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Final report

Development of a hazard screening protocol for Extreme Heat (Selection# 1228917)

Koen De Ridder, Dirk Lauwaet, Hans Hooyberghs and Filip Lefebre

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VITO NV
Boeretang 200 - 2400 MOL - BELGIE
Tel. + 32 14 33 55 11 - Fax + 32 14 33 55 99
vito@vito.be - www.vito.be

BTW BE-0244.195.916 RPR (Turnhout)
Bank 375-1117354-90 ING
BE34 3751 1173 5490 - BBRUBEBB

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SUMMARY

In this report, an overview is given of the data methodology used for extreme heat hazard determination, together with climate change impact statements, statements on risk reduction recommendations and links to additional information.

The **data methodology** is based on the simplified Wet Bulb Globe Temperature (WBGT), which represents both temperature and humidity impacts. While the WBGT was developed in a context of health, it is sufficiently generic to be of value also in other domains such as infrastructure and energy. The WBGT is derived from global daily maximum air temperature contained in ERA-Interim re-analysis fields for the period 1981-2010, which is considered of sufficient length to provide robust climate statistics. The 0.75° lat/lon fields are corrected for local-scale altitude effects by means of a high-resolution global digital elevation model, resulting in global daily maximum WBGT fields at a spatial resolution of approximately 10 km. These fields are temporally smoothed using a 3-day filter, so as to account for the cumulative effects of prolonged heat. These 30-year, 10-km resolution, 3-day smoothed daily maximum WBGT values are then employed to fit a Generalized Extreme Value (GEV) probability distribution function for each grid cell of the global domain. Considering return periods of 5, 20, and 100 years, 10-km hazard intensity maps have been calculated for each of these periods. To these hazard intensity maps, threshold values of 32°C, 28°C and 25°C, stemming from the scientific literature, subsequently are applied, resulting in a global heat risk map. This map is compared ('sanity check') to independent heat information available in the IPCC's 5th Assessment Report, showing a fair agreement, although our map has a slight tendency to categorize certain areas (e.g., Russia, France) at a higher extreme heat hazard level.

Statements on **climate change impacts** are made twofold. First, we consider a general (non-country specific) statement, making a reference to the IPCC's 5th Assessment Report, in particular to the 'virtual certainty' of the increase of the frequency, intensity, and duration of extremely hot episodes. In addition, we provide country-specific statements, accounting for the expected regional temperature increase. Using digital output fields from Global Climate Models, we have created a global map containing the expected warming trend (more specifically the rate of increase of Summer temperatures) between the current situation and the end of the century. Based on this map, and using quartile ranges, global land areas have been sub-divided into four categories, corresponding to different levels of expected temperature increase. From this, country-specific climate change impact information is derived.

Furthermore, regarding the statements on **risk reduction recommendations**, in order to maintain the cross-platform consistency, an analysis was first performed of the recommendations of two closely related (climatic) hazards featuring in the *ThinkHazard!* platform: 'water scarcity' and 'river flooding'. Based on that analysis, the following risk reduction recommendation categories were selected: 'vulnerability assessment', 'obtain pre-existing extreme heat hazard information', 'professional guidance', 'identify Heat Forecasting Systems', 'consider vulnerability of other assets', 'extreme heat management', and 'built infrastructure may alter heat hazard'. Detailed information (sitting behind the 'More information' link) for each of the retained risk reduction recommendations is made available in this report, and also as separate files, using the World Bank template for this purpose.

Finally, a list of **links to additional information** is compiled and presented.

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CHAPTER 1 INTRODUCTION

The scope of the project is to extend the ThinkHazard! platform to also include extreme heat, by providing suitable quantitative data as input to the platform, together with a classification strategy; and by providing appropriate recommendations to reduce extreme heat risk.

Heat waves are ‘silent killers’, claiming more victims than any other weather-related disaster (Borden and Cutter, 2008). Moreover, global climate projections consistently point towards an increase of the number, duration, and intensity of heat waves (Meehl and Tibaldi, 2004; Diffenbaugh and Giorgi, 2012).

This final report outlines the data development methodology and sanity check (Chapter 2) and proposes statements on climate change (Chapter 3) and risk reduction recommendations (Chapter 4), concluding (Chapter 5) with a list of links to additional information.

CHAPTER 2 DRAFT DATA DEVELOPMENT METHODOLOGY

2.1. PRODUCTION OF DAILY GLOBAL WBGT MAPS

The establishment of heat related hazard will be based on an existing and widely accepted heat stress indicator, the Wet Bulb Globe Temperature (WBGT). Being used all over the World, the WBGT has an obvious relevance for human health, but it is relevant in all kinds of projects and sectors, including infrastructure related, as heat stress affects personnel and stakeholders, and therefore the design of buildings and infrastructure. In general, the WBGT is a relevant enough proxy to quantify the strain on physical infrastructure (energy, water, transport), such as increased demands for water and electricity, which may also affect decisions related to infrastructure.

For this project, we employ the simplified wet bulb globe temperature (in °C), which is defined as (WMO, 2015):

$$\text{WBGT} = 0.567\,\text{T} + 0.393\,\text{VP} + 3.94,$$

with T the air temperature (in °C) and VP the vapour pressure (in hPa).

The required air temperature and dew point temperature (which can directly be converted to vapour pressure) data were derived from the ERA Interim (Dee et al., 2011) Global archive, which is distributed by the European Centre for Medium Range Weather Forecasting (ECMWF). These data have a global coverage at approximately 75 km spatial resolution, and a 3-hourly time increment. In order to build robust statistics, daily WBGT values are calculated for a 30-year period (1981-2010), which is the standard WMO time period to calculate climate statistics.

One drawback of the ERA-Interim data is its relative coarse spatial resolution (on the order of 75 km). In areas characterized by strong orographic variations, temperatures are known to vary at much shorter ranges, owing to the altitude effect. In order to account for this, we make use of the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010; Danielson and Gesh, 2011), which has a native resolution of 30 arc seconds (around 1 km). Such a high resolution is not really needed when producing global maps for Level 2 Administrative units (and would require hundreds of Terabytes to store the daily maps for the 30-year period), therefore we resampled the GMTED2010 DEM to 300 arc seconds (around 10 km) by linear interpolation, which seems an appropriate resolution for the aimed at level of detail.

The sub-grid altitude temperature correction is based on a constant vertical lapse rate of 6°C/km (10.8°F/km) (see, e.g., Wallace and Hobbs, 2006). To calculate the effect of height on vapor pressure, we assume a constant relative humidity, and use the altitude-corrected temperature to estimate vapor pressure from the Clausius-Clapeyron relation. Figure 1 demonstrates the effect of the altitude correction on example temperature data for the Himalaya region. Clearly, the orographic correction brings much more detail in the image.

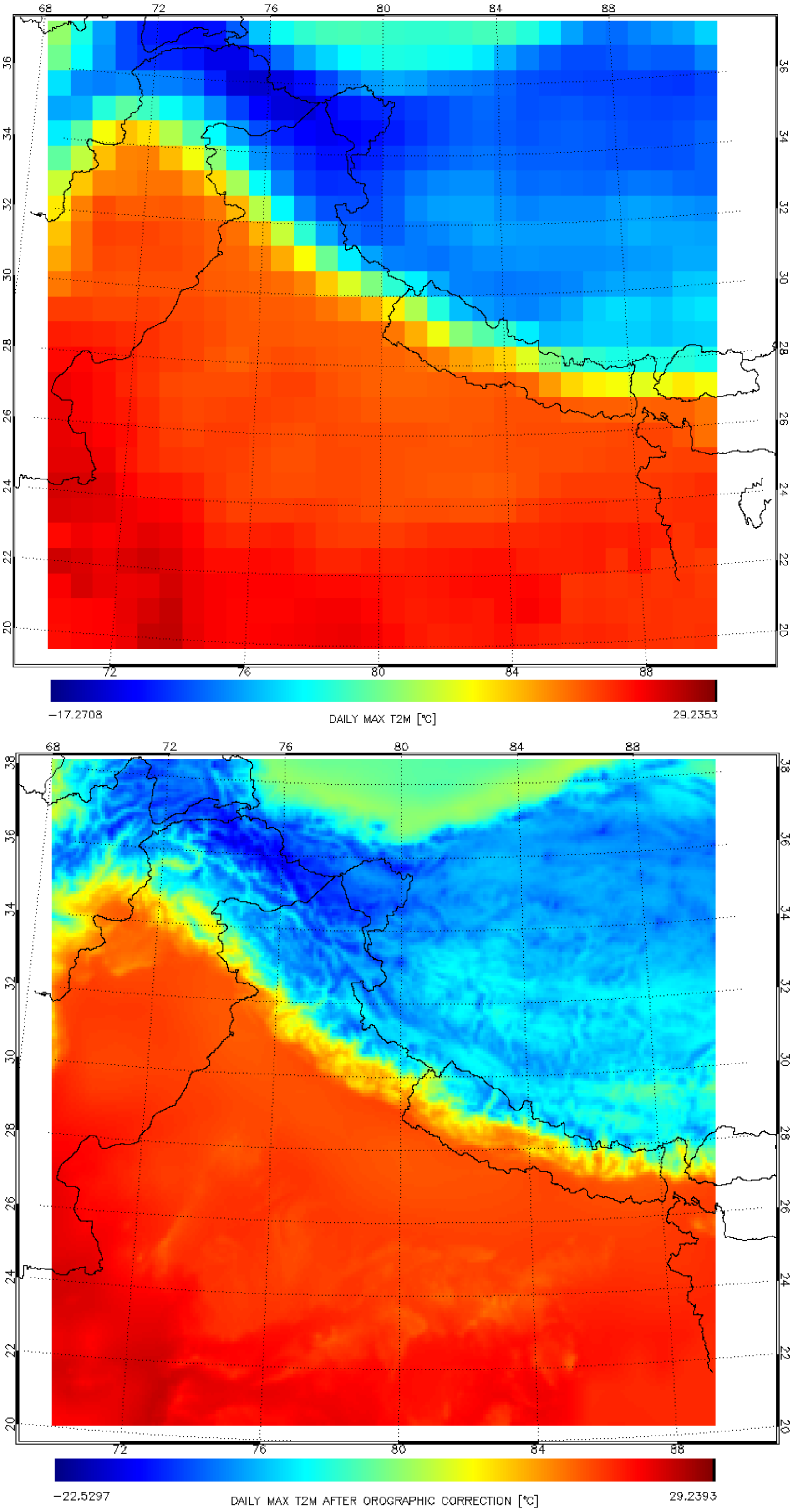

Figure 1: Example of the effect of the orographic correction on 2m air temperatures in the Himalaya. Top panel: the native ERA-Interim data. Lower Panel: the orographic corrected data.

When considering threshold WBGT values in the scientific literature (e.g. Willett and Sherwood, 2012), we found out that they were all based on actual (maximal) WBGT values. Therefore, we decided to base our further statistical analyses on daily maximal WBGT values, in order to be consistent with all international reported studies. These global daily maps have been calculated for the 30-year period (400 Gb of data in total) and form the basis for the calculation of the hazard intensity maps. An example image is shown in Figure 2.

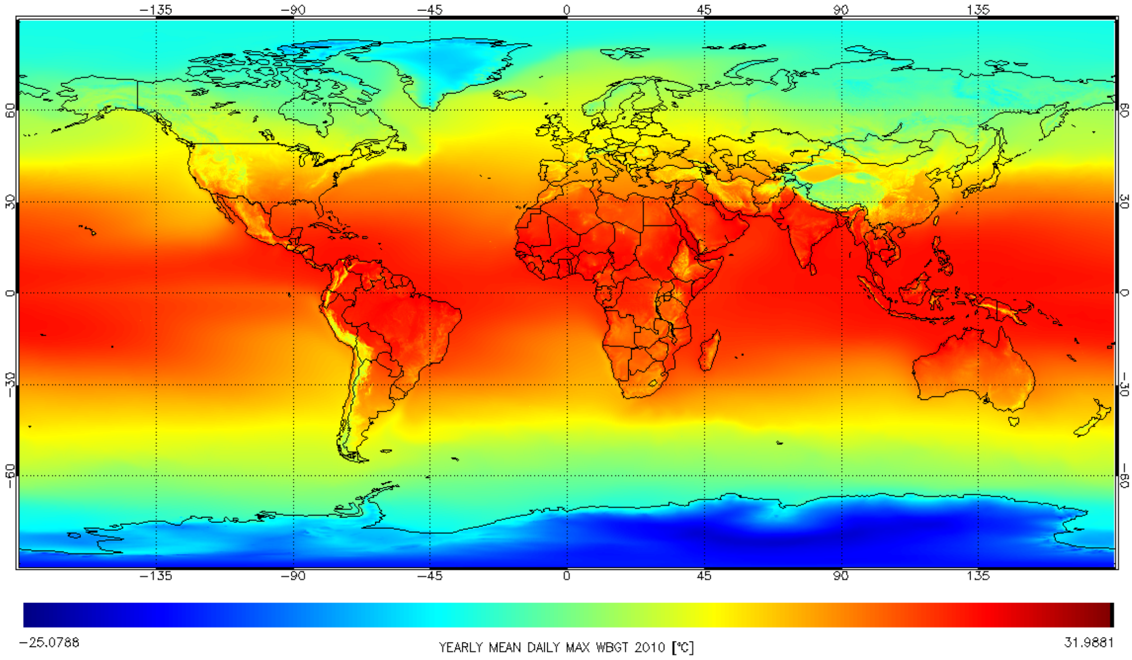

Figure 2: Example of the global daily max WBGT data.

2.2. PRODUCTION OF PROBABILISTIC HAZARD INTENSITY MAPS

Based on the daily maximal WBGT data, probabilistic hazard intensity maps for given return periods are composed using extreme value statistics. Section 2.2.1 focusses on the determination of the length of the return periods for extreme heat events, while Section 2.2.2 focusses on the calculation of the intensities corresponding to the return periods. In Section 2.2.3 the threshold values are defined to calculate the final Heat Hazard Classification Map, which is presented in Section 2.2.4.

2.2.1. DETERMINATION OF KEY RETURN PERIODS

According to the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013), (draft) documents of the World Meteorological Organization (WMO, 2015), and scientific literature (Kharin, 2013), there are no standard return periods used in research or engineering design concerning extreme heat events (as there are for flood and earthquake hazards). However, most scientific studies, including those cited in the fifth assessment report (AR5) of the (IPCC), use a twenty year return period in analyzing extreme heat events (IPCC, 2013). We therefore include this return period length in our analysis. Because of the consistency with existing literature, results for this return period can be easily compared and verified with previous studies.

In addition to the 20-year return period (or 5% probability of being exceeded in any given year), we propose a shorter period (5 years, or 20% annual probability) and a longer period (100 years, or 1% annual probability). Using the 5-year period, locations with frequent heat waves are identified, while five years is still long enough to average out the yearly variations in temperatures. The return period of 100 years is used to study the locations with few heat waves on a long term scale. One hundred years is the maximal possible extent that can be reached based on the 30 years of input data. For longer return periods, the uncertainties in projected intensity become too large due to the inherent uncertainties in the statistical processing of the input data.

2.2.2. DETERMINATION OF THE INTENSITIES CORRESPONDING TO THE RETURN PERIODS

Our overall approach is based on the method outlined in von Storch and Zwiers (2002). For each raster cell, we fit an appropriate function to the probability distribution function extracted from the 30-year long time series of daily WBGT values of heat hazard intensity (including the orographic correction, see Section 2.1).

In detail, at first we calculate 3-day running means of the daily maximal WBGT values. In this way, the cumulative negative effect related to prolonged exposure to extreme heat is taken into account. For each of the 30 years under consideration, we extract the annual maximal of these 3-day smoothed maximal WBGT values. According to extreme value theory, the distribution of these maxima will converge to a generalized extreme value (GEV) distribution (Coles, 2001). This GEV is a distribution with three parameters developed to combine the Gumbel, Frechet and Weibull families of distributions. The same asymptotic distribution has been used in the analysis of extreme temperatures by Zwiers et al. (2011). Using a maximum likelihood procedure, the three unknown parameters of the GEV-distribution are estimated for each raster cell using the 30 years of maximal WBGT values. Besides the GEV-distribution, the routine also includes some checks (for instance checking whether the desired parameter tolerance and number of iterations have been reached). In this way, grid cells with untrusted results are tagged.

For the tagged grid cells, the statistical procedure could lead to an inaccurate GEV-distribution, possibly yielding also inaccurate estimates for the extreme heat potential. The underlying reason are difficulties encountered in the statistical processing, for example badly conditioned sets of equations that have to be inverted (and these issues are thus unrelated to uncertainties concerning the input data). These tagged grid cells were subsequently analysed in more detail. In a first step to resolve the issues, we have increased the number of iterations and slightly decreased the tolerance of the GEV-fitting procedure. For most of the tagged grid cells, these small modifications resolved the initial problem, yielding a trustworthy extreme value distribution and trustworthy heat hazard intensities. The very few remaining tagged grid cells were further manually checked for errors. We have compared the resulting hazard intensities of these grid cells to those of adjacent cells. During this procedure, no irregularities have been detected, and the resulting hazard intensities were deemed reliable. In the end, all grid cells have been classified as ‘suitable for further use’.

This method assumes that the annual maximal WBGT-values are unaffected by climate change over the thirty year period ranging from 1981 to 2010. Hence, we neglect the effects of climate change over this thirty year period. As we are only interested in interregional differences, this reasoning is justifiable, as it boils down to the assumption that the interregional differences in the global warming over this 30 year period are much smaller than the worldwide gradient in maximal WBGT.

Based on the distribution of the annual extremes, hazard intensity levels can be derived for each of the three specified return periods. These hazard intensity levels are the thresholds that are, on average, exceeded once every return period. To deduce the hazard intensity from the GEV-functions, the upper quantiles of the fitted GEV-function are used, as outlined in detail in Coles (2001). The outcome of the procedure are three hazard intensity raster maps, each corresponding to a different return period (

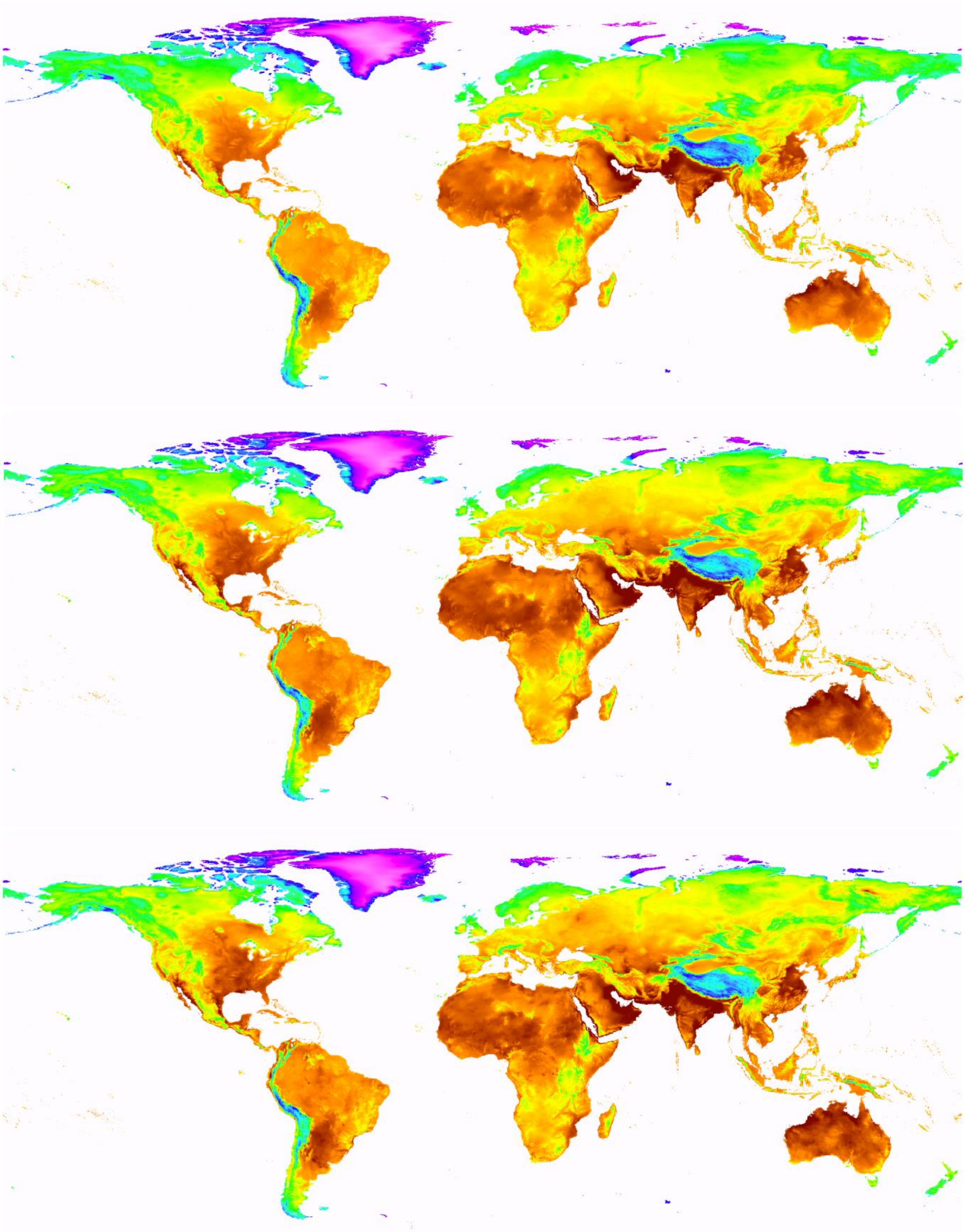

Figure 3). For each raster grid cell, a different intensity is reported, hence the maps provide a high resolution inventory for the heat stress on Earth.

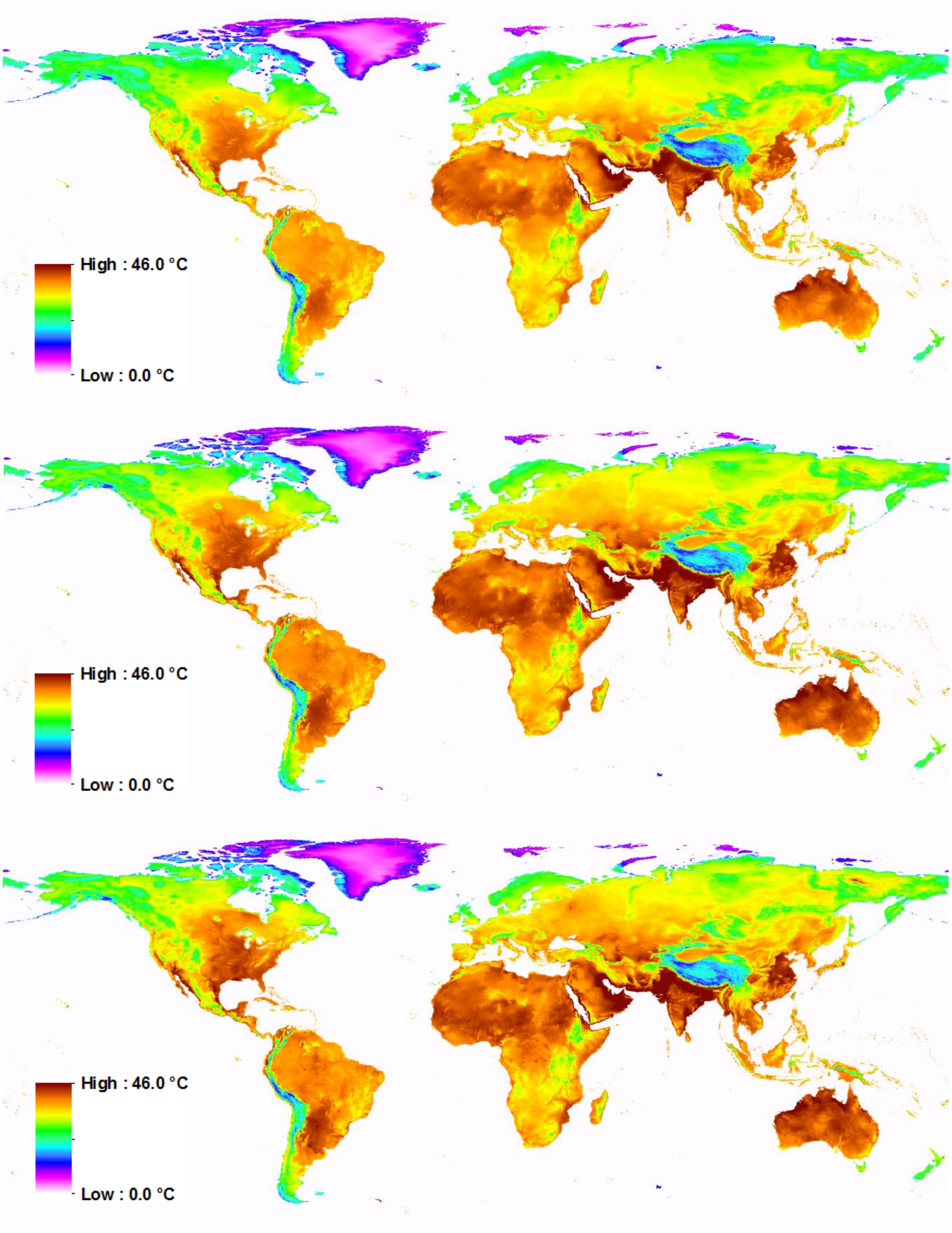

Figure 3: Heat hazard intensity maps. The maps show the hazard intensity level (in WBGT, °C) for the 5-year return period (top), the 20-year return period (middle) and the 100-year return period (bottom).

2.2.3. DETERMINATION OF THE THRESHOLD VALUES

The Wet Bulb Globe Temperature has a long tradition of being used as a thermal comfort index and is the ISO standard for quantifying thermal comfort (ISO, 1989). It is currently in use by a number of bodies including the US and UK Military, civil engineers, sports associations and the Australian Bureau of Meteorology (Willett and Sherwood, 2012). It is the only heat index to have known thresholds based on a large number of observations, developed by the U.S. Army (2003) (Table 1).

Category	WBGT °F	WBGT °C
1	≤ 78-81.9	≤ 25.6-27.7
2	82-84.9	27.8-29.4
3	85-87.9	29.4-31.0
4	88-89.9	31.1-32.1
5	≥ 90	≥ 32.2

Table 1. Heat stress category limits of the U.S. Army (2003).

Based on these values, heat stress studies in the scientific literature that make use of the WBGT apply thresholds of 28°C and 32°C to categorise heat stress risk in slight/low (<28°C), moderate/high (28-32°C) and severe/very high (>32°C) classes (e.g. Willett and Sherwood, 2012; Zhoa et al., 2015). Despite their development from a narrow demography (physically fit military males in full battle dress), the threshold values have been assessed to have some applicability worldwide within limits, as clothing or metabolic rate are not taken into account (Parsons, 2006).

Therefore we have chosen to adopt these values as the thresholds being used to determine the risk level for extreme heat from our return period maps. Table 2 shows the chronological implementation of the threshold values to the different return period maps. By following these step by step, every region in the world will be assigned a risk level. The end result of this process is shown in the next section.

Threshold value	Return period	Risk level
>32°C	5 years	High
>28°C	20 years	Medium
>25°C	100 years	Low
≤25°C	100 years	Very low

Table 2. Applied threshold values to assign risk levels.

2.2.4. FINAL HEAT HAZARD CLASSIFICATION MAP

In the ThinkHazard! Platform, hazard intensities are combined with the threshold values, yielding the final heat hazard risk levels (very low, low, medium, high) at the level of Administrative Units. For each ADM2-region, the risk level is equal to the maximal level observed in that region. We have performed an independent off-line testing of this procedure. Figure 4 shows the end result of this test.

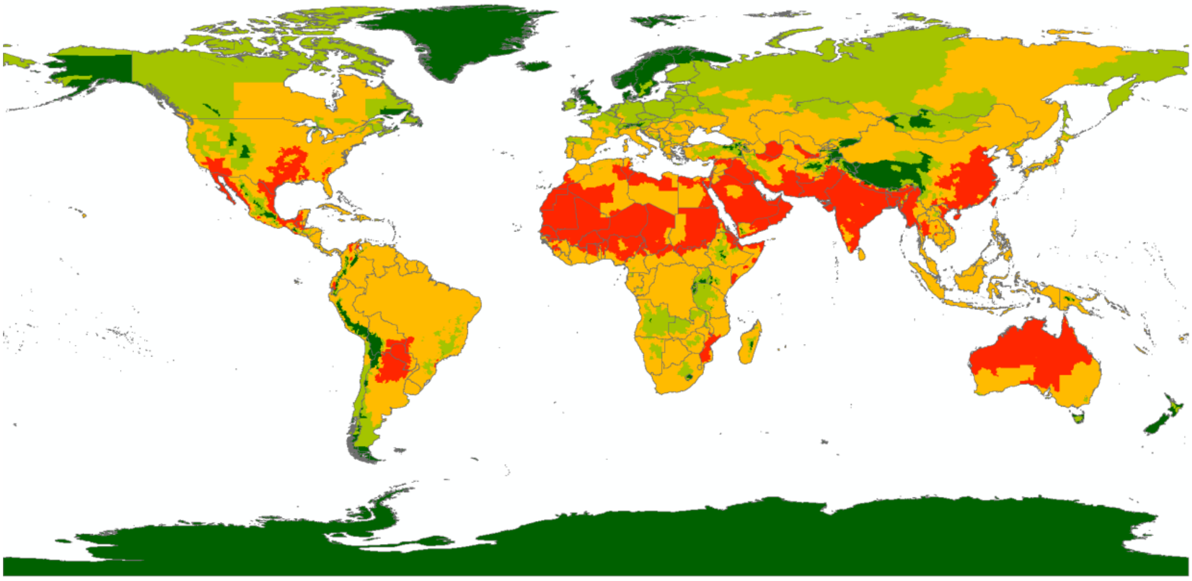

Figure 4: Heat hazard classification map at the ADM2-level. The figure visualizes the location with very low (dark green), low (green), medium (orange) and high (red) extreme heat risk.

2.3. SANITY CHECK OF HEAT HAZARD CLASSIFICATION

When comparing the heat hazard intensity maps for the different return periods (Figure 3), it may seem surprising that the maps are almost identical. There is not much difference in the WBGT values between the 100-year return period and the 5-year return period, which is in sharp contrast to the behavior for other classified hazards in the ThinkHazard! Platform as e.g. flooding. However, we are looking at yearly maxima of 3-day mean maximal air temperatures and humidity values. For a given location on earth with its specific climatic conditions, these values do not vary much from year to year. This may run counter to our intuition, since we only remember occasional heat waves that cause a lot of deaths, but the number of victims from a heat wave is not solely related to the highest temperatures during a heat wave, but also to other meteorological characteristics of the heat wave (e.g. mortality is known to be higher during a heat wave occurring in early summer after a mild winter; also the length of the period with high temperatures has an influence) and/or accurate measures taken by the government to protect vulnerable people (the elderly, young children).

The differences between the intensity maps for each return period are analyzed in more detail in Figure 5. Between the 20-year return period and the 5-year return period, the increase in the heat hazard intensity value is on average around 1°C, and maximal differences are around 2.5°C. Between the 100-year return period and the 5-year return period, the differences are a bit larger, as expected, with maximal differences up to 5.5°C. As explained above, these type of differences are to be expected when dealing with yearly maximal WBGT values.

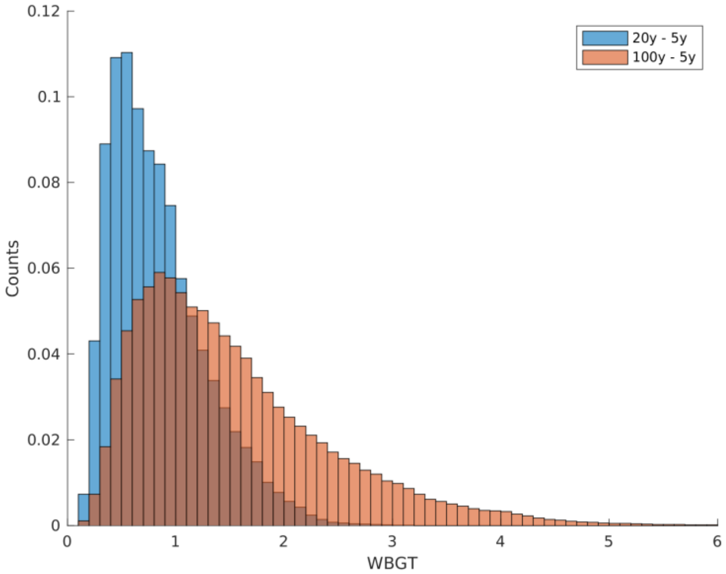

Figure 5: Histograms of the (over land) differences in WBGT values (°C) between the return period maps.

In order to assess the effect of the 3-day smoothing on the heat hazard intensity maps and the differences between them, we have performed the same statistical analysis on the non-smoothed daily maximal WBGT values and on 7-day smoothed values. Although the values of the heat hazard intensity maps are slightly different (being a little higher for the non-smoothed data and a little lower for the 7-day smoothed data), the differences histograms are very similar (Figure 6). The results for the chosen 3-day smoothing period (which accounts for cumulative effects related to an extended exposure to extreme heat, but not too long in order to not miss any events) are thus robust.

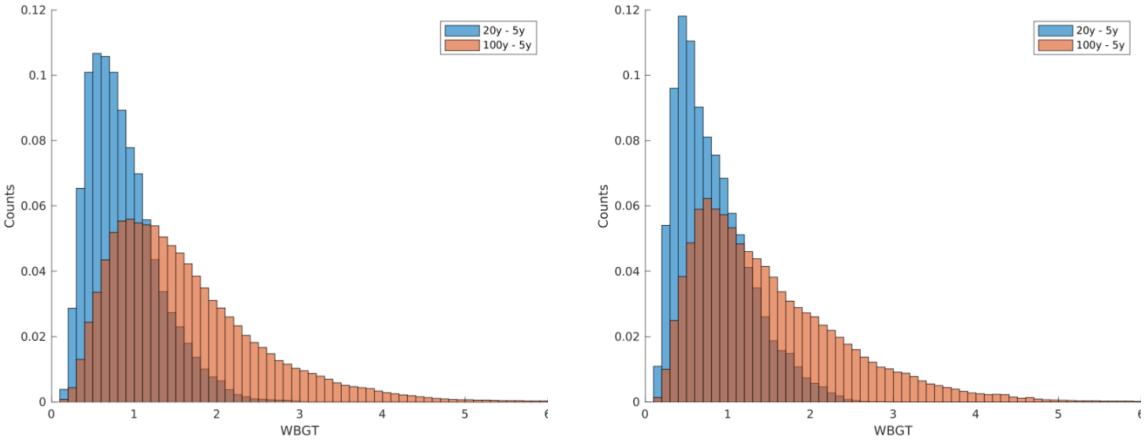

Figure 6: Histograms of the (over land) differences in WBGT values (°C) between the return period maps for non-smoothed daily maximal WBGT values (left) and 7-day smoothed values (right).

In a next step, we want to check our classification map in an objective and independent manner, using the heat exposure map that was published in the fifth assessment –working group 2 (AR5 – WGII) report of the IPCC (2013), in which three different risk categories are defined (Figure 7). Although this map is also based on the WBGT, it is calculated in a different way, using a different source dataset, and applies different threshold values (details can be found in Lemke and Kjellstrom, 2012). Clearly, the map corresponds very well to our heat hazard intensity maps regarding overall worldwide patterns of heat risk.

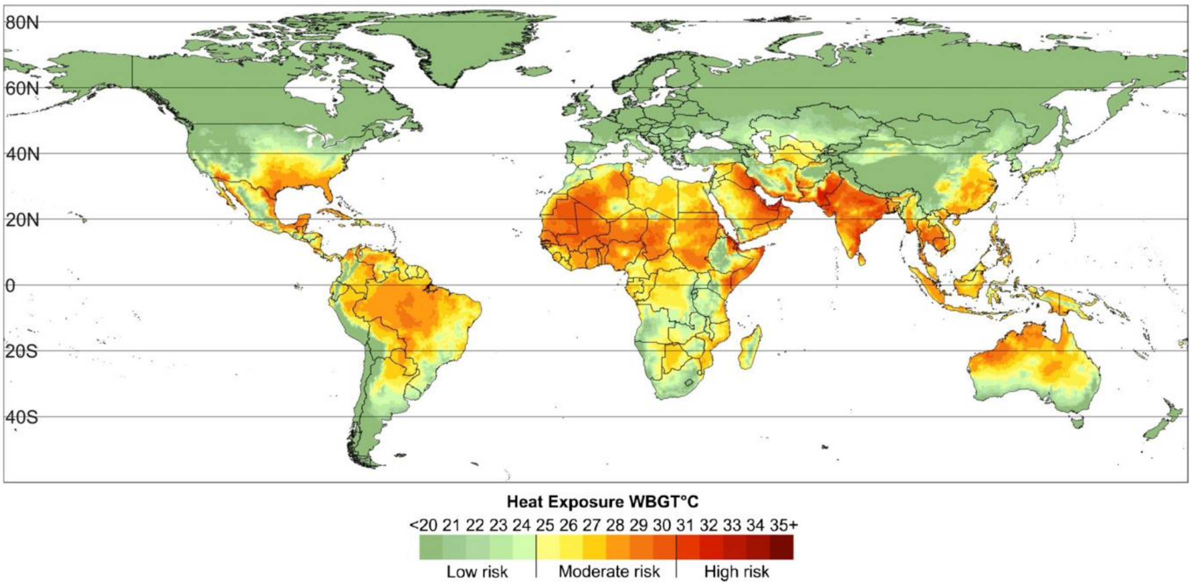

Figure 7: Thirty-year average (1980–2009) of monthly average daily maximal wet bulb globe temperature (WBGT). From Lucas et al., 2014.

From this figure, we have calculated the maximal risk category (low, moderate or high) for each country based on the thresholds proposed by Lucas et al. (2014). Figure 8 shows the result of this exercise. These results are compared to our own classification at country (ADM0) level for all IDA countries in Table 3. The hazard levels are relatively similar, although a lot more countries (especially in Africa) are in the 'high' category in our classification. Also fewer countries (especially in Southern/Eastern Europe and Asia) are in the 'low' category in our classification, leading to a more negative overall picture. It should be noted that the resolution of both datasets is different (around 10 km for our maps, around 50 km for the Lucas et al. (2014) map, which could play a role here.

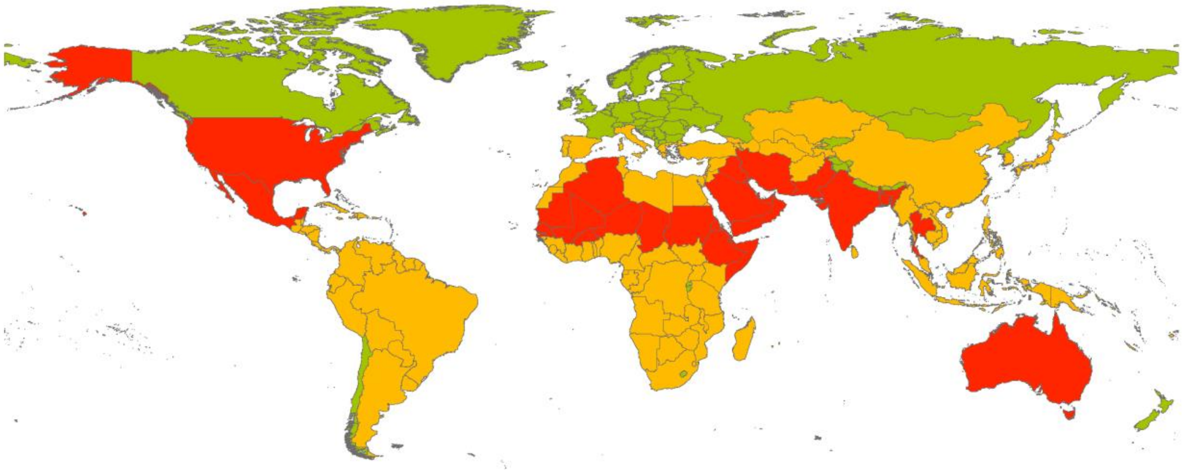

Figure 8: Heat hazard classification map on the ADM0-level from the Lucas et al. (2014) map. The figure visualizes the locations with low (green), moderate (orange) and high (red) heat risk.

Although our classification leads to a more negative (or cautious) heat hazard risk map, we believe this is justifiable. For example the low hazard level for France and Russia in the Lucas et al. (2014) map seems odd, given the recent extreme heatwave events (2003 and 2010 respectively, with France additionally in 2006 and 2010) that caused large mortality numbers. In our heat hazard classification map, large areas of these countries are classified as 'medium', which seems more appropriate.

Table 3: Comparison of heat hazard classification for all IDA countries.

Country or Area Name	**Region**	**Hazard level found with our method**	**Hazard level according to Lucas et al. (2014)**
Afghanistan	South Asia	High	Medium
Bangladesh	South Asia	High	High
Benin	Africa	High	Medium
Bhutan	South Asia	High	Low
Bolivia	Latin America and Caribbean	High	Medium
Burkina Faso	Africa	High	High
Burundi	Africa	Medium	Low
Cape Verde	Africa	Low	Low
Cambodia	East Asia and Pacific	High	Medium
Cameroon	Africa	High	Medium
Central African Republic	Africa	High	Medium
Chad	Africa	High	High
Comoros	Africa	Medium	Medium
Congo, Democratic Republic of the	Africa	Medium	Medium
Congo, Rep.	Africa	Medium	Medium
Côte d'Ivoire	Africa	High	Medium
Djibouti	Middle East and North Africa	High	High
Dominica	Latin America and Caribbean	Medium	Medium
Eritrea	Africa	High	High
Ethiopia	Africa	High	High
Gambia, The	Africa	High	Medium

Ghana	Africa	High	Medium
Grenada	Latin America and Caribbean	Medium	Medium
Guinea	Africa	High	Medium
Guinea-Bissau	Africa	High	Medium
Guyana	Latin America and Caribbean	Medium	Medium
Haiti	Latin America and Caribbean	Medium	Medium
Honduras	Latin America and Caribbean	High	Medium
Kenya	Africa	Medium	Medium
Kiribati	East Asia and Pacific	Medium	Medium
Kosovo	Europe and central Asia	Medium	Low
Krygyz Republic	Europe and central Asia	Medium	Low
Lao PDR	East Asia and Pacific	Medium	Medium
Lesotho	Africa	Low	Low
Liberia	Africa	Medium	Medium
Madagascar	Africa	Medium	Medium
Malawi	Africa	High	Medium
Maldives	South Asia	Medium	Medium
Mali	Africa	High	High
Marshall Islands	East Asia and Pacific	Medium	Medium
Mauritania	Africa	High	High
Micronesia, Federated States of	East Asia and Pacific	Medium	Medium
Moldova	Europe and central Asia	Medium	Low
Mongolia	East Asia and Pacific	Medium	Low
Mozambique	Africa	High	Medium
Myanmar	East Asia and Pacific	High	Medium
Nepal	South Asia	High	Low
Nicaragua	Latin America and Caribbean	Medium	Medium
Niger	Africa	High	High
Nigeria	Africa	High	Medium
Pakistan	South Asia	High	High
Papua New Guinea	East Asia and Pacific	Medium	Medium
Rwanda	Africa	Low	Low
Samoa	East Asia and Pacific	Medium	Medium
Sao Tome and Principe	Africa	Medium	Medium
Senegal	Africa	High	High
Sierra Leone	Africa	High	Medium
Solomon Islands	East Asia and Pacific	Medium	Medium
Somalia	Africa	High	High
South Sudan	Africa	High	Medium
Sri Lanka	South Asia	Medium	Medium
Saint Lucia	Latin America and Caribbean	Medium	Medium
Saint Vincent and the Grenadines	Latin America and Caribbean	Medium	Medium
Sudan	Africa	High	High
Tajikistan	Europe and central Asia	Medium	Medium
Tanzania	Africa	Medium	Medium
Timor-Leste	East Asia and Pacific	Medium	Medium
Togo	Africa	High	Medium
Tonga	East Asia and Pacific	Medium	Medium
Tuvalu	East Asia and Pacific	Medium	Medium
Uganda	Africa	Medium	Medium
Uzbekistan	Europe and central Asia	High	Medium
Vanuatu	East Asia and Pacific	Medium	Medium
Vietnam	East Asia and Pacific	High	Medium
Yemen, Rep.	Middle East and North Africa	High	High
Zambia	Africa	Medium	Medium
Zimbabwe	Africa	Medium	Medium

CHAPTER 3 STATEMENTS ON CLIMATE CHANGE IMPACT

Country-specific statements regarding the impact of climate change on extreme temperature episodes are composed. The scientific basis of the statements is rooted in the most recent assessment report (AR5) of the first working group (WG I) of the Intergovernmental Panel on Climate Change (IPCC). The WG I aims at assessing the physical scientific basis of the climate system and climate change, including the assessment of climate models and climate projections.

In the summary for policy makers of the AR5 report (IPCC, 2013), the IPCC provides several general statements on the future climate. Three of these are of special importance for the assessment of expected climate change in the ThinkHazard! tool:

- "Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions."
- "It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase. It is very likely that heat waves will occur with a higher frequency and duration. Occasional cold winter extremes will continue to occur."
- "Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform"

Based on these three statements, we propose a general (worldwide) statement, in which a country-specific part is embedded. The general statement summarizes the first two statements of the IPCC (concerning global warming and the increase in hot temperature extremes), while the regional text elaborates the regional differences. The general text also highlights the importance of robust project design.

General statement:

> According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. [… regional part here…] It would be prudent to design projects in this area to be robust to global warming in the long-term.

The country-specific part depends on the regional degree of warming. We identify four different zones, ranging from "much lower than average" to "much larger than average" warming. We propose the following four regional texts:

Country-specific part (four different zones):

- [zone1] In the area you have selected, the temperature increase in the next fifty years will be much lower than the worldwide average, but still significant.
- [zone2] In the area you have selected, the temperature increase in the next fifty years will be slightly lower than the worldwide average, but still significant.
- [zone3] In the area you have selected, the temperature increase in the next fifty years will be slightly higher than the worldwide average.
- [zone4] In the area you have selected, the temperature increase in the next fifty years will be much higher than the worldwide average.

The four zones are determined based on the warming projected by global climate models (GCMs). Based on scientific literature, the IPCC report states that "Twenty-year return values for high temperature events are projected to increase at a rate similar to or greater than the rate of increase of summer mean temperatures in most regions" (IPCC, 2013). Instead of processing data on the evolution of extreme heat periods, we thus rely on the (far easier to handle) information of the evolution of (summer) temperatures. To avoid complexities regarding the definition of the summer season, we use the 75th percentile (on a yearly basis) of mean daily temperatures as a proxy for the summer temperature.

The division into four classes is based on change of this quantity between the reference period (1986 – 2005) and the far future (2081 – 2100) period considered in the AR5-report. Locations where the warming is below the (worldwide) 25th percentile are classified in zone 1, locations where warming is between the 25th and the 50th percentile are classified in zone 2, locations where warming is between the 50th and the 75th percentile are classified in zone 3, and locations with a larger warming are classified in zone 4. To avoid the large warming potential of the (nowadays uninhabited) polar zones, and the smaller warming potential of uninhabited ocean areas, we neglect the oceans and the polar zones (where latitudes are larger than 75 degrees or smaller than -75 degrees) in determining the percentile thresholds. To obtain a single value for each country[1], the 90th percentile within the country is considered. In this way, extremes related to small regions in each country (e.g. the Alps in France) are neglected, while the results still indicate a 'worst-case' for each country.

The climate change statement for this country then comprises the general text and the regional text for this (most affected) zone. The resulting division in the four zones is visualized in Figure 9. For some large countries with important gradients in the projected temperature rise, the statements are further diversified, explicitly stating the difference between the different subregions. These specific statements are listed in Table 4.

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[1] The term 'country' is used to indicate the ADM0-levels contained in the shape-files used in the ThinkHazard! Platform.

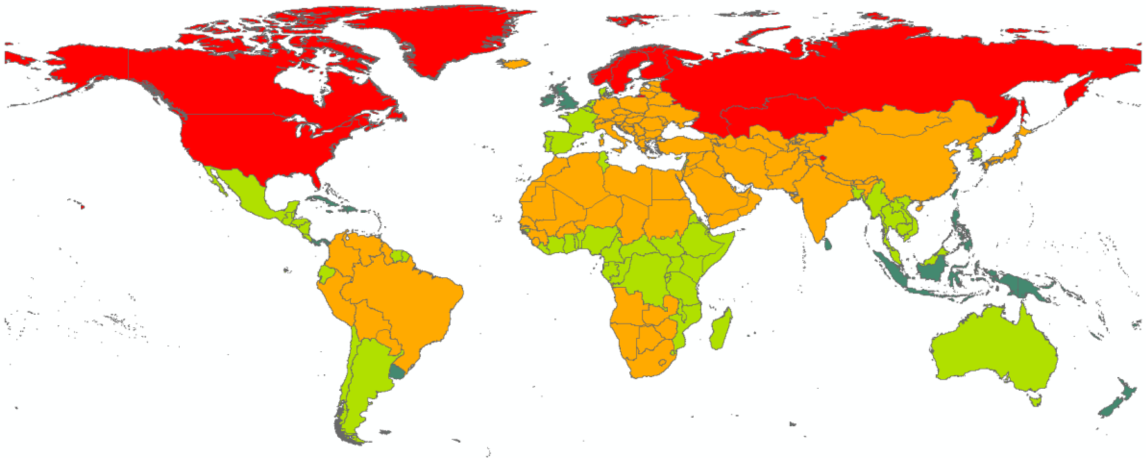

Figure 9: Division in the world according to the four zones outlined in the main text. The figure visualizes the locations of zone 1 (dark green), zone 2 (green), zone 3 (orange) and zone 4 (red).

Table 4: Country specific climate change statements.

Country	**Climate Change Statement**
India	According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. In the Himalayas, the temperature increase in the next fifty years will be slightly higher than the worldwide average. In other parts of India, the temperature increase in the next fifty years will be slightly lower than the worldwide average, but still significant. It would be prudent to design projects in this area to be robust to global warming in the long-term.
Brazil	According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. Warming will not be regionally uniform. In western Brazil, the temperature increase in the next fifty years will be slightly higher than the worldwide average. In the rest of Brazil, the temperature increase in the next fifty years will be slightly lower than the worldwide average, but still significant. It would be prudent to design projects in this area to be robust to global warming in the long-term.
China	According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. In south-eastern China, the temperature increase in the next fifty years will be slightly lower than the worldwide average. In other parts of China, the temperature increase in the next fifty years will be slightly higher than the worldwide average. It would be prudent to design projects in this area to be robust to global warming in the long-term.

Russian Federation	According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. In most of Russia, the temperature increase in the next fifty years will be much higher than the worldwide average. In south-eastern Russia, the temperature increase will be slightly larger than the worldwide average. It would be prudent to design projects in this area to be robust to global warming in the long-term.
United States of America	According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. In central and north-eastern continental USA, the temperature increase in the next fifty years will be slightly higher than the world wide average. In Alaska, the temperature increase in the next fifty years will be much higher than the worldwide average. In western and south-eastern USA, the temperature increase in the next fifty years will be slightly lower than the worldwide average, but still significant. It would be prudent to design projects in this area to be robust to global warming in the long-term.
Chile	According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. In northern Chile the temperature increase in the next fifty years will be slightly higher than the worldwide average. In southern Chile, the temperature increase in the next fifty years will be much lower than the worldwide average, but still significant. It would be prudent to design projects in this area to be robust to global warming in the long-term.
Argentina	According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. In northern Argentina, the temperature increase in the next fifty years will be approximately equal to the worldwide average. In southern Argentina, the temperature increase in the next fifty years will be much lower than the worldwide average, but still significant. It would be prudent to design projects in this area to be robust to global warming in the long-term.
Australia	According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. In central Australia, the temperature increase in the next fifty years will be slightly higher than the worldwide average. In other parts of Australia, the temperature increase will be slightly lower than the worldwide average, but still significant. It would be prudent to design projects in this area to be robust to global warming in the long-term.

Antarctica	According to the most recent assessment report of the Intergovernmental panel on Climate Change (IPCC, 2013), continued emissions of greenhouse gases will cause further warming, and it is virtually certain that there will be more frequent hot temperature extremes over most land areas during the next fifty years. Warming will not be regionally uniform. In the Antarctic peninsula, the temperature increase will be much higher than the worldwide average. In other parts of Antarctica, the temperature increase in the next fifty years will be much lower than the worldwide average, but still significant. The projected temperature increase for Antarctica comes with great uncertainty, hence it would be prudent to design projects in this area to be robust to global warming in the long-term.

CHAPTER 4 STATEMENTS ON RISK REDUCTION RECOMMENDATIONS

To be consistent with the current way the statements on risk reduction recommendations are formulated in the *ThinkHazard!* platform, we have sought inspiration in the recommendations for 'river flooding' and 'water scarcity'. As is the case for 'extreme heat', these are climate related hazards – in contrast to e.g. volcanic eruptions or earthquakes – and so we consider these to provide an appropriate template for the development of the recommendations for 'extreme heat'.

Both hazards, 'river flooding' and 'water scarcity' share most of their recommendations, while they are of course formulated slightly differently to correspond to the hazard considered. Table 5 provides a concise overview of these recommendations, together with a proposed list for the 'extreme heat' recommendations.

river flooding	**water scarcity**	**extreme heat**
vulnerability assessment	vulnerability assessment	vulnerability assessment
obtain pre-existing flood hazard information	obtain pre-existing water scarcity / drought information	obtain pre-existing extreme heat hazard information
professional guidance	professional guidance	professional guidance
consider relocation of the project	N/A	N/A
identify Early Warning Systems	identify Drought Monitoring / Drought Forecasting Systems	identify Heat Forecasting Systems
consider vulnerability of other assets	N/A	consider vulnerability of other assets
flood management	water scarcity / drought management	extreme heat management
built infrastructure may alter flood hazard	N/A	built infrastructure may alter heat hazard

Table 5. Overview of the list of recommendations in the 'water scarcity' and 'river flooding' hazard categories. The rightmost column shows the recommendations we consider relevant for 'extreme heat'.

The rationale for retaining / rejecting each of the recommendation types is as follows:

- All recommendations that are common to both river flooding and water scarcity ('vulnerability assessment', 'obtain pre-existing (…) information', 'professional guidance', 'identify (…) forecasting systems', '(…) management') are considered relevant for extreme heat, and so these are being retained.
- 'Consider relocation of the project' was not retained; while this is certainly a relevant category for the 'river flooding' hazard (which is very sensitive to the precise location of a project), it is deemed less relevant for extreme heat, the same as it is considered less relevant also for water scarcity.

- ‘Consider vulnerability of other assets’ is a recommendation only used for river flooding and not for water scarcity. We consider it relevant for extreme heat, though, as heat is known to be capable of triggering a chain of breakdown events, thus affecting sectors and assets beyond the one initially considered. (In the linked ‘More information’ page we will get more specific about such event chains, and ways of dealing with them.)
- ‘Built infrastructure may alter flood hazard’ a is a recommendation only used for river flooding and not for water scarcity. While perhaps a bit less relevant for heat than for flooding, larger projects (e.g., new city quarter, harbor zone, …) should consider this aspect. Indeed, large enough built-up areas will affect their microclimate so as to enhance the heat hazard, therefore deserving recommendations.

The resulting recommendations, adapted to suit the ‘extreme heat’ hazard, will be formulated as follows:

- VULNERABILITY ASSESSMENT: The high-level information available in ThinkHazard! indicates the presence of extreme heat hazard in your project area. Before committing significant resources to this issue, you should further evaluate if your project is vulnerable to extreme heat and whether a more detailed assessment and/or intervention should be considered.
- SEEK INFORMATION: Obtain pre-existing extreme heat hazard information. ThinkHazard! predominantly uses global datasets, therefore for more detailed project planning you should determine the availability of pre-existing local extreme heat hazard information to check whether your project is indeed located in region prone to extreme heat. In this respect, it should be noted that large built-up areas such as cities or harbors are more likely to experience excess heat than rural areas, because of the Urban Heat Island (UHI) phenomenon.
- PROFESSIONAL GUIDANCE: Consultation with engineering and climate impact assessment professionals will provide a more detailed understanding of the risk posed to your asset by extreme heat. The level of guidance required will depend upon the level of hazard present, the vulnerability of the asset and local legislation that might apply.
- MONITORING AND FORECASTING: Identify extreme heat monitoring and forecasting systems. These are designed to provide communities with advance warning of extreme heat based largely on information contained in weather forecasts, complemented with temperature monitoring. They can be used to trigger protocols (e.g., the deployment of heat-health action and emergency response plans) to mitigate against the effects of extreme heat.
- INTERDEPENDENCY: Consider vulnerability of other assets within the project's dependency network: If your project is interdependent with other projects, it is important to assess the vulnerability of the entire network if the service provided is critical.
- HEAT MANAGEMENT: Your project or development should consider heat management measures*, for example, technological adaptation, building design, or changing working practices*.
- AVOID INCREASING HAZARD: Built infrastructure may alter heat hazard: Constructing a significant piece of infrastructure can significantly alter the thermal properties of the area, generally inducing higher temperatures. Any new built infrastructure covering large enough areas (e.g., new city quarter or harbor zone) should be undertaken with consideration as to how this will influence the local microclimate.

Some of the above recommendations may be omitted for areas featuring the ‘very low’, ‘low’, or ‘medium’ risk category, as appropriate (see below). This is also being done currently for the ‘water scarcity’ and ‘river flooding’ hazard categories.

The detailed recommendations, which appear behind the 'More information' link, are given in the following pages, for each of the topics mentioned above. (The recommendations are also submitted in the World Bank template used for this purpose, as separate documents.)

The rationale for the selection of the recommendations for each of the categories (*high-medium-low-very low*) is as follows:

- The *high* and *medium* categories have the full text.
- For the *very low* category, the text is reduced:
    - information related to the health impact is mostly retained, because it is assumed that even relatively moderate heat stress (in an absolute sense) may cause health impacts in populations that are not adapted to it (a paragraph has been added to explain this, **see boldface blue text below**);
    - information regarding the impact on infrastructure (transport, energy, industry) and agriculture (crop yield, livestock) is *not* retained for this category, as we assume that damage-inducing temperatures are not (or extremely rarely) encountered; the portions of text that disappear for the 'very low' category are shown as blue text (non-boldface) in the recommendations.
- The *low* category also has the full text. The reason is that, with climate change, areas that are in the *low* hazard areas are increasingly being confronted with impacts, not only related to health, but also to infrastructural and other damage. See, e.g., the problem of buckling highway surfaces and the associated traffic jams (and repair costs) in Germany during a hot spell in 2013, or the wildfires in Southern Sweden during the 2014 heat wave (both areas are in the 'low' category). These damages/impacts may in part be related to the lack of adaptation (e.g., Germany's highways not being covered with proper heat-resistant asphalt), and therefore deserve a comprehensive level of information. **A paragraph (green/boldface below) has been added to describe this**, and to frame the importance of being aware of these issues, even for the *low* hazard areas.
- The 'seeking information' and 'avoid increasing hazard' texts are kept for all hazard intensity levels.

***VULNERABILITY ASSESSMENT**: (high-medium-low)*
The high-level information available in ThinkHazard! indicates the presence of extreme heat hazard in your project area. Before committing significant resources to this issue, you should further evaluate if your project is vulnerable to extreme heat and whether a more detailed assessment and/or intervention should be considered.

***VULNERABILITY ASSESSMENT**: (very low)*
The high-level information available in ThinkHazard! indicates the presence of very limited extreme heat hazard in your project area. Yet, before committing significant resources to this issue, you should further evaluate if your project is vulnerable to extreme heat and whether a more detailed assessment and/or intervention should be considered.

Extreme heat is a hazard that typically evolves over periods of days to weeks, affecting large geographical areas (extending over thousands of kilometers) and impacting multiple sectors, including human health, energy consumption and production, industrial plants operations, transportation infrastructure, livestock production, crop yield, forestry, tourism, and labor productivity. Heat waves can compromise public health, reduce productivity and constrain the functionality of infrastructure.

[*this paragraph is only used for the 'low' hazard category*] Even though your project area is labelled as having a low heat hazard intensity level, the increasing number, frequency, and intensity of heat waves warrants your being aware of a wide range of impacts arising from exposure to extreme heat. This is all the more important as low hazard areas have historically been affected by extreme heat to a limited extent, so may be less adapted to its impacts. Especially in the case of projects concerning infrastructure with an anticipated long lifetime, one should be aware of the projected increase in extreme heat hazard induced by climate change.

[*this paragraph is only used for the 'very low' hazard category*] Your area is labeled as having a very low heat hazard intensity level. There is expected to be few impacts of extreme heat on infrastructure (transportation, industry, energy production) and agricultural (crop yield, livestock) projects. Conversely, impacts could arise in the domain of human health, and associated labor productivity. Indeed, warm episodes that may be of a moderate intensity only, might cause impacts in your area whenever the temperature of such episodes deviates considerably from normal temperatures (i.e., climatological values). If your area is located at relatively high northern/southern latitudes (which explains its being relatively cool); it is precisely in those high-latitude zones that climate change is expected to be the strongest. In particular, such zones are expected to experience the highest changes in temperature extremes due to global warming. Therefore, when considering projects involving long-living infrastructure, you should consult guidelines for dealing with extreme heat that apply to areas characterized by higher intensity levels of extreme heat hazard.

The heat hazard information provided by ThinkHazard! should be considered as preliminary in defining heat hazard in your project area. To further determine the potential risk, a detailed assessment should be undertaken to identify the vulnerability of your project to extreme heat.

Particular consideration should be given to projects located in built-up areas such as cities or harbors since, as compared to rural areas, these areas are subject to an enhanced extreme heat hazard, owing to the urban heat island phenomenon.

Certain projects, such as those concerning individual buildings, or infrastructural components such as transformers in the electricity grid, may require a very fine local-scale extreme heat risk assessment, considering, for instance, indoor versus outdoor heat conditions, or sunny versus shaded locations, involving spatial resolutions down to a few meters.

The indicator used for extreme heat hazard in ThinkHazard! combines temperature and humidity in the Wet Bulb Globe Temperature (WBGT), which is related to human thermal comfort, and which may not necessarily be the most relevant indicator for your project. For instance, if your project concerns energy production, you might rather need an indicator quantifying cooling energy demand (e.g., cooling degree days). This should be sourced from sector specific analyses in the project area, as suggested in some of the links provided below.

You may want to consider the following sectoral vulnerabilities to extreme heat:

- **Human health**: extreme heat constitutes the single most deadly meteorological calamity, also because extreme heat events often coincide with high levels of atmospheric pollution. Urban populations and those working outdoors in urban or rural areas are most vulnerable. Further guidance is provided by a WMO/WHO (2015) report "Heatwaves and Health: Guidance on Warning-System Development", which is available from the following link: http://www.who.int/globalchange/publications/heatwaves-health-guidance/en/

- **Labor productivity** may be impacted by extreme heat, especially in the case of outdoor workers, or workers in poorly cooled or ventilated buildings. Agricultural, manufacturing, and construction workers are among the most vulnerable groups to outdoor heat. The WBGT is an appropriate metric in the context of labor productivity, although the assessment of indoor exposure to extreme heat could benefit from dedicated local estimates, done with commercially available WBGT measuring instruments.
- **Energy production**, especially electrical energy production, is particularly vulnerable, given that the infrastructure for production and transmission (e.g., transformers) of electrical energy may experience breakdowns in periods of extreme heat. Moreover, periods of extreme heat often go together with an increased electricity demand peak for active building cooling, and at the same time coincide with an increased difficulty in obtaining sufficient cooling water for thermal power generation during very hot conditions.
- **Renewable energy production**, in particular solar-based (photovoltaic (PV) panels and concentrating solar power (CSP) plants) may see their output reduced in periods of high temperature. In the case of PV modules, one should account for the temperature dependent electrical efficiency, and implement mitigating measures, such as installing PV panels a few inches above roofs to allow convective air flow to cool the panels.
- **Industrial plants** may have difficulties cooling, especially those that depend on natural cooling from wind. In addition, heat-induced energy production may decrease and negatively affect the operations at industrial plants.
- **Transport infrastructure** is also sensitive to extreme heat. Railway operations may be adversely affected by railway track buckling, material fatigue, and overheating of equipment. Road pavements may get damaged, and car tires may experience failure at high temperatures. Aviation may face damage to the runway surface, and take-off weight limitations during hot periods.
- **Crop yield** may be adversely affected by heat, especially if the heat is accompanied by drought. Under these conditions of combined heat and drought, there is an enhanced risk of forest fires, heat-induced tree mortality and decline in tree growth rates, impacting **forestry** projects. Dedicated species-specific growth curves, which express plant growth response as a function of temperature, can be used to estimate impact on forestry projects.
- **Livestock production** may become compromised during periods of extreme heat, especially intensive dairy cattle systems, owing to decreased fertility and increased mortality, reduced milk production and associated income losses. Poultry and pigs are also sensitive to extreme heat.
- In certain areas **Summer tourism** may undergo negative consequences of extreme heat, though other (cooler) areas might benefit from it. So-called ‘tourism climate indices’ have been established to evaluate this.

Apart from these sector-based considerations, be aware of the fact that your project’s vulnerability to extreme heat hazard may also arise from indirect sectoral impacts. For instance, an industrial production unit may see its operations compromised not only because of local heat stress conditions (affecting labor productivity or component failure), but also because of interrupted transportation and/or energy producing infrastructure affecting its supply lines.

Extreme heat hazard often occurs together with drought (water scarcity), information of which is also available on the ThinkHazard! platform. Heat and drought combined may reinforce each other’s impacts, e.g., during an extreme heat episode, an industrial plant may require enhanced cooling, but a concurring drought might limit the availability of cooling water.

Further resources:

- WMO and WHO 2015. Heatwaves and Health: Guidance on Warning-System Development, http://www.who.int/globalchange/publications/heatwaves-health-guidance/en/
- Queensland University of Technology 2010. Impacts and adaptation response of infrastructure and communities to heatwaves: the southern Australian experience of 2009, report for the National Climate Change Adaptation Research Facility, Gold Coast, Australia; https://www.nccarf.edu.au/publications/impacts-and-adaptation-responses-infrastructure-and-communities-heatwaves
- Information regarding 'Tourism Climate Indices' can be found in the following: https://earth-perspectives.springeropen.com/articles/10.1186/s40322-016-0034-y.

SEEK INFORMATION:

Obtain pre-existing extreme heat hazard information. ThinkHazard! predominantly uses global datasets, therefore for more detailed project planning you should determine the availability of pre-existing local extreme heat hazard information to check whether your project is indeed located in region prone to extreme heat. In this respect, it should be noted that large built-up areas such as cities or harbors are more likely to experience excess heat than rural areas, because of the urban heat island phenomenon.

As a first step towards obtaining local extreme heat hazard information for your project area, you should seek information from your National or Regional Meteorological Agencies, which often keep records and statistics about the occurrence of extreme heat.

In case your project is located in a built-up environment (city, harbor, or large industrial area), check for the availability of local heat maps, including a representation of the urban heat island phenomenon. Urban areas are generally warmer than their rural surroundings because of the differing thermal characteristics of buildings and paved surfaces compared to natural surfaces. While the resulting temperature difference is on average of a few °C, temperatures in urban or harbor areas may be higher than rural values by up to 7-8°C (12-14°F) and more at night-time under favorable conditions. These higher urban temperatures are not contained in the assessment of extreme heat hazard in the ThinkHazard! platform. Also, information gathered from the National Meteorological Service will most likely *not* contain urban effects, as their observational procedures typically avoid urban areas. The level of spatial detail in a local heat map should ideally be of the order of a few hundred meters or better, and allow to identify so-called hot-spot zones.

Evaluate whether local regulations exist for extreme heat, such as national or regional definitions used to define heat wave episodes. There is no generally accepted definition of heat wave, the definition differing between countries and economic sectors. Evaluate whether local regulations include heat-health action plans, and health and safety regulations such as compulsory labor rest times in case of extreme heat. In case of infrastructure projects, verify whether local regulations exist concerning building codes (e.g., containing reference to climate-resilient building practice or obligations, such as green roofs), resistance to heat of materials used in transportation infrastructure (e.g., railway buckling risk as a result of high temperatures, road asphalt melting temperature thresholds, maximum load capacity of devices cooling large IT infrastructure).

When collecting local information, make sure to consider the right type of indicator for your sector of interest. For projects involving potential health or labor productivity issues, a number of 'human thermal comfort' indicators are available. For the energy sector, an indicator based on the concept of 'cooling degree days' may be more relevant. Crop yield will be governed by other indicators, involving temperature thresholds that may vary by crop type, and that may need to be combined with an indicator of drought status.

Conduct interviews with sectoral organizations regarding local vulnerability, based on past experience. For extreme heat hazard, consider the following organizations:

- public health authorities
- labor associations
- transportation organizations (road, rail, water, air)
- the agricultural sector
- the electricity producing/distributing sector
- industrial plant operators

Try to obtain evidence of previous extreme heat events. If available, reports on previous extreme heat events may be very valuable, especially when providing recommendations and measures to cope with extreme heat.

It is also recommended to try and find examples of good practice in other countries, regions, and locations that exhibit a comparable level of extreme heat hazard, and of which the project exhibits similar characteristics (e.g., similar sector, same infrastructural or environmental characteristics). Indeed, the issues you may encounter when considering extreme heat hazard for your project could have been dealt with previously elsewhere, and it may be very efficient to learn from that. Sectoral or city networks play a crucial role in accelerating the diffusion of good ideas and best practices, both domestically and internationally. Examples of such networks are:

- REN21, the Global Renewable Energy Network (www.ren21.net/about-ren21/about-us/);
- ICLEI, Local Governments for Sustainability, a global network of more than 1,500 cities, towns and regions (www.iclei.org);
- IUC, the International Union of Railways, representing the railway industry (www.uic.org/).

In case your project concerns (or is located within) the built environment, a relevant starting point for obtaining examples of good practice is the Second Assessment Report on Climate Change and Cities (ARC3.2), published by the Urban Climate Change Research Network (UCCRN). In particular, the cases described in the 'Case Study Docking Station' (http://uccrn.org/casestudies/), which may be queried by geographic location or climate zone, provide very relevant information.

PROFESSIONAL GUIDANCE:

Consultation with engineering and climate impact assessment professionals will provide a more detailed understanding of the risk posed to your asset by extreme heat. The level of guidance required will depend upon the level of hazard present, the vulnerability of the asset and local legislation that might apply.

Professional guidance ranges from informal advice from local experts, to a detailed and comprehensive site-specific heat risk assessment. The required level of consultation will depend on the vulnerability of your project, and the anticipated level of extreme heat hazard.

As an initial step, obtain informal advice from local knowledge centers (research centers, universities), to gain a better understanding of extreme heat hazard. Researchers and academics, active in engineering and/or climate impact assessments and with expertise in your location of interest, may have an intricate knowledge of extreme heat hazard, and be able to recommend key datasets and information available in your project area.

A more detailed understanding of extreme heat hazard in your project area can be obtained from a heat risk appraisal. This will give a more detailed view of extreme heat risk than provided by the ThinkHazard! platform, while still providing a relatively broad view of heat risk. Such studies are typically performed remotely, attempting to provide a generic assessment of heat risk, by integrating available sector-specific information (e.g., considering cooling degree days in case of the energy sector, or crop type-specific temperature thresholds). At this level, coarse-scale modelling can be considered, including urban heat risk mapping in case a project happens to be located in an urban environment. A heat risk appraisal will highlight key areas where a more detailed study may be required.

A site-specific heat risk assessment constitutes the most detailed appraisal of heat risk at the project location and the impact of extreme heat on the heat-sensitive components of critical infrastructure. Such assessments can also provide information regarding the design process to minimize heat risk, and the appropriate level of adaptation required. Site-specific heat risk assessments should be conducted by consultants with a proven expertise (ask for references) in the domain of climate impact assessment, and in the considered sector. Consultants should be able to demonstrate their expertise in undertaking and delivering heat risk appraisal assessments, and have experience in the project area, including regarding available data and information, and local legislation. They should also be expert in assessing the impact of future climate projections, considering time horizons that are appropriate for the concerned project.

Often, a site-specific assessment will rely heavily on detailed computational impact modelling, such as, e.g., building energy modelling or crop yield modelling. Such models can also be used to simulate scenarios for adaptation, which may suggest solutions for combating extreme heat hazard. For instance, certain building energy models allow to calculate the impact of adaptive measures against heat stress, such as solar blinds, enhanced ventilation, or shading.

Further information:

- Building energy assessment through modelling, using the EnergyPlus model http://energy-models.com/software/energyplus
- Overview of crop yield modelling: https://en.wikipedia.org/wiki/Crop_simulation_model
- WMO and WHO, 2015. Heatwaves and Health: Guidance on Warning-System Development. World Meteorological Organization (WMO) and World Health Organization (WHO). WMO-No. 1142 (http://www.who.int/globalchange/publications/heatwaves-health-guidance/en/).

MONITORING AND FORECASTING:

Identify extreme heat monitoring and forecasting systems. These are designed to provide communities with advanced warning of extreme heat based largely on information contained in weather forecasts, complemented with temperature monitoring. They can be used to trigger protocols (e.g., the deployment of heat-health action and emergency response plans) to mitigate against the effects of extreme heat.

Heat early warning systems are instruments to prevent negative impacts during heat waves. If sufficient warning can be given, then mitigation procedures can be implemented. Heat early warning systems are based on weather forecasts, which are used to predict situations associated with adverse heat-related impacts. Heat early warning systems are generally triggered by the predicted exceedance of given temperature (or thermal index) thresholds. The efficient communication of the heat wave and prevention responses constitutes an important component. Most heat early warning systems target the health of the general population, attempting to induce behavioral changes, ensuring operational status of emergency systems, and to adequately provide information to vulnerable groups. For a description of intervention strategies, WMO/WHO guidance at http://www.who.int/globalchange/publications/heatwaves-health-guidance/en/.

Early warning systems may also be relevant for other sectors than health, allowing e.g. transport, energy production or industrial operators to trigger timely action in reducing the effects of hot-weather extremes on the concerned sector. However, for sectors other than health, it might be worthwhile to consider alternative heat stress indicators. For instance, in the case of energy producing plants, an indicator based on the concept of cooling degree days may be relevant.

If your project provides a critical service (energy production and distribution, railway operations), consider implementing measures to ensure the project can continue to function in case of extreme heat, such as local cooling measures (such as spraying water on sensitive sections of railway tracks to locally cool and avoid buckling), or having an alternative energy supply system (e.g., in hospitals).

Find out whether a heat early warning system exists for your area. In some cases, it is feasible to establish a real-time connection to the heat early warning system, through receipt of text messages or emails from the system's operator when critical thresholds of temperature or thermal indices are reached. Ensure that any received extreme heat forecast or warning can be rapidly and clearly communicated to all staff and project beneficiaries at the project location, and develop protocols that define actions to be taken when a warning is received. For critical or networked assets, protocols should warn of possible service interruption and highlight that backup asset services may be required.

INTERDEPENDENCY:

Consider vulnerability of other assets within the project's dependency network: If your project is interdependent with other projects, it is important to assess the vulnerability of the entire network if the service provided is critical.

When planning a project in whatever sector or geographic area, be aware of possible inter-sectoral effects, which are numerous and can exhibit a cascading character, with heat-related failures in one sector cascading down to other sectors.

This is related to a high degree of potential interdependency of sectors in which different projects may be situated. Some examples (non-exhaustive) of inter-sectoral impacts initiated by extreme heat are given below:

- Extreme heat causing transport system failure (e.g., overheating trains) can affect labor productivity by hampering commuters from going to their work. A reduced transport capacity may also affect the delivery of goods to their destination, which may also reduce productivity. Railway systems, constituting a sensitive group within the transport sector, may cool tracks by spraying water on them, and improve the stability and strength of railway tracks (for instance by using concrete instead of timber sleepers supporting the tracks) and using materials that limit shrink / swell of the trackbed. Air conditioning systems in trains may benefit from improved maintenance or by upgrading to systems with a higher heat tolerance to prevent early shut-off. Roads can be made more resilient to extreme heat hazard by using high-grade heat-resistant asphalt (to avoid excessive softening of asphalt under heat stress).

- Outdoor workers experiencing extreme heat stress may see their productivity reduced. In case of agricultural workers, this may affect food security in the project area, which may already be under pressure from the direct impact of heat stress on crop yield. Reduced food production may further induce an income loss for the agricultural workers. Labor productivity of outdoor workers may benefit from new work practices (e.g., adapted working hours during the cooler hours of the day), or through the provision of shade to avoid heat stress. Indoor workers' productivity will benefit from improved building design (improved insulation, enhanced thermal mass, solar blinds, using nocturnal 'flush' ventilation as a means of passive cooling). Also, natural shading by trees may considerably reduce the heat load on buildings.
- Heat-related failure of energy production facilities may lead to reduced productivity at industrial production plants. It may also impair the operation of building cooling systems, resulting in negative health effects and affecting the operational capacity of critical infrastructure such as hospitals. It may affect transportation by disrupting power to common systems such as traffic lights. Cooling of energy producing plants to minimize risk of failure may be achieved by technological means, considering, e.g., relatively simple and low-cost options such as exploiting non-traditional water sources and re-using process water, up to measures such as installing dry cooling towers, heat pipe exchangers, and regenerative cooling. The electricity distribution network may reduce overheating by increasing system capacity, increasing tension in the power line to reduce sag, and by adding external coolers to transformers.
- Many critical services, including the provision of health care, are highly sensitive to the ways in which climate extremes disrupt buildings, transportation, and electricity. Making urban infrastructure more resilient will lead to better health outcomes during future heat events. Also, essential services that depend on the stable supply of electricity (hospitals, airports) may want to consider the installation of stand-alone generators capable of operating during prolonged power outage.
- Heat events also put water resources under strain, affecting not only consumers of water consumption or power but industries reliant on water for transport or irrigation. For example, if drinking water is taken from a canal, the enhanced demand for water may compromise transport by cargo vessels on that canal. Conversely, irrigation may reduce water for drinking supply. In general, hot and dry periods lead to an enhanced competition for water resources.

Be aware of event chains that may lead to system collapse. Imagine an extreme heat episode, combined with drought. Energy provision gets compromised because of a lack of cooling water, and therefore active building cooling (air conditioning) ceases, perhaps also in hospitals (unless there is a provision of back-up electricity that withstands high temperatures). At the same time, problems in the transportation network hamper the transport of heat stroke victims to hospitals.

During extreme heat events, negative feedback cycles may develop, exposing high levels of sensitivity across systems to changes in operating conditions. For instance, in case an electricity system operates with little spare capacity or redundancy, it will have a consequent lack of resilience to an unexpected perturbation such as a heat wave, during which demand across the grid is higher than normal. The shutdown of only a small part of the electricity grid (owing e.g. to heat related asset failures such as that occurring in transformers under excessive heat stress), together with reduced transmission efficiency, may lead to outages of major transmission lines, load shedding and, ultimately, power blackouts.

Scenario testing should be undertaken for potentially hotter and more prolonged events on service continuity by infrastructure and essential service providers. Such analysis needs to be system wide to explicitly account for cascading effects. To gain insight into heat related chains of events that may lead to system collapse, see a report describing the impact of the severe 2009 heat wave that shook Southern Australia, and containing the description of a range of response strategies that were formulated in the aftermath: Queensland University of Technology 2010. Impacts and adaptation response of infrastructure and communities to heatwaves: the southern Australian experience of 2009, report for the National Climate Change Adaptation Research Facility, Gold Coast, Australia; https://www.nccarf.edu.au/publications/impacts-and-adaptation-responses-infrastructure-and-communities-heatwaves.

Finally, it should be noted that certain solutions for extreme heat mitigation may also be beneficial for other hazard types and assets. For instance, green infrastructure (including the use of green roofs, porous pavements, and urban parks) not only reduces heat stress (by evaporative cooling, and by providing shade), but it can also improve storm water management and thus reduce flood risk in cities. By allowing rain water to infiltrate into the soil, green infrastructure is also a relevant measure for combating drought in built-up areas. Finally, green infrastructure comes with a host of other co-benefits such as greenhouse gas mitigation, and an improved and more pleasant environment for city dwellers, including enhanced social benefits.

HEAT MANAGEMENT:
Your project or development should consider heat management measures appropriate to your sector of operation, for example, technological adaptation, building design, or changing working practices.

Appropriate measures to manage excessive heat situations depend on the sector considered.

- Livestock productivity may benefit from improved ventilation and housing conditions, and from genetic approaches for breeds that have a better resilience against heat stress. Grazing animals will benefit from the provision of shade.
- In agricultural projects, one ought to consider technological adaptation responses, such as stress-tolerant crop varieties, irrigation, and enhanced monitoring systems. This sector may also benefit from heat early warning systems. Forestry may benefit from an improved wildfire management.
- Labor productivity may benefit from new work practices (e.g., adapted working hours during the cooler hours of the day) to avoid heat stress among both indoor and outdoor workers. Indoor workers' productivity will benefit from improved building design (improved insulation, enhanced thermal mass, solar blinds, using nocturnal 'flush' ventilation as a means of passive cooling). Also, natural shading by e.g. trees may considerable reduce the heat load on buildings.
- During extreme heat events, indoor thermal comfort can obviously be improved by using active mechanical cooling (air conditioning). However, apart from contributing to enhanced greenhouse gas emissions, such devices shed heat to the outdoor air, thus increasing the urban heat island effect. Finally, air conditioning may be unreliable during heat events, in case electrical energy production or distribution gets compromised.
- Railway systems, which within the transport sector is a very sensitive group, may cool tracks by spraying water on them, and improve the stability and strength of railway tracks (e.g., by using concrete instead of timber sleepers supporting the tracks) and materials to prevent shrink/swell of the trackbed. Air conditioning systems in trains may benefit from improved

maintenance or by upgrading to systems with a higher heat tolerance to prevent early shut-off.

- Roads can be made more resilient to extreme heat hazard by using high-grade heat-resistant asphalt (to avoid excessive softening of asphalt under heat stress).
- Cooling of energy producing plants may be achieved by technological means, considering, e.g., relatively simple and low-cost options such as exploiting non-traditional water sources and re-using process water, to measures such as installing dry cooling towers, heat pipe exchangers, and regenerative cooling. The electricity distribution network may reduce overheating by increasing system capacity, increasing tension in the power line to reduce sag, and by adding external coolers to transformers.
- Solar energy production by photovoltaic panels may reduce output losses passively by natural air flows or actively by forced air or liquid coolants.
- Overall, essential services that depend on the stable supply of electricity (hospitals, airports) may want to consider the installation of stand-alone generators capable of operating during prolonged power outage.

AVOID INCREASING HAZARD:
Built infrastructure may alter heat hazard. Constructing a significant piece of infrastructure can significantly alter the thermal properties of the area, generally inducing higher temperatures. Any new built infrastructure covering large enough areas (e.g., new city quarter or harbor zone) should be undertaken with consideration as to how this will influence the local microclimate.

The thermal properties of urban construction materials, together with the spatial layout of built-up areas, induce the urban heat island effect, which is marked by overall higher surface and air temperatures in urban areas, compared to their rural surroundings. This phenomenon is particularly strong during the night, when a city may be 7-8°C (12-14°F) warmer than neighboring rural areas. It should be noted that other types of built-up areas, such as extensive industrial or harbor areas, may also exhibit a pronounced heat island effect.

Urban (or, more generally, built-up) density and form do have an impact on the overall intensity of the heat island effect. Therefore, when your project considers the construction of a significant piece of infrastructure, it is important to account for the impact of the project on altering the local microclimatic conditions, and any related extreme hazard.

As general (but very rough) guidance, modified surface characteristics affect the overlying atmosphere up to a height equivalent to 1% of the horizontal extent of the project area. For example, in the case of a new industrial facility extending over an area with a diameter of, say, one kilometer, the atmosphere will likely be affected up to a height of approximately 10 m. This means that, e.g., a piece of critical infrastructure such as a transformer in the project area could have its operation adversely affected by heat whenever it is located below 10 m. (Depending on the atmospheric conditions, and on the roughness structure of the project, this height may be less or more – again, the numerical values given here are at best rough indications.)

Climate adaptive options for the built environment that can help to avoid increasing heat hazard, may be sub-divided into three categories: grey, green, and soft measures.

- Grey measures are technological and construction-material (and infrastructural outlay) based measures. Examples include cooling through enhanced design, such as the use of insulation, solar blinds on exposed buildings, the creation of natural ventilation and of shade.

Selecting construction materials and reflective coatings (e.g., white roofs) can improve building performance by managing heat exchange at the surface. Modifying the form and layout of buildings and urban districts can provide cooling and ventilation that reduce energy use and allow citizens to cope with higher temperatures and more intense runoff. Active cooling by air conditioning devices also constitutes a grey measure, though this option should be considered with care, as it may lead to enhanced greenhouse gas emissions, and to an enhanced urban heat island effect through the shedding of heat to the outdoor environment.

- Green measures rely on vegetation as an adaptive measure. Investing in urban ecosystems and green infrastructure can provide cost-effective, nature-based solutions for adapting to climate extremes while also creating opportunities to increase social equity, green economies, and sustainable urban development. Increasing the vegetative cover in a built-up environment can simultaneously lower outdoor temperatures, building cooling demand, runoff, and pollution, while sequestering carbon. When boosting green infrastructure, it is important to implement an appropriate watering scheme to ensure the infrastructure’s sustainability. An important issue when considering green measures is that, while such measures can be very effective, sustainable, and yielding a host of co-benefits; their impact generally is very local. For instance, green roofing can have a large impact on the building it covers, but generally has a modest impact only on the overall urban heat island. And urban parks, while very effectively reducing heat stress, only do so within the park’s boundaries, the effect being lost quickly beyond these boundaries.
- Soft measures target awareness, and organizational and behavioral change to better cope with extreme heat hazard. General awareness raising is instrumental in the deployment of soft measures. Warning systems, heat action plans, and the establishment of appropriate institutional structures are also part of it, as are the preparedness of the health and social care system, and the adaptation of building codes. The development of heat-health action plans is an example of a soft measure.

CHAPTER 5 LINKS TO ADDITIONAL INFORMATION

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