COLD AIR PRODUCTION AND FLOW IN A LOW MOUNTAIN RANGE LANDSCAPE IN HESSIA (GERMANY)

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Abstract: This paper presents methods for analysing the impacts of different terrain parameters on cold air production, flow and cold air accumulation. These methods have been tested using a Digital Terrain Model (DTM) in combination with point source nocturnal temperature data observed during autochthonous calm and clear weather conditions. The gently undulated test site Melsungen in Northern Hessia features 130 single observation points representing a range of different morphological situations. Assuming the terrain reveals a seasonal varying influence on nocturnal air temperature patterns near ground, a comparative study was carried out between the meteorological transitional period showing active vegetation cover and the colder season without any active vegetation cover. Using stepwise multiple linear regression analysis, different terrain parameters have been tested. The results reveal changing influences of terrain attributes on nocturnal air temperature pattern depending on seasonal variations of vegetation cover. During the transitional period, a maximum variance of 55 % is explained by a combination of different terrain parameters and in the colder season even up to 68 %.

1 INTRODUCTION

Local climate is the result of complex interactive processes between different influencing factors. Small scale climate variability often is of great importance and relevance to human-bioclimatologic questions as for example with regard to thermal comfort and aeration conditions in built-up or residential areas. The most pronounced local climate effects occur during autochthonous weather conditions. These conditions are characterised by low wind velocities and a low relative humidity, a low-level cloud cover and increased radiation fluxes between the earth´s surface and the atmosphere.

However, nocturnal cold air production and flow require further fundamental influencing factors, which are substantially derived from land use and land cover, topography and topology. Determining surface parameters are thermal properties such as heat conduction and storage capacity of the subsurface, surface roughness and further on a multiplicity of different terrain attributes.

In the past a lot of climatologic investigations have been carried out relating to the influence of land use, but to a much lesser extent to the influence of topography and topology on local climate resp. thermal circulations in cities and rural areas. Against this background, nocturnal autochthonous near ground air temperatures have been investigated in a diploma thesis (DIETRICH 2006). The research aimed to improve and extend semi-empirical methods for climate spatial prediction and regional climate modelling, required in case studies and climate impact assessment e.g. in urban planning or agro-meteorological applications. Using land cover data and terrain parameters, it is possible to localise human bioclimatological relevant compensation spaces, connecting structures and ventilation paths etc. Additionally, it is a support in order to quantify the cold air potential of a cold air contributing area as well as to assess agro-meteorological risks due to frost danger in spring.

In 2005 and 2006 the measurement campaign started in the surrounding areas of the Hessian climatic health resort Melsungen. Using a mobile measuring unit, data of near ground air temperature have been collected. The acquisition of data focused on the nocturnal spatiotemporal variability of temperature anomalies, cooling rates and vertical gradients between 50 and 200 cm above ground. The campaign aimed to localise areas, which produce high volumes of cold and fresh air, to detect where katabatic winds preferably occur and where cold air accumulates in large quantities.

To obtain reasonable spatial high-resolution climate information about local observations of site-specific cold air distribution, it was necessary to estimate spatially continuous climate data from point source temperatures, using geostatistical interpolation and terrain parameterisation methods. For that purpose, controlling terrain parameters had to be identified by using a statistical model (stepwise multiple regression). In this context 10 terrain parameters have been analysed and evaluated. The derivation of terrain parameters from DTM as well as the subsequent spatialisation of local climate has been accomplished with SAGA 2.0.

2 STUDY AREA AND MATERIAL

The study area Melsungen in the Fulda Valley (city centre Melsungen 9°33'E, 51°08'N) is located 20 km southeast of Kassel, Hessia (Germany). The model domain containing the empirical data observation net covers an area of approximately 20 km² (Fig. 1). However, the DTM extent of about 42,7 km² exceeds the model domain in order to cover the cold air contributing areas (cf. Chapter 4). The area includes different topographic elements and can be divided into three principle components comprising (1) the central Fulda Valley, (2) the bordering mountain ranges, which gently and sometimes steeply rise up, and (3) two bigger tributary valleys (Kehrenbach, Kesselbach*)*, which lead out of the forested surroundings of Melsungen.

Sub routes 1 and 2 (Fig. 1) are primarily east exposed and present predominantly agricultural areas, whereas sub routes 3 and 4 have a higher percentage of west exposed settlement structures and show less homogeneity in exposition than the other sub routes.

The landscape has a height between 165 m at the bottom of the Fulda Valley and 430 m reached at the tops of the adjacent hills. Geologically being part of the German Trias, the region near Melsungen is situated in the Kurhessisches Bergland, which is dominated by New Red Sandstone with its typical steep terrain (GEOLOGISCHE KARTE VON HESSEN 1975). Besides agricultural activities in the Fulda Valley and the valley flanks, forestry can be found in the upper regions, whereas dense settlement structure resp. suburban and urban areas are restricted to the Fulda Valley. Particularly the valley flanks of the Fulda are structured by a bigger number of middle sized, rill-like slots, which have its seats in the upper parts of the valley flanks and which open out to the main and the two tributary valleys.

The climate of the region is characterised by a mean annual temperature of 8.6°C and a mean annual precipitation of 705 mm for the period of 1950-2003 (DWD 2005). The relative probability of calm and clear weather conditions being required to induce effective cold air production is almost 30% per year (after GERSTENGARBE *et al.* 1993). Actually the probability that thermal circulation patterns may occur is even higher in Central Europe with almost 40 % (HELDT & HÖSCHELE 1989), corresponding to own calculations. Containment criteria after HELDT & HÖSCHELE (1989) have been (1) wind velocity 10 m above ground <= 3 Bft. and (2) daily temperature range > 10°C. An accumulation of these weather types can be observed between April and October (GERSTENGARBE *et al.* 1993). Furthermore, the Fulda Valley shows below average annual wind velocities due to protecting effects of the surrounding terrain, so that the conditions for the development of thermal circulation within the research area can be categorised as well.

Empirical data has been collected at night by mobile temperature measurements. The measurement unit on a caravan has been equipped with three ventilated psychrometers, which have been installed at the forefront of the bus in three different heights above ground (50, 150, 200 cm). Temperature sensors have been technically inspected and calibrated Pt100 thermistors.

Basic substructure of terrain analysis and climate regionalisation has been a DTM with a grid cell size of 2500 m² (50 x 50 m). All terrain parameters, considered in chapter 4, have been derived from this source.

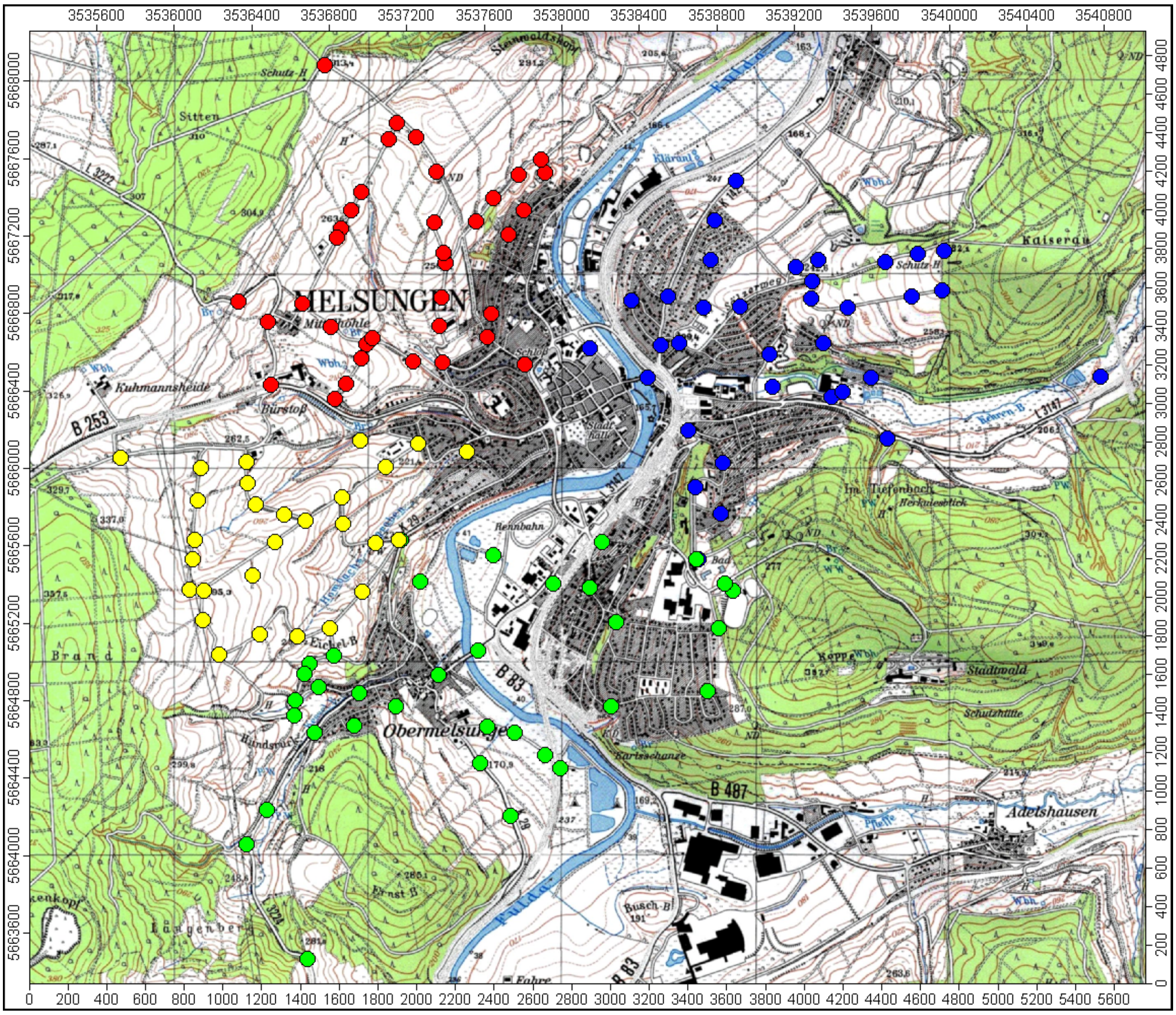

Fig. 1: Test site (observation net) of the climate health-resort Melsungen – route 1 (red), route 2 (yellow), route 3 (green) and route 4 (blue).

3 EMPIRICAL DATABASE

Mobile measurement campaigns deliver spatial high-resolution point source observations of climate parameters (KUTTLER & BARLAG 2002, KUTTLER & DÜTEMEYER 2003). This is an established method to localise areas of cold air production, flow and accumulation (KUNKA & OESTREICHER 2006). Against the background of mobile data collection, the research area has been divided into four individual sub routes including 130 measurement points. The local observation net was conceived under the dictum of a frequent recording of all topographically relevant terrain units like domes, depressions, crest lines, depth lines, valley flanks etc. in order to achieve a detailed topoclimatic representation.

All sub routes have been connected by a common initial and final point. This was necessary firstly to merge all sub routes and secondly to eliminate diurnal temperature variations which automatically would have influenced the results due to the duration of sampling (max. 1.5h for each sub route). In order to compensate this methodological error, temperature data of each sampling run had to be synchronised on the first moment of the sampling run (DANZEISEN 1983, STÜLPNAGEL VON 1987). Basis of the corrections have been the natural cooling rates of the initial point, which have been linearly allocated to the empirical temperature data (GROSS *et al.* 1996, PÜTTMANN 2002). Only after correcting, all data are comparable with each other (trend adjustment).

The empirical study about the influence of terrain attributes on cold air distribution was subject to a seasonal assignment. The analysis aimed to obtain information about seasonal variations in the behaviour of local thermal circulations caused by phenological variations and the resulting changes in the influences of the terrain. In contrast to a multitude of other climatologic investigations dealing with local climate during summer, this study tried to explore nocturnal autochthonous near-ground air temperature patterns in spring, autumn and winter. Hence, on the one hand the warmer part of the meteorological transitional period [TP] between winter and summer was inspected (April, May, September), and on the other hand the colder season [CS] without active vegetation cover except for withered grass and without any snow cover (November, December) which would have caused difficulties in carrying out mobile measurements. The specification of sample periods has been geared to the methodical differentiation of thermal seasons after RAPP & SCHÖNWIESE (1994). However, data volume of the colder season is not comparable to the amount of data of the transitional period owing to a rather infrequent occurrence of adequate synoptic weather conditions. By that reason, sub routes 3 and 4 could not be investigated in winter.

In order to comprehend the spatiotemporal process related differentiation of cold air production, flow and accumulation during the whole night, every measurement event was split up into four sections. The first sample section started directly after sunset and the second one immediately subsequent to the first one. The third section started approximately four hours before sunrise followed by the fourth section which finished directly before sunrise. The mobile measurement unit was stopped at every observation point for at least 90-120 seconds, so as to account for the intrinsic time constant of the thermistor and thus to minimise systematic errors as well as to intercept outliers. A total of more than 50 single sample runs have been carried out in 16 nights.

Three **temperature parameters** have been derived from the original data. First of all **anomalies** in two different heights above ground (50, 200 cm) have been calculated in order to match sampling runs featuring different temperature levels and to display positive and negative deviations of single local observation points resp. sub spaces of the research area (ROSNER 1992). The arithmetic mean of the corrected absolute temperatures of all observation points of a sub route acted as a reference isotherm (ROSNER 1992). The anomalies resulted from the deviation of a single value from the reference isotherm (temperature standardisation). The range of anomalies indicates the intensity of the spatial temperature pattern, the higher the range the more heterogeneous the pattern. Anomalies in 200 cm above ground have been considered in the subsequent regionalisation (Fig. 3).

Vertical **temperature gradients** as an absolute climate variable result from the differences between absolute temperatures in 50 cm and 200 cm above ground. Gradients do not have to be synchronised like anomalies because this parameter only serves as a pure snap-shot of the atmospheric condition in relation to specific locations. Basically, gradients inform about the near-ground atmospheric layering. Negative temperature gradients show a lower temperature level near the ground than in 2 m observations. Negative gradients indicate a stable layering with initial cold air production or flow, whereas positive gradients suggest heat emission of the surface, preferential in build-up areas. On this account temperature gradients have been generally used solely to detect sub spaces showing initial cold air production.

Finally, nocturnal **cooling rates** have been observed, but in opposite to the parameters mentioned above, only at a few selected measurement points. A specific cooling rate results from the temperature difference between two observations within one hour. The approach aimed to prove unequal cooling trends of different sub spaces. So only a few observation points had to be investigated. Moreover, cooling rates of the common initial and final point are of great importance referring to the elimination of diurnal temperature variations being inherent in original data.

4 TERRAIN ANALYSIS

There are many scientific publications dealing with digital terrain analysis and modelling of geo-systematic processes. Application fields of terrain analysis are for instance aeolian erosion processes (BÖHNER *et al.* 2004), pedological processes (BÖHNER & KÖTHE 2003, BÖHNER & SELIGE 2006), hydrological denudation (KREIKEMEIER *et al.* 2004) and regionalisation of soil-relevant climatic parameters (BÖHNER 2004). Terrain analysis can be seen as an efficient method for solving topo-climatic problems and analysing and understanding its controlling factors (cf. DIETRICH 2006).

Topo-climatology studies the impact of different land surface parameters on local climate and its spatial variations of near-ground atmospheric processes (BÖHNER & ANTONIC 2007). Spatial climate variability during autochthonous conditions mostly depends on land-cover and topographic variability. Besides terrain parameters like absolute height or slope inclination also the relation between a terrain segment and its environment further away plays a key role for topo-climate. This applies to thermal circulation, too. Already a few decades ago at an early stage of topo-climatic research GEIGER (1961) and HARRISON (1971) recognised the importance of topology for the development of small-scale spatial variability of climatic elements. It is essential to look at different spatial scales of cold air flow (THAMM 2000) because air flow is among the scale-invariant atmospheric phenomena with varying large reference areas resp. horizontal extensions (BENDIX 2004). In this context, the spatial relation to the surrounding area is absolutely indispensable for a sufficient characterisation of a specific terrain segment (BÖHNER & KÖTHE 2003). But considering topology, it is advisable to choose a adequate complex parameterisation of the terrain. Only by doing so, it is possible to accommodate the meaning of topology for small-scale climatic processes.

A total of 10 terrain parameters have been derived from the DTM (Tab. 1). The analysis has been carried out with regard to their impact on the development of slope winds, preferred flow paths, position and size of cold air pools. All below-mentioned terrain parameters are attributed to terrain analytical methods after WILSON & GALLANT (2000), BÖHNER & KÖTHE (2003), BÖHNER & SELIGE (2006) and BÖHNER & ANTONIC (2007).

Tab.1: Investigated terrain parameters.

Parameter	Unit	Description
hsl	[m]	height above sea level
inc	[°]	slope inclination
cao	[m²]	catchment area, original, run off area of above-situated grid cells
cam	[nondimensional]	catchment area, modified (lognormal), run off area of above-situated grid cells
hac	[m]	height above culmination reference to the height difference of immediate adjacent channel lines
hbc	[m]	height below crest line reference to the height difference of immediate adjacent crest lines
hno	[nondimensional]	height, normalised normalised height of the local environment
hst	[m]	height, standardised standardised height of the local environment
hma	[nondimensional]	height, middle slope
eno	[nondimensional]	aspect, normalised (eno) normalised distance of aspect to southwest

- **Catchment area**: The catchment area (cao) specifies the hydrologically defined contributing upslope area (WILSON & GALLANT 2000), frequently considered as an approximation for the cold air potential. The hydrologically defined catchment area, however, is closely related to the channel network and thus fails to model cold air flow particularly in broad valleys. Against this background, a modified catchment area (cam) has been implemented in SAGA (Fig. 2), which yields a better approximation of cold air distribution and accumulation (BÖHNER 2004).
- **Relative heights**: Height above culmination (hac) describes the vertical offset of a grid cell to its according channel line considering the local relief energy in relation to the local erosion base (BÖHNER 2004). Referring to linear depressions like valleys or rills this parameter records processes of cold air convergence and linear run off. Thus, the linear correlation between height above culmination and nocturnal minimum temperatures, which has already been described in HARRISON (1971), is sufficiently considered.
- **Height below crest line:** The height below crest line (hbc) refers to the relative height of a terrain position to a nearby ridge. Crest lines are always zones of cold air divergence with its typical positive temperature anomalies (VOGT 2001). Both channel lines and crest lines determine transport processes like cold air flow or hydrological run off and therefore display morphometrically structuring factors of the terrain concerning the elementary development of nocturnal temperature patterns.
- **Normalised and standardised height:** Besides the vertical offset of a grid cell, normalised height (hno) and standardised height (hst) also consider the extension of a catchment area of a specific terrain point (cf. BÖHNER & SELIGE 2006). Normalised height allots value 1 to the highest and value 0 to the lowest position within a respective reference area. Standardised height is the product of normalised height multiplied with absolute height. Hence, both parameters do not only relate to adjacent channel and crest lines but comprise the widespread topology. This is necessary to illustrate a procedural differentiation of local air flow, because divergent, convergent and linear cold air flow depend on the direct environment, the catchment area, and the relative height differences at the same time (THAMM 2000).
- **Mid-slope position:** The mid-slope position (hma) is commonly considered in topoclimatic analysis, to cover the warmer zones of slopes (BENDIX 2004). This parameter assigns mid-slope positions with 0, whereas maximum vertical distances to the mid-slope in both valley or crest directions are assigned with 1 in order to represent the temperature drop towards upper and lower parts of a slope.
- **Aspect**: Normalised distance of aspect (eno) aims to represent daily air and surface temperature maxima in the later afternoon or early evening caused by anisotrophic heating of slopes (BENDIX 2004). Besides the angle distance to southwest, this parameter also considers mean slope inclination of a terrain unit.

The analysis of relationships between independent predictor variables (terrain) and the dependent predictant variable (temperature) has been carried out using stepwise multiple linear regression ($Y \rightarrow X_1 + ... + X_n$) with a minimum significance of $p \leq 0,05$. Both seasonal observation periods have been studied separately to detect seasonal variations of the influence of the terrain on nocturnal air temperature distributions. In some cases the multiple regression analysis identifies only one predictor parameter, although the correlation matrix indicates more than one parameter being significantly correlated. This effect is called a multi-collinearity problem (BAHRENBERG *et al.* 2003) and advertises that several parameters are redundant, that is to say, some parameters have a similar climatologic functionality showing a high linear correlation.

In the following sections, only **anomalies** in **200 cm** above ground will be discussed in detail, primarily for the reason that these anomalies have the highest correlation of all observed variables. Furthermore, anomalies in 200 cm above ground are elementary of greater relevance to human-climatologic aspects. The high level of correlation in 200 cm above ground is caused by the fact that an increasing ground level strictly heightens the thermal impact of the land cover and simultaneously weakens the influence of the terrain (GEIGER 1961).

Table 2 shows a regression matrix of all sub routes and the cumulative measurement net. It is structured in two observation periods and four sections of a sampling event (one whole night). To the right all investigated terrain parameters are listed including the succession of identification by the stepwise multiple regression analysis as well as the corresponding regression coefficients. The coefficient of determination R^2 and the regression constant are given to the left.

Tab. 2: Correlation between temperature anomalies in 200 cm above-ground and specific terrain indices.

ANOMALIES 200 cm a. gr.					Terrain indices									
Route	Sample Section & "Season"	Regression-constant	R² (corrected)		cam	cao	hac	hbc	hno	hsl	hst	inc	eno	hma
1	**Trans. Period [TP]**													
	after sun set	-0.3999	0.44	succesion		1							3	2
				coefficient of gradient		-5,81E-06							16.0200	- 4,6751
	second section	4.1590	0.33	"	1									
				"	-0.3717									
	third section	3.8377	0.34	"	1									
				"	-0.3458									
	before sun rise	-0.6365	0.39	"		1		2						3
		(mean)	**0.37**	"		-4,56E-06		0.0147						- 1,821
	Colder Season [CS]													
	after sun set	2.7183	0.59	succesion	1					2				
				coefficient of gradient	-0.3570					0.0051				
	second section	***no regression (p ≤ 0,05)***		"										
				"										
	third section	-2.6906	0.56	"		2				1	3			
				"		-2,21E-06				0.0141	-0.0048			
	before sun rise	-	-	"										
		(mean)	**0.58**	"										
2	**Trans. Period [TP]**													
	after sun set	0.7185	0.49	succesion		1								
				coefficient of gradient		-8,02E-06								
	second section	0.3350	0.51	"		1								
				"		-4,44E-06								
	third section	-0.0409	0.56	"		1	2							
				"		-4,42E-06	0.0128							
	before sun rise	-2.0841	0.62	"		1				2				
		(mean)	**0.55**	"		-3,35E-06				0.0095				
	Colder Season [CS]													
	after sun set	3.5660	0.75	succesion	3	1				2		4		
				coefficient of gradient	-0.1162	-2,08E-06				-0.0070		-3.6205		
	second section	6.7328	0.57	"	1				2					
				"	-0.5241				-1.8151					
	third section	-	-	"										
				"										
	before sun rise	-2.0672	0.72	"						1				2
		(mean)	**0.68**	"						0.0100				1,9415
3	**Trans. Period [TP]**													
	after sun set	10.4226	0.51	succesion	4					2			3	1
				coefficient of gradient	-0.4403					-0.0199			6.8879	3,4884
	second section	1.9824	0.40	"					1	2				
				"					4.2240	-0.0148				
	third section	5.9781	0.46	"	1									
				"	-0.5161									
	before sun rise	0.8508	0.39	"										1
		(mean)	**0.44**	"										2,8838
4	**Trans. Period [TP]**													
	after sun set	***no regression (p ≤ 0,05)***		succesion										
				coefficient of gradient										
	second section	-1.1099	0.43	"							1			
				"							0.0120			
	third section	-0.7110	0.25	"					1					
				"					1.7231					
	before sun rise	-0.6958	0.22	"					1					
		(mean)	**0.30**	"					1.6735					
ENTIRE	**Trans. Period [TP]**													
ROUTE	after sun set	3.6892	0.36	succesion	2	1						3		
				coefficient of gradient	-0.2775	-3,40E-06						-3.2745		
	second section	-1.3496	0.40	"		2		3	1					
				"		-2,92E-06		0.0129	2.5184					
	third section	2.5461	0.43	"	1	2								
				"	-0.2366	-1,90E-06								
	before sun rise	2.2969	0.29	"	1	2								
		(mean)	**0.37**	"	-0.1941	-1,68E-06								
	Colder Season [CS]													
	after sun set	3.0018	0.39	succesion	1									
				coefficient of gradient	-0.2696									
	second section	0.1509	0.16	"		1								
				"		1,35E-06								
	third section	-	-	"										
				"										
	before sun rise	-	-	"										
		(mean)	**0.27**	"										

Terrain analysis of the transitional period [TP]: The aggregation of all sub routes implicates that the entire measurement net shows a lower correlation (R^2 [TP]: 0,29-0,43, mean [TP]: 0,37) than the separated sub routes (R^2 [TP]: 0,22-0,62, mean [TP]: 0,30-0,55). Presumably the weakening of the correlation of the entire observation net has to be ascribed to the combination of specific thermal land cover and terrain dependent characteristics of all sub routes, by which the detectable influence of the terrain could have been diminished.

During the warmer season the highest R^2 can be found at sub route 2 (R^2 [TP]: 0,49-0,62, mean [TP]: 0,55). By reason of predominant homogenous land cover, the heat balance consistently develops, so that the land cover signal only shows a weak impact on the temperature distribution near ground. Moreover, sub route 2 reveals only minor regional differences in aspect (cf. Chapter 2). Thus, the radiation balance is rather uniform, too. On that account, sub route 2 most likely validates the simplifying assumptions of the terrain parameters, followed by sub route 3 (R^2 [TP]: 0,39-0,51, mean [TP]: 0,44). But in consideration of stronger developed differences in aspect and a higher percentage of urban areas the correlation of sub route 3 is already lower.

Sub route 2 also exemplifies a gradual nocturnal increase of correlation (R^2 [TP]: from 0.49 up to 0,62). This can be explained by a constant influence of topographic factors and topology on temperature patterns, whereas other geographical factors have a decreasing effect on air temperature near ground later in the night (UPMANIS & CHEN 1999). It is to assume that the approximate ideally typical character of sub route 2 is responsible for a clear development of the chronological increase of terrain impact. All other sub routes predominantly show an inverse behaviour because of their higher percentages of urban land cover, which modifies the intrinsic thermal regime of the surface. Related to sub routes 1, 3 and 4, the urban land cover signal seems to overlay the influence of the terrain by intensified long-lasting heat emissions until early in the morning. Besides, higher surface roughness, which is a characteristic property of residential and urban areas, substantially influences orographically induced thermal circulation patterns by partially obstructing cold air flow alongside anthropogenic obstacles (cf. GROSS *et al.* 1996, SCHWAB 2000). This presumably leads to a chronologically diminishing impact of the terrain on temperature over the course of the night.

In the next step different terrain parameters have been analysed with regard to their percentage of explained variance of temperature distribution. In two cases no parameters could be identified by stepwise multiple regression ($p \leq 0,05$) due to the weather conditions. Referring to the entire route, catchment areas (cam, cao) are the most explaining terrain parameters during the whole night. The catchment area is applicable to the volume of cold air flow being expected at a specific position (WILSON & GALLANT 2000). Additionally, in the first half of the night also relative heights (hbc, hno) and slope inclination (inc) have been identified, but only to a moderate extent, whereas actually no definite temperature trend could be observed depending on absolute height (hsl). Most likely, this appears to be related to the fact that different levels of altitudes of the sub routes do not mirror an observable height determined trend of temperature distribution.

Discussing sub routes in the warmer transitional period [TP], it becomes apparent that there are large differences between sub routes 1, 2 and sub routes 3, 4. Similar to the entire observation net, temperature distribution of sub routes 1, 2 is essentially controlled by catchment area, too, whereas cold air production and flow within sub routes 3, 4 are predominantly determined by relative heights (hno, hma). The observed positive temperature trend with increasing normalised height (sub routes 3, 4) has different reasons. On the one hand, many local observation points, which show negative anomalies, are located in local depressions, such as the bottom of the tributary Kehrenbach- and Kesselbach Valleys, featuring low housing density with high potential of autochthonous cold air production. On the other hand, the higher parts of sub routes 3, 4 are dominated by west-exposed urban areas with its typical advanced nocturnal heat emission bringing out positive anomalies. For that reason, higher locations face fundamental positive anomalies associated with pronounced cool temperatures in lower regions at the same time.

Another result during the warmer season [TP] is the identification of the warmer mid-slope zones (hma) for sub routes 1 and 3. However, an oppositional trend could be observed. Focusing on sub route 3, west-exposed, residential areas located at mid-slopes and showing positive temperature anomalies might be responsible for an overdrawn indication of the warmer mid-slope zones and therefore also for a significant and strong temperature decrease towards upper and lower parts of the test site. In contrast to that, regarding sub route 1, a positive temperature trend towards upper and lower regions has been diagnosed, tantamount to obvious negative anomalies in medium elevation positions. This can only be explained by the position of numerous observation points near channel lines of rill-like slots alongside the wide-stretched flanks of the Fulda Valley (cf. Chapter 2). These linear depressions represent zones of cold air production resp. convergence and therefore effect negative temperature anomalies at an altitude, where - considering the terrain of the whole investigated region - usually positive anomalies should have been expected. So the typical warmer mid-slope zone has only been observed in parts due to the overbalance of effective local cold air production within the east-exposed and agriculturally used area. This apparent paradox unfolds the dependence of the expressiveness of empirical data on the sampling design of the observation net.

With regard to the first sampling section after sunset [TP], normalised distance of aspect (eno) has been identified twice by the regression analysis, but only ranking third in the order of detection (sub routes 1, 3). The almost total (statistical) disregard of normalised aspect (eno) and height below crest line (hbc) resp. height above culmination (hac) confirms the assumption that it is necessary to consider the extended topology, which is a substantial controlling factor on a large-scale cold air production and flow (THAMM 2000, VOGT 2001). The above-mentioned parameters only quantify the relative position and therefore are not able to reproduce and to explain the principle of cause and effect of micro-scale temperature distribution.

Terrain analysis of the colder season [CS]: The colder season is characterised by an explicit higher correlation. As expected, once again sub route 2 exhibits the strongest correlation (R^2 [CS]: 0.57-0.75, mean [CS]: 0.68), followed by sub route 1 (R^2 [CS]: 0.56-0.59, mean [CS]: 0.58). The nearly absence of vegetation cover effects an intense reduction of thermal differences specific to land cover with a simultaneous change in surface roughness (SPRONKEN-SMITH 2002, STREIFENEDER *et al.* 2002). By this means, on the one hand differences in thermal behaviour between several kinds of land cover are reduced, and on the other hand, the impact of the terrain on air flow induced by gravitation increases due to the decline of aboveground flow resistance. Both effects obviously lead to a stronger influence of the terrain on local thermal circulation patterns. Nevertheless, the same trend of a lower correlation with respect to the entire route can be observed during the colder season (R^2 [CS]: 0,16-0,39, mean [CS]: 0,27), at least for the available data of sub routes 1 and 2 together (R^2 [CS]: 0,56-0,75, mean [CS]: 0,58-0,68).

A further seasonal difference in thermal behaviour of local climate becomes evident, looking at the controlling terrain parameters. Although catchment areas play cross-seasonally the most important role, absolute height (hsl) has cumulatively been established by regression analysis, what is in opposition to the warmer period. In this regard, a predominant positive temperature variation with increasing absolute height has been discovered, what is a consequence of persistent and intense radiation inversions above the large cold air pool at the bottom of the Fulda Valley.

Further findings: In order to clarify the decreasing influence of terrain with increasing ground level (GEIGER 1961), an overview can be seen in Table 3 showing the lower correlation between other investigated temperature parameters and terrain attributes.

Tab. 3: Correlation between temperature anomalies, gradients and digital terrain information.

All temperature parameters				
Route	Sample Section & "Season"	Ano. 200 cm a.gr. R^2 (corrected)	Ano. 50 cm a.gr. R^2 (corrected)	Gradients (50-200 cm) R^2 (corrected)
ENTIRE	Trans. Period [TP]			
ROUTE	after sun set	0.36	0.19	0.28
	second section	0.40	0.25	0.19
	third section	0.43	0.28	0.16
	before sun rise	0.29	0.20	0.19
	(mean)	**0.37**	**0.23**	**0.21**
	Colder Season [CS]			
	after sun set	0.39	0.25	0.07
	second section	0.16	0.16	0.05
	third section	-	-	-
	before sun rise	-	-	-
	(mean)	**0.27**	**0.21**	**0.06**

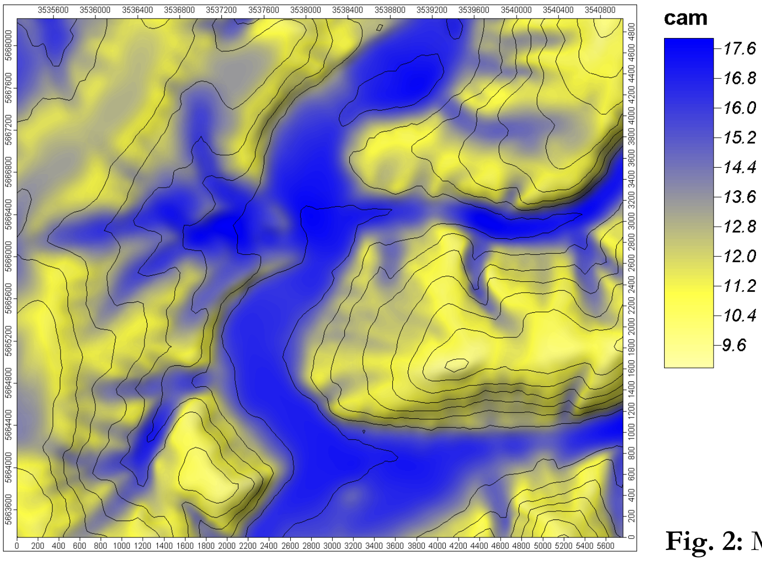

Fig. 2: Modified catchment area (cam)

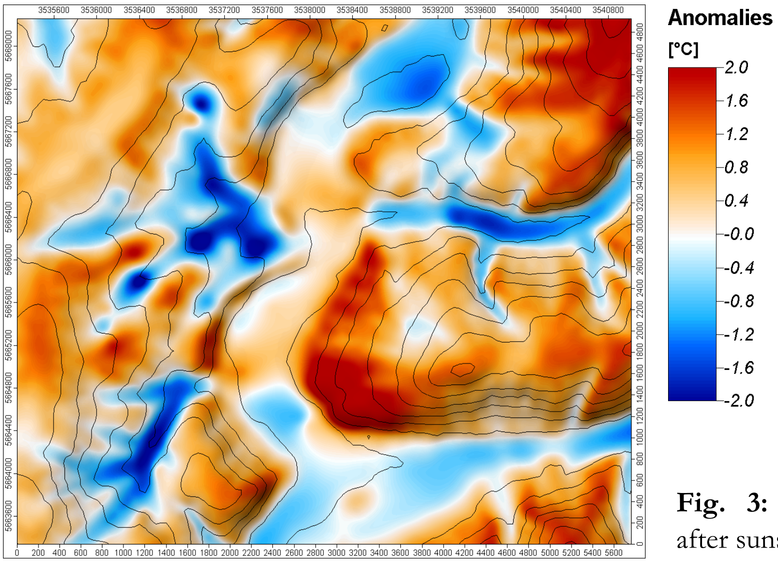

Fig. 3: Estimated Temperature distribution after sunset [TP]

5 CONCLUSIONS

Current terrain analysis techniques offer advanced opportunities for investigations of autochthonous local climate. Especially in a quite hilly topography, where cold air production and flow are related to the extended topology, morphometric terrain parameters are stringently required for comprising and reproducing the procedural complexity of thermal circulation patterns near ground. Complex terrain parameters like catchment areas or relative heights allow to sufficiently explain the topographically determined temperature distribution. In this context, as to be expected, particularly catchment areas play the most important role (cf. THAMM 2000, VOGT 2001). This indicates the imperative demand of considering a model domain, far in excess of the extension of the observation net itself.

Referring to several sub routes, stepwise multiple linear regression analysis on complex terrain parameters yields the highest coefficient of determination at an average of 68%, whereas the aggregation of all sub routes (entire observation net) only shows a lesser correlation at an average of 27-37 %. This is the result of the combination of sub-route-specific thermal land cover and terrain dependent characteristics. Moreover, it could be proved that the percentage of explained variance of temperature distribution basically increases within the colder season. This can be explained by decreased aboveground flow resistance as well as by alleviated thermal differences in land cover resulting from a decline of active vegetation cover in November and December. Preferentially during the warmer season, unexplained temperature variance has to be ascribed, in the first instance, to the factor of land cover and its consequences for thermal behaviour of the surface in terms of varying heat conduction, storage and emissivity (SPRONKEN-SMITH 2002, STREIFENEDER *et al.* 2002).

Above all, empirical observations of this investigation coincide with findings of OTAVIO & FITZJARRALD (2001), whereupon there is only a quantifiable but not a qualitative seasonal change in nocturnal air temperature patterns. Thus, the location of those sub spaces showing cold air production, flow or accumulation do not alter cross-seasonally but only become less pronounced in winter.

In general, the analysis results reveal that the role of the terrain as an important control for nocturnal temperature distribution, whilst the land cover is most likely responsible for a high percentage of unexplained variance. Additionally, in certain circumstances it becomes apparent that the explanatory power of observed empirical data is strongly dependent on the sampling design, restricted to trafficable roads and path networks.

The presented semi-empirical approach is obviously able to reproduce nocturnal temperature distributions sufficiently neglecting seasonal and phenological variations. Through coupling DTM and land cover information resulting e.g. from satellite imagery, it should be generally possible to precisely predict agricultural risks or to estimate negative human-bioclimatologic influences in dense built-up areas. With regard to high-resolution numerical simulation, the synthesis of terrain parameters and land cover data will be a main target of applied research in future, particularly within the scope of microscale topo- and urban-climatology. The primary aim must be to consistently enhance the accuracy of forecast and of analysis of local climatologic processes in heterogeneous rural and complex anthropogenic environments. But in addition to terrain and land cover, also potential flow obstacles have to be concurrently considered having equal priority in modelling thermal circulation systems. In this context it is essential to adopt statistical downscaling methods in order to integrate small obstacles and hence to be able to develop a precise and computational efficient forecasting tool.

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