fewer coping strategies and their more pronounced neuroplasticity (changes in cerebral structures and functions in response to external stimuli) makes them more susceptible to stress-induced neuroanatomical and endocrine changes [61, 62]. In international literature, Mammbrey et al. [33] identified the following risk factors for mental health outcomes in children and adolescents: intra-family...
Scoping review of climate change and mental health in Germany

Conflict, little social support, loss of social network due to relocation, and low socioeconomic status of parents.

Direct effects of temperature increase on the psyche

The increased prevalence of suicides reported for Germany at higher daily temperatures compared to the previous day has also been shown in international reviews, which found a correlation of suicide rates with an increase in daily temperatures compared to the previous day and with higher daily temperatures in general [13, 14]. The fact that this correlation is consistently reported for Germany for summer, but not for the colder seasons, could be related to the average temperature in autumn, spring, and winter being close to or below 21°C (for now), a daily average temperature considered comfortable. However, the increase in daily average temperatures will continue as climate change progresses [63]. The question remains whether suicide rates can be reduced through education and heat protection. Increased aggressive behaviour, as shown in psychiatric institutions by Eisele et al. [40], has been shown internationally for the general population [6, 11]. In addition to the effects on suicide risk, an increase in admissions to psychiatric hospitals at higher daily average temperatures has been reported in international studies [48]. A study conducted in the USA found fewer positive and more negative emotions in subjects when daily average temperatures exceeded 21°C [11]. People with pre-existing psychiatric disorders, children, and adolescents are particularly vulnerable to the effects of heat on mental health [48].

Perception and intra-psychological processing of climate change

As the negative impacts of climate change on mental health will increase in the future, there is a need for a better understanding of the transition from an adequate emotional response to climate change to clinically relevant mental health impairments. Surveys conducted in Germany show a high prevalence (40–73%) of general anxiety, sadness, and anger in all age groups, in line with international study results [64–67]. These feelings increased significantly nationwide after the July 2021 floods (by 20 percentage points [66]). It can be assumed that the media coverage of the floods had an influence on intra-psychological processing and the negative affects subsequently reported by the respondents. The role of the media in psychological adaptation processes to climate change and mitigation should therefore be discussed. To this end, media guidelines can serve as a recommendation for a style of reporting that neither aims to trivialise weather phenomena that occur nor to reinforce a sense of powerlessness [68]. In a report by the German Environment Agency on the emotional state of young people in the context of climate change, 26% of the respondents stated that concerns about the environment limited their sense of joy and caused sleep problems [69]. In a report by the German Environment Agency on the emotional state of young people in the context of climate change, 26% of the respondents stated that concerns about the environment limited their sense of joy and caused sleep problems [69]. International studies show that the majority of young people, regardless of gender, consider climate impacts when making reproductive choices [47]. A better handling of climate feelings and a strengthening of resilience factors requires good psychoeducation as well as opportunities for exchange with like-minded people and the experience of collective self-efficacy through opportunities for action to achieve societal transformation and climate protection [70].

For all topics examined, the state of knowledge for Germany is to be regarded as insufficient, which makes it difficult to draw final conclusions.
Sociological aspects of the psychological consequences of climate change

The current state of studies on sociological aspects of climate change-related impairments of mental health does not allow for clear statements on risk factors, effects, or possible countermeasures. In addition, there are currently no studies from the German-speaking region that examine the connection between climate change and specific sociodemographic or sociological factors and intersectional discrimination (i.e., the reinforcing effects of interdependent systems of discrimination such as patriarchy, capitalism, colonialism, ableism – the discrimination against people with limited mental or physical abilities [71–73]) in terms of mental health. In this context, sociodemographic factors such as ethnicity, family history of migration, and socioeconomic status would be of interest, as well as sociological factors such as spatial marginalisation (e.g., due to the stigmatisation and infrastructural deficiency of certain neighbourhoods in which certain ethnic, cultural, or religious groups are more strongly represented). Studies on the psychological impact of an extreme event, such as the COVID-19 pandemic, have shown that sociological factors, such as living in a neighbourhood disadvantaged in terms of health infrastructure, having few social contacts, and being part of a minority subjected to structural racism, can lead not only to higher mortality, but also to a significantly higher risk of psychological distress [74]. Climate change is expected to lead to an increase in social states of emergency due to heatwaves, supply shortages, floods, power cuts, or the collapse of public and private services. Therefore, an analysis of the different living environments in which sociological factors can have both positive and negative influences is indispensable for a psychologically sensitive approach to crisis situations caused by climate change.

Resilience factors for mental stability in the context of climate change

Climate change, through stressors such as heat, poor air quality, the possible loss of emotionally significant places and landscapes, and potentially even forced migration, reduces the possibilities of building psychological resilience, which underlines the importance of strengthening the existing psychological resources at the individual and collective level [11]. In the studies considered for Germany, different definitions of resilience emerged: on the one hand, factors such as biological sex are identified, which reduce the risk of developing psychological stress and thus establish resilience. On the other hand, factors that are actively protective, such as social support, are examined. Thus, when there is an increased risk, protective factors can lead to resilience. At the same time, if the risk of psychological distress is low, these protective factors are not relevant for psychological recovery after a distressing event. The classification as a resilience factor thus depends on the existing vulnerability of an individual. The results of the available studies are only of limited significance in this context. While Wullenkord and Reese [27] examine self-protective strategies as mechanisms for coping with climate change-related psychological distress, they do not consider them to be resilience factors in the sense of successful coping, rather as dysfunctional mechanisms (denial and avoidance). The factors identified by Klöckner et al. [37] similarly are considered reactive mechanisms and not successful coping. In
In addition to reducing our emissions, we need to expand social education and mental healthcare for vulnerable groups, as well as for those affected by extreme weather events.

In contrast, a report by the German Environment Agency, through qualitative interviews with young climate activists, identifies the following resilience factors: knowledge on how to deal with psychological distress, positive cognitive assumptions, support and appreciation, as well as social and societal support structures [69]. The international literature on resilience factors mainly refers to individual extreme weather events [35]. In contrast, the indirect factors, such as the effects of climate change on the psyche in regions that are currently not (yet) acutely affected by the consequences of climate change, have not yet been studied. Chen et al. [75] were able to identify an extensive list of resilience factors. Intact family structures and a higher level of education in particular have an active protective effect against psychological stress after extreme weather events. This indicates that it is not so much the individual’s psychological coping abilities that enable successful handling of psychological distress, but rather the societal and social embedding of the individual. It is therefore necessary to promote resilience factors on a collective or political level.

4.3 Recommendations

The recommendations listed in Table 2 result from the collected findings presented in this article. As there is still a great need for research in Germany, the identified fields of action result from a comparison with international literature. The measures derived were adapted to the German context according to the authors’ assessment. It is assumed that findings valid for the Anglo-American region can largely be transferred to the European context. Further reference can therefore be made to corresponding publications, for example those by the American Psychological Association [11]. The position paper on climate change and mental health of the German Association for Psychiatry, Psychotherapy and Psychosomatics (Deutsche Gesellschaft für Psychiatrie und Psychotherapie, Psychosomatik und Nervenheilkunde, DGPPN) [76] was also used as a source of information in the preparation of the recommendations and its considerations were adapted to public health context.

The recommendations made here refer specifically to health promotion through medical-psychotherapeutic treatment, structural, and behavioural prevention, thus focusing on the adaptation to the impact of climate change on mental health. An expansion of the psychiatric and psychotherapeutic care infrastructure appears all the more urgent as the current situation already falls far short of demand [77]. The inclusion of climate change and its impact on mental health in the training of psychotherapeutic professions is also aimed at the practitioners themselves: they must first find their own way to intra-psychologically process knowledge about climate change and its effects; only then can they ensure competent treatment of patients with climate change-related issues [78–80].

Considering the numerous negative consequences of climate change for the human psyche, it must be emphasised once again in all clarity that, in addition to the development of adaptation strategies, climate protection measures are imperative and have top priority in order to minimise an increase in psychological risks. In this sense, climate protection is the most effective form of health protection [81]. The healthcare sector, which in Germany is responsible for 5.2%–6.7% of national greenhouse gas emissions depending on estimates [82, 83], should be particularly
### Table 2
**Recommendations for health promotion through medical-psychotherapeutic treatment as well as through structural and behavioural prevention in order to adapt to the negative effects of climate change on mental health in Germany**

<table>
<thead>
<tr>
<th>Health promotion by incorporating the impact of climate change on mental health into adaptation processes</th>
<th>Approach/objective</th>
<th>Actors</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active participation of healthcare experts in political transformation processes</td>
<td>Inclusion of mental health in the identification of needs, resilience resources, and social adaptation to climate impacts in the context of political decision-making and transformation processes</td>
<td>Federal, state, and municipal levels</td>
<td>Financial and human resources at intervention level</td>
</tr>
<tr>
<td>Training those responsible for mental health issues and involving them in developing strategies for adapting and mitigating the consequences of climate change on mental health in public institutions, especially in the health sector</td>
<td>Protecting the mental health of the population through sustainable mitigation of the mental health impacts of climate change and adaptation</td>
<td>State and municipal levels</td>
<td>Financial and human resources, creation of positions for change agents</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Health promotion through psychosocial emergency care and psychotherapeutic treatment</th>
<th>Approach/objective</th>
<th>Actors</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training and expansion of psychosocial emergency care</td>
<td>Secondary prevention of long-term psychological consequences after extreme weather events</td>
<td>Federal and state levels</td>
<td>Expertise-based needs assessments, financial and human resources, establishment and expansion of existing structures</td>
</tr>
<tr>
<td>Adjustment when planning the demand for psychotherapeutic care by counselling centres and psychotherapists to the (increasing) climate change-related needs including peak demand after extreme weather events</td>
<td>Improving mental health across society through needs-based care and secondary prevention</td>
<td>Federal and state levels (politics and administration)</td>
<td>Expertise-based needs assessment, financial and human resources</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Health promotion by means of structural prevention</th>
<th>Approach/objective</th>
<th>Actors</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integration of knowledge about the connection between planetary and mental health into the education and training of health personnel and crisis intervention services.</td>
<td>Improving overall mental health in society through psychoeducation and structural prevention</td>
<td>Federal and state levels, those responsible for the preparation of study regulations, education and training guidelines</td>
<td>Teacher training, financial and human resources</td>
</tr>
<tr>
<td>Promote further research and development of interventions on mental health and the climate crisis</td>
<td>Improving prevention and treatment of climate change-related mental distress and disorders</td>
<td>Federal level, universities</td>
<td>Financial and human resources</td>
</tr>
<tr>
<td>Preparation of heat-health action plans, urban development changes towards sponge cities with more green spaces</td>
<td>Protection of vulnerable groups, promotion of mental well-being</td>
<td>Federal, state, and municipal levels</td>
<td>Financial and human resources at municipal level</td>
</tr>
</tbody>
</table>

Continued on next page
4.4 Conclusion

The effects of climate change on mental health are diverse and depend on individual and societal factors. Extreme weather events and rising average temperatures have a direct influence on mental health, an indirect influence is exerted by awareness of the human contribution to climate change and its consequences. For Germany, the state of research on these processes is highly insufficient, and both in Germany and internationally, there is a particular lack of knowledge on how to achieve successful adaptation to the effects of climate change on mental health. This should be a focus of further research. In addition to adaptation, mitigation must also be seen as a societal task. The healthcare system has a special role to play here, since it accounts for a considerable share of human greenhouse gas emissions. A successful reduction of this share would simultaneously protect the health of patients.

Table 2 Continued

<table>
<thead>
<tr>
<th>Measures/target group</th>
<th>Approach/objective</th>
<th>Actors</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establishment of climate councils in which representatives of socially marginalised and particularly vulnerable groups advise executive and legislative bodies on local/regional measures and participate in decision-making.</td>
<td>Participation of social groups to identify needs, resilience resources and social adaptation to climate impacts</td>
<td>Federal, state, and municipal levels</td>
<td>Financial and human resources at the intervention level, legislative changes may be needed to grant decision-making powers</td>
</tr>
<tr>
<td>Health promotion through behavioural prevention</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public relations work on the impact of climate change on mental health, on prevention and treatment options, and on ways to strengthen individual and collective resilience</td>
<td>Empowerment of (potentially) affected people and the general population by informing them about individual possibilities for action and about the measures taken to protect the population.</td>
<td>Federal, state, and municipal levels, service providers</td>
<td>Financial and human resources, further research with focus on Germany, reference to this research by public relations activities</td>
</tr>
</tbody>
</table>

Commitment to the health of the population and thus also to climate protection.

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Annex Table 1
Search queries of the literature search per focus topic, formatted for PubMed. Each second query per focus topic is aimed at internationally published reviews without reference to Germany.

Focus topic: Extreme weather events and psychological consequences in Germany

((climate change[Title/Abstract]) OR (global warming[Title/Abstract]) OR (climate[Title/Abstract]) OR (weather[Title/Abstract]) OR (flood*[Title/Abstract]) OR (heat wave[Title/Abstract]) OR (extreme weather[Title/Abstract]) OR (hurricane*[Title/Abstract]) OR (tornado*[Title/Abstract]) OR (greenhouse effect[Title/Abstract]) AND ((depression [Title/Abstract]) OR (anxiety [Title/Abstract]) OR (trauma [Title/Abstract]) OR (post-traumatic stress disorder [Title/Abstract]) OR (mood disorder [Title/Abstract]) OR (suicide [Title/Abstract]) OR (substance abuse [Title/Abstract]) OR (alcohol [Title/Abstract]) OR (mania [Title/Abstract]) OR (schizophrenia [Title/Abstract]) OR (bipolar [Title/Abstract]) OR (ptsd [Title/Abstract]) AND ((german[Title/Abstract]) OR (germany[Title/Abstract]) OR (deutsch[Title/Abstract]) OR (Deutschland[Title/Abstract])))

Focus topic: Direct effects of temperature increase on the psyche in Germany

((heat[Title/Abstract]) OR (hot weather[Title/Abstract]) OR (temperature rise[Title/Abstract]) OR (temperature regulation[Title/Abstract]) OR (heat wave[Title/Abstract]) OR (heat waves[Title/Abstract]) OR (rising temperature[Title/Abstract]) OR (rising temperatures[Title/Abstract]) AND ((aggression[Title/Abstract]) OR (cognition[Title/Abstract]) OR (cognitive dysfunction[Title/Abstract]) OR (crime[Title/Abstract]) OR (depression[Title/Abstract]) OR (anxiety[Title/Abstract]) OR (trauma[Title/Abstract]) OR (post-traumatic stress disorder[Title/Abstract]) OR (mood disorder[Title/Abstract]) OR (suicide[Title/Abstract]) OR (substance abuse[Title/Abstract]) OR (alcohol[Title/Abstract]) OR (mania[Title/Abstract]) OR (schizophrenia[Title/Abstract]) OR (bipolar[Title/Abstract]) OR (ptsd[Title/Abstract]) AND ((german[Title/Abstract]) OR (germany[Title/Abstract]) OR (deutsch[Title/Abstract]) OR (Deutschland[Title/Abstract])))

Focus topic: Extreme weather events and psychological consequences in Germany

((climate change[Title/Abstract]) OR (global warming[Title/Abstract]) OR (climate[Title/Abstract]) OR (weather[Title/Abstract]) OR (flood*[Title/Abstract]) OR (heat wave[Title/Abstract]) OR (extreme weather[Title/Abstract]) OR (hurricane*[Title/Abstract]) OR (tornado*[Title/Abstract]) OR (greenhouse effect[Title/Abstract]) AND ((depression [Title/Abstract]) OR (anxiety [Title/Abstract]) OR (trauma [Title/Abstract]) OR (post-traumatic stress disorder [Title/Abstract]) OR (mood disorder [Title/Abstract]) OR (suicide [Title/Abstract]) OR (substance abuse [Title/Abstract]) OR (alcohol [Title/Abstract]) OR (mania [Title/Abstract]) OR (schizophrenia [Title/Abstract]) OR (bipolar [Title/Abstract]) OR (ptsd [Title/Abstract]) AND ((german[Title/Abstract]) OR (germany[Title/Abstract]) OR (deutsch[Title/Abstract]) OR (Deutschland[Title/Abstract])))

Focus topic: Direct effects of temperature increase on the psyche in Germany

((heat[Title/Abstract]) OR (hot weather[Title/Abstract]) OR (temperature rise[Title/Abstract]) OR (temperature regulation[Title/Abstract]) OR (heat wave[Title/Abstract]) OR (heat waves[Title/Abstract]) OR (rising temperature[Title/Abstract]) OR (rising temperatures[Title/Abstract]) AND ((aggression[Title/Abstract]) OR (cognition[Title/Abstract]) OR (cognitive dysfunction[Title/Abstract]) OR (crime[Title/Abstract]) OR (depression[Title/Abstract]) OR (anxiety[Title/Abstract]) OR (trauma[Title/Abstract]) OR (post-traumatic stress disorder[Title/Abstract]) OR (mood disorder[Title/Abstract]) OR (suicide[Title/Abstract]) OR (substance abuse[Title/Abstract]) OR (alcohol[Title/Abstract]) OR (mania[Title/Abstract]) OR (schizophrenia[Title/Abstract]) OR (bipolar[Title/Abstract]) OR (ptsd[Title/Abstract]) AND ((german[Title/Abstract]) OR (germany[Title/Abstract]) OR (deutsch[Title/Abstract]) OR (Deutschland[Title/Abstract])))

Scoping review of climate change and mental health in Germany

Annex Table 1
Search queries of the literature search per focus topic, formatted for PubMed. Each second query per focus topic is aimed at internationally published reviews without reference to Germany.
Focus topic: Perception and intra-psychological processing of climate change in Germany

((climate change[Title/Abstract]) OR (global warming[Title/Abstract]) OR (climate crisis[Title/Abstract]) OR (climate[Title/Abstract]) OR (greenhouse effect[Title/Abstract])) AND ((climate anxiety[Title/Abstract]) OR (eco anxiety[Title/Abstract]) OR (eco-anxiety[Title/Abstract]) OR (solastalgia[Title/Abstract]) OR (climate grief[Title/Abstract]) OR (economic grief[Title/Abstract]) OR (eco depression[Title/Abstract]) OR (climate anger[Title/Abstract]) OR (eco anger[Title/Abstract]) OR (eco-guilt[Title/Abstract]) OR (climate distress[Title/Abstract]) OR (activist burnout[Title/Abstract]) OR (active hope[Title/Abstract]) OR (beyond hope[Title/Abstract]) OR (emotions[Title/Abstract]) OR (eco guilt[Title/Abstract])) AND ((german[Title/Abstract]) OR (germany[Title/Abstract]) OR (deutsch[Title/Abstract]) OR (Deutschland[Title/Abstract]))

Focus topic: Sociological aspects of the psychological consequences of climate change in Germany

((climate change[Title/Abstract]) OR (climate change[Title/Abstract])) OR (climate crisis[Title/Abstract]) OR (climate[Title/Abstract]) OR (temperature[Title/Abstract]) OR (heat build-up[Title/Abstract]) OR (heat[Title/Abstract]) OR (temperature fluctuation[Title/Abstract]) OR (variations in temperature[Title/Abstract]) OR (extreme weather events[Title/Abstract]) OR (drought[Title/Abstract]) OR (flood[Title/Abstract]) OR (flooding[Title/Abstract]) OR (sea-level rise[Title/Abstract]) OR (rise in sea level[Title/Abstract]) OR (hot house scenario[Title/Abstract]) OR (hot bulp[Title/Abstract]) OR (ipcc[Title/Abstract]) OR (political ecology[Title/Abstract]) OR (climate-related[Title/Abstract]) OR (climate justice[Title/Abstract]) OR (mental health[Title/Abstract]) OR (mental illness[Title/Abstract]) OR (mental illnesses[Title/Abstract]) OR (mental disorder[Title/Abstract]) OR (depression[Title/Abstract]) OR (anxiety[Title/Abstract]) OR (trauma[Title/Abstract]) OR (post-traumatic stress disorder[Title/Abstract]) OR (mood disorder[Title/Abstract]) OR (suicide[Title/Abstract]) OR (substance abuse[Title/Abstract]) OR (alcohol[Title/Abstract]) OR (mania[Title/Abstract]) OR (schizophrenia[Title/Abstract]) OR (bipolar[Title/Abstract]) OR (ptsd[Title/Abstract]) OR (suicidal[Title/Abstract]) OR (well being[Title/Abstract]) OR (well-being[Title/Abstract]) OR (quality of life[Title/Abstract]) AND ((emotional identification[Title/Abstract]) OR (terror management theory[Title/Abstract]) OR (communal well-being[Title/Abstract]) OR (communal well being[Title/Abstract]) OR (health infrastructure[Title/Abstract]) OR (social infrastructure[Title/Abstract]) OR (family cohesion[Title/Abstract]) OR (social determinants of health[Title/Abstract]) OR (aggression[Title/Abstract]) OR (violence[Title/Abstract]) OR (femicide[Title/Abstract]) OR (communal health[Title/Abstract]) OR (stress proliferation[Title/Abstract]) OR (disability[Title/Abstract]) OR (disabilities[Title/Abstract]) OR (lgbtq[Title/Abstract]) OR (indigenous[Title/Abstract]) OR (seniors[Title/Abstract]) OR (children[Title/Abstract]) OR (youth[Title/Abstract]) OR (neurodiversity[Title/Abstract]) OR (refugees[Title/Abstract]) OR (asylum[Title/Abstract]) OR (spatial disparity[Title/Abstract]) OR (spatial disparities[Title/Abstract]) OR (neighborhood[Title/Abstract]) OR (neighborhoods[Title/Abstract]) OR (neighborhood[Title/Abstract]) OR (neighborhoods[Title/Abstract]) OR (racism[Title/Abstract]) OR (ethnic minority[Title/Abstract]) OR (ethnic minorities[Title/Abstract]) OR (sint[Title/Abstract]) OR (roma[Title/Abstract]) OR (religion[Title/Abstract]) OR (islamophobia[Title/Abstract]) OR (antisemitism[Title/Abstract]) OR (antisemantisms[Title/Abstract]) OR (sexism[Title/Abstract]) OR (capitalism[Title/Abstract]) OR (patrarchy[Title/Abstract]) OR (colonialism[Title/Abstract]) OR (group based discrimination[Title/Abstract]) OR (education[Title/Abstract]) OR (inequality[Title/Abstract]) OR (inequality[Title/Abstract]) OR (inequality[Title/Abstract])) AND ((german[Title/Abstract]) OR (germany[Title/Abstract]) OR (deutsch[Title/Abstract]) OR (Deutschland[Title/Abstract]))
## Focus topic: Resilience factors for mental stability in the context of climate change in Germany

<table>
<thead>
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| ((climateChange>Title/Abstract)) OR (globalWarming>Title/Abstract)) OR (climateCrisis>Title/Abstract)) OR (climateChange>Title/Abstract)) OR (greenhouseEffect>Title/Abstract)) AND ((resilience>Title/Abstract)) OR (protectiveFactor>Title/Abstract)) OR (adaption>Title/Abstract)) OR (coping>Title/Abstract)) OR (adjustment>Title/Abstract)) OR (riskFactor>Title/Abstract)) AND ((mentalHealth>Title/Abstract)) OR (psychological>Title/Abstract)) OR (wellbeing>Title/Abstract)) OR (wellBeing>Title/Abstract)) OR (behavioral>Title/Abstract)) OR (behavioural>Title/Abstract)) OR (psychosocial>Title/Abstract)) OR (lifeSatisfaction>Title/Abstract)) OR (qualityOfLife>Title/Abstract)) AND ((germanTitle/Abstract)) OR (germanyTitle/Abstract)) OR (deutschTitle/Abstract)) OR (DeutschlandTitle/Abstract))

<table>
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</tr>
</tbody>
</table>
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**Annex Figure 1**
Flow charts of the literature selection per focus topic

**Annex Figure 1a (left)**
Extremes weather events

**Annex Figure 1b (right)**
Temperature increase

**Identification of studies: extreme weather events**
- Records identified in databases (n=99)
- Records excluded before screening:
  - Duplicate records (n=20)
  - Automatically removed records (n=0)
  - Records removed for other reasons (n=0)
- Records screened (n=79)
- Records retrieved (n=78)
- Records checked for suitability (n=78)
- Records excluded:
  - No reference to extreme weather events (n=73)
  - No reference to mental health (n=3)
  - No data on Germany (n=1)
- Studies included in review (n=1)

**Identification of studies: temperature increase**
- Records identified in databases (n=73)
- Records excluded before screening:
  - Duplicate records (n=15)
  - Automatically removed records (n=0)
  - Records removed for other reasons (n=0)
- Records screened (n=58)
- Records retrieved (n=57)
- Records checked for suitability (n=57)
- Records excluded:
  - No reference to ambient temperature (n=48)
  - No reference to mental health (n=7)
- Studies included in review (n=3*)

*One study was included after reviewing the entries for focus topic sociological aspects
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Identification of studies: intra-psychological processing

- Records identified in databases (n=79)
- Records excluded before screening:
  - Duplicate records (n=8)
  - Automatically removed records (n=0)
  - Records removed for other reasons (n=0)
- Records screened (n=71)
- Exclusion: not written in German or English (n=1)
- Records retrieved (n=70)
- Records that cannot be retrieved (n=1)
- Records checked for suitability (n=69)
- Records excluded:
  - No reference to climate change (n=52)
  - No reference to mental health (n=9)
  - No original data (n=2)
  - No German sample (n=2)
- Studies included in review (n=4)

Identification of studies: sociological aspects

- Records identified in databases (n=140)
- Records excluded before screening:
  - Duplicate records (n=44)
  - Automatically removed records (n=0)
  - Records removed for other reasons (n=0)
- Records screened (n=96)
- Exclusion: not written in German or English (n=0)
- Records retrieved (n=96)
- Records that cannot be retrieved (n=0)
- Records checked for suitability (n=96)
- Records excluded:
  - No reference to climate change and sociological aspects (n=91)
  - No reference to/no data on mental health (n=3)
  - Data mainly from outside Germany (n=1)
  - Qualitative data (n=1)
- Studies included in review (n=0)
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Identification of studies: resilience factors

- Records identified in databases (n=95)
- Records excluded before screening:
  - Duplicate records (n=24)
  - Automatically removed records (n=0)
  - Records removed for other reasons (n=0)

- Records screened (n=71)
- Exclusion: not written in German or English (n=0)

- Records retrieved (n=71)

- Records checked for suitability (n=71)
  - Records excluded:
    - No reference to climate change (n=47)
    - No reference to mental health (n=12)
    - No reference to resilience (n=10)

- Studies included in review (n=2)
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