DIE ERDE
Journal of the Geographical Society of Berlin

Vol. 144, No. 3-4 · Research article

Past and future evolution of nighttime urban cooling by suburban cold air drainage in Aachen

Timo Sachsen[1], Gunnar Ketzler[1], Achim Knörchen[1], Christoph Schneider[1]

[1] Geographisches Institut, RWTH Aachen University, Wüllnerstr. 5b, 52056 Aachen, Germany, timo.sachsen@geo.rwth-aachen.de

Manuscript submitted: 24 July 2013 / Accepted for publication: 16 February 2014 / Published online: 28 April 2014

Abstract

In urban areas situated downstream of rural areas, cold air drainage flow contributes to reduced nighttime temperatures and reduced pollutant concentrations. In this study, the impact of historical, present and possible future land-use changes upon evening cooling by suburban cold air drainage flow is analysed by using the numerical cold air drainage model KLAM_21 of the German Weather Service (DWD). In order to do this, land-use patterns of the year 1810 and 1910 are reconstructed. Furthermore, potential land-use scenarios are developed, considering both a scenario with beneficial cold air drainage characteristics and a second adverse scenario. Past, present and future land-use data are used as model input. To validate model results in the present land-use situation, empirical data from field measurements are used to compare modelled and effective cold air drainage flow characteristics. Model data for 14 reference areas – including suburban and inner city sites – are compared with regard to the cooling rate 3 h after sunset. The results show distinctive effects of accumulated long-term urban land-use changes on the suburban cold air drainage flow. In the city centre, for example, the modelled mean cooling rate decreases from 3.6 K in 1810 to 2.8 K in 1910 and to 2.4 K in 2010. In contrast to this, appropriate measures to stop or even reverse the trend of decreasing cooling rates are shown. Intensified urban cooling by nocturnal cold air drainage can contribute to mitigating probable future global warming effects.

Zusammenfassung

Bei Städten in Tallage können nächtliche Kaltluftabflüsse zur Reduktion der Lufttemperatur und Verbesserung der Luftqualität beitragen. Mit Hilfe des numerischen Kaltluftabflussmodells KLAM_21 des Deutschen Wetterdienstes (DWD) werden in der vorliegenden Studie die Auswirkungen historischer und zukünftiger Änderungen der Landnutzung auf die Bildung und den Abfluss von Kaltluft untersucht. Dazu wurde die Landnutzung im Jahr 1810 und 1910 rekonstruiert. Des Weiteren wurden Landnutzungsszenarien entwickelt, die sowohl eine für den Kaltluftabfluss optimierte Landnutzung, als auch eine für den Kaltluftabfluss nachteilige Landnutzung berücksichtigen. Zur Validierung der Modellergebnisse wurden im Untersuchungsgebiet Daten erhoben, die die Eigenschaften des Kaltluftabflusses zeigen. An insgesamt 14 inner- und randstädtischen Referenzflächen im Kaltluftabflussgebiet wurde die Abkühlungsrate drei Stunden nach Sonnenuntergang und in Abhängigkeit von der jeweils zu Grunde liegenden Landnutzung ermittelt. Die Auswertungen zeigen in der Summe den nachteiligen Einfluss anthropogener Landnutzungsänderungen auf randstädtische Kaltluftabflüsse. Im innerstädtischen Bereich ergeben sich beispielsweise sinkende mittlere Abkühlungsraten von 3,6 K im Jahr 1810, 2,8 K im Jahr 1910 bis hin zu 2,4 K im Jahr 2010. Dementgegen werden anhand von Szenarien Möglichkeiten aufgezeigt, wie dieser negative Trend gestoppt werden kann. Gelingt dies, können Kaltluftabflüsse zur Minderung hoher und zukünftig weiter steigender innerstädtischer Temperaturen beitragen.

Sachsen, Timo, Gunnar Ketzler, Achim Knörchen and *Christoph Schneider* 2013: Past and future evolution of nighttime urban cooling by suburban cold air drainage in Aachen. – DIE ERDE **144** (3-4): 274-289

DOI: 10.12854/erde-144-19

Keywords Urban climate, urban heat island, cold air drainage flow, cooling rates, cold air transfluence

1. Introduction

In 2007, for the first time, the IPCC extensively addressed the specific situation of cities and their population under climate change conditions (IPCC 2007). On account of increasing temperatures, the IPCC predicted that heat waves will occur more frequently, with negative effects on the urban population (e.g. *Della-Marta* et al. 2007, *Meehl* and *Tebaldi* 2004). Especially high nocturnal temperatures – e.g. those recorded in summer 2003 in Europe (*Robine* et al. 2008, *Koppe* et al. 2004) – have led to increasing mortality rates among vulnerable population groups such as children or the elderly (*Coutts* et al. 2008). Cold air drainage in suburban areas affects the urban heat island by advection of cold air, thus reducing temperatures. Therefore, questions related to climate effects on cities located in valleys are currently of increasing interest in applied atmospheric science (WMO 2010).

The effect of cold air drainage at local or regional scales has been studied depending on weather conditions and topography (e.g. *Bigg* et al. 2012, *Clements* et al. 2003). Its interaction with warm and polluted air in urban areas is influenced by urban structures, which is why cold air drainage flow typically is subject to urban climate analysis mapping (*Ren* et al. 2011, *Scherer* et al. 1999) and planning directives (VDI 2003). The cumulated effects of long-term urban development on urban cooling have been investigated in several studies (e.g. *Chow* and *Svoma* 2011). The mitigation potential of such a development, however, has not been analysed systematically in the context of future climate conditions.

Within the project 'City2020+ – The City under Global Demographic and Climate Challenges' (*Schneider* et al. 2011), different issues related to climate, health, urban society and planning were investigated as part of an interdisciplinary assessment. Investigating the mitigation of urban heat island effects by optimising suburban valleys for nocturnal cold air drainage flow was one of the research objectives within the project City2020+. As the cold air drainage flow is linked to clear sky conditions, which in summer are often connected to hot weather situations, these cooling effects are expected to play a relevant role in heat wave mitigation.

This study aims at quantifying the urban cooling potential of cold air drainage flow directed into the city and its relation to urban development. The general framework is a model-based comparison of effects of different land-use patterns – historical and possible future ones – on suburban cold air drainage flow using the model KLAM_21 of the DWD (German Weather Service, *Sievers* 2005). In a first step, model results for the present situation within a suburban valley in the city of Aachen are compared with data from measurements. Afterwards, historical urban development and possible future changes are simulated. The model results for specific reference areas with different urban functions are analysed. Aside from the evening cooling effect, the intensity of cold air drainage flow – given by the cold air volume flow – is analysed, as the latter indicates the capacity of cold air flow to compensate for urban warming effects. Moreover, cold air flow intensity is relevant for air quality issues, especially in connection with urban multiple exposures (*Merbitz* et al. 2012).

In the study area, a general warming trend can be detected for the period under investigation. In the decade before 2010, mean air temperature at the suburban weather station Aachen-Wetterstation was 10.8 K (2000-2009). A reconstruction of data for the earliest period of instrumental measurements in Aachen results in a mean temperature of 9.0 K (1830-1839; *Ketzler* 2010). Thus, a general warming in the study area of about 1.5-2.0 K for this historical period can be assumed. The warming can probably be attributed to both global warming and effects of urban development. Under climate change conditions, an additional warming of + 1.9 °C can be expected for the period 2031-2060 on a regional scale as indicated by the Ministry for Climate Protection, Environment, Agriculture, Nature Conservation and Consumer Protection of the German state of North Rhine-Westphalia (MUNLV 2009). In this context, knowledge on past and future factors affecting cooling by local cold air drainage can contribute to effective climate change mitigation strategies in urban areas.

Additionally, effects of cold air drainage flow over hydrological catchment boundaries, in this study referred to as cold air transfluences, are investigated. This new topic is expected to be of practical importance since positive results of a model-based detection of sites of cold air transfluence indicate that this phenomenon brings about urban cooling effects. Cold air transfluences can possibly be intensified by measures of urban and landscape planning. Cold air transfluences were detected through accidental findings of very intense cold air drainage flow in a suburban valley of the city of Aachen and a simultaneous flow of cold air over the watershed from a nearby valley, which does not belong to the catchment area in which the city of Aachen is situated. At two additional possible sites of cold air transfluence, automatic weather stations (AWS) were installed in January 2013, of which first results are presented here.

2. Study area, data and methods

2.1 Study area

Field work and model runs are carried out in small valleys in the suburban area of the city of Aachen, Germany (50°45'40" N, 6°04'20" E). The city is located in a basin with a diameter of 5-8 km and a relative depth of about 50-200 m. Small rivers like Kannegießerbach, Dorbach and Johannisbach have formed valleys with catchment areas of typically about 1 km^2 (*Fig. 1*). They extend from a low mountain ridge in the south-west towards the city centre in the north-east and have been subject to a set of climate investigations in the recent past (e.g. *Ketzler* et al. 2010). Cold air transfluences are currently under investigation in the two south-eastern catchments of Beverbach and Haarbach by the authors.

Aachen has been chosen as area of investigation because of its well-known urban climatology, size and geographical position. Aachen has about 250,000 inhabitants and is, thus, a medium-sized Central European city. The location in the surroundings of the Central European Uplands with altitude differences in the catchments of about 200 m constitutes a fairly typical situation for large areas in Central Europe. Additionally, urban and relief-induced cooling effects here proved to be in the same order of magnitude (*Ketzler* et al. 2006).

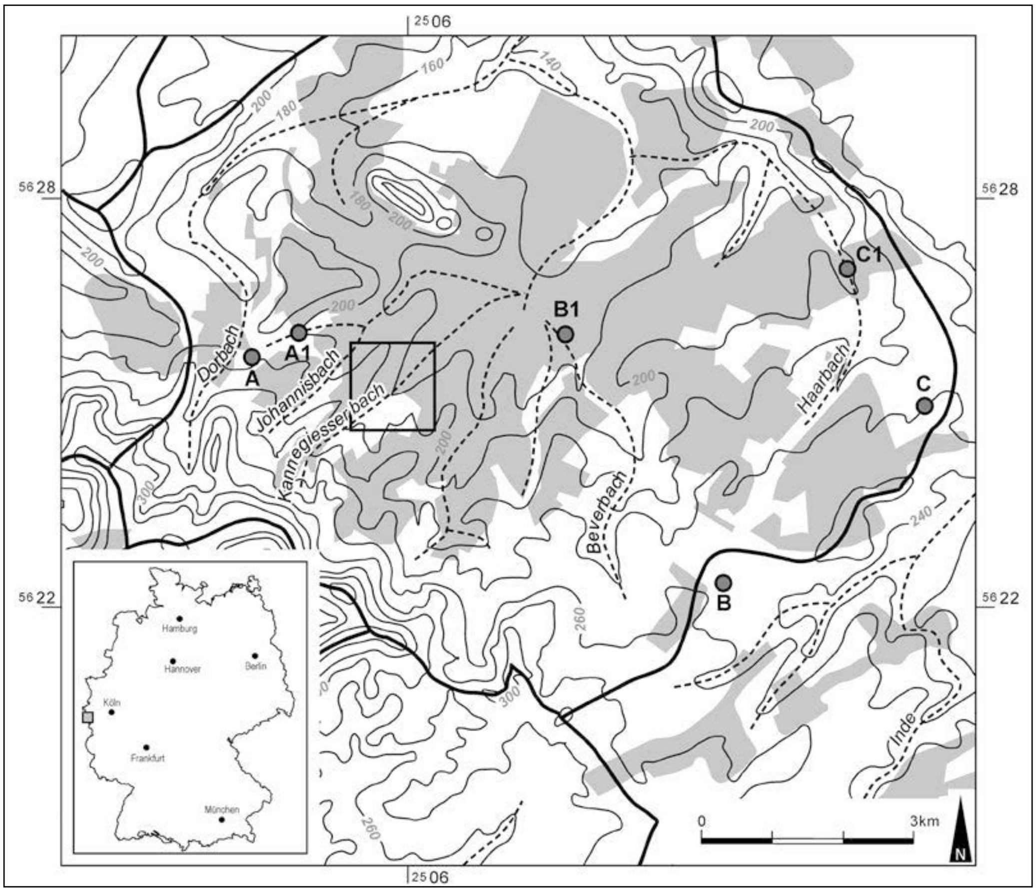

Fig. 1 Study area – small valleys and the hydrological drainage system in the city of Aachen (Germany). Solid lines: main watersheds, dashed lines: valley axes, grey: urbanised area in the city of Aachen, rectangle: special investigation area Kannegießerbach Valley with measurements and reference areas 1-14 (see 3.2), A, B, C: cold air transfluence areas, A1, B1, C1: reference areas for cold air transfluence analysis (see 3.3)

2.2 Land-use data

For the Kannegießerbach Valley, historical land use information for the year 1810 (*Fig. 2, A*) was derived from maps produced by French cartographers during the Napoleonic occupation (Landesvermessungsamt NRW 1973). Since these maps do not meet present-day data standards, the climatologically relevant information had to be filtered and analysed by means of historical analysis. The result is a generalised digital land-use map for the adjacent suburban areas (*Ketzler* et al. 2010). For the inner city, building structure data were taken from a cadaster map of 1812-1820 (Katasteramt Aachen n.d.). Urban structures in 1810 were characterised by low building heights and a very small city area with unpaved roads and extensive gardens. The building area and gardens did not exceed the medieval city walls. The surrounding landscape was a spacious agricultural area with few obstacles, like hedges or single trees (*Ketzler* et al. 2010).

The land use in 1910 (*Fig. 2, b*) is reliably recorded in maps of different types, beside topographic maps e.g. by technical maps of inner urban road types and maps of landscape architecture for the development of new park areas. From 1810 to 1910, the built-up area had increased considerably. In the area studied, mainly perimeter blocks had been developed in this period. Extensive industrial installations, like factories and mills in the built-up area and along the valley bottom, were developed. Furthermore, a railway embankment with a height of about 6 m – crossing the valley directly outside the 1910 city limits – formed a new obstacle for urban ventilation. The embankment's situation is visible in the map for 2010 as a ring-like open space around the city centre (*Fig. 2, c*).

The current land use in the valley ('2010'; *Fig. 2, c*) was obtained from official cadaster data and a vegetation model based on airborne radar data (*Ketzler* et al. 2010). The 3D building structure model of the regional administration (Bezirksregierung Köln 2013a) provides information on positions and types of building and on calculated building height. This information is transferred into nine building classes with heights from 3 up to 70 m (*Fig. 2*). Vegetation structure is calculated from radar data (*Ketzler* et al. 2010). Based on airborne interferometric synthetic aperture radar data (*Havlik* et al. 2000), a 2 m resolution surface elevation model was generated using kriging interpolation over the lowest original radar data points in all 50 m grids. The height difference between the original radar data and the surface elevation model outside the built-up area was used to derive a 4 m resolution vegetation canopy model. On the basis of field studies in the area of investigation, vegetation structures with an average height ≤ 3 m were defined as 'unsealed area', as 'park' with a height of > 3 m and ≤ 10 m, and as 'wood' with a height of > 10 m. Land-use information for non-built-up areas was obtained from digital cadaster data (Städteregion Aachen 2013) and transferred into the standard KLAM_21 land-use classes (*Sievers* 2005). All non-defined areas inside the city were assigned to a class 'half-sealed area', outside the city to a class 'unsealed' area.

Within the time period analysed (*Fig. 2*), the city grew substantially which resulted in a reduction of open space (all non-built-up areas like parks, gardens, agricultural areas e.g.) in the Kannegießerbach Valley cold air catchment from 3.37 km^2 in 1810 to 0.98 km^2 in 2010. Suburban high-standard housing areas have been developed especially along the ridges between catchments leaving the valley floor less developed (*Ketzler* et al. 2010). The open space area, mostly agricultural area in 1810, nowadays features park-like structures with groups of trees along the creeks.

Beside the historical and current situation, two different land use scenarios based on the present situation are developed for the investigation (*Fig. 2, d/e*). The 'best case' scenario represents improved cold air drainage flow conditions. A land-use pattern with the desired effect can be achieved by massively modifying the vegetation structures within the valley. The model shows the effects that could be theoretically obtained. In contrast, the 'worst case' scenario assumes massive urban development. According to vegetational aspects, this scenario seems to be even more realistic at the moment, as an increasing number of dense and high hedges and trees have grown up at the sides of the valley within the last few decades.

The 'best case' scenario keeps the same area of buildings and vegetation in the valley as in the present situation, but represents an alternative urban development with buildings and vegetation only situated along the valley slopes. The valley floor partly remains without buildings and free of higher vegetation stands. The 'worst case' development includes a substantial increase of the built-up

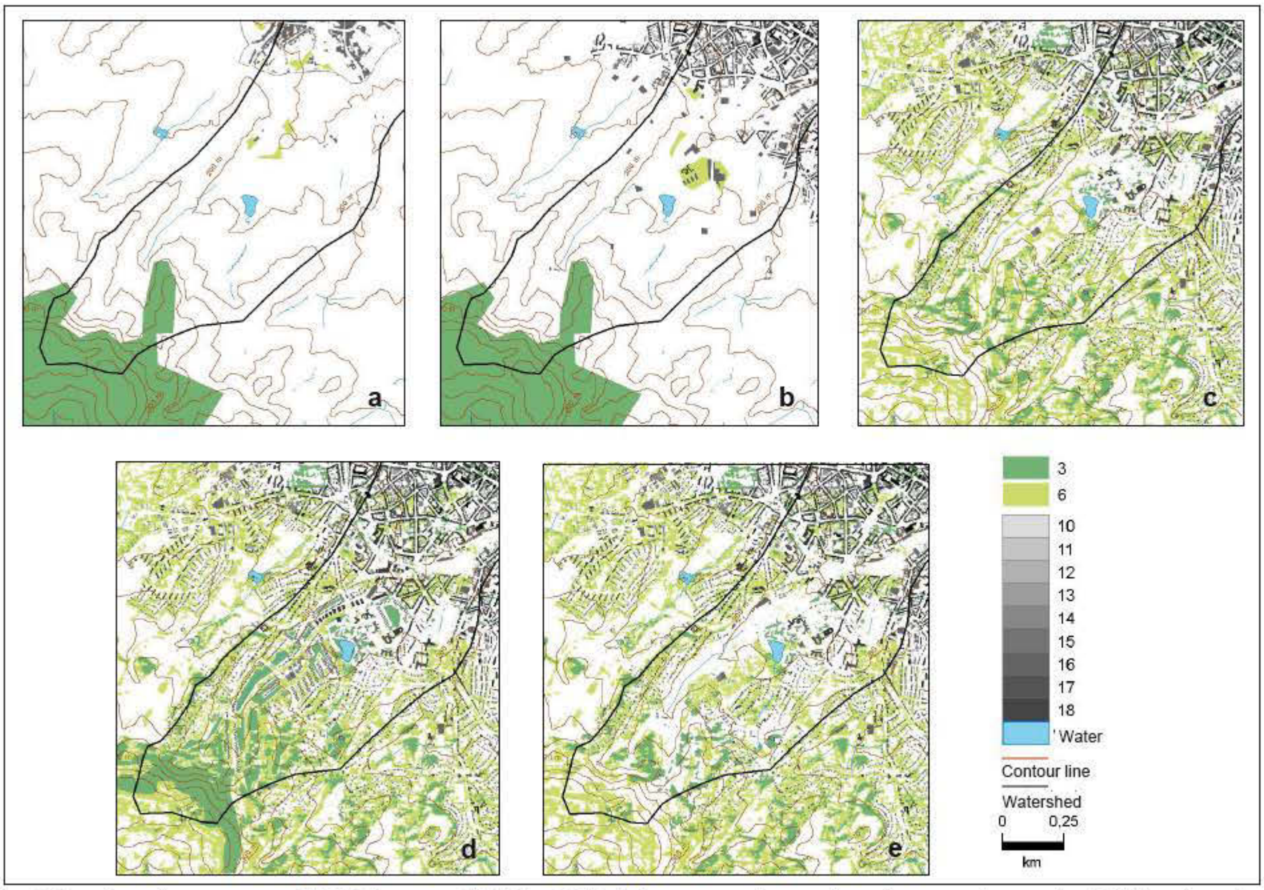

Fig. 2 Land-use data. a: around 1810, b: around 1910, c: 2010, d: 'worst case' scenario, e: 'best case' scenario; Buildings based on cadaster maps or data; agricultural and forestry areas not differentiated in 1810 and 1910; vegetation in 2010 modelled on the base of radar data. Land-use classes: 3: forest, 6: park, 10-14: low buildings in 3 m height classes, 15-18: high buildings to begin with 25 m in 10 m height classes, 9: water, open space land-use classes (4: half-sealed area, 7: unsealed area, 8: sealed area): all white and not differentiated in the map, classes 1, 2 and 5: not used.

area along the valley floor on account of a number of mostly single family and duplex type homes in combination with areas covered by high vegetation. Such a development is based on an estimated extrapolation of land-use changes and building applications in this cold air catchment in the past 30 years. It represents a development triggered by the currently high demand for high standard construction area. In both scenarios, the physical characteristics of the land use classes remain unchanged.

The built-up area in the cold air catchment area defined as the overall building area increased from 0.08 km^2 in 1810 (2.0 %) to 0.32 km^2 in 1910 (7.7 %), and to 0.61 km^2 in 2010 (14.4 %), while the open space decreased from 4.1 km^2 (1810) to 3.9 km^2 (1910), and to 3.6 km^2 (2010). The two future scenarios represent a built-up area of 0.61 km^2 in the 'best case' (identical with the situation in 2010; 14.4 %) and 0.71 km^2 in the 'worst case' scenario (16.9 %, the open space will decrease to 3.5 km^2).

2.3 Modelling, model data processing and measurements

KLAM_21 is a 2-dimensional numerical model for the calculation of cold air drainage flow in complex terrain (*Koßmann* and *Sievers* 2009, *Sievers* 2005). The model calculates temporal and spatial characteristics of nocturnal cold air drainage flow within a stable surface layer in a dry atmosphere. Based on land-use and orographic data, the model calculates energy loss, velocity and depth of a cold air layer (*Sievers* 2005). Land-use data and digital elevation data are transferred from a GIS system as input data for KLAM_21 with a horizontal resolution of 4 m (15 m for the investigation on cold air transfluence, see *3.3*). The model is run with the default values of KLAM_21, a standard value for net energy loss of -30 W m^{-2}, representing the overall energy balance of the cold air volume, and a standard urban start offset for surface temperature of 0.5 °C (*Sievers* 2005). All model runs are performed for a 3-hour period. The period is chosen because empirical data indicate a decrease in intra-urban cooling rate differences after about 3 h after sunset (*Holmer* et al. 2007). Model output is transferred back into the GIS system as average energy loss, height of cold air drainage and wind vectors. Energy loss is then processed to provide cold air cooling rates as a grid. The wind vectors and cold air height are used to calculate cold air volume flow. Subsequently, the results are mapped and analysed for reference areas in the lower central part of the valley. These reference areas of 2000 m² are each expected to be representative for different phases in urban development in the late 19th century, open space areas and parks along a longitudinal down valley section towards the city centre (see *3*).

The effect of cold air transfluence is analysed for the land-use situation for the year 2010 (Bezirksregierung Köln 2013b, USGS 2006) with a horizontal resolution of 15 m, comparing two different cold air transfluence scenarios. In one case a digital elevation model is used, which includes all external catchment areas with potential contribution to cold air transfluences. In the other case a digital elevation model was applied, which excludes all these external catchments.

Model validation is performed by comparing it with measured data in the study area. In the Kannegießerbach Valley (*Fig. 1*), the 2010 model results can be compared with recent measurements of temperature and cold air flow characteristics (*Sachsen* 2013). Cold air drainage flow data was collected by several automatic weather stations within the Kannegießerbach Valley to obtain information on cold air drainage flow frequency and characteristics from March 2009 to March 2011. The data was complemented by mobile cross valley section and tethered balloon measurements (*Sachsen* et al. 2012), as well as by measurements taken from busses carrying GPS equipment and temperature sensors (*Merbitz* et al. 2012, *Buttstädt* et al. 2011). Data related to cold air transfluences are collected by tethered balloon measurements at cold air transfluence area A and A1 (*Fig. 1*).

2.4 Validation of the data

The model results can be compared with data from recent field measurements (see *3.4*). The following data were used: Measurement data of evening cooling rates for the time 3 h after evening cooling begins is available from a frequency distribution of air temperature data taken from an automatic weather station (AWS) at reference area 2 in the Kannegießerbach Valley. Net radiation measured 2 m above ground and additional cold air depth data from single tethered balloon measurements are available for the points *A* and *A1* and *3* and the frequency of cold air transfluence events determined by AWS data at C (*Fig. 1, Fig. 8*).

3. Results

The following chapter includes the results of the model runs, first presenting general historical land-use changes and possible future developments for the area under study, Kannegießerbach Valley (*3.1*). In *Section 3.2* these changes and scenarios are analysed for different reference areas, before focusing on model results for the analysis of cold air transfluences in a greater catchment area (*3.3*). Finally, the model results are compared to results of field measurements (*3.4*).

3.1 Historical land-use changes and future urban development scenarios

The results indicate that nocturnal cooling in clear and calm nights for the time 3 h after nighttime begins differs substantially between the present (2010) and the historical situations (1810 and 1910). For the 1810 situation, modelled cooling is very intense (up to 3.7 K), and apparently, the whole basin in which the present city is located was filled up with a cold air pool (*Fig. 3, a*). The figure additionally shows a decrease in cooling in great parts of the area under study of about 0.5 K in the 1910 situation (centre) compared with 1810 and 1.0-1.5 K in 2010 compared with 1810. The decrease occurs both in the oldest parts of the city centre and for the districts developed ever since. A pronounced decrease in cooling rates of about 1.5 K was found in the results for 2010 for the areas downstream in the inner city and on the lateral watersheds (*Fig. 3, c*). These areas are almost devoid of cold air in 2010 even in the downstream parts of the valley. Both findings were different in the case of 1810 and only to a small degree in the simulation of the situation of 1910.

The results for different future land-use scenarios show further changes in nocturnal cooling (*Fig. 4*). For the 'worst case' scenario (*Fig. 4, b*), cooling is additionally reduced by approximately 1.0 K compared to the situation in 2010 for the city centre (in the north-east of the study area). For the 'best case' scenario (*Fig. 4, c*), cooling in the central valley area increases slightly.

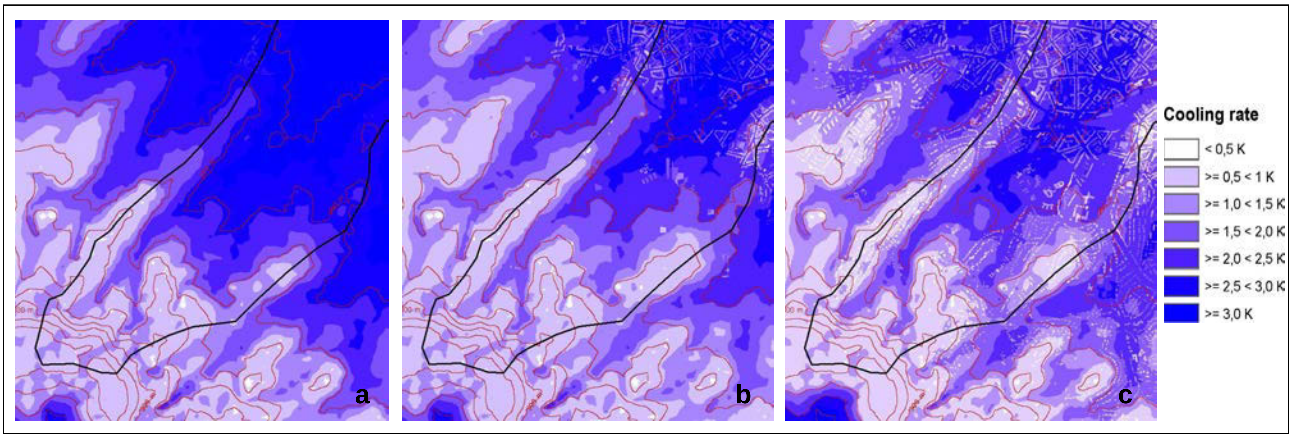

Fig. 3 Nocturnal cooling in Kannegießerbach Valley for the situation in 1810 (a), 1910 (b) and 2010 (c) during the first 3 h after sunset.

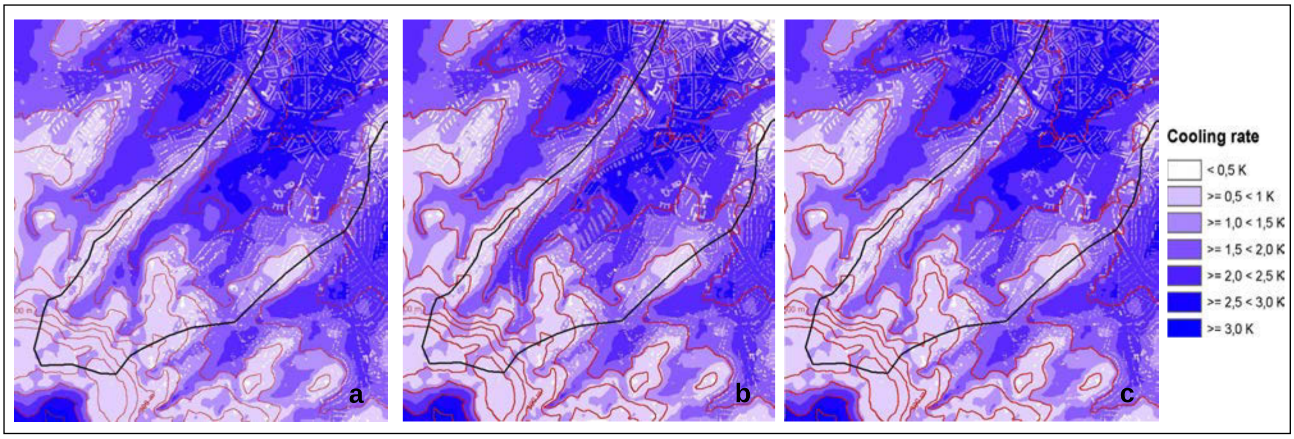

Fig. 4 Nocturnal cooling in Kannegießerbach Valley for the present situation (2010; a), a 'worst case' scenario (b) and a 'best case' scenario (c) during the first 3 hours after sunset.

Figure 5 (*a*) shows the details of the cooling differences for the 'worst case' scenario compared to the 'best case' scenario. A substantially decreased cooling of more than 0.5 K occurs in the city centre (red color) while the upstream parts of the catchment partly cool more (up to -0.5 K, blue color). Intensified cooling in the 'best case' scenario compared to the 2010 situation (*Fig. 5, b*) is weak for the time 3 h after evening cooling begins (0.1-0.3 K) and is concentrated in the inner city. After evening cooling begins (+ 1.5 h), cooling is more intensive but located more upstream from the inner city (*c*). This indicates that the enhanced cooling effect in the 'best case' scenario mainly has the characteristics of a wave running down the valley through the urban area in the early evening.

While evening cooling generally decreases in the present urbanised areas from the 1810 over the 1910 and the 2010 towards the 'worst case' scenario, cold air volume flow intensity increases in the 1810-1910 period and decreases not until 1910 (*Fig. 6*). In the 'best case' scenario, cold air volume flow is intensified clearly as compared to 2010 (*Fig. 7*), whereas evening cooling is only slightly intensified (*Fig. 4*). In the 'best case' scenario the cold air flow is focused on the valley axis, while in the 'worst case' the flow is weaker and more braided than in 2010.

3.2 Reference areas

The evening cooling data extracted at the 2000 m^2 reference areas (*Fig. 8*) for the different model runs are presented in *Table 1*. The results show decreasing cooling rates in the inner city as represented by mean values of areas 10-14 of 3.62 K (1810), 2.84 K (1910) and 2.38 K (2010). This is a total reduction of 0.78 K in the first and of 0.46 K in the second period.

The additional cooling reduction of the 'worst case' scenario compared to the present situation is

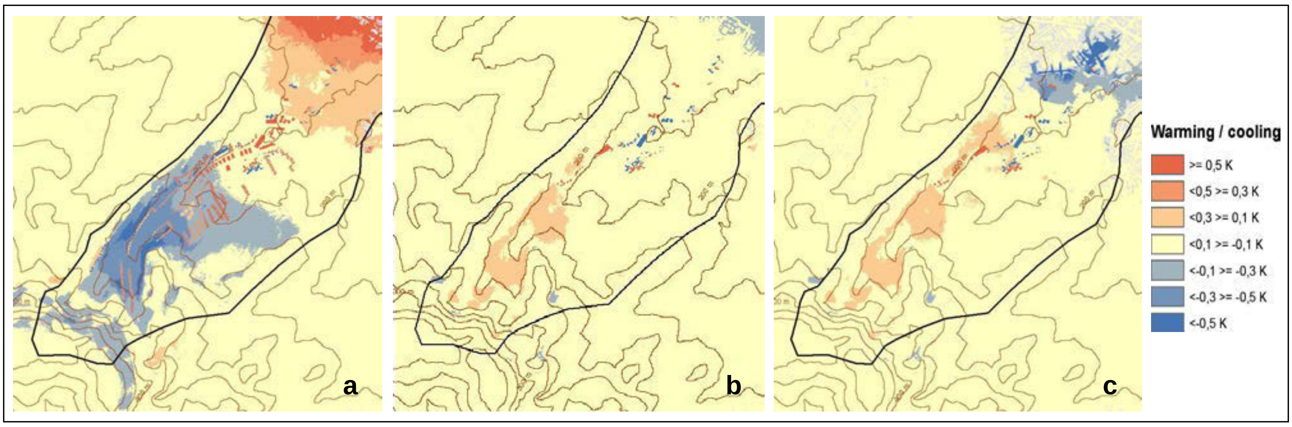

Fig. 5 *Changes in nocturnal cooling. a: differences between 'worst case' scenario and 'best case' scenario 3 h after evening cooling begins, b: differences between 'best case' scenario and 2010 situation 3 h after evening cooling begins, c: differences between 'best case' scenario and 2010 situation 1.5 h after evening cooling begins*

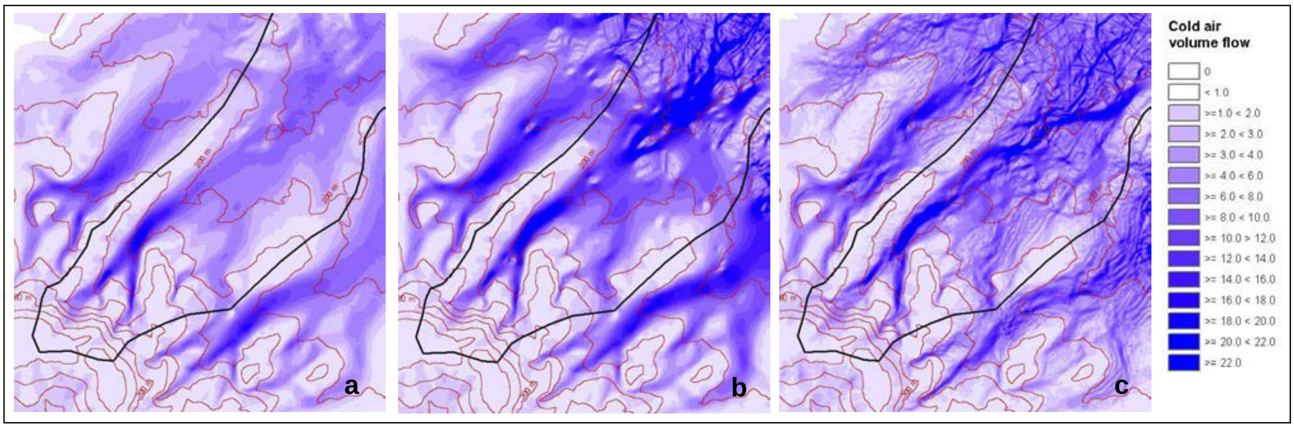

Fig. 6 *Cold air volume flow [m^3 m^{-2} s^{-1}] in the Kannegießerbach Valley for the situation in 1810 (a), 1910 (b) and 2010 (c).*

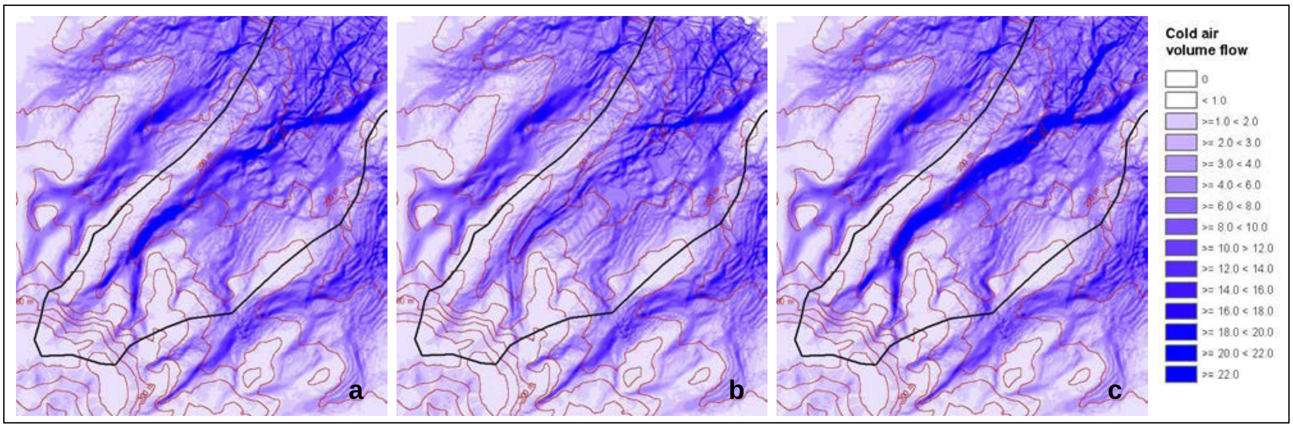

Fig. 7 *Cold air volume flow [m^3 m^{-2} s^{-1}] in Kannegießerbach Valley for the present situation (2010; a), a 'worst case' scenario (b) and a 'best case' scenario (c).*

0.62 K. The increased cooling in the 'best case' scenario compared to 2010 is small with an average of 0.1 K for the reference areas 10-14 and a maximum value of 0.2 K in the densely developed part of the inner city (14). However, results of model runs for 1.5 h after the evening cooling begins show considerable differences located upstream of the inner city. At reference area 11 for example, the modelled evening temperature is 0.6 K lower in the 'best case' scenario compared to the situation in 2010.

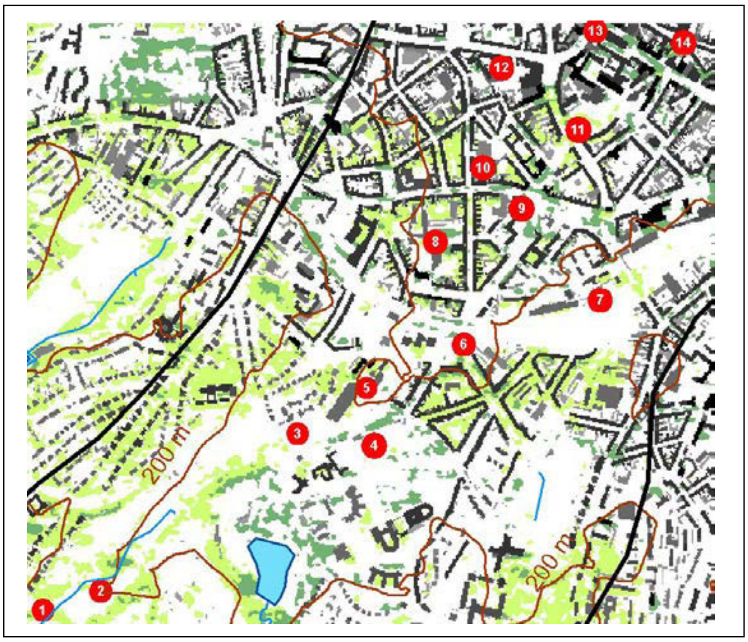

Fig. 8 Location of reference areas in the Kannegießerbach Valley (legend as in Fig. 2) for data presented in Tab. 1 and as discussed in the text

Table 1 shows different area types having partly different effects from land-use changes on evening cooling. The reference areas situated in the upper parts of the valley and outside the present developed area cool down, in part, more intensely in 2010 than in 1910. Even the 'worst case' scenario shows partially higher cooling rates (e.g. "Brüsseler Ring") (*Fig. 5 a*). The transition from increased to decreased cooling takes place between reference area 5 and 6 and, thus, near the building line.

In all inner city areas, evening cooling has decreased since 1810. The reduction from 1910 to 2010 is moderate in the courtyards (0.2 K and 0.3 K at areas 8 and 10) and very variable for open spaces (0.1 K for the suburban areas 5 and 6, 0.3 K and 0.1 K between the perimeter blocks at areas 9 and 11 and 0.4 K and 1.0 K in the city centre at 13 and 14). According to the model results, cooling rates for the 'worst case' scenario would continue to decrease and the evening cooling in the inner city areas 12-14 would finally fall by more than 50 % in relation to 1810 with a maximum value of 2.6 K.

In the present developed area, between the 1910 and the 2010 model runs, cold air volume flow decreases substantially from 19.8 to 11.7 $m^3\ m^{-2}\ s^{-1}$ (*Tab. 2*). In contrast to this, this volume generally increases for the reference areas upstream of area 7 (*Fig. 8*). In the 'worst case' scenario, cold air volume flow decreases at all reference areas compared to 2010. At reference area 14, the reduction in the 'worst case' scenario is 74 % compared with that of 2010 and 87 % compared with 1910. Here, the reduction in 2010 compared with 1910 is 51 %. The 'best case' model run leads to a generally increasing cold air volume flow when compared to that of 2010. The average increase at the urbanised reference areas 10-14 is 5 %.

While for all reference areas the 1810 model run shows the highest evening cooling rates of the historical modeling, the cold air volume flow values of 1810 are smallest with the exception of area 12. However, cold air volume flow has its maximum mostly in the 1910 model run with the exception of areas 2-6. These areas have a maximum value in the 2010 model run.

3.3 Cold air transfluences from external catchment areas

The results of the model runs for the whole Aachen basin show sites of cold air transfluence for which the areas around A, B and C are analysed (*Fig. 9*). Model results are extracted for reference areas representing built-up areas affected by cold air transfluence (see *A1, B1* and *C1, Fig. 1*). The distance between the reference areas and the sites of cold air transfluence is 0.6 km at *A1* and about 3.9 km in both other cases. The urban area affected by a cooling difference like at *A1* is small (0.5 km^2), but it is

Tab. 1 Modelled cooling for 3 h after evening cooling (K) begins for reference areas in Kannegießerbach Valley. Results for different land use patterns connected to different urban development phases

Reference area	Type	1810	1910	2010	Best case	Worst case
1 Brüsseler Ring	Meadow	2.2	1.7	2.0	1.8	2.1
2 Kannegießerbach	Meadow	2.6	2.1	2.3	2.2	2.4
3 Goethestraße	Car park	3.1	2.6	2.6	2.6	2.4
4 Altes Klinikum	Park	3.1	2.6	2.7	2.6	2.6
5 Schillerstraße	Public space	3.3	2.8	2.7	2.8	2.6
6 Goethestraße	Public space	3.4	2.9	2.8	2.8	2.6
7 Central Station	Railway track	3.2	2.6	2.4	2.4	2.3
8 Südstraße	Courtyard	3.4	2.8	2.6	2.5	2.5
9 Boxgraben	Public space	3.6	3.0	2.7	2.7	2.6
10 Kasernenstraße	Courtyard	3.6	2.8	2.5	2.5	2.3
11 Franzstraße	Public space	3.6	2.9	2.8	2.9	2.5
12 Krankenhaus	Park	3.6	2.8	2.3	2.4	1.8
13 Stadttheater	Public space	3.7	2.9	2.5	2.6	1.7
14 Wirichsbongard	Public space	3.6	2.8	1.8	2.0	1.0
Mean cooling (10-14)		**3.62**	**2.84**	**2.38**	**2.48**	**1.86**

larger in both other cases which are related to the larger areas of cold air transfluence. In the tributary valley of Johannisbach Valley (*A1, Fig. 1*), the difference between the model results with external catchments included and excluded is substantial. The additional cooling effect by cold air transfluence is 1.9 K (*Tab. 3*). At reference area *B1* and *C1* the effect is considerably smaller or absent. Cold air volume flow in the reference areas increases when cold air transfluences are enabled in the model. At reference area *A1* the effect is 176 %; at the other areas it is much smaller (*B1*: 8 %, *C1*: 1 %, *Tab. 3*).

3.4 Comparison with measurements

Evening cooling as calculated in the 2010 model run is compared with recent temperature data of an automatic weather station (AWS) in the Kannegießerbach Valley ('Brüsseler Ring'; *Fig. 8, A1*) for the period March 2009 to March 2011. For this comparison, AWS data for the evening hours were filtered to exclude all days with or without questionable cold air drainage flow conditions in the evening. For the remaining days with optimal conditions, average evening cooling during the first 3 h after sunset is 3.1 K. The modelled evening cooling for this site is 2.0 K. When the modelled data are compared with a frequency distribution of measured evening cooling, the model data represent a situation which is attained or exceeded in 75 % of all cases with favourable conditions for cold air drainage.

In the evening of 25th September 2009, during a calm and clear night, tethered balloon measurements were performed at reference area 2 (*Fig. 8*). Cold air depth was determined to be 32.8 m. For the evening hours of this day, an average net radiation of 31 W m^{-2} was observed. The modelled cold air depth was 25.5 m. To compare these two results, model and measured heat flux conditions have to be analysed. The model run is

Tab. 2 Modelled cold air volume flow for 3 h after night time begins ($m^3\ m^{-2}\ s^{-1}$) for reference areas in Kannegießerbach Valley. Results according to Table 1

Reference area	Type	1810	1910	2010	Best case	Worst case
1 Brüsseler Ring	Meadow	11.4	16.8	16.5	20.8	11.9
2 Kannegießerbach	Meadow	10.2	17.6	19.2	20.0	12.0
3 Goethestraße	Car park	5.0	20.1	23.7	25.9	5.1
4 Altes Klinikum	Park	7.5	9.0	14.6	8.0	9.9
5 Schillerstraße	Public space	5.1	11.5	15.4	29.8	13.8
6 Goethestraße	Public space	7.9	25.8	26.5	25.2	23.3
7 Central Station	Railway track	7.1	14.7	13.9	9.1	12.6
8 Südstraße	Courtyard	6.2	18.0	17.5	17.2	15.8
9 Boxgraben	Public space	8.2	28.2	16.6	22.8	15.8
10 Kasernenstraße	Courtyard	4.8	19.8	11.6	9.0	10.6
11 Franzstraße	Public space	4.3	24.2	17.6	20.6	17.1
12 Krankenhaus	Park	5.6	8.9	5.3	5.7	3.1
13 Stadttheater	Public space	1.1	20.7	11.6	12.4	7.2
14 Wirichsbongard	Public space	4.4	25.4	12.4	13.7	3.3
Mean (10-14)		**4**	**19.8**	**11.7**	**12.3**	**8.3**

performed with the KLAM_21 model standard energy loss, a cold air energy balance of -30 W m^{-2} (*Sievers* 2008). This is very close to the measured net radiation in the specific night. Since the other fluxes of the energy balance (except for radiation), such as sensible, latent and ground heat flux, are expected to be small but positive in total, the measured net radiation is expected to represent an energy balance which is less negative than 31 W m^{-2}. Thus, the measured situation represents a slightly less negative energy balance than the model run and, accordingly, the model underestimates the cold air depth by at least 22 %.

Results from tethered balloon measurements on 13th October 2010 in a calm and clear night at *A1* in the axis of the tributary valley of Johannisbach Valley (*Fig. 1*) can be compared with model results. From the measurements, at *A1* a cold air depth of 32.5 m and an average cold air speed of 0.16 m s^{-1} can be calculated, resulting in a cold air volume flow of 5.2 $m^3\ m^{-2}\ s^{-1}$. During the evening hours, average net radiation was -57.9 W m^{-2}. The measured cold air volume flow clearly exceeds the value of 2.5 $m^3\ m^{-2}\ s^{-1}$ of the model run without cold air transfluences, but is less than the 9.4 $m^3\ m^{-2}\ s^{-1}$ with cold air transfluences enabled. Since the high value of cold air volume flow may, at least partly, be caused by considerable negative net radiation, this result is not necessarily caused by cold air transfluence. In order to gather additional information on cold air transfluence, a tethered balloon measurement on the watershed (*Fig. 1*, *area A*) is analysed. As a result, a flow of air colder than the surroundings from the neighbouring Dorbach Valley into the catchment was observed, which is not caused by the synoptic airflow. The quantity of additional cold air volume flow through a 100 m wide watershed section free of obstacles with a cold air layer depth of about 17.5 m and an average wind speed of 0.25 m s^{-1} is calculated to 440 $m^3\ s^{-1}$. The model results show a cold air volume flow of about 1170 $m^3\ m^{-2}\ s^{-1}$ on the

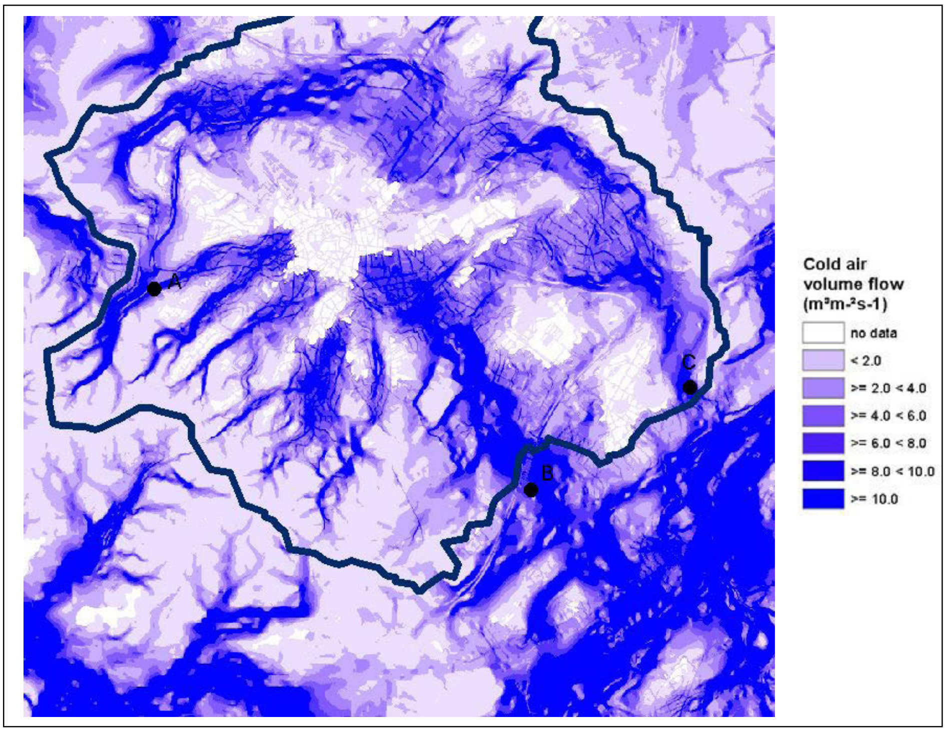

Fig. 9 Modelled cold air volume flow in the study area according to Figure 1 and sites of cold air transfluence A, B and C (solid line: main watershed of Aachen basin)

watershed into the catchment (*A1, Fig. 1*). Thus, cold air transfluence with considerable quantity is both observed and reproduced by the model even though absolute values differ considerably between measurement and model due to model configuration and model design. Since measurements were only performed in one night, the difference between measurements and model cannot be analysed in more detail.

Two AWS are operated on the watersheds between Inde, Beverbach and Haarbach Valley (at points *B* and *C, Fig.1*). Data of the ongoing measurements are available for *C*. AWS data are analysed to verify the existence and frequency of events of cold air transfluence. Wind speed, wind direction and air temperature are measured at a height of 6 m above ground level (a.g.l.) which corresponds to 50 % of the modelled cold air depth at the site. For the evaluation events of cold air transfluence on these watersheds are defined as follows: Wind has to be directed from the Inde Valley into the Beverbach Valley (> 125° and < 200°), respectively Haarbach Valley (> 100° and < 190°) with a deviation from the reference station AC-Hoern of > 30° (*Fig 1.*). Air temperature has to be > 1 K cooler than at reference station AC-Hoern outside the cold air transfluence area. These conditions were observed in 15 of 92 nights (16 %) in the period March to May 2013 for at least 3 h. The frequency of these events is close to the frequency of cold air flow events of 25 % in open valleys in Aachen based on other data (*Ketzler*

Tab. 3 Modelled cooling (K) and cold air volume flow ($m^3\ m^{-2}\ s^{-1}$) 3 h after night time begins for reference areas of cold air transfluence in Aachen. Results of two model runs with cold air transfluence enabled (e) and disabled (d).

Reference area	**Cooling** (K) e	d	**Difference** (K) e - d	**Cold air volume flow** ($m^3\ m^{-2}\ s^{-1}$) e	d	**Difference** ($m^3\ m^{-2}\ s^{-1}$) **e - d** (**% increase** e / d)
A1	2.6	0.7	1.9	9.4	2.5	6.9 (176 %)
B1	2.9	2.7	0.2	10.5	9.7	0.8 (8 %)
C1	2.0	2.0	0.0	7.2	7.1	0.1 (1 %)

2002). This is consistent with the result in the study of Sachsen et al. 2012. In this study cold air drainage flow occurs in 26.5 % of all nights (see *2.3*) in the Kannegießerbach Valley. The latter was also obtained without consideration of events in nights with the same wind direction in and outside the valley. Since the measurement height of 6 m above ground represents the centre of the modelled cold air depth of 12 m at this site, it is assumed that the measured events at least approximately represent the modelled cold air transfluence events, also with respect to other cold air characteristics regarding temperature and volume flow. At area B some events of cold air transfluence were detected. However, the measurement site proved to be too far away from the cold air transfluence site. Therefore, the measurement site had to be changed resulting in an incomplete dataset. Altogether, we conclude that cold air transfluence events detected in the model results actually occur with remarkable frequency and considerable cold air volume flow.

4. Discussion

Model results show decreasing evening cooling rates from 3.62 K in 1810 to 2.84 K in 1910, and to 2.38 K in 2010 in the inner-city area of Kannegießerbach Valley as the result of historical land-use changes. This amounts to a total reduction of 1.24 K in the whole period (*Tab. 1*). For the 'worst case' scenario the cooling rate would be reduced by an additional 0.62 K, while the 'best case' scenario would lead to slightly increased cooling rates, especially in the early evening. According to model results, cold air volume flow decreased from 19.8 m^3 m^{-2} s^{-1} to 11.7 m^3 m^{-2} s^{-1} in the period from 1910 to 2010 in the inner city (*Tab. 2*), while it increased in the upper part of the valley, characterised by grassland and single trees. For the 'worst case' scenario, the reduction is 74 % compared with 2010 and 87 % compared to 1910 in the inner city (*Tab. 2*, reference area 14). The 'best case' scenario shows slightly increasing cold air volume flow compared to 2010 at most of the reference areas (10 % at reference area 14, *Tab. 2*) and a reduction in the built-up area (46 % at reference area 14, *Tab. 2*) compared to 1910. Contrary to the evening cooling, the 1810 and 1910 model runs show a change of cold air volume flow with smaller values for 1810 and the 1910 model run representing optimal conditions.

In three valleys of the Aachen basin, cold air transfluences beyond watersheds were analysed. The modelled additional cold air transfluence cooling and volume flow effect is considerable in a small catchment situated near the inner city (1.9 K, 6.9 m^3 m^{-2} s^{-1}, *Tab. 3*) and small in greater catchments, especially those far away from the transfluence site (*Tab. 3*). Furthermore, it is shown that greater transfluences affect greater areas.

As a comparison with measurements shows, modelled evening cooling in Kannegießerbach Valley outside the built-up area represents a typical to slightly underestimated situation which is attained or exceeded in 75 % of all nights with good cold air drainage conditions. The modelled cold air depth is slightly smaller than observed (based on measurements in one night with conditions comparable to model settings). Cold air transfluences as found from model results have proved to exist at all three areas of cold air transfluence indicated by the model (*Fig. 9*), while intensity and frequency cannot yet be reliably evaluated.

In an earlier study on Kannegießerbach Valley, using an alternative model (SIMKLA, developed at RWTH Aachen, *Ketzler* et al. 2010) and low-resolution land-use data for only the 1810 and 2010 situation, a reduced evening cooling of 1.7 K was calculated for a reference area (*Ketzler* et al. 2010). This area is located around the reference areas 10 to 14 (*Fig. 8*). These reference areas show an average cooling rate reduction of 1.24 K in the present study (*Tab. 1*). While cold air volume flow decreased from 1810 to 2010 in the study of *Ketzler* et al. 2010 (38.0 to 25.8 m^3 m^{-2} s^{-1}), this is only the case for the period of 1910 to 2010 according to the KLAM_21 model results (19.8 to 11.7 m^3 m^{-2} s^{-1}). In the present study, the 1810 volume flow is much smaller (4.0 m^3 m^{-2} s^{-1}) and even the 2010 flow is considerably smaller than in the earlier study. While the different cooling rates, in comparison to the models, are small, and additionally there are indications for slightly underestimated cooling rates in KLAM_21, the reduction of evening cooling for the period 1810-2010 can be finally estimated to be between the values of 1.24 K and 1.7 K, or approximately 1.5 K. The future scenarios modelled with KLAM_21 may, thus, also be realistic in the order of magnitude, possibly appear to underestimate the temperature effects. *Ketzler* et al. 2010 found indications for the overestimation of volume flow of their model with 4700 m^3 s^{-1} vs. measured 1700 m^3 s^{-1} along a profile at the building line (*Ketzler* et al. 2010). This relation of a factor of almost three is in the same order of magnitude as the relation between the above-named results of both models for 2010 in the inner city, which has a factor of 2.21. Thus, there is some indication that the results of cold air volume flow using KLAM_21 are close to reality.

An increased, rather than decreased, cold air volume flow between the 1810 and 1910 KLAM_21 model runs would not be expected as an effect of the land-use changes in the valley, such as the new railway embankment crossing the valley and the urban development. Since the valley gradient declines towards the inner city, which is situated in the centre of a basin, the 1810 situation is characterised by cold air accumulation. This may be related to the formation of a cold-air pool in the whole basin. Thus, cooling is considerable but cold air flow is retarded. A possible explanation for more intense cold air drainage flow in spite of urban development is an overcompensation mechanism. Decreasing evening cooling and increasing volume flow might be the effect of an urban heat island of at least minimal intensity and extent, which reduces cold air accumulation without completely dissolving the cold air. This might be combined with the formation of an urban-rural circulation. The decreasing volume flow in the later period of 1910 to 2010 coincides with further urban development ('suburbanisation') and enhanced energy use. At the same time the vegetation structure has changed towards higher vegetation (e.g. trees, hedges) with more friction as a result of less intense agriculture and more park like landscape conservation.

The differences between 'best case' scenario, 'worst case' scenario and the 2010 model run indicate the existence of a tipping point. For reference areas 1-9 in the rural and suburban part of the valley the cooling differences between the scenarios are small. From area 10 to 14, in the inner city, the three model results diverge. Especially the cooling reduction in the 'worst case' is considerable.

The different change of evening cooling and, in part, cold air volume flow in the upper and lower part of the catchment – especially since 1910 and for the 'worst case' scenario as resulting from model runs – cannot be caused by direct urban warming alone. As cooling and volume flow, in part, not only decrease in the lower and stay constant in the upper valley, but also partially increase in the upper valley, a secondary effect of urban development must exist. This is probably due to cold air flow retard caused by increased friction, which has a damming effect and leads to cold air accumulation in the upper valley, a partially increased slope in the upper cold air and increased flow intensity. Another special effect, caused by reduced obstacles in the 'best case' scenario, is the intensified early evening cooling (1.5 h after beginning of the night) despite almost unchanged cooling rates during the later evening (+3.0 h). This is supposed to be a consequence of reduced friction, which leads to faster cold air flow and, thus, earlier onset of evening cooling downstream.

Reduced evening cooling during clear and calm nights as an effect of historical and possible future land-use changes is superimposed by long-term temperature trends. Thus, for urban areas in the Kannegießerbach Valley, it is not only the general temperature trend of 1.5-2.0 K in the last 200 years – as discussed above – which is relevant. Since the weather stations used for this 200-year time series are not situated in valleys with intense cold air drainage, a reduced local cold air effect due to urban development in the valley itself also has to be considered as it induces additional nighttime warming. As described above, this effect of reduced evening cooling in clear and calm nights can be expected to be in the range of 1.5 K or more. Until 2050, the predicted increase in air temperature of + 1.9 K will also likely be intensified by further reduction of cold air effects with additional evening warming of + 0.5 K in the 'worst case' scenario. As such effects are typically connected to clear sky conditions and, thus, to hot days, the evening of a typical hot day in the inner city of Aachen following the 'worst case' scenario in 2050 might not only be + 1.9 K but + 2.4 K warmer than in 2010. Such effects may be regarded as typical for many European cities in valleys.

However, mitigation effects of a 'best case' scenario with similar building and vegetation development, but improved arrangement in relation to cold air drainage flow compared to 2010, especially including a cold air pathway free of obstacles, would lead to slightly enhanced cooling in the built-up area; this area would see a maximum of up to 0.6 K at least for early evening hours upstream of the inner city. In some areas, cold air transfluence from other catchments can lead to intensified evening cooling. The effect is small in terms of temperature reduction in two cases (up to 0.2 K) and up to 1.9 K in one case (*Tab. 3*). There is some indication of an inverse relation between cooling effect and distance to areas of cold air transfluence with respect to the affected area. In the case of considerable temperature effects, cold air transfluence is clearly intensified by a line of poplars blocking the main valley and forcing air flow over the watershed. In the other cases, there is an indication of a reduced cold air transfluence due to trees or buildings on the watershed. Thus, these effects may also be used for mitigation strategies inasmuch as vegetation arrangement is variable. For mitigation strategies related to cold air drainage flow, appropriate vegetation patterns are generally of particular importance. Since existing building structures along ventilation paths cannot be easily moved, adapted arrangement of vegetation can contribute to enhanced cold air flow without necessarily reducing vegetation quantity.

The ratio of evening cooling in the present city centre ('mean cooling' in *Tab. 1*) and open space area in the cold air catchment (see *2.2*) decreases from 0.87 K km^{-2} in 1810 to 0.73 K km^{-2} in 1910, and to 0.66 K km^{-2} in 2010 and is 0.53 K km^{-2} in the 'worst case' scenario. A linear extrapolation of the data would imply that evening cooling by cold air drainage might not exist at all in the city centre in the case of a decrease of the open space area in the cold air catchment to values smaller than 2.5 km^2.

5. Conclusion

Historical and future changes in land use show considerable effects on cold air drainage in suburban valleys and, thus, on urban cooling effects within cities. In a historical perspective, the cooling rates decrease from 3.62 K in 1810 to 2.38 K in 2010. Scenarios for the future show a further decrease caused by continuing urbanisation (1.86 K). A scenario with optimised ventilation pathways shows a high cooling potential of 2.48 K. The effects of urban cooling can be even enhanced by increasing volumes of cold air flowing towards the city centre as a result of cold air transfluences. Depending on the reference area, even the main cooling potential can be attributed to cold air transfluence (1.9 K of 2.7 K). Consequently, a critical review on land use changes, caused by building activities or growth, planting and reduction of vegetation within suburban valleys can be helpful to city planners, as cold air drainage can be affected both positively and negatively.

In general, a good match between modelled and measured data has been achieved by using high-resolution land use data. This allows the results of KLAM_21 to be transferred to surrounding valleys. As a further step, the interdependency of cold air and the urban structure, e.g. regarding heat flux rates, has to be analysed in detail to improve inner-urban model results of KLAM_21.

Acknowledgements

The project 'City 2020+' was funded by the Excellence Initiative of the German federal and state governments through the German Research Foundation (*Deutsche Forschungsgemeinschaft, DFG*). Regional cold air drainage flow analysis is a subtopic of the INTERREG-IVa project PMLAB financed by the European Union. Land-use data was kindly provided by Bezirksregierung Köln and Städteregion Aachen. The comments from two anonymous reviewers on this paper largely improved this manuscript and are gratefully acknowledged.

References

Bezirksregierung Köln 2013a: 3D-Gebäudestrukturen (3D-GS). – Online available at: http://www.bezreg-koeln.nrw.de, 24/06/2013

Bezirksregierung Köln 2013b: ATKIS – Basis-DLM. – Online available at: http://www.bezreg-koeln.nrw.de, 24/06/2013

Bigg, G.R., S.M. Wise, E. Hanna, D. Mansell, R.G. Bryant and *A. Howard* 2012: Synoptic climatology of cold air drainage in the Derwent Valley, Peak District, UK. – Meteorological Applications, published online first – doi: 10.1002/met.1317

Buttstädt, M., T. Sachsen, G. Ketzler, H. Merbitz and *C. Schneider* 2011: A new approach for highly resolved air temperature measurements in cities. – Atmospheric Measurement Techniques **4**: 1001-1019

Chow, W.T.L. and *B.M. Svoma* 2011: Analyses of nocturnal temperature cooling-rate response to historical local-scale urban land-use/land cover change. – Journal of Applied Meteorology and Climatology **50** (9): 1872-1883

Clements, C.B., C.D. Whiteman and *J.D. Horel* 2003: Cold-air-pool structure and evolution in a mountain basin: Peter Sinks, Utah. – Journal of Applied Meteorology and Climatology **42** (6): 752-768

Coutts, A.M., J. Beringer and *N.J. Tapper* 2008: Investigating the climatic impact of urban planning strategies through the use of regional climate modelling: a case study for Melbourne, Australia. – International Journal of Climatology **28** (14): 1943-1957

Della-Marta, P.M., M.R. Haylock, J. Luterbacher and *H. Wanner* 2007: Doubled length of Western European summer heat waves since 1880. – Journal of Geophysical Research **112** (D15)

Havlik, D. und *G. Ketzler* 2000: Gesamtstädtisches Klimagutachten Aachen. – Aachen

Holmer, B., S. Thorsson and *I. Eliasson* 2007: Cooling rates, sky view factors and the development of intra-urban air temperature differences. – Geografiska Annaler **89** (4): 237-248

IPCC – Intergovernmental Panel on Climate Change (2007): Fourth assessment report (AR4) – climate change 2007: impacts, adaptation and vulnerability. – Online available at: http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg2_report_impacts_adaptation_and_vulnerability.htm, 15/05/2013

Katasteramt Aachen (n.d.): Urkataster 1812-1820. – Aachen

Ketzler, G. 2010: Die Aachener Temperaturreihe 1829-2009. – In: *Schneider, C.* und *G. Ketzler* (Hrsg.): Beiträge zur Klimaforschung in Aachen. Sonderausgabe zum 30-jährigen Bestehen der Klimamessstation Aachen-Hörn des Geographischen Instituts der RWTH Aachen. – Aachener Geographische Arbeiten **47**: 17-23

Ketzler, G., K. Eßer und *T. Sachsen* 2010: Veränderung von Belüftungsfunktionen durch lokalen Kaltluftabfluss im Zuge historischer Stadtentwicklung – eine Modellstudie Aachen 1810-2010. – In: *Schneider, C.* und *G. Ketzler* (Hrsg.): Beiträge zur Klimaforschung in Aachen. Sonderausgabe zum 30-jährigen Bestehen der Klimamessstation Aachen-Hörn des Geographischen Instituts der RWTH Aachen. – Aachener Geographische Arbeiten **47**: 77-97

Ketzler, G., C. Schneider, D. Havlik and *G. Peschel* 2006: Analysis of urban climate and detection of urban climate change in the city of Aachen over a 30-year period. Temperature variation and trends in complex terrain. – In: Proceedings of the 6th International Conference on Urban Climate, June 12-16 2006, Göteborg, Sweden

Koppe, C., S. Kovats, G. Jendritzky and *B. Menne* 2004: Heat waves: Risks and responses. – Health and Global Environmental Change Series **2**. – World Health Organization, Regional Office for Europe. – Copenhagen

Koßmann, M., S.W. Hoch, C.D. Whiteman and *U. Sievers* 2009: Modelling of nocturnal drainage winds at Meteor Crater, Arizona using KLAM_21. – Annalen der Meteorologie **44**: 182-183

Schmidt, R. und *H. Müller-Miny* 1973: Die Kartenaufnahme der Rheinlande durch Tranchot und v. Müffling (1801-1828). – Erläuterungen zum Geschichtlichen Atlas der Rheinlande 010; Publikationen der Gesellschaft für Rheinische Geschichtskunde 012. – Köln

Meehl, G.A. and *C. Tebaldi* 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. – Science **305** (5686): 994-997

Merbitz, H., M. Buttstädt, S. Michael, W. Dott and *C. Schneider* 2012: GIS-based identification of spatial variables enhancing heat and poor air quality in urban areas. – Applied Geography **33**: 94-106

MUNLV – Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen 2009: Anpassung an den Klimawandel. Eine Strategie für Nordrhein-Westfalen. – Düsseldorf

Ren, C., E.Y.-y. Ng and *L. Katzschner* 2011: Urban climatic map studies: a review. – International Journal of Climatology **31** (15): 2213-2233

Robine, J.M., S.L.K. Cheung, S. Le Roy, H. Van Oyen, C. Griffiths, J.P. Michel and *F.R. Herrmann* 2008: Death toll exceeded 70,000 in Europe during the summer of 2003. – Comptes Rendus Biologies **331** (2): 171-178

Sachsen, T. 2013: Die Wirkung von Vegetation in randstädtischen Luftleitbahnen: Studien zur Kaltluft in der Stadt Aachen. – Ph.D. thesis. – RWTH Aachen

Sachsen, T., G. Ketzler and *C. Schneider* 2012: The reduction of urban heat stress by optimized vegetation structures. – Conference Proceedings, ICUC8 – 8th International Conference on Urban Climates, 6th-10th August, 2012, UCD, Dublin, Ireland

Scherer, D., U. Fehrenbach, H.-D. Beha and *E. Parlow* 1999: Improved concepts and methods in analysis and evaluation of the urban climate for optimizing urban planning processes. – Atmospheric Environment **33** (24-25): 4185-4193

Schneider, C., C. Balzer, M. Buttstädt, K. Eßer, S. Ginski, J. Hahmann, G. Ketzler, M. Klemme, A. Kröpelin, H. Merbitz, S. Michael, T. Sachsen, A. Siuda, M. Weishoff-Houben, M.F. Brunk, W. Dott, H. Hofmeister, C. Pfaffenbach, C. Roll and *K. Selle* 2011: "CITY 2020+": Assessing climate change impacts for the city of Aachen related to demographic change and health – a progress report. – Advances in Science and Research **6**: 261-270

Sievers, U. 2005: Das Kaltluftabflussmodell KLAM_21: Theoretische Grundlagen, Anwendung und Handhabung des PC-Modells. – Berichte des Deutschen Wetterdienstes **227**. – Offenbach

Städteregion Aachen 2013: Migration in das Amtliche Liegenschaftskataster-Informationssystem (ALKIS). – Aachen. – Online available at: http://www.staedteregion-aachen.de, 24/06/2013

USGS 2006: Shuttle Radar Topography Mission (SRTM). – Online available at: http://seamless.usgs.gov/, 01/02/2006

VDI – Verein Deutscher Ingenieure 2003: Environmental meteorology – Local cold air. – VDI Directive 3787-5. – Berlin

WMO – World Meteorological Organization 2010: WMO Inter-regional CLIPS Training Workshop on Urban Climatology 2010. – Online available at: http://www.wmo.int/pages/prog/wcp/wcasp/UrbanClimate.html, 15/06/2013