04.12 Future Climatic Change and Thermal Load (2010 Edition)

Overview

The Environmental Atlas has for more than 25 years gathered information and data on urban climatology (see SenStadtUm 1985). With the results of the application of the FITNAH Climate Model, **comprehensive information about today's climatic situation in the municipal area** and the nearby surrounding areas is available (see Map 04.10 in Climate Model Berlin, Analysis Maps, 2009 edition, and Map 04.11 in Climate Model Berlin: Evaluation Maps, 2009 edition). Knowledge of the local urban climate, particularly the location and extent of urban heat islands and the climatic functional relationships between residential and green spaces, are important aspects of environmental precautionary policy and urban development.

For some years, the range of challenges has been increasing dramatically: the assessment of the effects of the changes to be expected from **global climate change** on thermal, hygric and air-purity conditions, particularly in metropolitan areas, requires additional answers to support the demands summarized under the concepts of "**mitigation**" and "**adaptation**".

Climate protection has been an integral part of Berlin environmental policy for years (see Ziele und Grundlagen der Klimaschutzpolitik in Berlin (Goals and foundations of the climate protection policy in Berlin – German only)). The city has a long tradition of implementing numerous programmes on:

- increasing energy efficiency,
- using renewable energies,
- promoting energy savings.

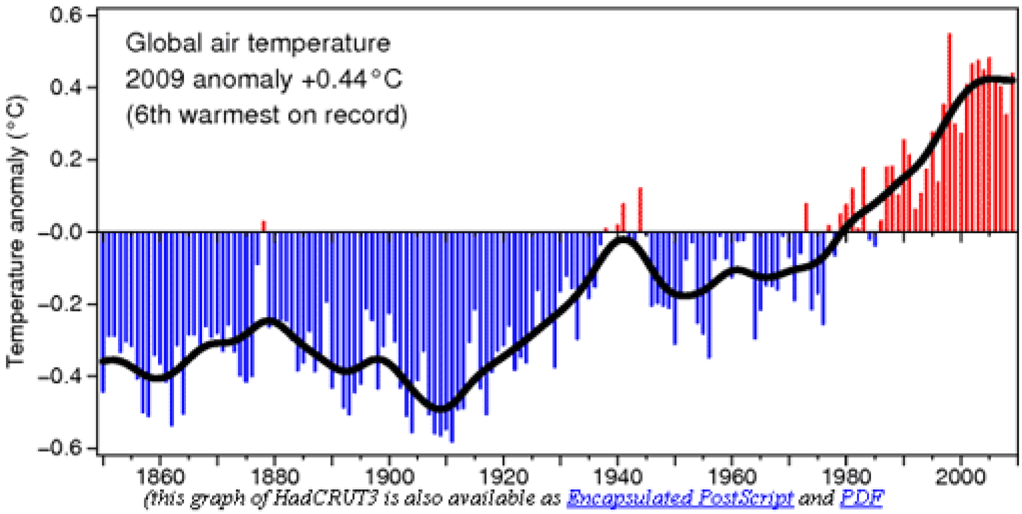
Nonetheless, adaptation to climate change has been a topic of only marginal interest to date. However, the normal conduct of municipal administration is no longer conceivable without addressing the need to adapt to climate change. With the acceptance of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) of 2007, both the fact of climate change and the high probability that it is anthropogenically caused have been internationally recognized.

Observation data shows that the climate has been warming since the last century. The global mean near-surface air temperature rose by approx. 0.74°C during the period from 1906 to 2005. On average, mountain glaciers and snow cover have decreased worldwide. Such extreme events as heavy precipitation and heat waves – such as during the "summer of the century" in 2003 – have become more frequent, and since the 1970s, more intensive and longer lasting droughts have occurred in larger areas in the tropics and subtropics. The expected risks are increasing with rising temperatures (see Federal Environment Agency).

The global mean near-surface air temperature has been rising since the beginning of industrialization. The higher concentration of greenhouse gases caused by the **anthropogenic** burning of fossil fuels in the atmosphere has led to an overall warming of the lower layers of the atmosphere (see Fig. 1).

1: Global Temperature Record

Phil Jones



(this graph of HadCRUT3 is also available as Encapsulated PostScript and PDF suitable for publication, and the data are available as Comma-Separated Values)

Fig. 1: Deviation from the global mean of near-surface air temperature from the average value, 1961 through 1990 (Source: Climatic Research Unit – University of East Anglia)

According to the forecasts of the IPCC, the following changes are to be expected in Germany by 2050:

- summer temperatures will be some 1.5°C to 2.5°C higher than in 1990,
- the winters will be between 1.5°C and 3°C warmer,
- summer precipitation could be reduced by up to 40%,
- winter precipitation could rise by up to 30%
(for more detailed information, see: Climate Atlas of Germany).

In order to be able to better assess the regional impacts of these future climate changes in Germany, so-called **regional climate models** have been used to compile data to project possible future developments, for example, under contract for the Federal Environment Agency.

The climate models are based on assumptions about the development of emissions during the coming decades, which in turn depend on possible – worldwide – demographic, societal, economic and technological developments. The IPCC's Special Report on Emissions Scenarios (SRES) are the authoritative basis for most climate projections. For most projection calculations, Scenario A1B is used, which is based on the following assumptions:

- steady economic growth,
- decreasing world population from the middle of the century on,
- introduction of new and efficient technologies,
- reduction of regional differences in per capita incomes,
- "balanced use" of all energy sources.

All SRES scenarios assume no additional climate initiatives, i.e. none of the scenarios include consideration of the effects of the implementation of international climate agreements.

The resolution level of the regional model is 10 km x 10 km per grid square. Although this is a considerable quality leap compared with global models, which use grid sizes of 200 km x 200 km, it is still far from being sufficiently precise for urban planning purposes.

Two of the best known models in Germany are the dynamic regional model REMO and the statistical method WettReg.

At the federal level, the **German Strategy for Adaptation to Climatic Change** (DAS) was adopted by the cabinet on December 17, 2008. This is the federation's contribution to create a framework for adaptation to the impacts of climate change in Germany, which needs to be further developed by the cities and metropolitan areas, according to local impacts (see here for more information).

The point of departure for better assessing this local impact for Berlin is the cooperation agreement concluded in early 2008 between the **Deutscher Wetterdienst (DWD), Climate and Environmental Consultancy Department, and the Berlin State Senate Department for Urban Development, Geo-Information Section, Office of City and Environment Information System**, which was successfully completed at the beginning of 2010. The project report submitted for this purpose has also provided essential contributions to the text presented here (DWD 2010).

The approach of the maps and data presented here was thus to address the question as to how thermal conditions might develop in Berlin, on the basis of information and model data existing today. This is also of special interest because it must be assumed that areas of the city that are not yet affected by thermal load will very likely be subjected to much higher summertime temperatures during the coming decades, due to continued climate warming. This applies both to expected absolute temperature peaks and to the duration of heat waves.

The goal was thus essentially **to take stock of the expected climate impacts,** particularly in built-up areas, where the vulnerability of city dwellers – and especially older inhabitants – is the greatest.

The methodology for studying the possible impacts of global climate change at a local level is still a new area of research: it is not at all standardized, and therefore the interpretation of results always involves certain uncertainty factors (see Methodology).

Statistical Base

The Urban Bio-Climate Model UBIKLIM

The atmosphere and hence the climate are part of the environment with which the human organism must constantly deal in order to maintain a balance of life functions and thus of human health. The required adaptation performance can be calculated from human heat budget models (VDI 1998), which objectively ascertain the connection between human beings and the atmosphere, both qualitatively and quantitatively. They take into account not only the air temperature, but also wind, humidity and solar radiation conditions, as well as the activity and clothing of the people. The **DWD uses the Klima-Michel Model** (Jendritzky et al. 1990). It is based on Fanger's Comfort Equation (1972), including a correction by Gagge et al. (1986) that improves its ability to account for hot and humid conditions. It combines all quanta relevant for the human heat budget, and provides a statement about the average subjective feeling of humans (comfort, thermal load, cold stress). The theoretical person thus assessed is named "Michel" - an average male, 35 years old, 1.75 m in height, and 75 kg in weight.

Perceived Temperature, measured in °C, is used to describe thermal sensation (Staiger et al.1997). It compares the actually existing conditions found with the temperature that should prevail in a standard environment in order to create an identical feeling of warmth, comfort or coolness. It is assumed that clothing always varies on a scale between light in summer and heavier in winter, so that a person always feels as comfortable as possible. In Table 1, the Perceived Temperatures are assigned to human thermal sensation, and to the respective load stages.

Tab 1: Relationship between Perceived Temperature, thermal sensation and load stages		
Perceived temperature [°C]	**Thermal sensation**	**Load stages**
< -39	very cold	extreme load
-39 to -26	cold	strong load
-26 to -13	cool	moderate load
-13 to 0	somewhat cool	weak load
0 to 20	comfortable	no load
20 to 26	somewhat warm	weak load
26 to 32	warm	moderate load
32 to 38	hot	strong load
> 38	very hot	extreme load

Tab. 1: Relationship between Perceived Temperature, thermal sensation and load stages

Since the possibilities for adaptation are rather limited under warm or hot conditions, and relief can only be obtained by moving to cooler surroundings (in extreme cases, to air-conditioned rooms), and in addition, since cities are subject to greater thermal load than the surrounding countryside, the heat or thermal load share of the bio-climate is of particular significance with relevance to human feelings of well-being, and in some cases, to physical health.

UBIKLIM uses the aforementioned Klima-Michel Model and helps to identify local differences in bio-climate, and evaluate Perceived Temperature as per Directive 3787 Sheet 2 (VDI 2008).

In order to reference not only the local municipal situation, but also the regional bio-climate, on the basis of which a connection to the climate scenarios of the future can then also be created, it has been necessary to extend the urban bio-climate model to a **"combined urban bio-climate model"** (see further explanations in the chapter on Methodology).

Use of Land Use Data

The application of simulation models requires a spatial survey of land use data and basic meteorological conditions extending beyond the area under investigation. The examination area therefore consists of the municipal area of Berlin, with approx. 890 sq. km, and a section of the surrounding areas, of approx. 850 sq. km. It thus encompasses an area of 46.1 x 38.0 km (see Fig. 2).

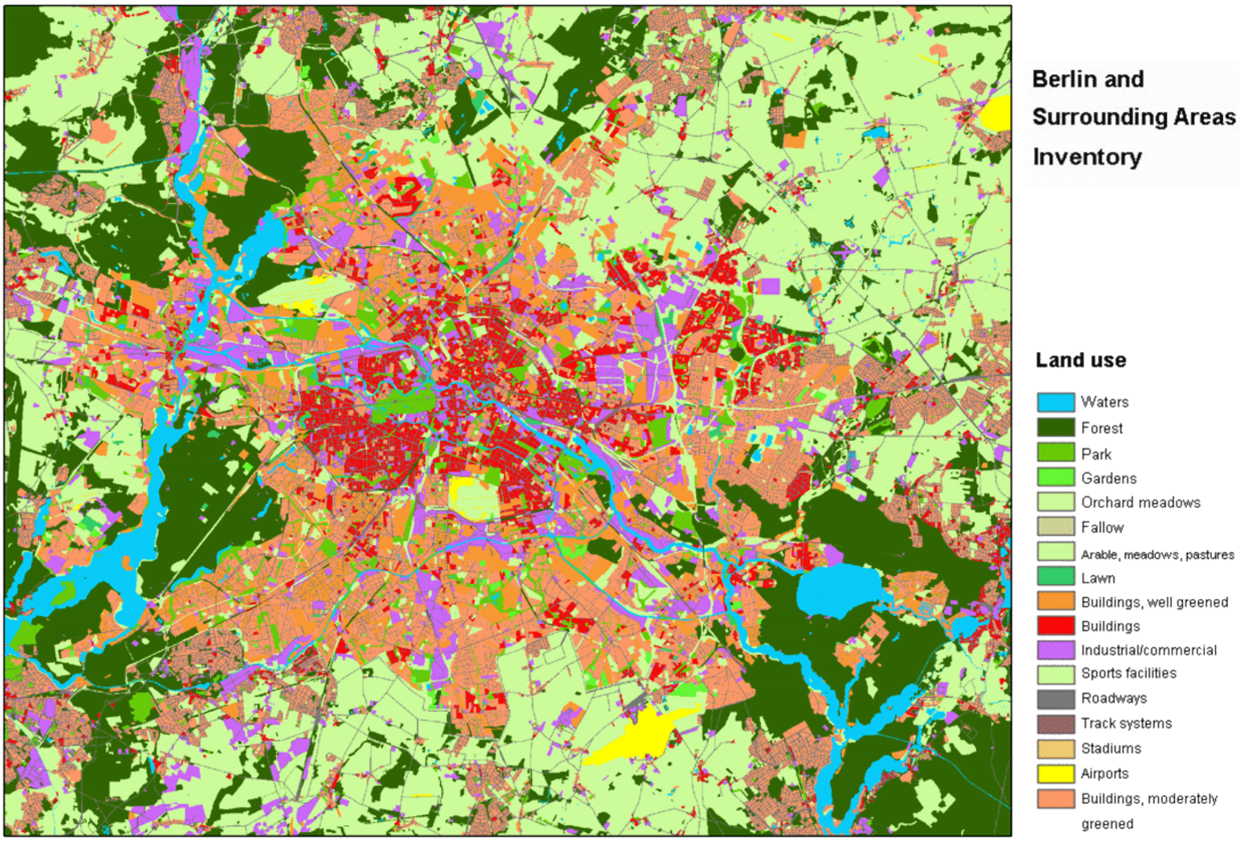


Fig. 2: Classification of land use for the application of the model. A legend with 17 use classes is used, which is adapted to the requirements of the UBIKLIM model

The data are provided using a grid of 25 m x 25 m, resulting in approx. 2,800,000 segments altogether.

The parameters used for the municipal area of Berlin were taken from the data held by the City and Environment Information System (ISU) of the Senate Department for Urban Development, which is available for various evaluations and calculations. It contains approx. 25,000 segments in a spatial reference system which had to be converted to a regular grid for the UBIKLIM simulations:

- **Land use**. The land use data show the state of use at the end of 2005, and are based on an evaluation of aerial photography, borough land use maps, on-site examinations and additional documents for the Environmental Atlas (see Maps 06.01 and 06.02, SenStadt 2008a). Approx. 30 use types are distinguished.
- **Urban structural types** (Map 06.07, SenStadt 2008 b). The data were further improved via the ISU use file, which includes type-specific information on the height of buildings and on vegetation structures within each urban structural type.
- **Soil sealing** (Map 01.02, SenStadt 2007).

The preliminary work for the implementation of the EU Directive on Ambient Noise provided a file of buildings including height data, which could be fed in; it contains data as of 2005 on the 550,000 buildings in the automated property map (ALK) of the State of Berlin, as well as on 231,445 buildings in Brandenburg in a ring 3 km wide around the municipal area.

The ALK map, the illustrative section of the so-called property register, shows not only the property boundaries, but also the buildings including the number of storeys, with sharp precision, and is therefore suitable as basic information on building structures (see Map 4.10., Fig. 2).

With regard to the integration of the ALK data in the evaluation process, it must be taken into account that facilities in railway areas urban rail (S-Bahn) stations, buildings in industrial and commercial areas, and summer cottages in allotment gardens are not always recorded.

Tab 2: Classification of surface types and construction parameters for the application of the UBIKLIM bio-climate model

	Surface type	degree of impermea-bility in %	no. of buildings per 100,000 sq.m	mean building height in m	built-up surface share in %	green space share
	Municipal area of Berlin:					
1	Closed rear courtyard	84	32	15	53	n
2	Rear courtyard	78	36	16	45	n
3	Decorative garden yard	65	32	13	35	p
4	Rehabilitation by de-coring	63	39	16	33	n
5	Preservation-oriented restoration	74	40	16	42	n
6	Shed courts	61	28	12	29	n
7	Post-war block edge construction	66	35	15	35	n
8	Haphazard reconstruction	67	51	19	35	n
9	Large-scale high-rise development	49	32	13	19	n
10	Large courtyards	52	29	13	27	m
11	Row housing, since the ‘50s	44	27	13	20	m
12	Schools, old construction	58	31	13	26	n
13	Schools, new construction	51	31	13	20	m
14	Schools	45	31	13	16	m
21	Village	38	26	12	17	m
22	Row gardens	34	25	12	16	m
23	Gardens	34	24	11	16	m
24	Park-like gardens	36	23	11	18	p
25	Semi-private gardens and green surroundings	39	27	12	20	m
26	Open-style apartments	29	24	12	13	m
27	Cemeteries	10	3	10	2	p
29	Core areas	81	40	16	44	n
30	Low density industrial areas	68	31	13	27	n
31	Densely developed industrial areas	57	32	14	18	n
32	Supply and disposal areas	57	32	14	18	n
33	Mixed areas II, low density	65	25	12	29	n
34	Allotment gardens with low percentage built-up area	15	30	3	8	p
35	Allotment gardens with high percentage built-up area	20	60	3	10	p
37	General horticulture	15	30	3	8	p
38	Mixed area II, dense development	83	29	15	48	n
39	Mixed area I	43	22	11	20	n
41	Security and law enforcement	41	26	13	15	n
42	Postal facilities	68	47	16	23	n
43	Administration	60	34	14	28	n
44	Universities and research	53	29	13	26	m
45	Culture	58	39	15	28	n
46	Hospitals	40	25	13	20	m
47	Child care	40	36	15	15	m
49	Churches	43	32	14	18	n
50	Retirement homes	49	27	13	23	m
51	Youth centres	26	15	11	11	p
58	Campsites	15	10	4	2	p
59	Weekend cottages	26	21	11	10	m
60	Community facilities in general	45	27	12	13	m

71	Residential estates, ‘80s & ‘90s	55	31	15	20	n
72	Row houses, ‘20s, (only East Berlin)	51	37	15	25	m
73	Residential areas, ‘90's, compact	60	27	13	26	n
74	Residential areas, ‘90's, loose	51	23	12	17	m
150	Cemeteries	15	6	10	2	p
160	Allotment gardens	20	27	3	3	p
161	Allotment gardens (permanent residents </=10%), only East Berlin	30	28	10	7	p
162	Allotment gardens (permanent residents >10%), only East Berlin	37	31	13	10	p
180	Campsites	12	12	9	1	p
	Surrounding areas:					
205	Allotment gardens	19	27	5	3	
206	Core areas	81	16	10	11	n
208	Dense settlement	63	15	10	10	m
211	Industrial areas	65	12	10	7	n

1) Information on green space: n: not greened; m: moderately greened; p: park-like green

Tab. 2: Classification of surface types and construction parameters for the application of the UBIKLIM bio-climate model

To enable application of the one-dimensional urban climate model MUKLIMO_1 (see 'Methodology' section), the extension of each individual land use segment must be considerably greater than a 25 m x 25 m pixel. This means that small streets are not resolved, but are assigned to the surrounding use categories.

Evaluation of the Climatological Time Series Data

Time series climate data from various weather stations have also been recorded for Berlin, some of which provide data over extended periods. Evaluations of characteristic parameters of the air temperature at various locations in the city subject to different urban effects show the effect on thermal load on average over a year, or during extreme weather situations.

The map (Fig. 3) shows the position of the two climate stations Berlin-Tegel and Berlin-Tempelhof. Both airport sites are situated in relatively open urban areas in the midst of Berlin, with few buildings. By contrast, the surrounding area of the climate station at Berlin-Alexanderplatz, is characterized by dense construction, as an inner-city area with a high degree of soil sealing. The other stations display the features of an urban peripheral location.

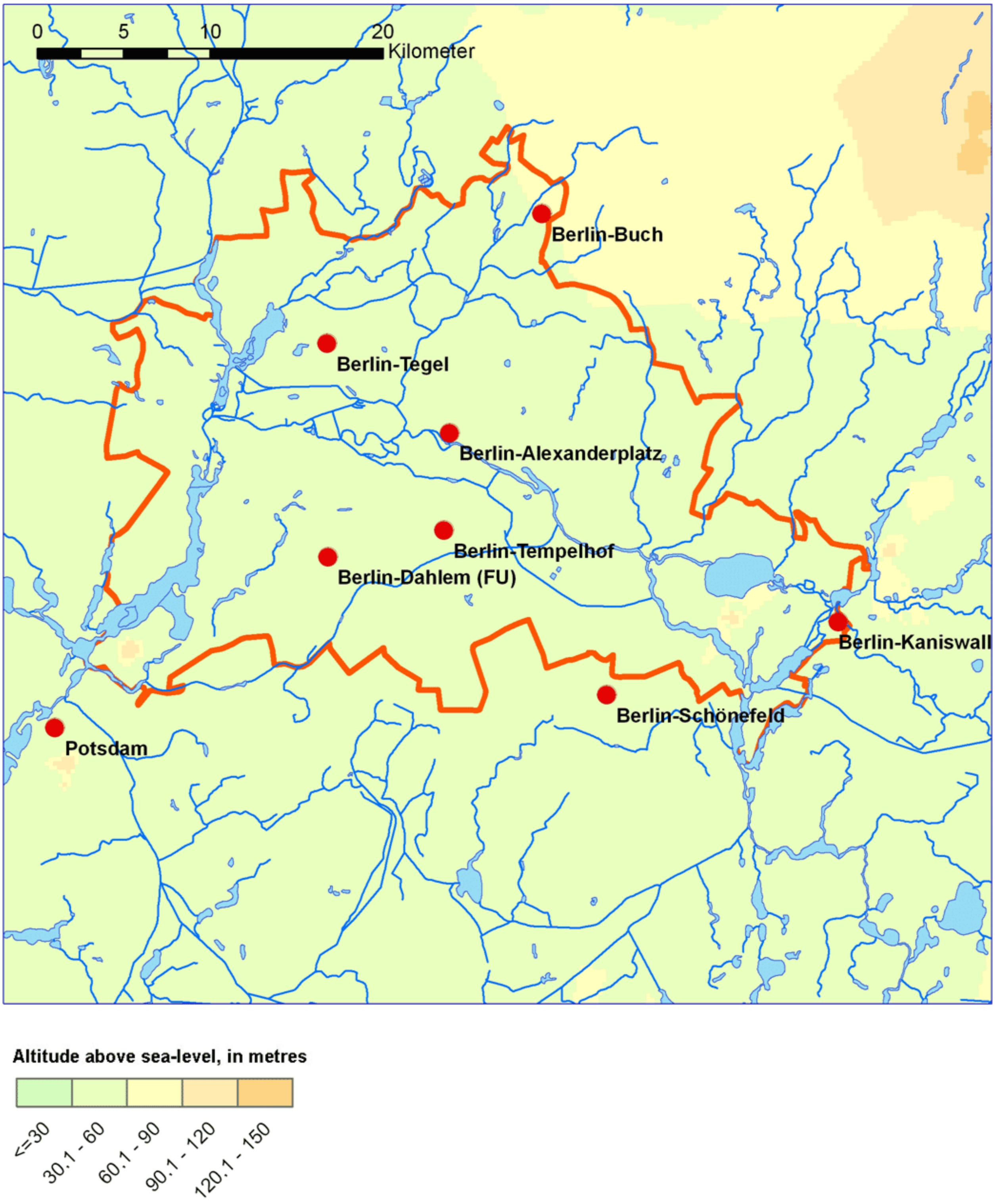


Fig. 3: Location of the climate stations used for the modelling process in the city area and immediate surrounding countryside

Fig. 4 shows the development of the air temperature at the Tempelhof station between 1949 and 2008. The positive trend, particularly of the last 20 years, is clearly recognizable. After one cold year in 1996, all average annual air temperatures were above the long-term annual mean value of 9.6°C. The warmest year of the entire observation series was 2000, with 11.1°C. The increasing warming affects the entire conurbation; nonetheless, the thermal results in particular Berlin neighbourhoods differ widely.

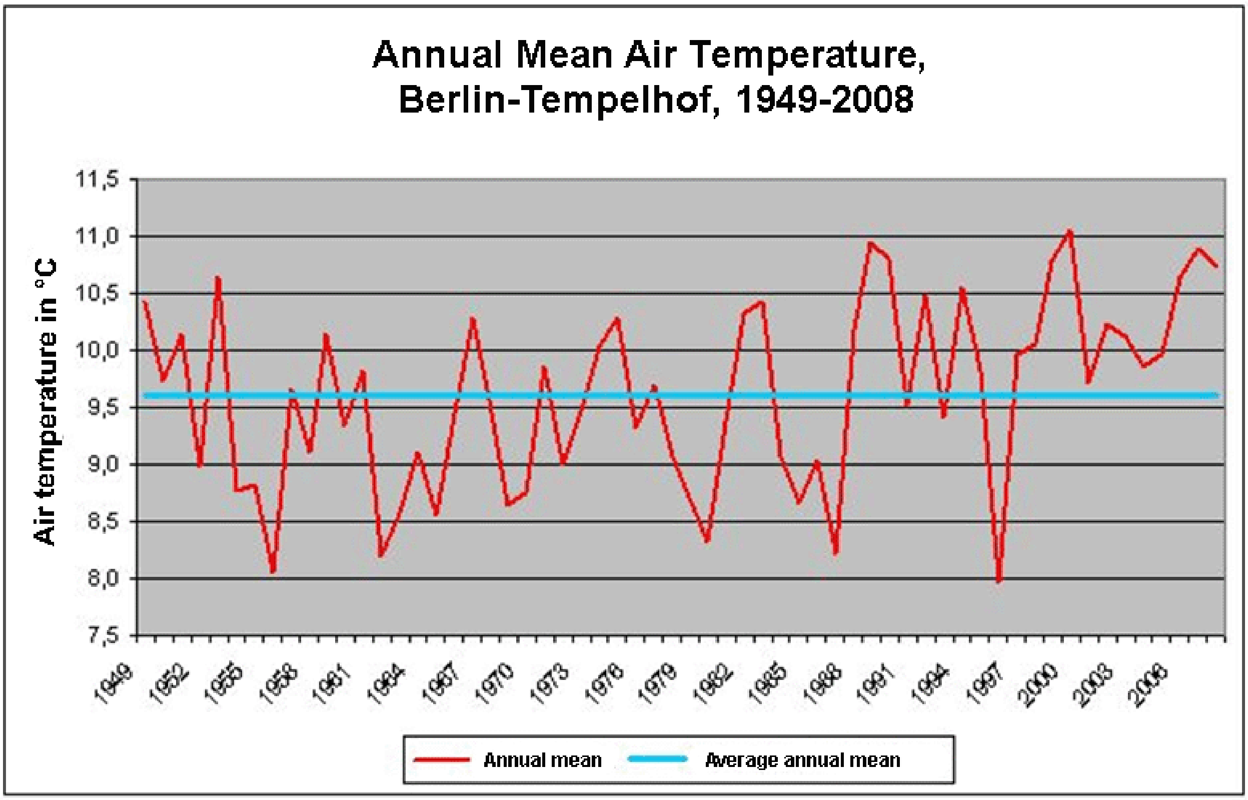


Fig. 4: Annual mean air temperatures at the Berlin Tempelhof station (1949-2008)

Tropical nights are rare in Germany. Table 3 shows the number of tropical nights (temperature minimum >/= 20°C), and the resulting increase of the "heat island effect", with its advance into the immediate urban core of Berlin. The different time periods provide information about the increase in thermal load, particularly in the over-heated inner city. There is a mean increase of five tropical nights in the inner city during the 1999 – 2008 period, compared with the 1967 – 1990 period, an increase of 0.2 in the built-up municipal area, and an insignificant drop of 0.1 in the outskirts of Berlin (see Table 3).

Tab 3: Average number of tropical nights at various climate stations				
		Outskirts	Urban area	Inner city
		Schönefeld	**Tempelhof**	**Alexanderplatz**
a	1967-1990	0.2	1.0	2.1
b	1981-2000	0.2	1.5	3.6
c	1993-2007	0.1	1.5	4.7
d	1999-2008	0.1	1.2	7.1
e	2003	-	3.0	10.0
	Difference, b-a	0.0	**0.5**	**1.4**
	Difference, c-a	0.0	**0.5**	**2.6**
	Difference, d-a	**0.1**	**0.2**	**5.0**

Tab. 3: Average number of tropical nights at various climate stations

Periods of extreme heat, such as during the summer of 2003, lead to a very great thermal load in densely built-up inner-city areas. At the Alexanderplatz station, ten tropical nights were registered, and there were still three in the built-up municipal area, while no such event occurred at all in the adjacent surrounding countryside.

The Alexanderplatz climate station is characteristic of the situation in an urban heat island. However, since urban structures are not spatially homogeneous, urban heat islands also form in other parts of the city with high development density, high degrees of soil sealing and/or very little green space. On the other hand, in areas with large parks, temperatures that hardly differ from those of the surrounding countryside are recorded.

Methodology

Evaluation of thermal load situations can be carried out using various criteria. "The most frequently used is Fanger's Comfort Equation (1972), and the Perceived Temperature (PT) calculated from it, by means of which the thermal effect complex is determined" (VDI 2008).

The urban bio-climate model UBIKLIM (Urban Bio-Climate Model) is a model method which builds upon those criteria. It was developed for practical application in urban planning by the Deutscher Wetterdienst (DWD), and has been applied in Berlin since 1996 to assess the thermal situation of a typical summer's day (see SenSUT 1998).

The unusual methodological-technical feature of UBIKLIM was the development of a projection of the bio-climate for time periods subject to climatic change, i.e., over the next 30 – 70 years. Since no standardized methods yet exist for this purpose, the results presented here regarding the application of UBIKLIM in the context of climate projections should be considered as **estimates of the future development of the climate**. Based on climate projections, climate change scenarios which represent possible plausible developments of the climate in the future can be designed. They cannot, however, be treated as exact forecasts or even as weather forecasts (UBA; German only).

Input Quanta and Procedures at UBIKLIM

As input quanta, UBIKLIM needs not only a high-resolution height model, but also suitable land use information. For this purpose, the area under examination is subdivided into a finite number of sections with the same or similar uses. Built-up areas are further subdivided and clearly characterized according to degree of soil sealing, proportion of built-up areas, building height, number of buildings per unit of area, and proportion of green space. Using these input data, UBIKLIM calculates the meteorological quanta for the entire area under examination at a height of 1 m above ground on a cloudless, low-wind summer's day, in several steps – primarily by using the 1-dimensional urban climate model MUKLIMO_1 – and then analyses the results pixel by pixel using the Klima-Michel Model (see flow chart, Fig. 5). The resolution of the resulting bio-climate map is 10 to 25 metres.

UBIKLIM permits ascertainment of local differences in the bio-climate. However, these results do not provide any reference to the regional climate, and thus do not provide the basis for absolute information.

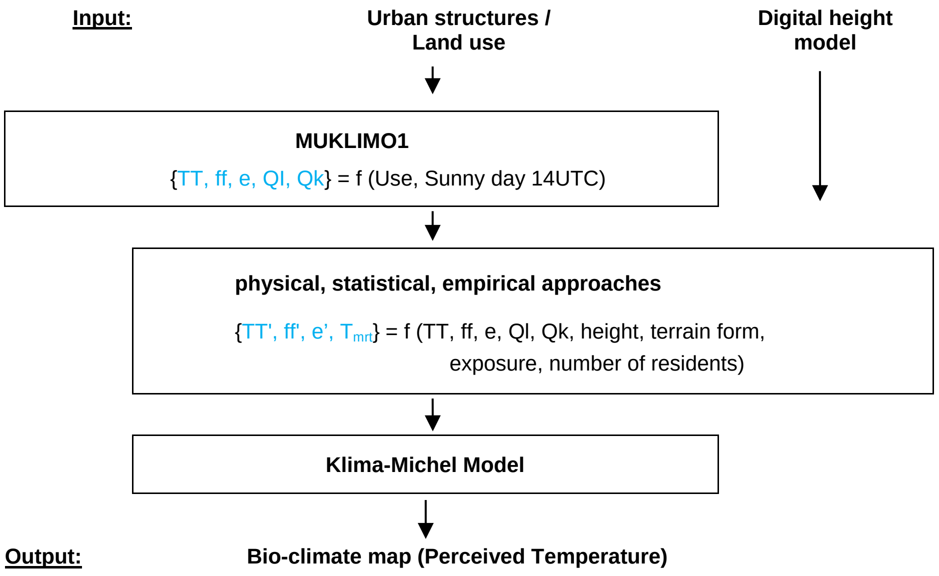


Fig. 5: Schematic structure of the urban bio-climate model UBIKLIM
(TT: air temperature; ff: wind speed; e: humidity; Ql: long-wave solar flux, Qk: short-wave solar flux; T_{mrt}: average radiant temperature of a human; values for 1 m above ground)

Advancement of UBIKLIM to a Comprehensive Urban Bio-Climate Model

Bio-climate maps that reference the regional bio-climate and local differentiation can be generated by linking the UBIKLIM results to regional bio-climate information, which disregards land use and which is hereinafter described as the "background load". The urban bio-climate model is thus expanded to a combined urban bio-climate model, which consists of UBIKLIM, the bio-climatically prepared background information, and a statistical model equation which is used to combine the different scales.

To be representative of a broader surrounding area, the weather data, largely unaffected by land use, are gathered at synoptic stations according to the specifications of the World Meteorological Organization (WMO). They are thus suitable for obtaining the required background information. Certain stations that differ considerably from the specifications are excluded. Their readings are characteristic of the climate in the immediate surroundings of the station, such as Berlin-Alexanderplatz, the "city centre".

The 30-year average number of days with thermal load is used to determine the background thermal load outside the urban area. A thermal load day is defined as a day on which the Perceived Temperature reaches or exceeds 32°C – high thermal load – at a minimum of three hourly measurements between 9 and 15 UTC (Coordinated Universal Time) over the course of the day. This definition was chosen because it generally includes the days on which heat warnings are issued, i.e., which are of high thermo-physiological relevance.

In order to ascertain the connection between the thermal conditions on a sunny summer day and the mean climatic conditions, various urban and use structures were imposed on the weather data gathered from the synoptic stations in Germany for the 1971 – 2000 period. In other words all measurements for temperature, humidity, wind, and solar radiation derived from cloud cover data were modified according to land use. The modification parameters for the various urban structures were determined from MUKLIMO_1 simulations.

All data were then analysed with the Klima-Michel Model, and examined for thermal load days. The following regression equation was then derived from the data set obtained:

$$\mathbf{WB = (r_1 * WB_{frei} + r_2 * dGT + r_3 WB_{frei} * dGT + r_4 * nn + r_5 * br + r_6 * lä + r_{konst})} \quad \text{(Equation 1)}$$

WB	Thermal load days at an arbitrary point in the city
WB_{frei}	Background load
dGT	Perceived Temperature at an arbitrary point in the city minus Perceived Temperature above open spaces outside the urban area (as per UBIKLIM)
nn	Altitude above sea level
br	Latitude
lä	Longitude
r_i	Regression coefficients

Since the UBIKLIM results refer to sunny days, the thermal load days that are not sunny must also be taken into account, in order to couple the model with the regional bio-climate model. The resulting equation thus consists of both a regression equation and a weighting function. A sunny day is defined as the average of the 6, 12 and 18 UTC hourly values for cloud cover (N) and wind speed in 10 m above ground (v). On a sunny day, N<= 4 eighths, and v <= 3 m/s.

The coupling of the local and the regional bio-climate information is achieved by the following equation:

$$\mathbf{WB = (r_1 * WB_{frei} + r_2 * dGT + r_3 WB_{frei} * dGT + geo) * strant + WB_{frei} * (1 - strant)} \quad \text{(Equation 2)}$$

geo	f (latitude, longitude and altitude) = constant for Berlin
strant	percentage share of sunny days among thermal load days.

Application of the Urban Bio-climate Model UBIKLIM

Using the land use data of Berlin and its surrounding areas (see Use of Land Use Data), UBIKLIM calculates the distribution of the Perceived Temperature as it typically develops on the afternoon of a low-wind, cloudless summer day (see Fig. 8).

For **comparison,** it was possible to use the observation values of the climate stations at the Schönefeld (10385) and Tegel (10382) airports, the former Tempelhof airport (10384), and the urban climate stations Dahlem (10381) and Alexanderplatz (10389).

Twelve sunny summer days were selected from the time period 1990 - 2000. This comparatively low number is related to the fact that only a few complete data sets were available for the calculation of the Perceived Temperature at the Alexanderplatz station. While temperature, humidity and cloud cover, which served to parameterize the effects of the sun's radiation, were used directly for the calculation of the Perceived Temperature, wind speed was calculated down to a height of 1 m, in accordance with the logarithmic approach of the standard model used by the DWD to calculate the Perceived Temperature. Different roughness lengths were assumed, depending on the descriptions of the station surroundings (DWD 2008).

Tab 4: Comparison of Perceived Temperature as calculated as per UBIKLIM (GT UBIKLIM), with the average Perceived Temperature values ascertained from measurements at five stations in Berlin, on twelve sunny summer days (GT Station), 1990 – 2000

Meteorological Station	$GT_{Station}$ [°C] 12 UTC	$GT_{UBIKLIM}$ [°C] 14 UTC	Wind height above ground [m]	Roughness length [m]
Schönefeld	32.5	25.9	10	0,01
Tegel	32.1	25.8	10	0,03
Tempelhof	32.4	26.2	10	0,06
Dahlem	35.0	29.5	26	0,15
Alexanderplatz	35.6	30.4	368	0,65

Tab 4: Comparison of Perceived Temperature as calculated by UBIKLIM ($GT_{UBIKLIM}$), with average Perceived Temperature values ascertained from measurements at five climate stations in Berlin, on twelve sunny summer days ($GT_{Station}$), 1990-2000

Table 4 shows the Perceived Temperatures from the model, compared with the average measurements at selected climate stations in the city for twelve sunny days. Clearly, the differences between urban structures are shown fairly well. Both the measurements and the model calculations show that similar thermal conditions prevail at the three airports. The Perceived Temperatures are approx. 2.5 to 3.5°C higher at the two urban stations; in the model, the difference is approx. 4°C, and reflects very well the respective situations of these urban stations – on the one hand, the city centre (Alexanderplatz); on the other, detached family homes with gardens (Dahlem).

However, this comparison should not be overstated, since point-based values (station data) are compared to area mean values (model data). Since an interpretation precise down to the pixel is impossible according to model philosophy, the model temperatures have been taken as representative for the approximate area of the station, However, since the data of the climate stations are considered representative of the surroundings, and in addition reflect a mean of several days, the comparison is nevertheless considered quite valid.

In the next step, the relationship to regional climate conditions was established. This was necessary in order to combine UBIKLIM with the data of the regional climate models REMO and WettReg used for future projections.

Application of the Comprehensive Urban Bio-Climate Model UBIKLIM

For the combined urban bio-climate model, in addition to the UBIKLIM input parameters, values for the background load and the percentage of sunny days are also needed. In the case of Berlin, these can be obtained from the data from the Berlin-Schönefeld climate station. The annual mean value is 9.9 thermal load days for the 1971 – 2000 period, with 47% sunny days. The geographical data, summarized as the quantum "geo" (see Equation 2), are assumed to be constant, due to the relatively small area involved.

Map 04.12.1 (see Fig. 8) shows the distribution of the thermal load days as a result of the model application for the 1971 – 2000 period.

It provides absolute information which can be compared with evaluations obtained in the same manner, e.g. from other cities, or also simply with the background load of any area.

Similarly to the comparative representation of the Perceived Temperatures in Table 4, Table 5 compares the station evaluations of the frequency of thermal load days with the model values. Unfortunately, the readings for the Alexanderplatz station were far from sufficient to ascertain – or even estimate – a 30-year mean. The station and model values show a good level of agreement. All three airport stations show approximately the same load level, while seven thermal load days more per year are shown for the area of the Dahlem urban station.

Tab 5: Comparison of no. of thermal load days calculated as per UBIKLIM (WBUBIKLIM), with no. of thermal load days calculated from the data from four Berlin climate stations (WB Stations) (ref. period: 1971-2000)

Station	$WB_{Station}$ [days]	$WB_{UBIKLIM}$ [days]
Schönefeld	9.9	9.2
Tegel	8.6	9.0
Tempelhof	9.2	9.9
Dahlem	16.6	16.0
Alexanderplatz	-	17.5

Tab 5: Comparison of no. of thermal load days calculated as per UBIKLIM (WBUBIKLIM), with no. of thermal load days calculated from the data from four Berlin climate stations (WB Stations) (ref. period: 1971-2000)

Projection of the Bio-Climate to Periods of Climate Change

Global climate models grew out of weather prediction models, and have been used since about 1940 to arrive at an understanding of future climate development. A range of scenarios is provided which differ according to their initial assumptions on future basic conditions, particularly regarding the emission of greenhouse gases and aerosols, and depend on socio-economic and technological developments. This scenario-based approach implicitly indicates the great fuzziness of climate projection, which should not be forgotten, even if only one scenario (Scenario A1B of the IPCC'S SRES Emissions Scenarios) is being considered as described below.

Global climate models have only a low resolution, which can however be increased considerably through regionalization. Both statistical and dynamic methods are considered. The present study, relies on the results of the dynamic regional model REMO (Jacob 2005) and the statistical regional model WettReg (Kreienkamp & Enke, 2006), both driven by simulations of the global climate model ECHAM5-MPI-OM created by the Max Planck Institute for Meteorology (Roeckner et al. 2006).

Only by **downscaling regional climate projections** it is possible to consider together the changes to be expected by global climate change and the influences caused by municipal land use. With the combined urban bio-climate model, both factors of influence can be taken into account, the background load being defined by the global climate or the regional climate derived from it.

To ascertain the future background load, the results of regional climate models were consulted; REMO and WettReg data were evaluated for the control period 1971 – 2000, and for the projection periods 2021 – 2050 and 2071 – 2100.

Additional detailed information about the implementation of the two projection models and the application of statistical methods for carrying out an adequate evaluation of thermal load can be seen under Methodology/Supplementary Notes.

Methodology / Supplementary Notes

Ascertainment of Background Load

The background load for the REMO data was ascertained using an area of 3 x 3 grid points in the southwest of Berlin which is largely unaffected by land use considerations (Deutschländer et al. 2009). At each grid point, time series of all physiologically relevant meteorological quanta were available for the desired periods. Evaluation with respect to thermal load days was carried out pixel by pixel for the three time periods, after which the area mean was determined. The percentage of sunny days was determined analogously.

WettReg generates results that are specific to climate stations. In the present case, the data from the Schönefeld and Lindenberg stations were evaluated separately with respect to number of thermal load days and percentage of sunny days. The arithmetical average of the values from both stations thus represents the background load that is characteristic of the Berlin area. The WettReg stations at Müncheberg and Zehdenick, which could theoretically also have been considered as additional bases for the investigation, were not used for the evaluation, since the bias corrections described below could not have been implemented there, due to very fragmentary measurement and observation data.

Unlike REMO, WettReg always provides only one value per day. In order to be able to carry out an adequate evaluation of thermal load, full-day runs and hence hourly values were generated for the calculation of the quanta required for Perceived Temperature with the aid of statistical methods specifically adjusted to the measurements from the Schönefeld and Lindenberg climate stations. The quanta used were temperature maximum, temperature minimum, daily mean air temperature, wind speed, humidity and cloud cover. This is certainly not sufficient data to permit a realistic representation for each and every day. This procedure must also be criticized in that for the calculation of Perceived Temperature a contemporaneous assignment is necessary as a matter of principle, due to the fact that the weather parameters often develop in opposite directions. However, since a thermal load day is not fixed to a single point in time, but is rather defined by three time measurements during a day (see Methodology), and also since an extended time period is used, it is certainly possible to obtain a realistic picture.

The evaluation of the measured data from the Schönefeld climate station and the REMO and WettReg data for the 1971 – 2000 period (see Table 6) indicates that thermal load days are slightly underestimated by REMO, but are overestimated by WettReg. The deviations for sunny day percentages are considerably greater.

Tab 6: Number of thermal load days (WB) and the percentage (strant) of sunny days, as an annual average for the period 1971-2000, from the measured data from the Schönefeld climate station (10385), and the corresponding time series of REMO and WettReg

	10385	REMO	WettReg
WB [days]	9.9	9.4	13.0
strant [%]	47	30	61

Tab 6: Number of thermal load days (WB) and the percentage (strant) of sunny days, as an annual average for the period 1971-2000, from the measured data from the Schönefeld climate station (10385), and the corresponding time series of REMO and WettReg

Application of Statistical Methods / Bias Correction

The deviation of the model value from the expected value according to the measurements is described as **model bias**. Bias corrections permit the model results to be improved. For this purpose, the respective percentiles for the threshold values for Perceived Temperature, wind speed and cloud cover are determined from the distribution frequency of measurement data from Schönefeld and Lindenberg. Then, in reverse, the distribution frequency of the model data which fall at these values in these percentiles is used to define new threshold values (Deutschländer et al. 2009). The bias is thus reduced considerably for thermal load days for WettReg, and for the sunny day percentages for both models (see Table 7).

Tab 7: Number of thermal load days (WB) and the percentage (strant) of sunny days, as an annual average for the period 1971 – 2000, calculated using the REMO and WettReg time series, with bias correction

	REMO	WettReg
WB [days]	10.4	10.8
strant [%]	42	49

Tab 7: Number of thermal load days (WB) and the percentage (strant) of sunny days, as an annual average for the period 1971 – 2000, calculated using the REMO and WettReg time series, with bias correction

The bias corrections identified for the control period were also applied to the evaluations of the future periods 2021 - 2050 and 2071 - 2100. Table 8 shows the results. By the middle of the century, according to both models, thermal load days will increase by approx. 50%. At the same time, the percentage of sunny days will also increase by 5% according to REMO, and by 6% according to WettReg. By the end of the century, the thermal load situations in the undisturbed surrounding countryside will almost double again, while the percentage of sunny days will not change further significantly.

Tab 8: Number of thermal load days (WB) and the percentage (strant) of sunny days, as an annual average for the projection periods 2021 – 2050 and 2071 – 2100, calculated using the REMO and WettReg time series, with bias correction

		REMO	WettReg
2021 - 2050	WB [days]	14.9	15.5
	strant [%]	47	55
2071 - 2100	WB [days]	26.6	26.4
	strant [%]	47	53

Tab 8: Number of thermal load days (WB) and the percentage (strant) of sunny days, as an annual average for the projection periods 2021 – 2050 and 2071 – 2100, calculated using the REMO and WettReg time series, with bias correction

Application of Statistical Procedures / The Confidence Method

In order to be able to better assess how well the data from the models correspond to those from the measurements, **confidence intervals** for the 90% **significance level** were calculated based on the thermal load days ascertained during the 1971 - 2000 period (see Fig. 6). There is a 90% probability that the value for the background load will be found in the area between the two thin cross-lines. The deviations among the three confidence intervals (the results of the measurement and of the models, respectively) are low, which permits the conclusion that the background load from the models reflects the background load observed at the stations fairly well.

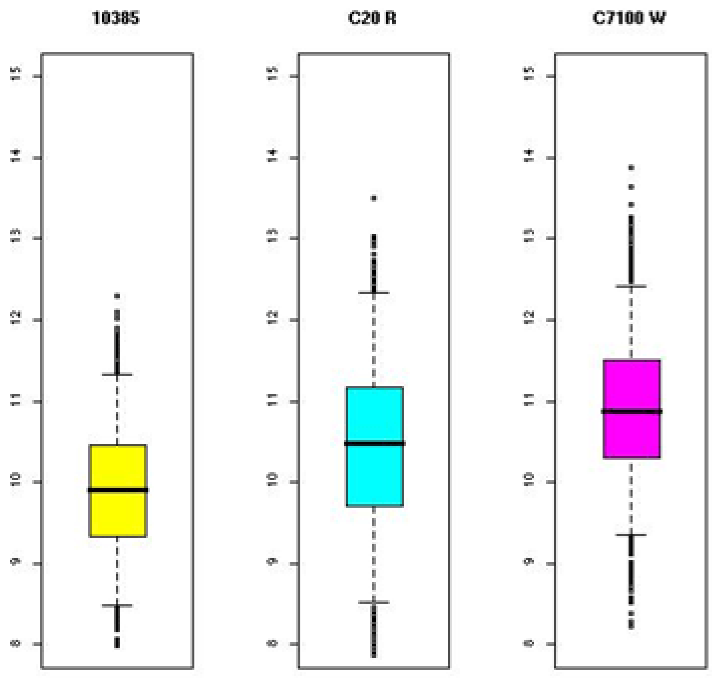


Fig. 6: 90% confidence intervals for the thermal load days during the 1971 – 2000 period (10385: Schönefeld climate station, C20R: control series REMO, C7100W: control series WettReg)

Fig. 7 additionally shows the 90% confidence intervals of the future projection periods. Those of the 2021 - 2050 projection period overlap those of the control period only to an insignificant degree. This permits the assumption of a slight but significant rise in the number of thermal load days by the middle of this century. For 2071 - 2100, the increase in thermal load days is more considerable.

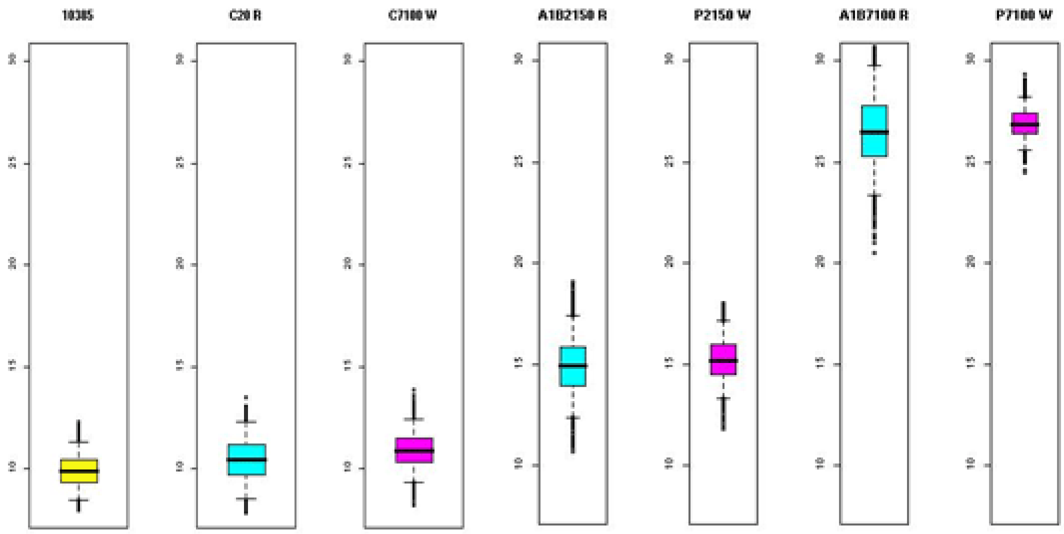


Fig. 7: 90% confidence intervals for thermal load days during the 1971 – 2000 period (10385: Schönefeld climate station, C20R: control series REMO, C7100W: control series WettReg), and in the projection periods 2021 - 2050 (A1B2150R: REMO, P2150W: WettReg) and 2071 - 2100 (A1B7100R: REMO, P7100W: WettReg)

Map Description

The combined bio-climate model was run with the values for background load and sunny day percentages from Tables 7 and 8. Based on an initial status quo of use distribution and factors of influence, such as soil sealing, extent of greening, etc., a **case example** is used to demonstrate how possible land use changes, which are to be expected over such a long observation period, could become a factor of additional impact.

Map 04.12.1 Annual Mean Number of Thermal Load Days for the 1971 - 2000 Period, for Berlin and the Surrounding Area / Map 04.12.4 Total of Thermal Load Days for the 1971 - 2000 Period, for Berlin and the Surrounding Area

Using the real use data of the project area (see Statistical Base), the distribution of the Perceived Temperature as it would typically develop on the afternoon of a low-wind cloudless summer day was first calculated (Fig. 8).

The differences between the various uses and urban structures are clearly apparent. The increase in thermal load towards the densely built-up inner city is notable. The Großer Tiergarten, a central park area, stands out strikingly in the urban centre, however. There, a Perceived Temperature of approx. 5°C lower than in the inner city breaks up the structure of the thermal load. Often, in summer, the adjacent built-up area may already suffer under thermal load, but it is still possible to escape to cooler surroundings here. Other large open areas such as Britzer Garten, Südgelände or Treptower Park also fulfil comparable functions. On the other hand, the open space of the former inner-city airport at Tempelhof shows increased temperature values, due to lacking shade from trees and unhindered sunshine onto the meadow areas during the whole day; moreover, compared with normal parks, the area has a much reduced degree of cooling through evaporation.

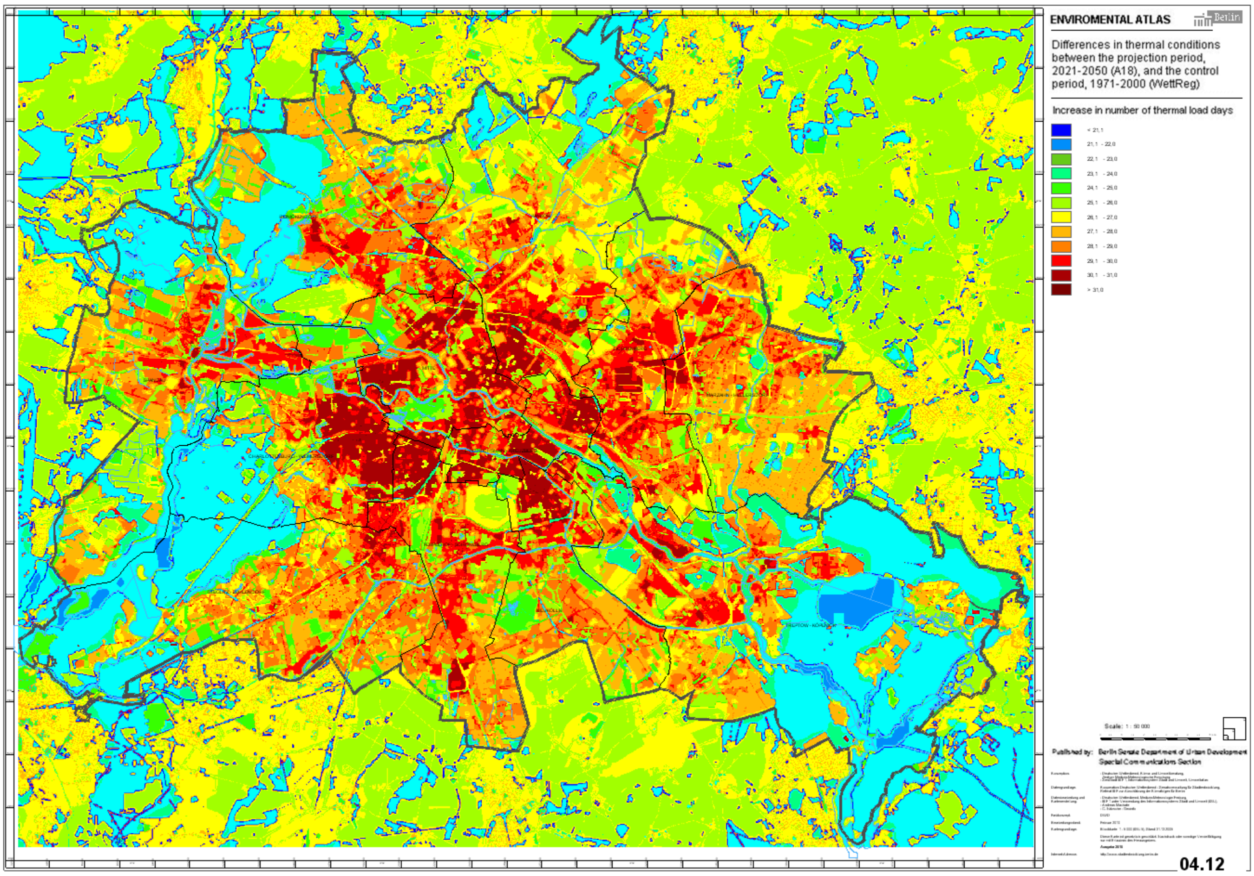


Fig. 8: Perceived Temperature in °C on the afternoon of a low-wind, cloudless summer day in Berlin and the surrounding area

Using the modelling of this typical specific situation as the point of departure, an **assessment of the long-term current situation** for the 30-year period from 1971 – 2000 was carried out by the inclusion of values for the background load with the aid of the combined urban bio-climate model.

It is evident that in comparison with the surrounding countryside, the threshold value for strong thermal load is exceeded considerably more frequently – in fact, approx. twice as often – in the densely built-up inner city. At the same time, in the inner city parks, this threshold is reached hardly more frequently than in the surrounding countryside. This means that in half the cases, the inner city parks still provide tolerable thermal conditions when thermal load prevails in the surrounding built-up areas.

Due to the inclusion of the background load in the assessment, the map provides absolute statements. These can be compared with evaluations arrived at in the same manner, e.g. for other cities, or simply with the background load of any other area.

Map 04.12.2 Increase in the Number of Thermal Load Days 2021 - 2050, in Comparison with the Control Period 1971 - 2000 / Map 04.12.5 Total of Thermal Load Days for the 2021 - 2050 Period, for Berlin and the Surrounding Area

The combined bio-climate model was run on REMO data, using the values for background load and sunny day percentages from Tables 7 and 8. Land use changes were not taken into account.

Figure 9 shows that the thermal load has already been intensifying, particularly in the areas already most frequently subject to thermal load. While in the surrounding countryside, according to both modelruns, thermal load is expected to become about 50% more frequent by the middle of the century, with 3 - 5 more days, more than seven additional thermal load days are expected in the densely built-up inner city. For the purpose of comparison, the model was also run using WettReg data; in this case (see Fig. 9), the difference between the city and the surrounding countryside is even slightly greater, which can mainly be put down to a slightly stronger increase in sunny days. At the same time, the changes in the large non-built-up inner city areas are in both cases roughly the same as those in the surrounding areas.

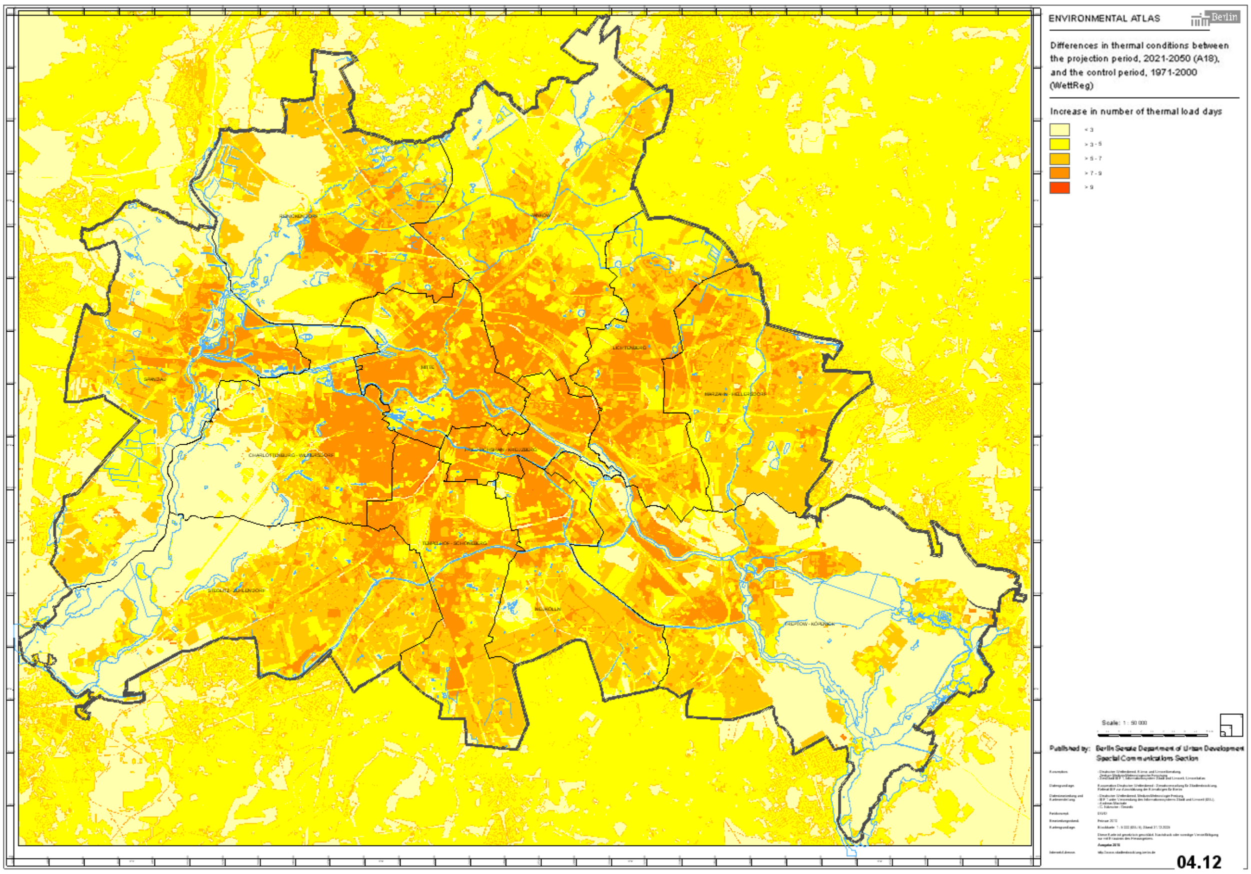


Fig. 9: Change in the number of thermal load days per year for the 2021 - 2050 projection period, compared with the control series, 1971 – 2000, run with WettReg

Map 04.12.3 Increase in the Number of Thermal Load Days, 2071 - 2100, in Comparison with the Control Period 1971 - 2000 / Map 04.12.6 Total of Thermal Load Days for the 2071 - 2100 Period, for Berlin and the Surrounding Area

The projected development of the future thermal picture shows that the number of thermal load days will rise considerably in the second half of the century.

The results of both REMO and WettReg runs (see Fig. 10), reveal that an increase of 25 days and sometimes more in the inner city, or an increase of approx. 150% as compared with the status quo is to be expected. Even for the less built-up areas on the outskirts of the city and in large green spaces, including woodlands, a doubling of load days is projected.

Clearly, the global effect of climate change will have a considerable impact in all urban areas by this time, if not before, unless adequate measures are initiated in a timely manner to reduce these effects.

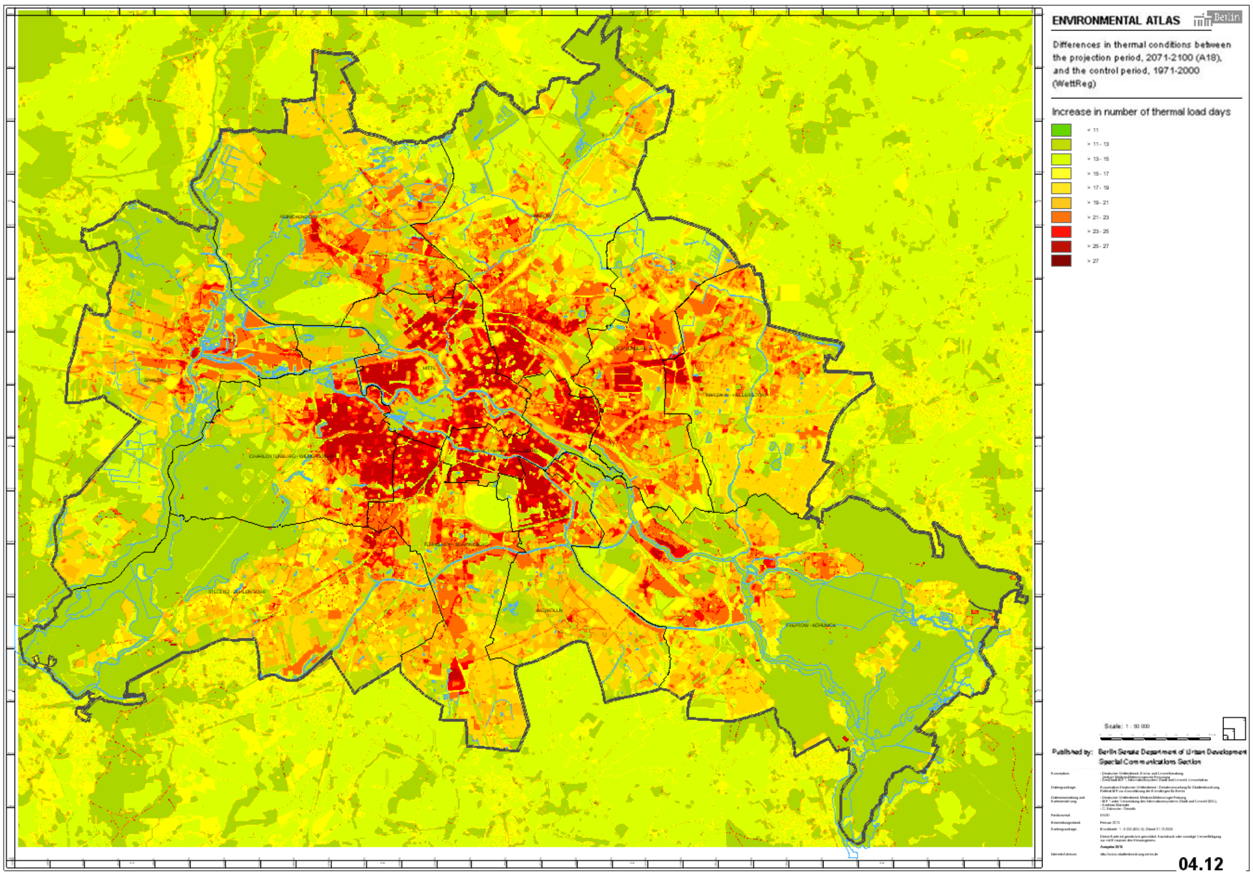


Fig. 10: Change in the number of thermal load days per year for the 2071 – 2100 projection period, compared with the control period 1971 – 2000, run with WettReg

Case Example Result with Simultaneous Use Change

The additional effects of possible land use changes, which are not addressed in the projections presented so far, are illustrated by the example shown in Fig. 11. This is not a "play-through" of a real situation, but rather the demonstration of the additional – but possibly also mitigating – effects of planning measures.

The left part of the figure shows how the effect of the global temperature increase can be counteracted by the transformation of an area hitherto containing buildings into a park. By contrast, the portions of the map shown in various shades of red show a simulation of the effects of possible construction projects of various densities on areas hitherto used as green space or as farmland.

In such areas the threshold of strong thermal load would be exceeded 1.5 times more frequently than today by the middle of the century; such values would otherwise be expected only in the last third of the century.

Fig. 11: Change in the number of thermal load days due to area use changes (buildings) and global climate change per year for the 2021 - 2050 projection period, compared with the control series, 1971 - 2000, based on a REMO data (case example).

Concluding Remarks

As referred to above, interpretation of model outputs is subject to technical limitations imposed by the wide range of possible emission scenarios, the pilot nature of the study and various other factors of influence on the future climate not to be foreseen yet. Nevertheless, the results of this cooperative effort with the DWD provide essential support for the efforts which the responsible authorities in the Berlin Senate are making to develop necessary measures of adjustment to climate impacts that are already inevitable. In addition, they represent an important source of information for the interested public.

Literature

[1] **Deutscher Wetterdienst (DWD) 1996:**
Klimakarten für das Land Berlin [Climate maps for the State of Berlin], Part 1: Report for the Senate Department for Urban Development, Environmental Protection and Technology (unpublished).

[2] **Deutscher Wetterdienst (DWD) 2008:**
Vorschriften und Betriebsunterlagen Nr.8. Metainformationen zum Mess- und Beobachtungsnetz des Deutschen Wetterdienstes. Internal documents of the Deutscher Wetterdienst.

[3] **Deutscher Wetterdienst (DWD) 2010:**
Berlin im Klimawandel – Eine Untersuchung zum Bioklima [Berlin in climate change: an investigation of the bio-climate], final report for the cooperative effort between the Deutscher Wetterdienst and the Senate Department for Urban Development, Section. III, Office of the City and Environment Information System (ISU), Potsdam, Freiburg, unpublished.

[4] **Deutschländer, T., Koßmann, M., Steigerwald, M., Namyslo, J., 2009:**
Verwendung von Klimaprojektionsdaten für die Stadtklimasimulation [Use of climate projection data for urban climate simulation]. Climate Status Report 2008, Deutscher Wetterdienst, Offenbach, pp. 13-17.
Internet:
https://www.dwd.de/DE/leistungen/klimastatusbericht/publikationen/ksb2008_pdf/a2_2008.pdf?__blob=publicationFile&v=1
(Accessed 17 September 2020)

[5] **Fanger, P.O., 1972:**

Thermal Comfort, Analysis and Applications in Environmental Engineering. McGraw-Hill, New York.

[6] **Friedrich, M., Grätz, A., Jendritzky, G., 2001:**
Further development of the Urban Bioclimate Model UBIKLIM, Taking Local Wind Systems into Account. *Meteorol. Z.* Vol. 10, pp. 267-272.

[7] **Gagge, A.P., Fobelets, A.P., Berglund, L.G., 1986:**
A Standard Predictive Index of Human Response to the Thermal Environment. In: *ASHRAE trans*. Vol. 92, pp. 709-731.

[8] **Jacob, D., 2005:**
REMO Climate of the 20th Century run no. 006210, 1950 – 2000 and A1B scenario run no. 006211, 2001 – 2100. UBA Project, 0.088 degree resolution, 1 h data.
Internet: http://cera-www.dkrz.de (Accessed 21 May 2010)

[9] **Jendritzky, G., Menz, G., Schirmer, H., Schmidt-Kessen, W., 1990:**
Methodik zur raumbezogenen Bewertung der thermischen Komponente im Bioklima des Menschen [Methodology for a spatially referenced assessment of the thermal component of the human bio-climate] (extended Klima-Michel Model). *Beitr. Academy Raumforsch. Landespl.* Vol. 114.

[10] **Kreienkamp, F., Enke, W., 2006:**
WettReg 20C control run 1961 – 2000 and WettReg A1B scenario run 2001 – 2100, UBA Project.
Internet: http://cera-www.dkrz.de (Accessed 21 May 2010)

[11] **Roeckner, E., Brokopf, R., Esch, M. et al., 2006:**
Sensitivity of Simulated Climate to Horizontal and Vertical Resolution in the ECHAM5 Atmosphere Model. *J. Climate* Vol. 19, pp. 3771 – 3791.

[12] **Staiger, H., Bucher, K., Jendritzky, G., 1997:**
Gefühlte Temperatur. Die physiologisch gerechte Bewertung von Wärmebelastung und Kältestress beim Aufenthalt im Freien mit der Maßzahl Grad Celsius. [Perceived Temperature. The physiologically appropriate assessment of thermal load and cold stress while out of doors, using degrees centigrade as the measurement standard]. In: *Annalen der Meteorologie* Vol. 33, Offenbach, pp. 100 – 107.

[13] **VDI (Association of German Engineers) 1997:**
Guideline VDI 3787, Sheet 1, Klima- und Lufthygienekarten für Städte und Regionen [Climate and clean air maps for cities and regions], Düsseldorf.
Internet: http://www.vdi.de/ (Accessed 21 May 2010)

[14] **VDI (Association of German Engineers) 2008:**
VDI Guideline 3785, Sheet 1, Methodik und Ergebnisdarstellung von Untersuchungen zum planungsrelevanten Stadtklima [Methodology and presentation of results of investigations of the planning-relevant urban climate], Düsseldorf.
Internet: http://www.vdi.de/ (Accessed 21 May 2010)

[15] **VDI (Association of German Engineers) 2008:**
VDI Guideline 3787, Sheet 2: Umweltmeteorologie – Methoden zur human-biometeorologischen Bewertung von Klima und Lufthygiene für die Stadt- und Regionalplanung [Environmental Meteorology: Methods for the human bio-meteorological assessment of climate and clean air for urban and regional planning], Part I: Climate, Düsseldorf.
Internet: http://www.vdi.de/ (Accessed 21 May 2010)

Analogue Maps

[16] **SenStadtUm (Berlin Senate Department for Urban Development and Environmental Protection) (ed.) 1985:**
Berlin Environmental Atlas, 1985 Edition: Map 04.04 Temperatur- und Feuchteverhältnisse bei mäßig austauscharmen Wetterlagen [Temperature and humidity conditions in weather situations with limited exchange], 1: 50,000, Berlin.

[17] **SenSUT (Berlin Senate Department for Urban Development, Environmental Protection and Technology Berlin) (ed.) 1998:**
Berlin Environmental Atlas 1998 Version, Map 04.09 Bio-climate – Day and Night, 1:75,000, Berlin.

Digital Maps

[18] **SenStadt (Berlin Senate Department for Urban Development) (ed.) 2008:**
Berlin Environmental Atlas, updated and expanded edition, 2008, Map 06.07 Urban Structure, 1:50,000, Berlin.
Internet: http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/eic607.htm
(Accessed 13 July 2010)

[19] **SenStadt (Berlin Senate Department for Urban Development,) (ed.) 2009:**
Berlin Environmental Atlas 2009 Edition, Map 04.10 Climate Model Berlin - Analysis Maps, 1:50,000, Berlin.
Internet: http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/eda410_01.htm#top
(Accessed 13 July 2010)

[20] **SenStadt (Berlin Senate Department for Urban Development,) (ed.) 2009:**
Berlin Environmental Atlas 2009 Edition, Map 04.11 Climate Model Berlin – Evaluation Maps, 1:50,000, Berlin.
Internet: http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/eda411_01.htm#top
(Accessed 13 July 2010)