

04.10 Climate Model Berlin - Analysis Maps (Edition 2009)

Overview

Due to their close substantive interrelationship, there are common explanatory texts for the Maps 04.10.01 through 04.10.12 in the chapters Overview, Data Base and Methodology. In the chapter Map Description, a breakdown by map is provided as follows, with individual **evaluations** for:

- Near-ground temperatures (10 PM)
- Near-ground temperatures (6 AM)
- Air exchange and air-mass currents (10 PM and 6 AM) in the entire area;

The results obtained in the context of the previous climate investigations for the Berlin Environmental Atlas, as documented in Maps 04.02 through 04.07 and 04.09 (SenStadt 2001a-e and SenSUT 1998), have essentially been based methodologically on the execution of a stationary and mobile measurements, as well as the interpretation of basic information, such as regional planning or sealing data. These methods have, however permitted the investigation and delimitation of local and regional wind- circulation systems, which are of unquestioned fundamental significance for the urban climate of a metropolitan area, especially in a largely flat region.

A modern climatic analysis designed for practice must particularly encompass the process system of air-exchange flows, and attempt to make a connection between these processes and the structuring of the area under investigation into spaces which are favorable and unfavorable, respectively, in terms of urban climate and air-quality. These two terms describe, from a climatic viewpoint, the structure of an area into compensation spaces, affected spaces and connecting structures (air-stream channels), and an understanding of such an area as a construct consisting of compensation and stress areas. "A **compensation space** is thus an undeveloped space characterized by vegetation, which by generating cool and fresh air, can reduce or eliminate air-quality or bio-climatic burdens in an affected space via functional exchange interaction. An **impact area** is a space which is burdened, built-up or planned for construction, and which is connected to an adjacent compensation space via air exchange processes, or to a non-adjacent compensation space via an **ventilation lane**" (cf. Mosimann, Frey, Trute and Wickenkamp 1999). This procedure thus breaks fundamentally with the previously common static view based on urban climate zones, which subdivided the area of investigation into spatial units in which the micro-climatically most important factors were relatively homogeneous and the effects hardly differed (cf. VDI 1997).

Accordingly, a uniform digital climatic model designed to make the investigation of these aspects possible in a high spatial resolution has been applied for the first time 2003/2004 (SenStadt 2003 und SenStadt 2004b) in the context of a project for the entire urban area of Berlin. A central component of this procedure is the FITNAH procedural package (cf. Methodology chapter). This approach incorporates the following important advantages:

- The comparability of results in the overall area is ensured.
- In addition to the qualitative statements designed to characterize particular urban climatic phenomena, quantitative statements concerning climate-ecological conditions and exchange processes are also possible.
- Climate-ecological compensation and process spaces are localized in the urban area and represented in their spatial dimensions as precisely as possible.
- An important aspect of the climate-ecological compensation potential of open areas - the cold-air balance - has been investigated on a comprehensive city-wide basis for the first time in Berlin.
- FITNAH provides also the extensive calculation of the dispersion of air pollutants within the assumed meteorological conditions.

This investigation, too, supports the repeatedly confirmed connection between the climate of various urban areas and their structure in terms of buildings, open areas and vegetation. However, the typical local climate is not only generated by the structure of an urban area but also by its situation within the

city. Hence, different areas of a city can interact mutually, or with the surrounding countryside. The temperature differences between neighboring areas are of decisive importance for the climatic exchange. A reduction of these differences, e.g. due to an increase in the structural density, or the uniformization of structures, will cause the urban climate to deteriorate. More detailed information on these topics, and on the effects of overall weather situation on the local climate are found in the explanatory text for Map 04.07 Climate Functions (SenStadt 2001e).

The purpose of the present updated Maps 04.10.01 - 04.10.12 is to present the results of the application of the regional simulation model FITNAH. In order to achieve comparability with the climate parameters already published in the Digital Environmental Atlas, the distribution of air temperature during two time segments is also presented, although a direct comparison of the map representations based on measurements and analogical conclusions with the results of simulations of model applications requires that the differing frameworks be taken into account. This advice has also be considered when **comparing the results of the both FITNAH model applications** of the 2003/2004 edition and 2009. As on the one hand scope and level of detail of the input data, and, on the other hand, model enhancements may result in differing findings and classifications.

Moreover, the representations of the spatial delimitation and quantification of the autochthonous air exchange processes are of special significance. The term "autochthonous" describes climatic events which occur locally or independently (that is without outside effects, e.g. extensive wind flows; the opposite is "allochthonous"). They are based in the climatic effectiveness of the particular utilization structures in their respective environments, and thus provide a sound basis for the derivation of concrete planning recommendations.

Statistical Base

The application of numerical simulation models requires acquisition of basic data and of meteorological ancillary conditions in a territory extending beyond the actual investigation area. This is designed to assure that the model can "swing itself into place", so as to be able to simulate conditions as realistically as possible at the margins of the actual project area (for the methodology of the FITNAH climate model used here, cf. (Methodology)). Hence, the investigation area consists of two major components: the approx. 890 km² area of the city of Berlin, and an approx. 900 km² area in the suburbs (cf. Fig. 1).

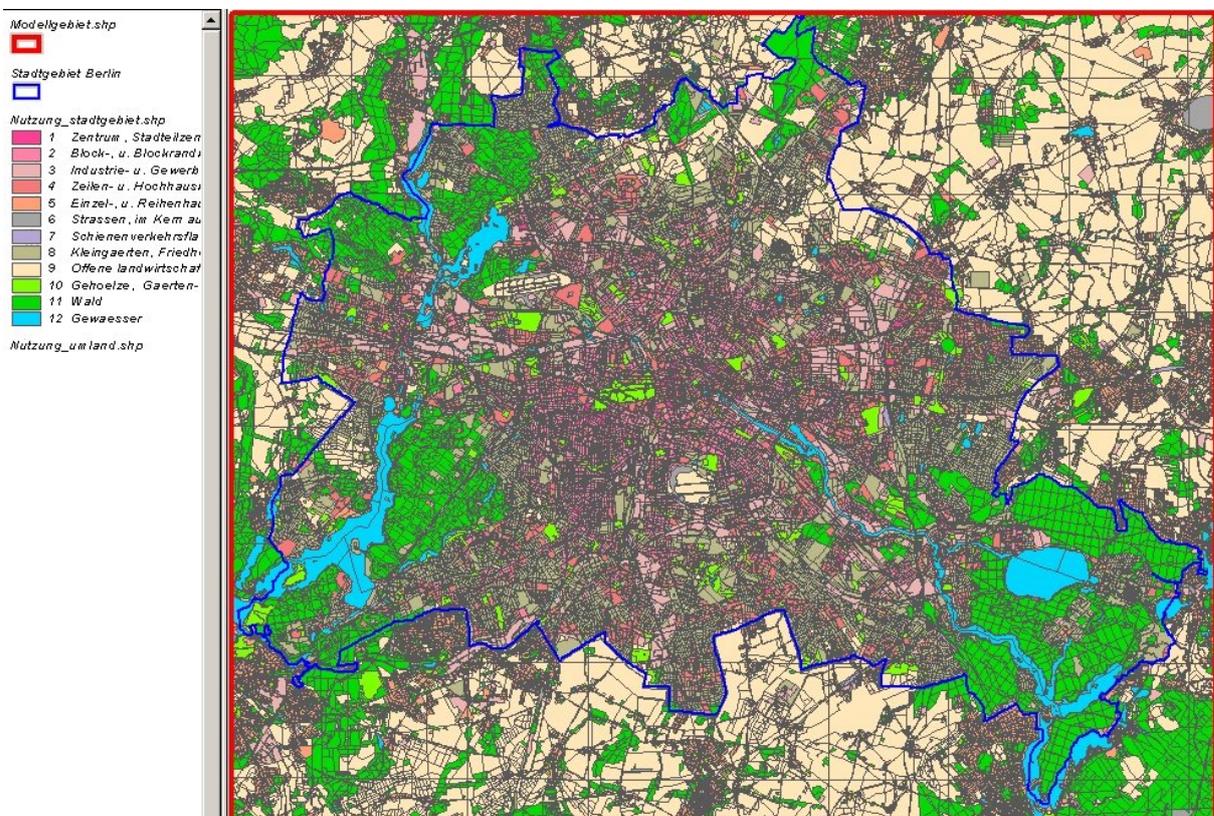


Fig. 1: Classification of the land use for the model application. A key with 12 use classes is used, adjusted to the requirements of the FITNAH model.

Only a few of the parameters used for the **Berlin urban area** were obtained especially for this project; for the most part, data bases developed over the years of work on the Environmental Atlas and for the Berlin ISU which are available for various evaluations and calculations. The [Urban and Environmental Information System \(ISU\)](#) of the Senate Department of Urban Development contains approx. 25,000 individual areas in a spatial reference system, which has been made available for the calculation of the climatic quanta in the ISU:

- Land use. The data on **land use** show the status of year-end 2005 and are based on the evaluation of aerial photography, borough land use maps and additional documents for the Environmental Atlas (cf. Map 06.01 and Map 06.02, SenStadt 2008a). Some 30 types of use are distinguished.
- Urban structural types (Map 06.07, SenStadt 2008b). A further improvement of this data was carried out via a factual database, which contains type-specific details on the heights of buildings and vegetal structures within the individual urban structural types.
- Sealing (Map 01.02, SenStadt 2007).
- A digital terrain elevation model (DGM5) was available for the downtown area and partially for the north and southeast of the city. For the remaining area, a DGM25 has been at hand.

From the preliminary work for the conversion of the European Union guideline to the ambient noise, a building file with elevation data (date 2005) has been used which contains all 550,000 buildings of the Automated Property Map (ALK) of the federal state of Berlin as well as 231,445 buildings of the federal state of Brandenburg within a distance of 3 km around Berlin.

The ALK, as the illustrative section of the so-called Property Register, shows not only the lots, but also the buildings in their precise size, including numbers of storeys, and is therefore well suited as an information base for the illustration of building structures (cf. Fig. 2).

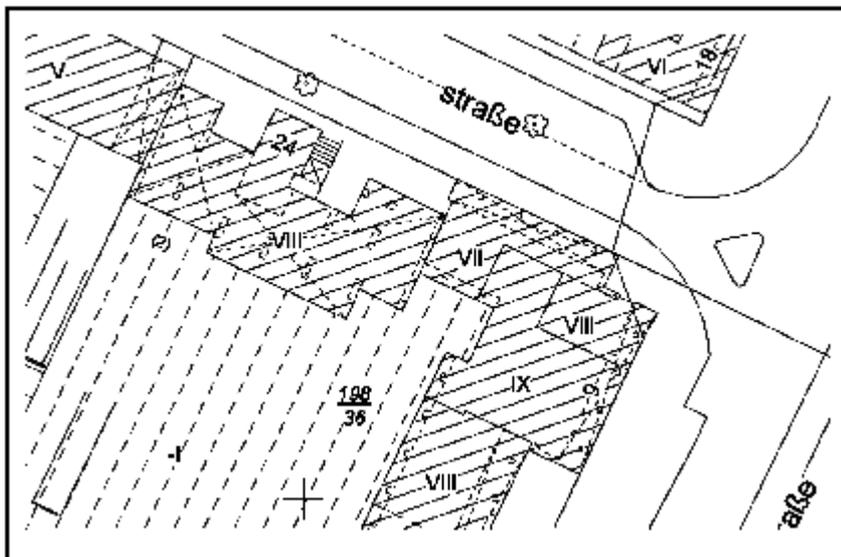


Fig. 2: Detail from the Automated Property Map (indication of numbers of storeys in Roman numerals).

With regard to the first application of the climate model 2003/2004, in this edition also air quality aspects have been taken into account with an extensive analysis. For that purpose, data of the **traffic emission register 2005** of the Department of Health, Environment and consumer protection has been used (cf. SenGesUmV 2008).

The followings data bases were of use for the incorporation of the areas **outside of Berlin**:

- [ATKIS](#) (Official Cartographic Information System). The map collection encompasses the first implementation step of the basic landscape model DLM 25/1. The basic data stock contains various types of object and attributes. The streets, paths, railroads, bodies of water and boundaries form a geometrically exact line structure of the landscape. It is filled out by the two-dimensional landscape elements, such as residential areas, etc.
- The terrain altitudes were taken from the data stock of the [CORINE](#) Project. Corine stands for “Coordinated Recording of Information on the Environment,” and is a program established in 1985 by the Commission of the European Union to record environmental data.

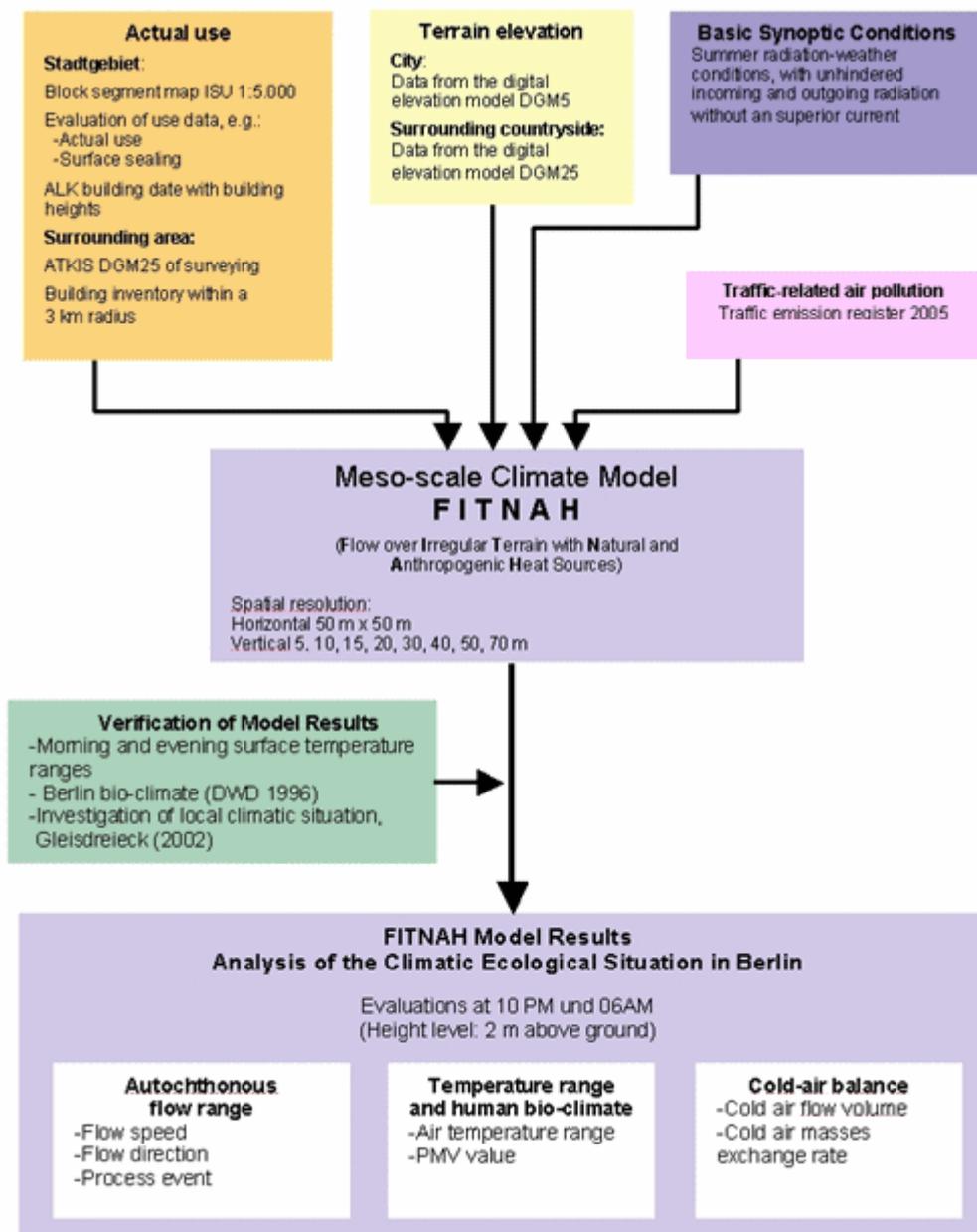


Fig. 3: Database and data flow for the application of the climate model FITNAH

Methodology

One important factor in the creation and formation of an urban climate are the soil and surface characteristics, which have been changed in the urban area in relation to the surrounding countryside. The result is urban overheating and also the local urban wind circulation. Wind and temperature as well as quanta derived from them are the dominant factors affecting the assessment of urban climate from the aspects of human bio-meteorology and air quality.

The **investigation and recording of the urban climate** can be carried out with the help of various methods. These include field measurements, long-range ascertainment methods, wind tunnel studies, and the application of numerical simulation models.

Direct numerical simulation models are particularly well capable of representing the meteorological quanta, which are spatially and temporally very strongly variable, due to the great complexity of the building structure.

The detailed calculation of the wind and temperature conditions in the Berlin area within the scope of this actualization has been carried out using the **FITNAH (Flow over Irregular Terrain with Natural and Anthropogenic Heat Sources)** model. Groß 1993 and Richter & Röckle o.J. present detailed mathematical and physical descriptions of the model. Further detailed indications for the basic

structure and approach of the three-dimensional FITNAH model, and for the interpretation of the model results, can be seen herein, on the basis of an exemplary comparison with measurement data, under Methodology/Supplementary Notes.

Generally, numerical simulation models are accepted for use in many fields of meteorology, since the data obtained provide important basic information for many areas of life (cf. Overview of the Most Important Models). The weather forecast for the next 1-5 days is obtained almost exclusively by means of such complex and extensive computer models. Knowledge of possible changes of our global climate over the next decades can also be derived from such calculations. And finally, models of a similar type are used to calculate the local and the regional distributions of meteorological variables in the atmosphere (Groß 2002).

Solely by the use of models the immission characteristics of air pollutants in the atmosphere can be simulated. On basis of the FITNAH calculation results it was possible to simulate a realistic dispersion of the relevant gas nitrogen dioxide. In doing so, the flow- und turbulence fields, which have been calculated with the 3D-model FITNAH, were used. The results of the calculated NO₂-concentration within green spaces are shown in the evaluation map 04.11 and explained in the accompanying text.

The above-mentioned computer models for the various scales and task definitions, and also the FITNAH model used here, are all based on the same mathematical-physical system of equations. Only in detail are there scale-specific differences.

Meteorological Framework Conditions for the Model Calculation

In addition to the internal model definitions, the meteorological ancillary conditions play a major role. During high-pressure weather situations, the local climatically relevant particularities of a landscape are particularly noticeable. Such a weather situation is indicated by a cloudless sky and an only very light superimposed synoptic wind. The extensive synoptic framework conditions were fixed correspondingly for the numerical simulations carried out here.

Notes on Interpretation of the Model Results

In the horizontal dimension, FITNAH is based on a uniform grid, and in the vertical dimension on a stretched grid. By means of a proportionate assignment of the initial parameters, such as land use, terrain altitude, etc. to this grid, only a representative value can be calculated for every grid volume, which represents a weighted mean average value of all data obtained (cf. Methodology / Supplementary Notes).

Verification of the Results of the FITNAH Climate Model

The information derived from the model runs was checked by means of data from a study of local climatic functions of open spaces in the Gleisdreieck area of Schöneberg. On the basis of an extensive comparison, the measurement results of the study were compared with the simulation results of the model application.

As a result of this comparison, a **good level of agreement** can be established between the results of the measurement project and the modeling of the local air-current field in the Gleisdreieck area using FITNAH.

The self-generated, local current phenomena postulated by the model calculations can largely be confirmed by the measurements. Details on flow direction and speed are within the same range. The relevant air exchange processes – small-scale, orographically caused cold-air outflow from the Viktoriapark area of Kreuzberg and thermally induced compensation currents between the open areas of the Gleisdreieck and the adjacent buildings – are recorded and represented equally, both qualitatively and quantitatively (cf. Vogt 2002a, pp. 26 *et seqq.*). However, a more regionally characterized compensation flow between central Berlin and the surrounding countryside cannot be confirmed by either of the two methodological approaches (cf. Methodology / Supplementary Notes).

Methodology / Supplementary Notes

In the following, extensive additional information on the topical complex of the methodological processing of the Berlin climate model is provided. The text thus complements the contents of the chapter Methodology.

The Concept and Methodology of the FITNAH Climate Model

The **basic structure of the three-dimensional FITNAH model** consists of the conservation equations for impulse, mass and internal energy, as well as balance equations for moist components and additive elements to the air. The various turbulent currents are connected to the calculable mean quanta with the aid of empirical inclusions. The turbulent diffusion coefficient appearing in that context is calculated from the turbulent kinetic energy, for which an additional equation is solved.

The warming and cooling rates in the atmosphere due to the divergence of the long-wave radiant fluxes are calculated by means of a procedure in which the emissivity of the water vapor in the air is taken into account.

For detailed simulations in real terrain, the orography, and particularly the **effect of wooded areas and urban structures** on the distribution of the meteorological quanta must also be taken into account in a realistic manner. For this purpose, FITNAH is provided with special parameterization.

A forest or grove will be incorporated into the model via stock-specific quanta, such as tree height, stock density and tree species. This permits, among other things, the simulation of the reduction of the mean speed in the stock, the rise of the turbulence in the crown area and the strong nightly cooling in the upper crown third, in agreement with available observations. With consideration for the city-specific quanta building height, sealing and degree of construction coverage, and anthropogenic waste heat, the typical formation of an urban heat island at a reduced mean air current can be simulated (cf. Groß 1989).

The entire system of equations, including the parameterization, is transformed into a coordinate system which corresponds to the terrain. That permits, in particular, the formulation of the ancillary conditions of the various meteorological quanta in a problem-specific manner, specifically at the lower edge, the ground. The calculation of the earth surface temperature is carried out via an energy-flux balance, in which perceptible and latent heat current, the soil heat flow, short and long-wave radiation components, and anthropogenic heat flow are considered.

The differential equation of the equation system used is transferred to finite-difference equations and solved on a numerical grid. The spatial grid size Δx used here is 50 m in the two horizontal dimensions. The vertical grid interval is not equidistant, and the calculation areas are particularly dense in the near-ground atmosphere, in order to incorporate the strong variation of meteorological quanta realistically. The lowest calculation areas are located at heights of 5, 10, 15, 20, 30, 40, 50 and 70 m. The interval Δz becomes ever greater as the height increases, and the top limit of the model is located at a height of 3,000 m above ground. This is the altitude at which it is assumed that the disturbances caused by orography and land use at ground level (cf. Fig. 4) will have faded away.

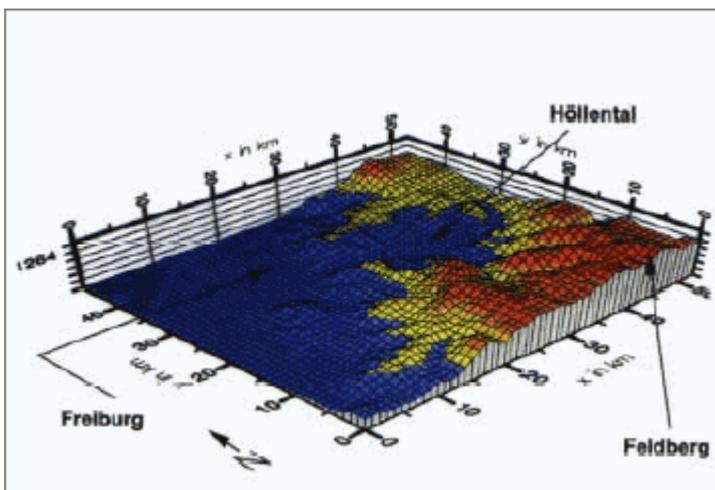


Fig. 4: Example for the representation of a natural landscape, in model-terrain character (from: Richter & Röckle o.J.)

Synoptic Framework Conditions for the Model Calculation

During high-pressure weather situations (autochthonous weather conditions), the local climatic particularities of a landscape can have a particularly strong effect. Such a weather situation is indicated by cloudless sky and an only very light overlaying synoptic wind. In the numerical simulations carried out here, the extensive synoptic framework conditions were established accordingly:

- coverage degree: 0/8
- geostrophic wind speed: 0 m/s
- relative humidity of air mass: 50%.

Notes on Interpretation of the Model Results

Due to the horizontal grid size of 50 m, such items as single houses and buildings cannot be explicitly resolved. Rather, the model calculates a value representation of this grid volume ($\Delta x \cdot \Delta y \cdot \Delta z$) which represents a weighted mean average value of the land uses present.

This can be elucidated using the example of wind speed U: If 40 % of the grid volume is filled with buildings ($U_{\text{Haus}} = 0$ m/s) and 60 % without flow obstacles (e.g. $U_{\text{Frei}} = 1$ m/s), then the representative wind speed, which is also calculated by the model, will be:

$$40 \% \cdot U_{\text{Haus}} + 60 \% \cdot U_{\text{Frei}} = 0,6 \text{ m/s}$$

Water	Area share 20 %	T_{Water}	= 18 °C
Open area	Area share 40 %	T_{Frei}	= 14 °C
City	Area share 30 %	T_{Cityt}	= 17 °C
Woods	Area share 10 %	T_{Woods}	= 16 °C

then a representative value of $T_{\text{Modell}} = 15,9$ °C is calculated for the grid.

Verification of the Results of the Climate Model FITNAH

To check the informational levels derived from the model runs, a study of local climatic functions in the open spaces of the Gleisdreieck area can be used. The orienting investigation on current and temperature fields in the Gleisdreieck area is methodologically composed of:

- stationary measurement, summer semester 2001 (four measurement operations); and
- mobile measurements, winter semester 2001-2002 (four measurement operations).

The meteorological framework conditions seemed suitable to permit self-generated current systems to develop in the area of the Gleisdreieck (cf. Vogt 2002a and Vogt 2002b).

The following working hypotheses were to be checked by the measurement operations:

1. There is an autochthonous, regional current which transports cold air over the low-friction structures of the track area (i.e., an air-stream channel) from the Teltow area into the center of Berlin;
2. The Gleisdreieck area, which is characterized by open spaces, provides cold air to the immediately adjacent built-up neighborhoods;
3. There is a cold-air outflow from the area of Viktoria Park in Kreuzberg, which intrudes into the open spaces of the Gleisdreieck area.

These assumptions agree with the hypotheses on the formation of autochthonous current systems between differently structured urban areas in this investigation, and therefore should be ascertainable again in the model results of the FITNAH simulations as well. The measurement data on the current field can therefore be used to check the plausibility of the model results herein.

However, a restricted applicability of this comparison must be assumed:

- The meteorological framework conditions for measurement were not in every case ideal for the clear development of self-generated current systems.
- A mobile and stationary measurement can always have only a random-sample character (spatially and temporally).
- The mobile measurements carried out during the winter semester were conducted during periods of extreme sub-freezing temperatures.
- "Virtually stationary" short-term measurements are involved, since at each of the 37 measurement points in sequence, the wind field parameters were ascertained for approx. 4 minutes. The measurement procedures for the recording of the wind field for this area probably lasted about 4 to 5 hours. Thus, what is represented is not a wind field for a defined

period of time.

- In the model runs which were used for the comparison, ideal framework conditions for the formation of self-generated flow systems were assumed, i.e. the top current has a speed of 0 m/s.

Check of the Working Hypotheses on the Autochthonous Current Field

In this comparison, the results achieved within the early nighttime hours at 2.5 m above ground are to be considered as a matter of priority. Thus, far-reaching comparability of the model vs. the measurement results is ensured in this regard. The comparison is carried out on the basis of an established working hypothesis on flow conditions in the area under investigation:

- **There is an autochthonous, regional current which transports cold air over the low-friction structures of the track area (i.e. a ventilation lane) from the Teltow area into the center of Berlin.**

Neither in the measurement procedure nor in the model calculations can any regional current be ascertained which uses the low-friction open spaces of the railway facilities as an air-stream channel.

Any such current system would have had to be demonstrated in the measurements at the Monumentenbrücke measurement point (cf. Vogt 2002a, p. 14). However, all that could be ascertained from the measurement operations was the intervention of the top current into the relatively low-friction, vegetated areas of the Gleisdreieck. Even the mobile, winter measurement ascertained no such current (cf. Vogt 2002b, pp. 78 *et seqq.*).

The model result, too, would not support any extensive exchange flow. The flow field (10 PM) shows a locally determined mosaic of small-scale air exchange cells, which are for the most part thermally induced. As a rule, the spatial extent of these "flow cells" is between 500 m and 1,200 m (cf. Fig. 5).

- **The Gleisdreieck area, which is characterized by open spaces, provides cold air to the immediately adjacent built-up neighborhoods.**

The measurement provided clear indications of the existence of these local equalization currents (cf. Vogt 2002a, p. 15). However, the less-than-optimal meteorological framework conditions during many of the measurement procedures and the temporal delay at mobile measurements prevented a comprehensive illustration of these current systems.

On the other hand, the model results generated by FITNAH provide a comprehensive picture of the spatial character of these local, primarily thermally induced current systems. In addition to the item-related statements of the measurements, the model results permit statements concerning the range (i.e., penetration depth) of the flows into the adjacent built-up areas. The area between the Lützowstraße and Kurfürstenstraße test points on the western edge of the Gleisdreieck area can be taken as an example. The cold air formed locally here penetrates approx. 500 m into the built-up area.

The flow speeds measured or modeled achieve very similar orders of magnitude. As a rule, these thermally induced current systems are accompanied by wind speeds of from 0.1 to 0.5 m/s. The measurement projects indicate that these values were achieved both in the summer and the winter semesters (cf. Vogt 2002a, pp. 19 and 22). There is also a cold air flow at the Möckernstraße, whereas the penetration range amounts up to 150 m.

- **There is a cold-air outflow from the area of Victoria Park in Kreuzberg.**

The measurement results on local cold-air outflow from the area of Victoria Park in Kreuzberg confirm these FITNAH simulation calculations (cf. Vogt 2002a, p. 17). The measurements confirmed the canalization of the cold-air outflow through the Kreuzbergstraße and Großbeerenstraße. This flow was accompanied by low wind speeds of 0.7 to 0.2 m/s.

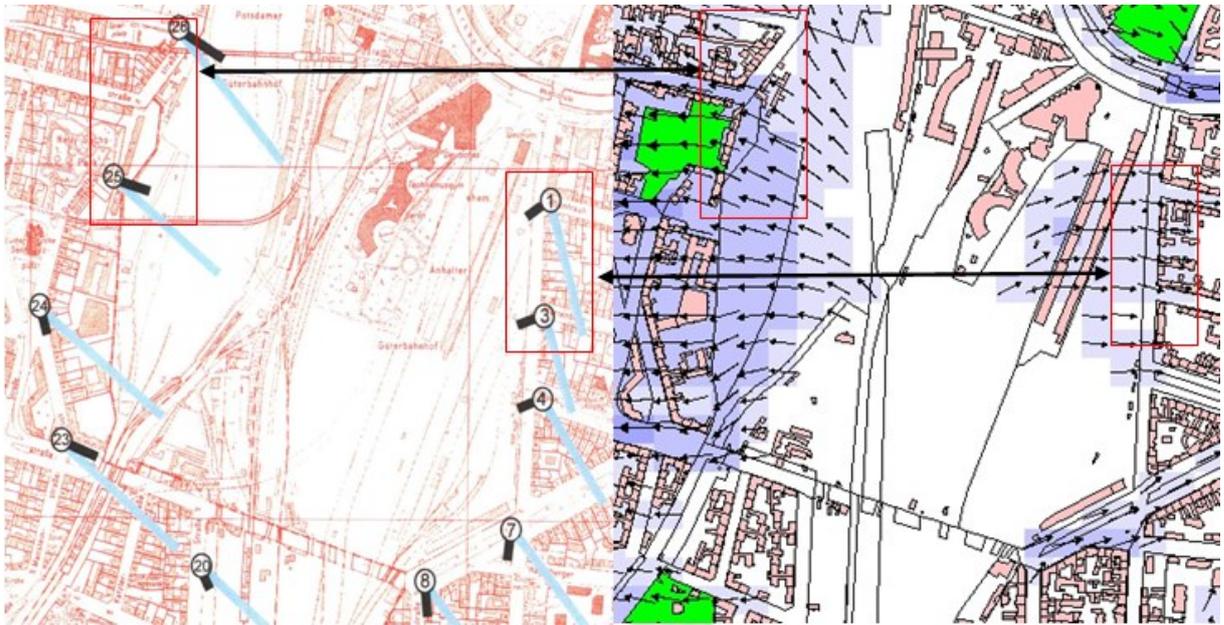


Fig. 5: Verification of the results of the climate model FITNAH (Fig. right) on the basis of stationary and mobile measurements in the area of Gleisdreieck (Fig. left: from Vogt 2002a and Vogt 2002b); in the left Figure, the lines emanating from the measurement points point in the direction from which the wind comes; in the right Figure, the wind arrows point in the flow direction.

Result

Overall, there is **good agreement** between the results of the measurement procedure and the modeling of the local current field in the Gleisdreieck area using FITNAH.

The self-generated, local current phenomena postulated by the model calculations can largely be confirmed by the measurements. Data on flow direction and speed are within the same ranges. The relevant air exchange processes - small-scale, orographically-determined cold-air outflows from the Viktoriapark in Kreuzberg and thermally induced compensation currents between the open spaces of the Gleisdreieck and the adjacent built-up neighborhoods - have been ascertained and represented equally, both qualitatively and quantitatively (cf. Vogt 2002a, pp. 26 *et seqq.*). However, it was not possible, by either of the two methodical approaches, to support any regionally-characterized compensation current between central Berlin and the surrounding countryside.

Map Description

The following is a common description for all single evaluations of the model calculations. Links to the individual main emphasis areas are provided for faster orientation in the text:

- Near-ground temperatures (10 PM)
- Near-ground temperatures (6 AM)
- Air exchange and air-mass currents (10 PM and 6 AM)

The model calculations were started every day at sundown, and continued until sunrise the following day. The points in time, at which the model results are to be readout, can, in principle, be chosen freely (minutes up to hours). The time segments 10 PM and 6 AM were evaluated and represented in the form of maps for the individual climate parameters. The 10 PM point in time represents the reversal from an irradiation to an extradiation situation shortly after sundown, and stands for the beginning of a phase with great cooling-down dynamics in the variously structured spaces in the urban area. The 6 AM point in time shows the maximum cooling-down within the urban structure.

In the following, single exemplary results of the model calculations for the entire urban area will be briefly described. Fig. 3 provides a summary of the respective climatological parameters evaluated.

Near-Ground Temperature, General Remarks

The representation of the near-ground temperature field involves the grid instrument of temperature at the near-ground layer of the atmosphere (0-5 m above ground). If several land uses with different area

shares are present within a grid cell, the temperature shown is calculated from the proportional weighting. Thus, the simulated temperature values are comparable only for larger areas with a uniform or comparable land use with ground-bound measurements.

Decisive for the temperature distribution are the land-use dependent soil and surface characteristics, as well as their interactions with the atmospheric processes in the near-ground boundary layer. Within the soil, heat and temperature conductivity are of importance in this regard. The greater the heat conductivity of the soil, for example, the faster and more deeply heat can penetrate into the corresponding material - but also: the faster it can escape again.

The surface composition of natural and artificial areas determines, via the albedo (reflection capacity) and the emissivity, the quantity of energy available in the short and long-wave ranges of radiation for warming/cooling. Finally, the turbulence condition of the near-ground atmosphere plays a major role in the transportation of perceptible and latent energy to and from the ground.

All processes mentioned are interconnected via the energy balance of the soil, and determine the temperature of the surfaces and the layers of air above them.

Near-Ground Temperature

The temperature conditions of the near-ground atmosphere **10 PM** in the entire area are shown in Map 04.10.01. Due to the great variety of differences determined by land use of these effect quanta, a **strongly structured spatial distribution of near-ground temperatures** is simulated. Within the early nighttime hours (10 PM) the main land uses stand out against each other in a characteristic manner.

At this time, the **wooded areas** are approx. 1 K cooler than the surrounding open fields, and considerably colder than the built-up areas.

The **open areas** are heated up strongly during the day, and cool down after sundown just as strongly. Due to the relatively high evening base temperature, this cooling has on the whole not yet progressed sufficiently at the chosen point in time to reach the level of the cooler wooded areas.

Urban areas stand out considerably from their surroundings by an overall higher temperature level. However, the temperature distribution is spatially differentiated strongly in built-up areas, since, e.g., grid cells with detached house buildings, core areas, industrial areas and transportation facilities show strongly differing ground and surface characteristics. Moreover, the higher mean temperature level is interrupted by inner-city parks like the Great Tiergarten and the Tempelhof and Tegel airports.

Depending on the individual surface characteristics of the various land uses, the ground will cool down differently strongly during the night; Map 04.10.02 shows the **temperature distribution at 6 AM**.

While this cooling is very low for **bodies of water**, due to their good heat-accumulating qualities, open areas like **fields and meadows** show a strong drop in temperature. In **wooded areas**, the crowns of the trees protects the near-ground atmosphere below from cooling off strongly; therefore, forests stand out in the temperature distribution as relatively warm areas.

In the **urban areas**, cooling is reduced considerably by the presence of heat-storing materials like concrete and stone. For one thing, the quantity of heat stored during the day causes the temperature not to decline so strongly. Moreover, the low wind speeds of turbulent and latent heat currents, which might otherwise remove warm air, are reduced. The urban areas thus remain warmer overall. While the temperature difference vis-à-vis the undeveloped surrounding countryside is typically 2 K during the evening hours, this value increases to K 6 by the early morning hours. These great horizontal differences are not quite achieved in the inner-city open areas. Here, the proximity to the relatively warm built-up areas manifests itself.

Air Exchange and Air Mass Current as Criteria for Climate Compensation Measures

Good ventilation of residential areas can lead to a reduction in human bio-meteorological burdens (cf. Moriske and Turowski 2002). During the nighttime hours, the introduction of cooler air from the surrounding countryside can reduce the temperature level of the warmer air masses stored in the city, thus leading to a reduction of anthropogenic thermal pollution during the summer months. If this introduced cooler air (fresh air) is not burdened by air pollutants, the ventilation will also lead to an improvement in the air-quality situation.

Consequently, evaluation of the ventilation situation requires an appropriate **assignment of burdened areas and compensation areas**, which can make the appropriate unburdened air available, as well as

a circulation system to ensure the transportation of the air mass.

Climate-ecological compensation effects originate in undeveloped areas scattered throughout the urban area. They are characterized by a high vegetal proportion as well as a low degree of sealing of less than 20%, and improve the local climatic situation even in the densely built-up cores areas of Berlin (cf. Maps 04.10.03 through 04.10.06).

The compensatory effect is produced via topographically generated (thermally) and/or orographically induced current systems. The following delimitation criteria were used to identify the open areas which provide neighboring built-up areas with fresh and/or cold air, and to be able to assign them to the various exchange processes. The self-generated compensation currents should achieve at least a speed of 0.2 m/s in climate-ecologically relevant open areas during a low-exchange, cloudless summer night. The compensation currents can be described as slope or valley winds if slopes or valley-floor inclinations of $> 1^\circ$ occur. Thermally induced current systems can be found in the relatively flat areas (cf. Fig. 6).

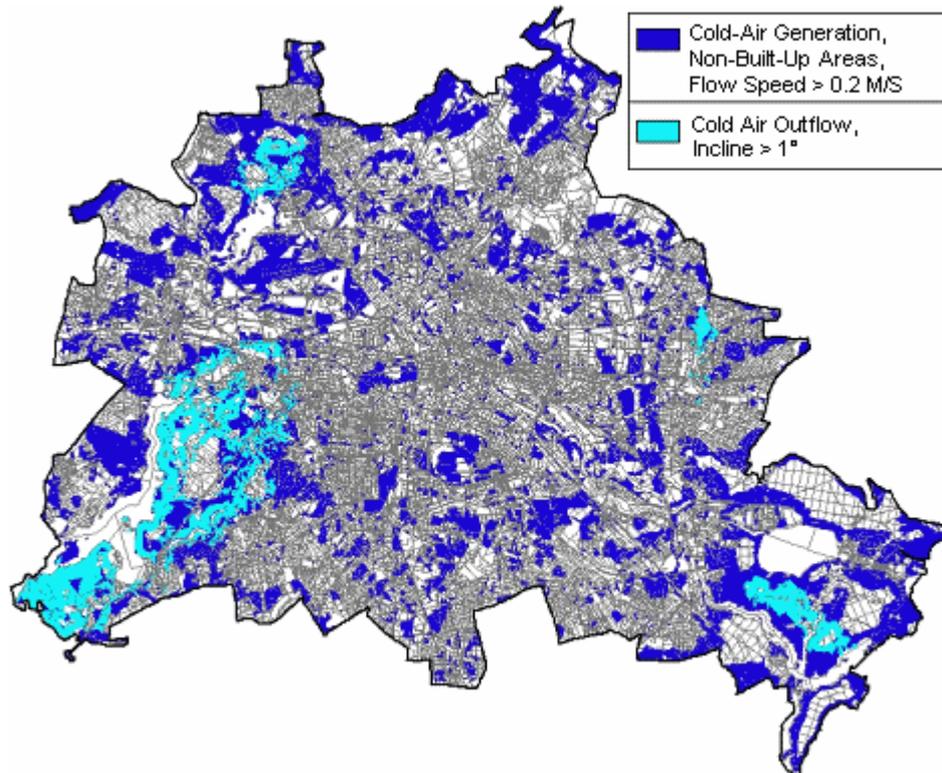


Fig. 6: Areas involved in cold-air generation or cold air out-flow in the urban areas of Berlin during a low-exchange cloudless summer night (10 PM; grid resolution: 50 m)

Significant compensation can be expected from the large coherent forest and parkland areas which are very extensive, particularly on the edge of Berlin. Due to the high cooling rates during the evening and nighttime hours, these areas can be considered as important cold-air provision areas. Table 1 shows the proportional space of the city area involved in the formation of topographically generated winds and cold-air outflows:

Process	Area share in % 10 PM	Area share in % 6 AM
Thermally induced current systems	24.2	37.2
Orographically induced current systems	4.7	5.0

Tab. 1: Proportion of spaces in the city area involved in the formation of autochthonous current systems. The thermally and orographically (relief-caused) induced current systems are distinguished.

Thus, **more than 30% of the city area is involved in the formation of compensation flows**, with the proportional area increasing slightly over the course of the night from 28.9% at 10 PM to 42.2% at 6 AM. This increase can be explained by the fact that additional undeveloped areas are involved in the

cold-air generation process, particularly in the northeast of Berlin as well as around the Müggel Lake and in the Grunewald forest.

However, the result is that while in the early morning a larger undeveloped area is involved in cold-air generation with a current speed > 0.2 m/s, this occurs at a lower level than at 10 PM. A comparison of the mean air-exchange rates of all grid cells in the entire urban area shows notably that the mean cell value climbs from 14.4 at 10 PM to 17.4 at 6 AM. On the other hand, the maximum cell value of 93.1 drops to 90.6. Thus, while the mean air exchange rate climbs overall, the maximum values reached at the 10 PM time segment, and the intensity of air exchange, are no longer achieved, due to the increased leveling of temperature differences.

The compensation from the open areas reaches large parts of the built-up areas of Berlin. A city-wide balance sheet yields the following results:

- About 37% of the built-up areas are reached or penetrated at the 10 PM time segment by autochthonous currents with a speed of at least 0.2 m/s.
- Over the course of the night, the compensation benefits from the open areas rise, due to the increase of cold air influx from open spaces outside of Berlin, to a spatial coverage of approx. 63% of that portion of the urban area characterized by built-up development (time segment: 6 AM).
- At the same time, the cold air flow from most intra-urban green spaces is decreasing. This can be traced back to the fact that they are located within a warmer vicinity and thus the cooling-down in the course of the night is less intense compared with the open spaces outside of Berlin.

Due to the close interaction between built-up areas and open areas, **Berlin has a high climate-ecological compensation potential overall.** However, cold-air *out-flows* account for a relatively small share of this. They occur extensively primarily in the following areas:

- the eastern Havel shore along the Grunewald;
- the eastern edge of the Grunewald; and
- south of the Great Müggel Lake, in the Berlin Bürgerheide City Forest.

Large, linearly shaped open areas with relatively low surface friction function as air-stream channels for cold-air transportation. In this regard, three areas of the Havel and Spree Valleys are significant. First, the Havel section between Pichel Lake and Ruhlebener Straße which conducts cold air toward the borough of Spandau along an approx. 3 km corridor; second, Rummelsburg Lake, a part of the Spree, stands out as an area through which cold air streams from old Treptow and from the Plänterwald woods toward Rummelsburg; and finally, a section of the Dahme should be mentioned, along the Grünauer Straße-Regattastraße corridor. These results coincide with the results of a report of the German Meteorological Service (DWD 1996).

However, due to the hardly distinctive orography, such relief-determined ventilation lanes are rather rare. An essential contribution to the transportation of cold air from the countryside surrounding Berlin into the urban area cannot be ascertained; rather, only some parts of the river valleys within the urban area function as air-stream channels.

As examples of the compensation provided by open areas, three locations are discussed in detail under [Map Description/Supplementary Notes](#) so as to elucidate the dynamics of the cold air balance in the border area of cold-air producing open area to the built-up areas.

In conclusion, let us address the cold-air balance of Berlin as a whole. For this purpose, the air mass current is to be used, in which cold-air movement is quantified on the basis of 10 PM values in an 8-hour night. Accordingly, 2.3 trillion m³ of cold air are moved in the urban area of Berlin in a low-exchange cloudless summer night. This corresponds to a flow-through rate of 0.29 trillion m³ of cold air per hour. The total mass of cold air moved, broken down by borough, is shown in Table 2.

Borough	Mass flow in Bn m ³ per 8-hour night
Friedrichshain-Kreuzberg	42.93
Mitte	82.27
Neukölln	86.94
Tempelhof-Schöneberg	118.03
Lichtenberg	126.76

Marzahn-Hellersdorf	131.96
Charlottenburg-Wilmersdorf	212.01
Pankow	249.84
Spandau	250.01
Reinickendorf	257.87
Steglitz-Zehlendorf	308.83
Treptow-Köpenick	450.38

Tab. 2: Cold-air volume flow in the Berlin boroughs during a cloudless summer night

The borough-related results coincide with the expectations with regard to size and location within the urban area. It is apparent here that such core areas as Friedrichshain-Kreuzberg or Mitte, with high degrees of built-up areas and of sealing, have relatively weak mass currents. The situation is different in the Boroughs of Pankow, Reinickendorf and Köpenick.

Here, too densely-built areas are apparent toward the city center, but this is compensated for by the large undeveloped spaces in the interaction areas with the surrounding countryside. The non-built-up, cold-air generating areas of the edge boroughs thus make the largest contribution to the cold-air mass current.

Map Description / Supplementary Notes

In the following, extensive additional information is provided on the dynamics and significance of the cold-air balance of open areas, with selected examples. The text completes the contents of the chapter Map Description. The legend classification of cold air volume flow and air exchange is geared to the standardization procedures of the z-transformation as described in the VDI-guideline 3785 sheet 1 (VDI 2008). This statistical approach is related to the local/regional value level and evaluates the deviation of a climate parameter from the average conditions within an investigation area. In order to classify the results, the VDI-guideline defines four evaluation categories (most favourable / favourable / less favourable / unfavourable), with which the classification of the model results complies.

Cold-Air Producing Open Areas and their Effect on Built-Up Areas

In Fig. 7, three locations are identified, which are to provide an example for discussing in a more detailed manner the cold-air balance on the basis of a selected corridor sections of 10 grid cells with 500 m of section length. For the characterization of the dynamics of the cold-air balance, these examples were placed along the boundary area of cold-air-generating open areas and built-up areas. For an overall comparison of the values within the 50 m grid, a mean grid cell value was then determined based on the cells along the corridor section.

As examples of the compensation potential of open areas, transition zones were used: The southwestern section of the former Tempelhof Airport (A) represents a location with an intra-urban character, whereas the Spandau region (B) shows the influence of cold air generation areas at the western outskirts of Berlin. Between these both locations, the example Grunewald/Wilmersdorf (C) shows an interim location.

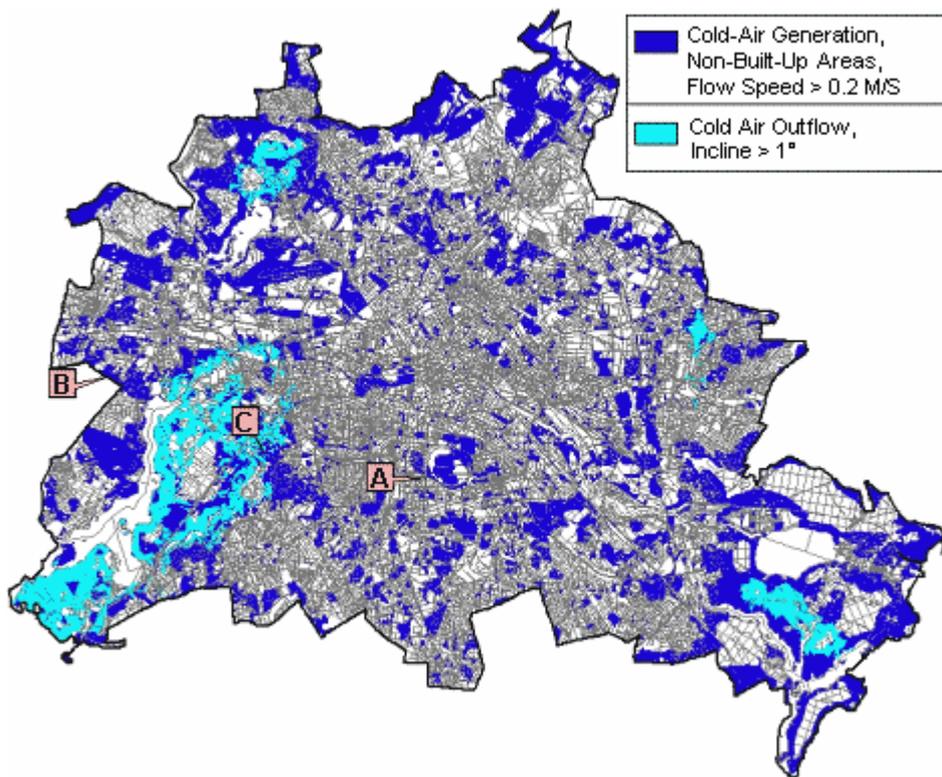


Fig. 7: Situation of the test areas A, B and C for the clarification of the processes "cold air generation" and "cold-air out-flow" during a low-exchange cloudless summer night (10 PM; grid resolution: 50 m)

Example: Tempelhof Airport

For the consideration of the cold air budget at intra-urban locations, the southwestern part of Tempelhof Airport with a 500 m long section along Tempelhofer Damm was selected (cf. Fig. 8). The former Tempelhof Airport shows, due to its size and location within the city of Berlin, a **high relevance for urban climate** and a significant local contribution for the reduction of summery thermal stress in the adjacent settlement area.

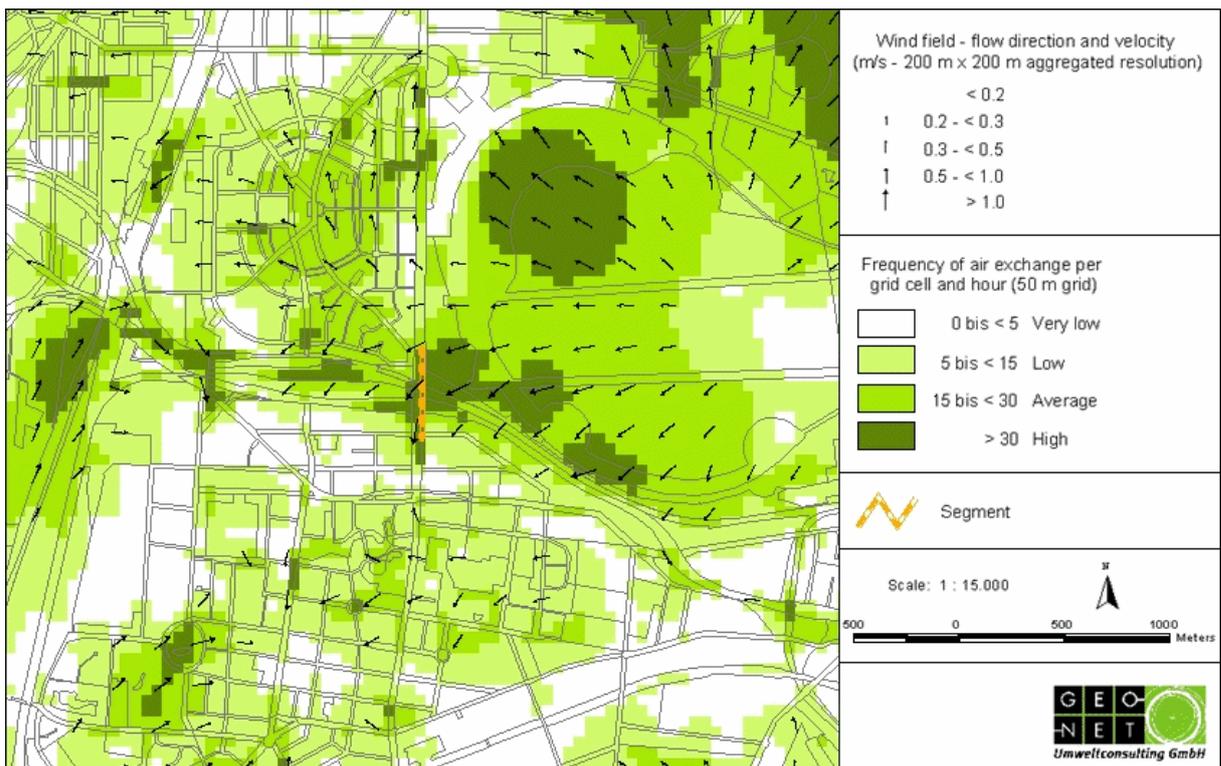


Fig. 8: Air exchange per grid cell and autochthonous current field in the area of Tempelhof Airport during a low-exchange cloudless summer night (10 PM; grid resolution: 50 m)

With regard to the air exchange rate, two **areas with relatively high hourly air exchange rates** of over 30 per grid cell are recognizable in the airport area, including its apron area, and the intersection of Tempelhofer Damm and the A 100 freeway. Despite the high air-exchange rate, even in terms of broad extent, the generation of the topographically generated wind over the apron area is impaired by the air terminal both at 10 PM and at 6 AM. Due to its low surface roughness, the street and rail track located in the southwest of the former airport, allows the cold air from the Tempelhof field to flow to a western direction. The range of this flow amounts, starting from the Tempelhofer Damm, to approx. 700 m (cf. Fig. 8). At this time, it is juxtaposed to an eastward cold-air flow from the allotment-garden colonies of the Schöneberg South Terrain, whereas both topographically generated winds extend up to the Alboinstraße.

By 6 AM, the latter topographically generated wind from the allotment-garden area has come to a virtual standstill, while the range of the topographically generated wind starting from Tempelhof Airport has doubled to approx. 800 m and penetrates up to 400 m to the south to Tempelhofer Damm.

Table 3 summarizes the results for the grid cells located along the considered segment. It can be observed, that the calculated values decrease slightly over the course of the night. This is ascribed to the fact, that the temperature level within the developed areas is decreasing and thus reduces the thermal gradient as a “driving mechanism” for air exchange processes.

Time	Mean air exchange rate/hr. per 50 m grid cell	Mean volume flow in m ³ /s per 50 m grid cell	Mean flow velocity of the topographically generated wind in m/s
22.00 PM	50	793	0.72
06.00 AM	45	715	0.58

Tab. 3: Mean air-exchange rate, volume flow and flow speed of the topographically generated wind per grid cell along a corridor section in the Tempelhof Airport area during a low-exchange cloudless summer night (grid resolution: 50 m)

The average air exchange rate per grid cell decreases from 50 at 22.00 PM to 45 at 06.00 AM, which means a reduction of 10 percentage points. The cold air volume flow also decreases approx. 10 percentage points from 793 m³/s to 715 m³/s. The average flow velocity also decreases for approx. 19 percentage points. In general, intra-urban cold air generating green spaces show the tendency of a decreasing cold air influx in the course of the night. Due to the size of the former airport, the intensity of air exchange processes in the vicinity can be considered as high. Thus, the reduction of cold air influx of the remaining and mostly smaller intra-urban green spaces is often much more distinctive and can disrupt totally.

Example: Spandau

The borough of Spandau is characterized by its location on the outskirts as well as by its urban settlement structures. For this example, a section along the Weinmeisterhornweg with a length of 500 m is considered. The area generating the cold air for this example is located westerly of the Potsdamer Chaussee outside of Berlin in the region Seeburg. As Fig. 9 shows, a high level of air exchange is connected with allotment sites and one-family houses next to the open spaces. Structures with a low density like these act as local ventilation lanes and support the cold air influx into settlement areas. This function is based on the low surface roughness in combination with a high share of vegetation. With air exchange rates of more than 30, these areas are considerably different from the adjacent and more densely developed areas.

At 22.00 PM, the cold air flows beyond the Heerstraße into the built-up area, so that the reach of the cold air amounts more than 600 m. To the east of this position at Fahremundstraße, the cold air flow extends to Blasewitzer Ring. Starting at the Weinmeisterhornweg, there is a flow distance of approx. 1300 m, until the flow speed decreases below 0.2 m/s and the air exchange reduces to a very low level.

Up to 06.00 AM, the dynamic of cold air exchange processes are increasing. Whereas at the begin of the night the penetration of cold air into the build-up areas is geared to structures with a low density, the cold air influx now has an extensive character. Along with this, a high penetration reach of the cold air flow with locally more than 2000 m is observed.

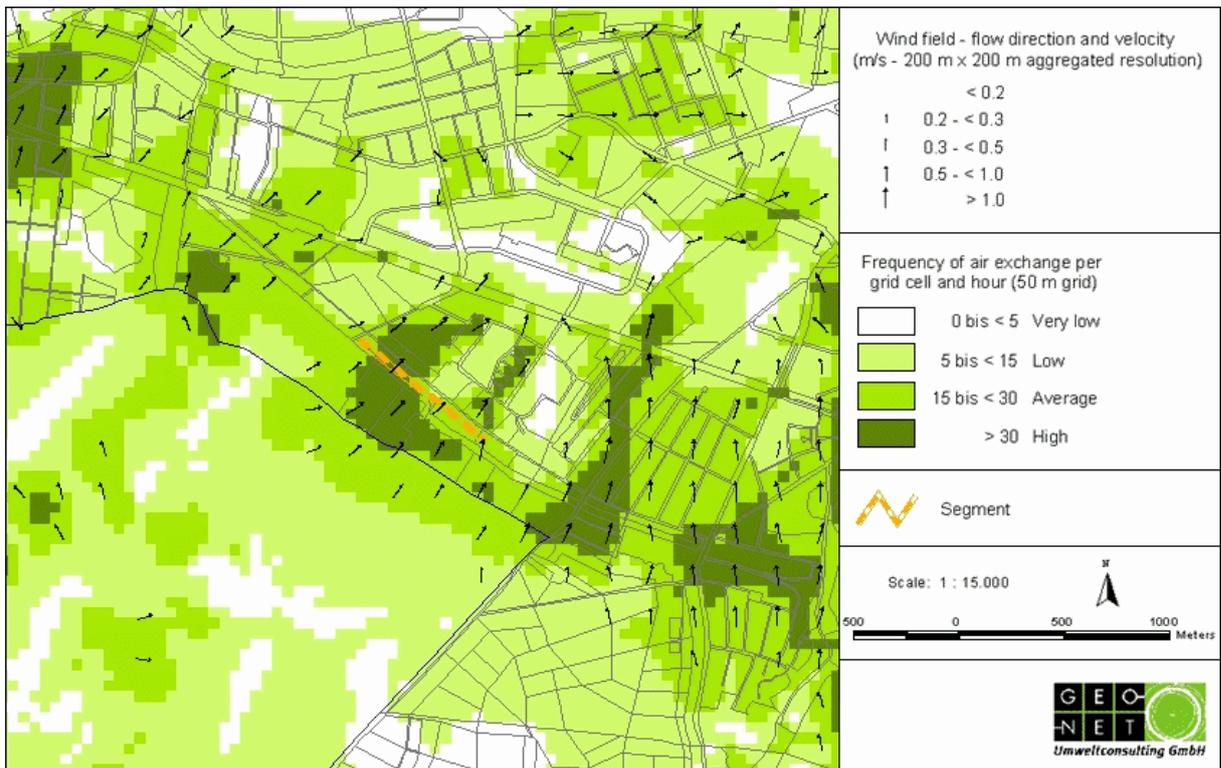


Fig. 9: Air exchange per grid cell and autochthonous flow field in the Spandau area during a low-exchange cloudless summer night (10 PM; grid resolution: 50 m)

The intensification of air exchange processes is based on the steadily increasing cold air volume, which is generated by the wide open spaces at the outskirts of Berlin. This interrelation is represented by the determined results (Tab. 4).

Time	Mean air exchange rate/hr. per 50 m grid cell	Mean volume flow in m ³ /s per 50 m grid cell	Mean flow velocity of the topographically generated wind in m/s
22.00 PM	28	409	0.34
06.00 PM	44	744	0.75

Tab. 4: Mean air exchange rate, volume flow and flow speed of topographically generated wind per grid cell along the corridor section in Spandau during a low-exchange cloudless summer night (grid resolution: 50 m)

The average air exchange rate grows from 28 to 44, which means an increase of 57 percentage points with regard to the 22.00 PM date. A significant increase can also be observed for the cold air volume flow, which is rising from 409 m³/s per grid cell to 744. That means an increase of 82 percentage points. The highest increase of 121 percentage points is showing the mean flow speed, which rises from 0.34 m/s to 0.75 m/s.

Example: Grunewald Forest

With more than 3000 hectares, the Grunewald forest is among the largest wooded areas in the city area. Along a corridor of approx. 11 km, parts of the Boroughs of Charlottenburg-Wilmersdorf and Zehlendorf-Steglitz, located to the east of the forest, profit particularly from the high cold-air productivity. Fig. 10 shows the transition zone from the Grunewald to the detached-home areas in Wilmersdorf; here, the air interchange per grid cell and hour is relatively high, with exchange rates of over 30.

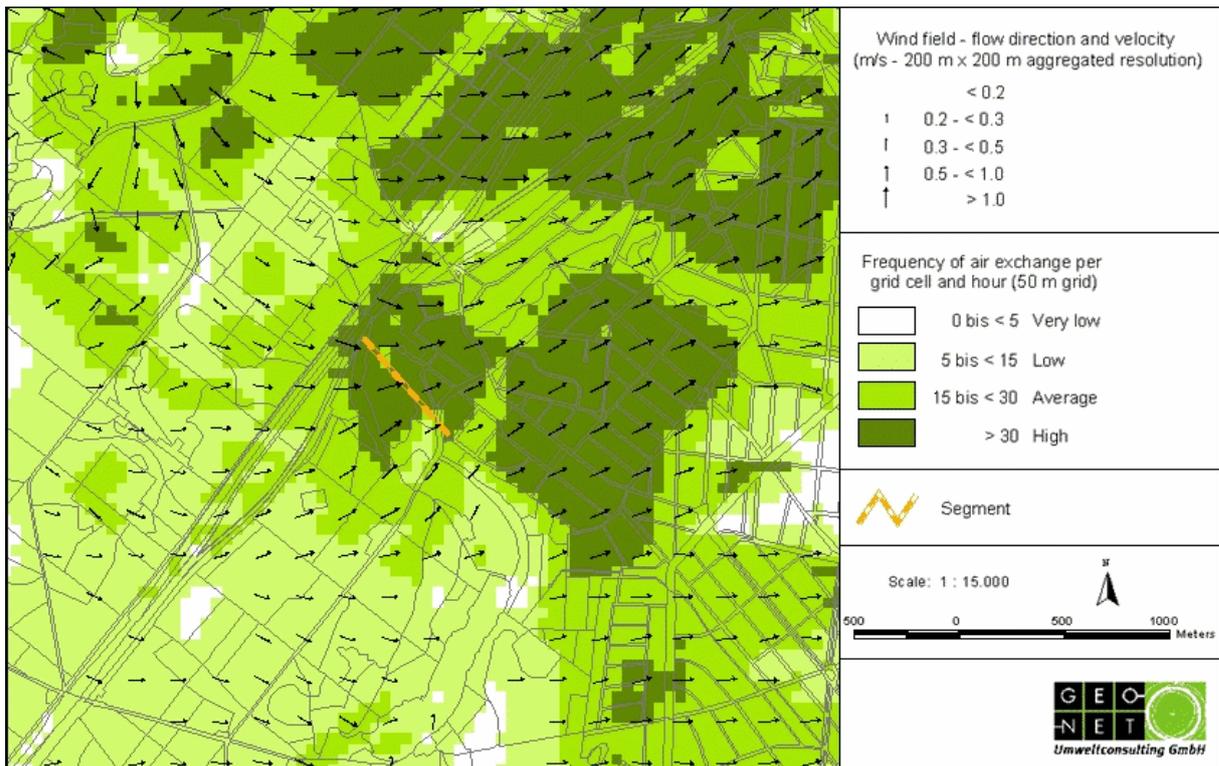


Fig. 10: Air exchange per grid cell and the autochthonous current field in the Grunewald-Wilmersdorf transition zone during a low-exchange cloudless summer night (10 PM; grid resolution: 50 m)

The correspondingly **long range of the cold-air flow** is most strongly in evidence in Wilmersdorf at 10 PM, with up to 3,000 m, which is due to the low-density detached-home structure of the area. In Steglitz, by contrast, a value of only approx. 1,250 m is achieved, due to the increasing density of the built-up area. At 6 AM, the cold air only penetrates approx. 1,200 to at most 2,100 m into the built-up area.

For the 500 m long section, the mean value of the air exchange per grid cell, the volume flow as well as the flow speed of the topographically generated wind were exemplarily calculated (cf. Table 5). This corridor starts at Auerbachstraße at the AVUS Freeway, and leads to Königsallee.

Only a slight decrease of the mean grid cell value in the course of the night is apparent. The air-exchange rate declines by approx. 3 percentage points, from 33 to 32. The same applies to the cold air volume flow, which is reduced some more by approx. 10 percentage points. In contrast, flow speed of the topographically generated wind increases slightly about 9 percentage points from 0.47 m/s up to 0.51 m/s. It must be stated that, despite the decrease of air exchange rate und volume flow, all three **climate parameters remain on a high level up to the 06.00 time.**

Time	Mean air exchange rate/hr. per 50 m grid cell	Mean volume flow in m ³ /s per 50 m grid cell	Mean flow velocity of the topographically generated wind in m/s
22.00 PM	33	568	0.47
06.00 PM	32	510	0.51

Tab. 5: Mean air-exchange rate, volume flow and flow speed of the topographically generated wind per grid cell along the corridor section in the Grunewald-Wilmersdorf transition zone during a low-exchange cloudless summer night (grid resolution: 50 m)

Conclusion

The evaluation of climate parameters for an intra-urban (Tempelhof airport), a peripherally (Spandau) as well as an intermediate location (Grunewald) have shown the spatial characteristics of cold air dynamics within the City of Berlin. The example Tempelhof reveals the tendency of intra-urban green spaces to have a high level of cold air generation at nightfall and a decrease to the end of the night. Despite that, the flow systems of cold air generating areas at the outskirts of Berlin show their highest level in the second half of the night, after appropriate cold air volume has been generated over the

open spaces. The example Grunewald shows characteristics of intra-urban sites as well as peripheral locations and thus has an intermediate position between both situations. With regard to the evaluation of green and open spaces, the position within the investigation area should always be taken into account.

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