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Urban heat island and bioclimate studies in Freiburg, Germany

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ABSTRACT

The city of Freiburg has a long tradition in urban climate issues because of the specific perception of the population on climate by the local wind system developed by the complex surrounding topography. The first comprehensive climate analysis were performed in the beginning of the seventies of the 20th century, where car traverses have been implemented in the analysis and the beginning of the development of climate function maps. In the following decades only specific modifications the area of the city have been analyzed like the development of new residential areas or the increase of the site of the football stadium or the new railway station. In the beginning of the 21st century the Freiburg city council begun to update the city's master plan and to adjust it for the year 2020. Local climate and air pollution were considered in this scheme through the application of a spatial urban climate analysis of the entire area. The analysis has built the basis for future analyses of individual areas in the context of building applications in the meantime. After 2015 the city of Freiburg decided to implement the issue of climate change for a vulnerability analysis.

Introduction

Freiburg belongs to one of the warmest cities in Germany because of its geographical location in the upper Rhine valley (Nübler 1979). More than 30 days with heat stress can be detected each year (REKLIP 1995). During extreme summers like the one in 2003, the number of days with heat stress is much higher. Air pollutants are dominantly produced by car traffic due to the absence of industrial emissions (UMEG 2003). Freiburg is located at the foothills or plains of the Black Forest, specifically at the exit of the Dreisam valley. In general, during cloudless and less windy weather conditions, a mountain breeze is formed. During the daylight hours, air masses move in the direction of the Black Forest and an air mass exchange is produced. During the night time hours, cold airflows from the slopes of the valleys are formed, and the induced cold air flows to the city of Freiburg from the east, affecting the climate conditions there. This local wind system called "Höllentäler" is very well known and is accompanied with the ventilation of parts of the city of Freiburg (Parlow 1983; Nübler 1979). The cold airflows depend on the synoptic conditions with a diverse intensity and range. In the Dreisam valley the local wind system occurs during 65% of the night hours per year (Parlow 1983).

Therefore, Freiburg has a specific role because of its location in the south of Germany and its complex topography. It combines many relevant aspects of climate and the effects of urbanization and topographical effects, not only due to the Black Forest, but also due to its location in the upper Rhine valley.

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Nevertheless, since the 1960s, several studies concerning local climates and urban effects in the city have been conducted in the vicinity of Freiburg. In the 70s, a whole approach for the quantification of the urban climate in Freiburg was conducted and was the basis for the authorities and decision makers of the city. This was followed by specific urban climate studies and had effects on diverse projects, i.e. new building areas or the modification of sport facilities were only limited in terms of single effects concerning wind conditions. At the start of the 21st century, the municipality realised the importance (not only because of climate change issues) of urban climate and demanded a new integral climate analysis for Freiburg (Röckle et al. 2003; Matzarakis et al. 2008; Matzarakis 2013).

Method

In order to obtain and quantify the distribution of the climatological and air pollution conditions, several approaches based on measurements and modelling have been performed and applied (VDI, 1988; Helbig, Baumüller, and Kerschgens 1999). Several factors, e.g. air temperature, wind, human bioclimate, and air pollutants have been aggregated and summarised into maps (Röckle et al. 2003; Matzarakis et al. 2008).

In detail, the following methods and results have been applied:

- Measurements
  - Thermal imaging by airplanes
  - Thermal mapping (day and night)
  - Screen level measurement campaigns
  - Tracer gas experiments
- Modelling
  - Cold air drainage flow simulation
  - Ventilation analysis
  - Analysis of thermal bioclimate
  - Analysis of air pollution situation
  - Affect analysis
- Maps
  - Climate function map
  - Planning advices map.

The aforementioned methods and data were the basis for the development of an integral analysis of the urban climate conditions of Freiburg. The aim of the study was that the produced results were based on the latest scientific methods and findings and are applicable in the urban planning process in Freiburg.

Measurements and Results

In this chapter the most relevant information for the production of the final maps are described. First, an inventory of existing data was performed and all data was considered for the study. In addition, required data was obtained through measurements and models. This chapter is divided into measured and modelled data.

Thermal Imaging

Thermal imaging to acquire spatial information about the thermal situation of a surface at a very high resolution has been applied. In order to detect day and night dynamics, two flights for the period with the highest heating of the surface (8^{th} July 2002, afternoon) and highest surface cooling (9^{th} July 2002, before sunrise) during high pressure weather conditions were carried out. The delivered result is not the surface temperature but the radiation received by the detector of the airplane. Despite lower radiation temperatures during the night (an average of about 17°C in contrast to the daytime of 26°C), the urbanised areas are significantly warmer than the surrounding areas; the inner city area is significantly dominated by warmer conditions in the nocturnal thermal image. Streets and buildings are heated from the short wave radiation during the day and release their heat as long wave radiation to the air during the night.

Screen Level Measurement Campaign

In addition to the thermal images measurements on the 8^{th} and 9^{th} of July 2002, a 24-hour screen level measurement campaign was carried out. Its aim was to record the meteorological variables: wind direction, wind speed, air temperature, and air humidity. These were the basic measurements required in order to have basic variables for estimating the thermal bio-climate of the whole area of Freiburg. The analysis of measured data shows the locations and times at which the highest air temperatures are observed in the investigation area. During times of maximum air temperature e.g. at the main center of Freiburg, the air temperature is about 2.5°C warmer than in green areas in the west of Freiburg. By contrast, during the times of minimum of air temperature the difference is about 5.5°C, showing that the highest intensity of the urban heat island takes place during the night.

Tracer Gas Experiments

Using tracer gas (SF6) experiments at six specific locations, the dispersion of gas in the evening and night hours was detected. The dispersion experiments show both the course of the cold air drainage flow and the degree of influence at these specific sites. The results of the tracer gas experiments are in accordance with the cold air flow simulations by modelling.

Modelling and Results

Cold Air Drainage Flow Simulations

For the cold air drainage flow for the whole area during the nocturnal flow, a numerical simulation model (Röckle 1992) for a typical weather situation with less wind and radiation was conducted and a 50m spatial resolution was applied. During the night, the area of Freiburg is dominated by a local wind system called “Höllentäler”. Such an effect is present not only in the eastern parts of Freiburg, which are affected by the Black Forest, but also in the northern parts. The local wind system is evident outside of the small valleys of the Black Forest for some hours after sunset. In the early evening hours, the local cold air flows coming from several small- and medium-sized valleys dominate the wind flow conditions. They fit the huge east-west flow and are affected strongly by this flow.

Ventilation Analysis

A ventilation analysis was performed with a numerical wind flow model (Röckle and Richter 1998). The basis for the analysis was the information on the buildings of the city of Freiburg, allowing for a high spatial resolution of 5m; the 5m resolution was aggregated to 20m for a more appropriate overview. The analysis shows the areas in which the wind fields near the surface are modified the most. The analyses were performed for the main wind directions and allow the detection of ventilation paths, i.e. railway tracks or river areas. The inner part of the city is less ventilated because of the relatively tall and compact buildings. Similar conditions can be also found in other dense areas such as trade districts (Röckle et al. 2003).

Analysis of Thermal Bioclimate

In applied climatology and biometeorology, thermal comfort is described by using thermal indices, which include the combination of air temperature and/or air humidity or wind speed. Thermal perception and thermal comfort can not only be expressed by air temperature, but also by the influence of radiation conditions (depending on the diurnal and annual variation of solar radiation, shade of buildings and vegetation, infrared radiation of buildings, etc.), wind speed, and also air humidity (VDI 1998; Matzarakis 2001). Urban climate is usually characterised by a modified climate and expressed by the urban heat island, which can also be expressed in an urban bioclimate island for humans. This leads to pronounced additional heat stress, which usually occurs during the afternoon hours. In contrast, during the night, the thermal bioclimatic conditions are lower in rural areas due to the course of air temperature and the absence of solar radiation (Fig. 1). For the evaluation of the thermal component of urban climate, this can be also expressed as thermal bioclimate indices, based on the energy exchange of the human body; the Physiologically Equivalent Temperature (PET) is used (Höppe 1999; Matzarakis et al. 1999; 2007). The calculations are based on different land use information (representing the building mass and other urban characteristics), elevation, measurements from campaigns, and thermal imaging data. A summer day was selected for the construction of maps and the background data used; the PET was calculated for 1500 CET by using the radiation and bioclimate model RayMan (Matzarakis, Rutz, and Mayer 2007; 2010).

The highest PET values are found in locations with increased sealing factors and lower green percentages. The suburban parts of the rural areas are exposed to heat stress, which can be explained by the low buildings that are not able to produce shadows like the taller buildings in the inner parts of the city. In the higher areas of the Black Forest, there is no heat stress. During the nighttime hours especially at 0300 CET, PET values range between 6 and 11°C, meaning that people are affected by a slight cold stress during that time.

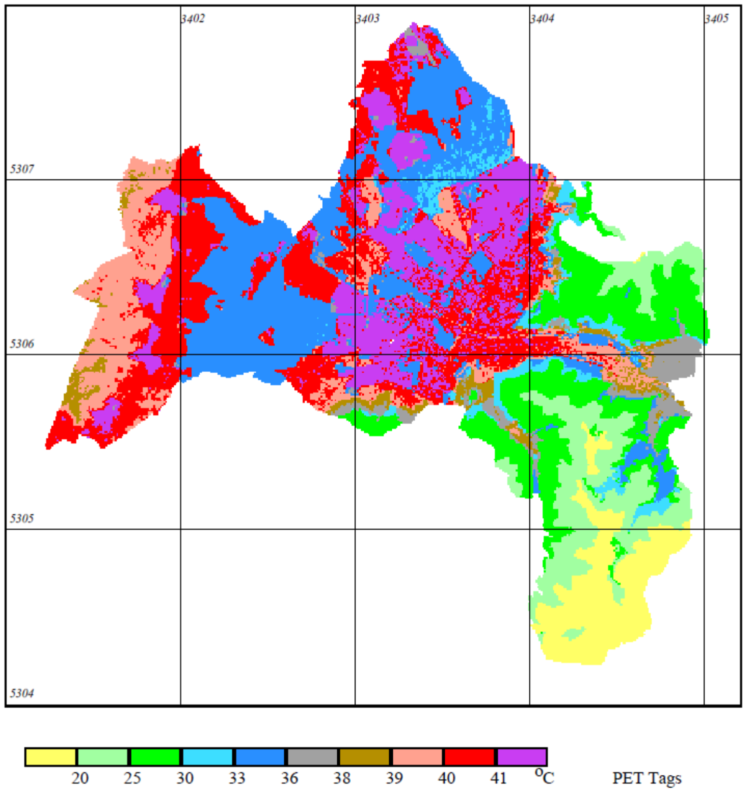

Figure 3. Map of PET. Source: Matzarakis et al. 2015

Analysis of the Air Pollution Situation

The air pollution situation in Freiburg, due to the absence of large emission sources, is primarily dominated by car traffic (Matzarakis, Röckle, and Mayer 2015). Estimations for NO_2, Benzene, and particulate matter (PM10) were performed for this source group. For the consideration of the complex topography of the area, five different meteorological dispersion classes were calculated (Richter and Röckle 1995). The estimated time horizon was fixed to the year 2005. It is assumed that emissions will be reduced by 2020 because of the specific reductions of air pollutants by cars. The highest estimated concentrations occur, as expected, along the highway (Autobahn A5), at the crossing points of the highway, and in the portal of the traffic tunnels in the eastern part of Freiburg. The limit values for NO_2 can sometimes be exceeded. Based on the estimated values of Benzene, NO_2, and PM10, an air pollution index for the human-biometeorological quantification was applied (Mayer et al. 2002). Most of the areas of Freiburg are less loaded by air pollutants, apart from the streets and their affected areas. During winterly inversions, air polluted situations are more pronounced, in contrast to the heat stress conditions in summer, as air exchange is limited.

Results and hints for urban planning

Affect Analysis

For the assessment of thermal stress or air pollution situation, the intensity as well as the number of people who are affected by these conditions is of importance. For this reason, two maps of affect analysis for day and night were made. During the day, the inner part of the city is characterized by strong heat stress. During the night, the areas in the west of Freiburg with a high density of buildings are related to thermal load. The most urbanized areas are usually found in the "moderate" and "strong" class of heat stress during the day and night. The thermal classes "low" and "very low" are less frequently found in the urban area. In general, Freiburg shows 'high problem areas', which are a result of thermal stress. Based on that, the importance of green- and free areas has to be considered and assessed. In the inner city, most of the areas are characterized by 'high problem areas', especially during the summer. Aside from the daytime situation, the night-time situation is also of importance because of the absence of cooling effects for regeneration from the climatic point of view (cooling of building mass and transportation of polluted air and warm air masses). In this context the ventilation possibilities and especially the cold airflow with less polluted air should not be reduced (Röckle et al. 2003).

Urban Planning Maps

A climate function map as well as a planning advices map was produced based on the information derived above and the knowledge from previous investigations (e.g. Nübler 1979; Rudloff 1993; Friedrich 2000). The spatial dimension of climate information is a possibility for the quantification of the recent and future effects of the structure plan concerning the local climate and air pollution situation in a city.

Planning Oriented Maps

Climate Function Map

Climate function maps are focused on the spatial and detailed distribution of the present thermal and air pollution conditions (Matzarakis, Röckle, and Mayer 2015). Focus is also placed on the autochthonous weather conditions, i.e. weather situations with high solar radiation and less wind exchange. With the consideration of air paths or ventilation paths based on the long term wind conditions of the area, a more realistic mean condition approach is reached. Finally, a climate function map is based on a general assessment of several existing climate factors (i.e. slope aspect of topography, land use, etc.), measured climate information (i.e. air temperature, wind, radiation properties of the surfaces, air quality), and results from modelling approaches (ventilation, cold air drainage flow, bioclimate). In the climate function map only atmospheric processes are included, which occur at the screen level considered, so the interactions between different climate relevant areas (climatopes) are not sharply separated (VDI 1997), i.e. the areas have to be seen as transitions areas. In addition, the signatures or legends used have a symbolic character without including exact and quantitative information about, for instance, the range or intensity of flows. The climatopes included in the climate function and planning advices maps are based on the VDI-guideline 3787, Part 1: Environmental meteorology: Climate and air pollution maps for cities and regions (VDI 1997).

Planning Advices Map

The aforementioned and -explained climatic properties and characteristics are part of the climate function maps. Based on the climate function maps, which are somewhat static, and under the consideration of existing air pollution data (measured and modelled) and the affect analysis maps, a detailed planning advices maps has been constructed (Figure 2). In contrast to the climate function map, where the information is not assessed by specific spaces or areas, information is indicated with a specific value: free spaces based on their climatic/air pollution function and urban structures concerning their sensibility in relation to higher urban density. The urban air paths are separated into polluted and non-polluted quantities (Mayer et al. 1994). Air polluted areas are expressed based on their traffic load. The extracted information is prepared with emphasis on planning advices for the level of city planning.

The most relevant and important findings in the planning advices map are summarised as follows: Urban areas are classified into areas of low, medium, and high sensibility in relation to urban development or extension based on the affect value (for the thermal and air pollution situation) and their importance to the surrounding areas. For Freiburg, the free spaces in west to east and north to south directions are conspicuous. Mostly located in the east and south of Freiburg are areas with very high climatic and air quality compensation potential. This means, that from those areas cooler or less polluted air is transported to areas with higher thermal load or higher air-pollution (Matzarakis, Röckle, and Mayer 2015). This is an effect of the local wind system formed by the topographical properties of the nearby valley in the Black Forest. This local wind classified as a cool mountain breeze is of importance during specific weather situations and is responsible for the ventilation of the city area, therefore, the source area (forest areas in the southeast and east of Freiburg) of the wind systems is classified as a high priority area. Areas near the river and the small valleys in the eastern and south-eastern part are also classified with the highest climatic priority. Free spaces on the slopes in the south are also of specific climatic relevance, as is the airport area in the north-east and the forest areas in the west of Freiburg. Inner city areas like cemeteries and other green areas have a high climatic potential and are classified by the highest category of positive effects. Free spaces with low and moderate building densities are classified as having improved climatic and air pollution compensation functions. Moderate compensation function concerning climate have less residential buildings density or moderate trade/industrial areas during weather situations with heat stress. Spaces with no particular cold air production and areas with no residential relation are classified in the category of low climatic-air pollution compensation function, but this category does not exist in Freiburg.

Aside from the assessment of free and residential areas, the planning advices maps also include several elements of the air exchange. The effect of mountain breezes from two different directions during the night and day including the cold air drainage flow of the mountain breeze play an important role in the regional and local significance of the wind conditions in the urban climate conditions of the city of Freiburg. They are an important issue in the planning advices map and are indicated and quantified by polluted and unpolluted urban air paths. Urban air paths are areas with less roughness, sufficient length and width, and preferably straight courses contributing to the ventilation of urban areas (Mayer, Beckröge, and Matzarakis 1994). Regional urban air paths are of importance because of the transport of unpolluted air masses from rural environments to city areas. Local urban air paths contribute to the air exchange in urban areas. The efficiency of urban air paths is dependent on the dominant wind direction of a region and/or area.

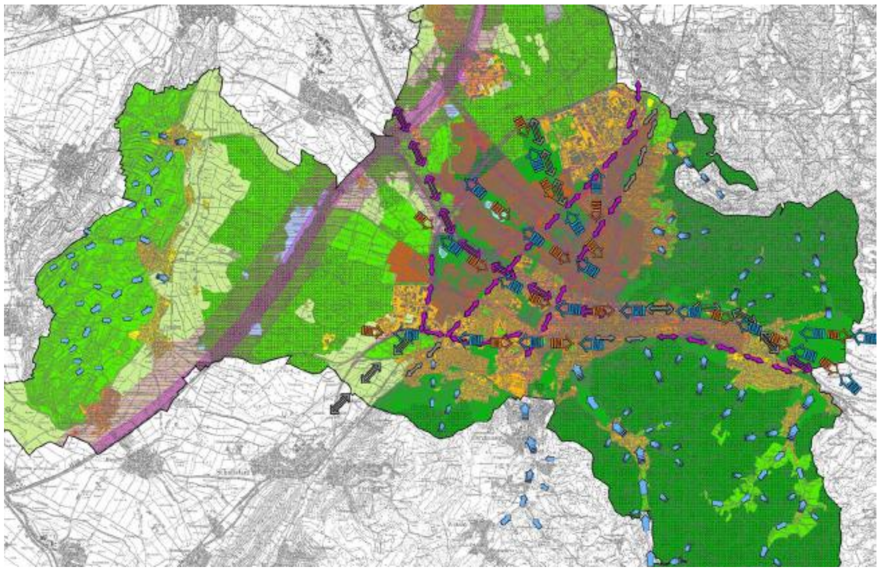

Figure 2. Planning advices map. Source: Röckle etal. 2003; Matzarakis, Röckle, and Mayer 2015.

Discussion and conclusion

The general and specific aim of assessing areas for future or planned urban development was quantified by an ecological risk analysis. The impact of an area modified by a microclimate is dependent on:

a) Intensity, range, and direction of the effect,
b) Sensitivity and value (significance) of the area in contrast to a specific effect of the modification planned.

For the quantification, the frequency of use by humans (estimated from the land use), the human biometeorological thermal stress (here quantified by PET), and the air pollution situation have been considered. It is a fact that after building up an area, the physical properties of that area are modified and changed (i.e. heat balance, ventilation, air pollution, and so on). The range of effects on surrounding areas depends on the transport of these properties by synoptic, regional, local wind conditions. Concerning human thermal bioclimate, a separation between diurnal and nocturnal conditions has to be performed because of different air exchange conditions during hot days and especially in areas (such as cities) embedded in complex topographies, where local wind systems can be developed. All of the modified conditions have to be estimated based on the microclimatic effects (including bioclimate and air pollution) and the sensitivity of the area of interest.

The final climatic consequences for planners can be summarised as follows (Matzarakis et al. 2008):

1. Maintenance of urban climate relevant air paths (for fresh- and cold air) transport,
2. Micro-scale climate manipulations to avoid diurnal heating of buildings. Possibilities include planting trees with broad leaves (spending shade), or the surface management of materials with a high reflectance of short wave radiation (albedo management).

Furthermore, for an improved outdoor quality of life, high climate diversity is of an advantage, preferably in short spatial and temporal accessibility. This can be performed by considering affect factors and analysis. It has to be noted that it is less meaningful to analyse and assess separate and single urban structures. A master analysis under consideration of climatic factors and conditions should be included in any master plan analysis.

The analysis of the specific climate of urban structures and cities should not be an alibi, but the possibility of solid appreciation of values for decision makers should be assessed and known. This is especially valid for cities, which are under expansion pressure and are increasing in the density of their urban structures. The climatic properties in cities are going to be more important not only because of climate change discussion but also as a factor of quality of life. Finally, urban structures and cities in general can use urban climate modifications and manipulations as a possibility for mitigation and adaptation strategies facing climate change (Matzarakis 2013).

The update of the described analysis and approach is under investigation. For this specific issue the Municipality of Freiburg run at the moment two additional analysis a) urban climate analysis including climate change factors in a similar spatial resolution and also identifying recent and future hot spots b) vulnerability analysis for the identification and development of adaptation strategies.

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