4.1 HUMAN THERMAL COMFORT IN SUMMER IN DIFFERENT URBAN QUARTERS OF A MID-SIZE CENTRAL EUROPEAN CITY

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## 1. INTRODUCTION

Regional climate simulations for Central Europe result in the reliable likelihood that not only the near-surface air temperature will increase but also extreme heat waves in summer will be more intense and frequent as well as longer lasting (Meehl and Tebaldi, 2004). This change of the thermal background conditions is strengthened in cities by their dynamic features and processes, which form specific urban microclimates.

Against this background, the demand for human-biometeorologically based concepts is continuously increasing in urban planning, by which the stronger impairments of human thermal comfort for citizens in the future can be reduced. A comprehensive analysis of human thermal comfort within cities during large-scale heat conditions requires a method to describe and quantify human thermal comfort in a thermo-physiologically significant way. This can be achieved by a coordinated combination of different approaches: (i) experimental investigations and numerical simulations to calculate comfort-relevant thermal assessment indices, (ii) questionnaires with respect to the individual perception of the local thermal environment and (iii) monitoring of behaviour patterns of citizens in urban open spaces.

## 2. JOINT RESEARCH PROJECT KLIMES

The joint research project "Development of strategies to mitigate enhanced heat stress in urban quarters due to regional climate change in Central Europe", abbreviated by KLIMES, meets this demand. As a detailed website (www.klimes-bmbf.de) is available, the concept of KLIMES is introduced only in form of a brief overview.

KLIMES is carried out by four German research groups within the scope of the research initiative "*klimazwei*" funded by the German Federal Ministry of Education and Research (BMBF) from 2006 to 2009 (Katzschner et al., 2007, Mayer 2008; Mayer et al., 2008). Based on an overview on the state-of-the-art in the planning-related urban human-biometeorology and identification of deficits, working hypotheses were derived, which lead to the general aims of KLIMES:

- update of human-biometeorological methods available to quantify the perception of heat by citizens,
- quantification of the perception of human thermal comfort in different urban quarters during extreme summer heat,
- development and verification of urbanistic strategies based on human-biometeorological results to mitigate the negative impacts of climate trends and extreme weather on citizens in different urban quarters (optimisation of human thermal comfort under consideration of objectives of environmental protection, e.g. abandonment of electric air conditioning),
- synthesis of all results in a guideline for urban planning orientated to the challenges due to regional climate change in Central Europe.

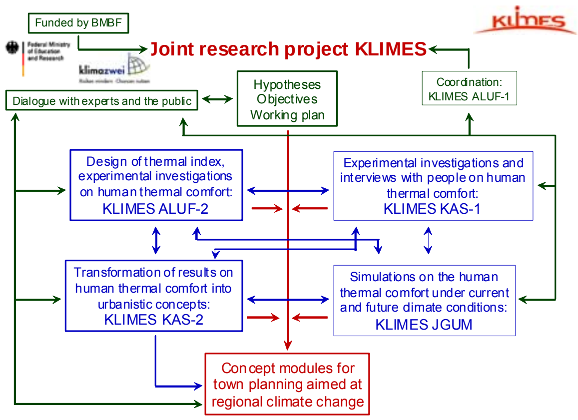


Fig. 1: Schematic diagram indicating the structure of the joint research project KLIMES, the subjects of the KLIMES subprojects ALUF-1, ALUF-2, KAS-1, KAS-2 and JGUM as well as their cooperation

To achieve the aims, a coordinated design of different approaches is applied in KLIMES (Fig. 1):

- experimental investigations on the perception of heat by citizens in different urban quarters in Freiburg (SW Germany), which is the warmest city in Germany,
- interviews with citizens about their current perception of heat under consideration of their thermal history and their use of open spaces,
- model-based simulations of human thermal comfort in different urban quarters under current and future thermal conditions using the steady model ENVI-met (Bruse and Fleer, 1998) and the unsteady model BOTworld (Bruse, 2007),
- development of human-biometeorologically based strategies for urban planning to optimise human

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thermal comfort facing the likelihood of extreme heat in the future,
- permanent dialogue with the planning practice and the public.

## 3. EXPERIMENTAL METHOD TO INVESTIGATE HUMAN THERMAL COMFORT IN DIFFERENT URBAN QUARTERS

The experimental method applied in KLIMES to analyse human thermal comfort in different urban quarters in Freiburg is described in Fig. 2.

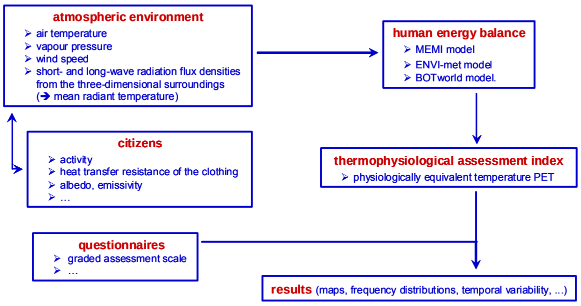


Fig. 2: Experimental method to analyse human thermal comfort in different urban quarters in Freiburg (SW Germany)

The procedure to analyse the perception of heat by citizens is explained in detail by Mayer et al. (2008). Therefore, it is sufficient here to mention that the well-known physiologically equivalent temperature PET (Mayer and Höppe, 1987; Matzarakis et al., 1999, Ali-Toudert and Mayer, 2006, 2007a, 2007b) is used as thermo-physiological index to assess the level of human thermal comfort within different urban quarters on typical summer days.

Fig. 3: Steady human-biometeorological measuring system applied in the project KLIMES ALUF

The meteorological variables required to calculate PET in dependence on different atmospheric environment conditions are determined by use of specific measurements with a steady human-biometeorological measuring system (Fig. 3) and a mobile human-biometeorological measuring system (Fig. 4). Technical details of both systems are described by Mayer et al. (2008)

Fig. 4: Mobile human-biometeorological measuring system applied in the project KLIMES ALUF

Results of different investigations on human thermal comfort in summer (Matzarakis et al., 1999; Ali-Toudert and Mayer, 2007a, Mayer et al., 2008) show the mean radiant temperature $T_{mrt}$ to be the major influencing factor on PET in Central European cities. In the experimental part of KLIMES, $T_{mrt}$ is determined by measured short- and long-wave radiation flux densities. For these purposes, the steady human-biometeorological measuring system consists of a specific design of six pyranometers and six pyrgeometers (see also Thorsson et al., 2007), which measure the short- and long-wave radiation flux densities from the three-dimensional surroundings that are received by a standardised standing person. The mobile human-biometeorological measuring system includes a combination of one pyranometer and one pyrgeometer, which can be turned around a horizontal and a vertical axis. It also enables the determination of the short- and long-wave radiation flux densities coming from the three-dimensional surroundings of a standing person.

## 4. RESULTS

### 4.1 *NW-SE oriented street canyon in Freiburg, Rieselfeld*

Up to now, experimental investigations on human thermal comfort were carried out in 16 different urban quarters in Freiburg (Fig. 5), mainly during typical summer days, but also sporadically on cloudless winter days. In addition to these 1-day point measurements, the spatial distribution of PET on a typical summer day was simulated for selected urban quarters using the ENVI-met model (KLIMES JGUM). Comparing the simulation results with those of point measurements, a validation of simulation results could be realised.

In order to characterise the influence of urban design on the level of human thermal comfort in summer, Figs. 9 to 17 exemplarily show results from point measurements in Freiburg, Rieselfeld, conducted with both human-biometeorological measuring systems on 19 June 2007.

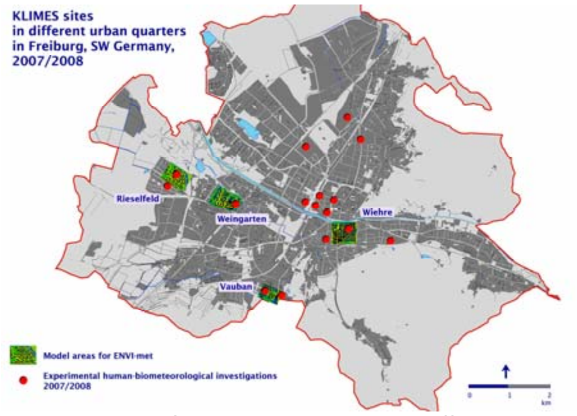


Fig. 5: KLIMES investigation sites in different urban quarters in Freiburg (SW Germany)

The measuring points were located in a neighbour-hood in the western part of Freiburg planned and built since the nineties of the last century. It is characterised by modern, three- to four-storey block buildings. Some streets are tree-lined and have small grass-covered front gardens. The steady measurements were conducted in the middle of a SW oriented sidewalk within a NW-SE street canyon (H/W=0.49), which is separated by a 3 m wide front garden from the house wall (Figs. 6 to 8)

Fig. 6: NW-SE oriented street canyon in Freiburg (SW Germany) with steady human-biometeorological measurements on a SW oriented sidewalk (view to NW)

The diurnal course of the near-surface air temperature $T_a$ in 1.1 m a.g.l. (Fig. 9) indicates that the investigation day (19 June 2007) was a typical summer day for Central European conditions. The 1-hr mean peak value of $T_a$ exceeded 30 °C. The height of 1.1 m a.g.l. is the standard height for human-biometeorological investigations on human thermal comfort in Central Europe (Mayer, 1993).

Fig. 7: NW-SE oriented street canyon in Freiburg (SW Germany) with steady human-biometeorological measurements on a SW oriented sidewalk (view to SE)

Fig. 8: NW-SE oriented street canyon in Freiburg (SW Germany) with steady human-biometeorological measurements on a SW oriented sidewalk

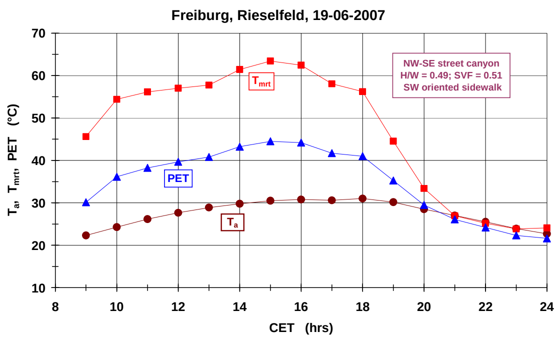


Fig. 9: 1-hr mean values of air temperature $T_a$, mean radiant temperature $T_{mrt}$ and physiologically equivalent temperature PET at a SW oriented sidewalk within a NW-SE oriented street canyon in Freiburg, Rieselfeld, on a typical summer day

The mean radiant temperature $T_{mrt}$ in 1.1 m a.g.l. can be regarded as the radiation heat absorbed by a standardised standing person. For the site situation shown in Fig. 9, it becomes apparent that $T_{mrt}$ was clearly higher than $T_a$. The peak difference (32.9 °C) occurred in the 1-hr period between 14 and 15 CET.

To assess the different levels of human thermal comfort, the physiologically equivalent temperature PET, also in 1.1 m a.g.l., was determined. Besides the peak values of PET, the time period of exceeding selected PET threshold values is significant. According to different investigations (e.g. Matzarakis et al., 1999), PET > 40 °C indicates strong heat stress. For the site conditions in Fig. 9, 1-hr mean PET values exceeded the 40 °C threshold value from 12 to 18 CET, i.e. the investigated site had a high level of thermal discomfort continuously during six hours in the afternoon of a typical summer day.

Urban planning measures to reduce the thermal discomfort level require information on urban design factors influencing human thermal comfort. On principle, it is mainly governed by the regional thermal background conditions, but strengthened by a "Δ" within cities due to their processes and structural features dependent on spatial and temporal scales. Only the "Δ" can be mitigated by urban planning in combination with human behaviour, which is adapted to a thermally stressful regional background situation.

As the radiation flux densities from the three-dimensional surroundings have the major influence on PET within Central European cities during hot summer weather, particular emphasis is put in KLIMES on the pattern of the short- and long-wave radiation flux densities.

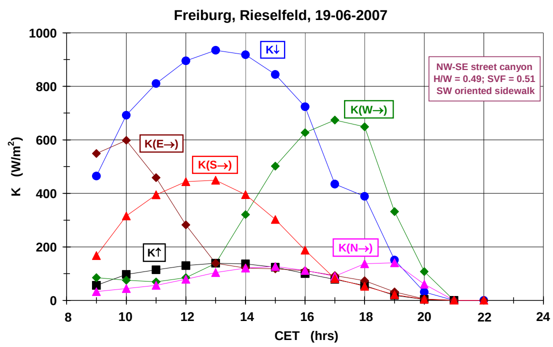


Fig. 10: 1-hr mean values of short-wave radiation flux densities K from the three-dimensional surroundings at a SW oriented sidewalk within a NW-SE oriented street canyon in Freiburg, Rieselfeld, on a typical summer day

The results in Fig 10 demonstrate the impacts of (i) the design of the urban street canyon and (ii) the site of the steady human-biometeorological measurements on the short-wave radiation flux densities K from the local three-dimensional surroundings. Comparing the results in Fig. 10 with those in Fig. 11, it becomes obvious how the position (standing) of the standardised person, which represents the collective of citizens being the target for the assessment of the thermal environment, determines the amount of the absorbed short-wave radiation flux densities.

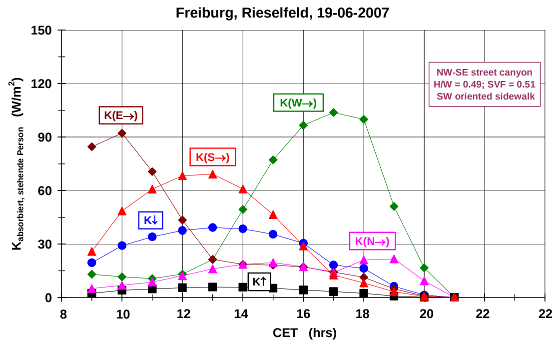


Fig. 11: 1-hr mean values of short-wave radiation flux densities K from the three-dimensional surroundings absorbed by a standing person at a SW oriented sidewalk within a NW-SE oriented street canyon in Freiburg, Riesel-feld, on a typical summer day

The pattern of the long-wave radiation flux densities at the Rieselfeld site (Fig. 12) is characterised by (i) relatively low values for the incoming long-wave radiation flux density L↓, (ii) relatively high values for the outgoing long-wave radiation flux density L↑ and (iii) intermediate values for the long-wave radiation flux densities from the four horizontal cardinal directions. Analysing the long-wave radiation flux densities absorbed by a standardised standing person (Fig. 13), the significance of the absorbed long-wave radiation flux densities from both vertical directions is reduced, whereas it is increased for the absorbed long-wave radiation flux densities from the four horizontal directions.

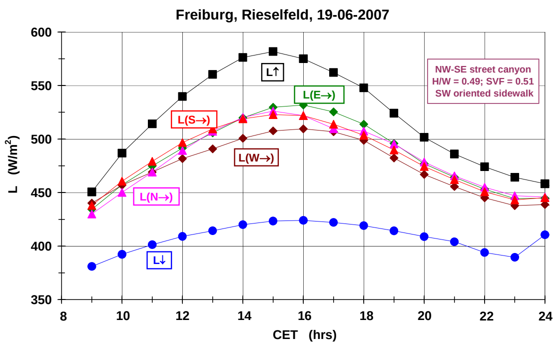


Fig. 12: 1-hr mean values of long-wave radiation flux densities L from the three-dimensional surroundings at a SW oriented sidewalk within a NW-SE oriented street canyon in Freiburg, Rieselfeld, on a typical summer day

The results in Figs. 11 and 13 indicate a particular importance of the absorbed short- and long-wave radiation flux densities originated from horizontal directions. This enables their reduction by local planning measures, e.g. options of “cool” surface materials or green façades.

Adding all single absorbed short-wave radiation flux densities to K* and all single absorbed long-wave radiation flux densities to L* (Fig. 14), the dominant significance of L* on $T_{mrt}$ is apparent. The contribution of L* to $T_{mrt}$ increased during the day from approximately 70% in the morning to approximately 90% before sunset.

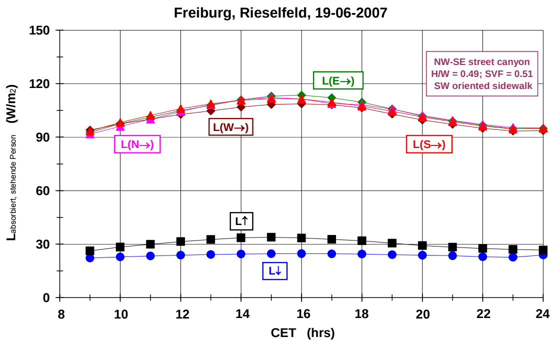


Fig. 13: 1-hr mean values of long-wave radiation flux densities L from the three-dimensional surroundings absorbed by a standing person at a SW oriented sidewalk within a NW-SE oriented street canyon in Freiburg, Rieselfeld, on a typical summer day

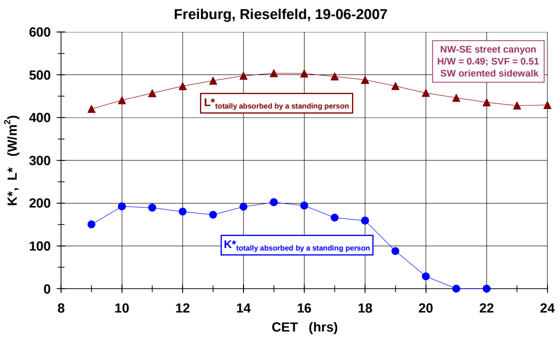


Fig. 14: 1-hr mean values of total short-wave radiation flux density K* and total long-wave radiation flux density L* from the three-dimensional surroundings absorbed by a standing person at a SW oriented sidewalk within a NW-SE oriented street canyon in Freiburg, Rieselfeld, on a typical summer day

The effect of the exposure to the sun on PET could be structurally investigated by results for opposite sidewalks of the NW-SE oriented street canyon in Freiburg, Rieselfeld. They are based on measurements using (i) the steady human-biometeorological measuring system at the SW oriented sidewalk and (ii) the mobile human-biometeorological measuring system at the NE oriented sidewalk. While the $T_a$ difference between both micro-sites was negligible in the morning (Fig. 15), $T_a$ was higher at the SW oriented sidewalk in the afternoon and early evening. The peak difference was about 2 °C in the late afternoon.

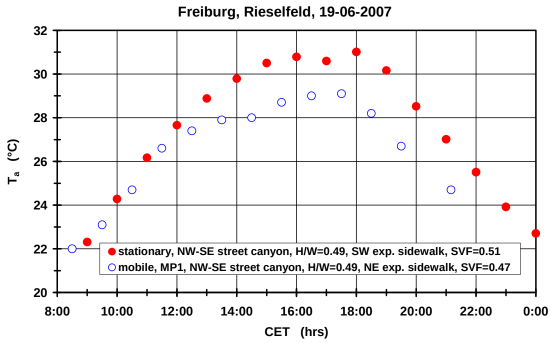


Fig. 15: Air temperature $T_a$ at opposite sidewalks of a NW-SE oriented street canyon in Freiburg, Rieselfeld, on a typical summer day

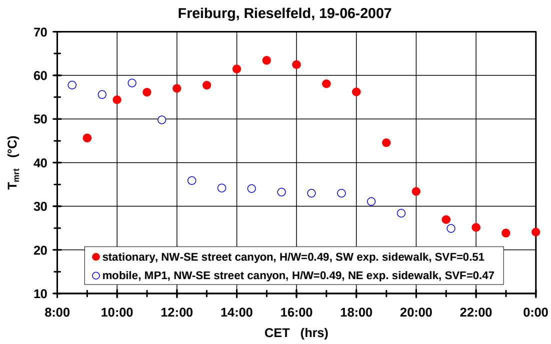


Fig. 16: Mean radiant temperature $T_{mrt}$ at opposite sidewalks of a NW-SE oriented street canyon in Freiburg, Rieselfeld, on a typical summer day

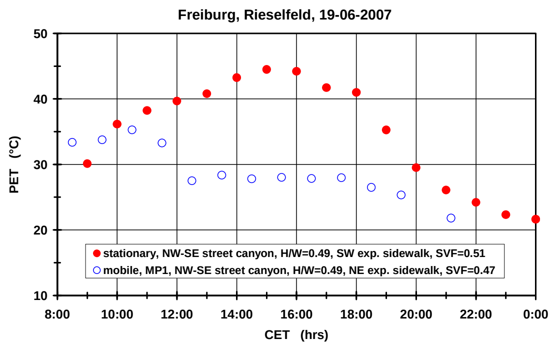


Fig. 17: Physiologically equivalent temperature PET at opposite sidewalks of a NW-SE oriented street canyon in Freiburg, Rieselfeld, on a typical summer day

The analogous patterns of $T_{mrt}$ (Fig. 16) and PET (Fig. 17) differ from the patterns of $T_a$ (Fig. 15), as they are characterised by a pronounced influence of the direct sun radiation. $T_{mrt}$ and PET clearly dropped as soon as the micro-site at the NE oriented sidewalk was shaded. The reduction amounted by 30 °C for

$T_{mrt}$ and 17 °C for PET. The drop of PET can be interpreted as a change from “strong heat stress” to “slight heat stress” (Matzarakis et al., 1999).

### 4.2 *WNE-ESE oriented street canyon in Freiburg, Vauban*

To investigate the significance of the urban heat island for the thermal comfort of citizens in outdoor urban spaces, results from KLIMES measurements in another neighbourhood in Freiburg, Vauban, can be used. Figs. 18 to 21 and 23 are suggestive of the urban structures within the new quarter Vauban.

Fig. 18: Steady human-biometeorological measuring system at the NEE oriented sidewalk within a WNW-ESE oriented street canyon in Freiburg, Vauban

Fig. 19: Steady human-biometeorological measuring system at the NEE oriented sidewalk within a WNW-ESE oriented street canyon in Freiburg, Vauban, view to W

The steady human-biometeorological measurements were conducted on a typical summer day at the NEE oriented sidewalk within a WNW-ESE oriented street canyon (Fig. 18 to 23).

Fig. 20: Steady human-biometeorological measuring system at the NEE oriented sidewalk within a WNW-ESE oriented street canyon in Freiburg, Vauban, view to WNW

Fig. 21: Steady human-biometeorological measuring system at the NEE oriented sidewalk within a WNW-ESE oriented street canyon in Freiburg, Vauban, view to WNW

Fig. 22: Steady human-biometeorological measuring system at the NEE oriented sidewalk within a WNW-ESE oriented street canyon in Freiburg, Vauban, view to NW

Fig. 23: Steady human-biometeorological measuring system at the NEE oriented sidewalk within a WNW-ESE oriented street canyon in Freiburg, Vauban, view to E

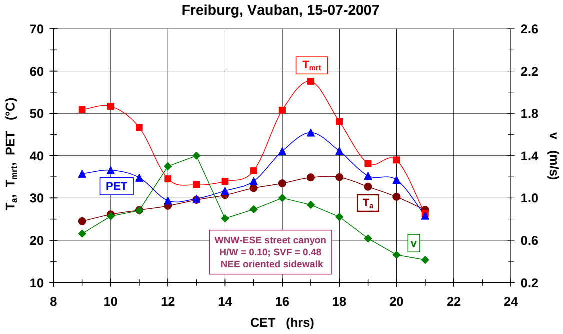


Fig. 24: 1-hr mean values of air temperature $T_a$, wind speed v, mean radiant temperature $T_{mrt}$ and physiologically equivalent temperature PET at the NEE oriented sidewalk of a WNW-ESE oriented street canyon in Freiburg, Vauban, on a typical summer day

The results in Fig. 24 show 1-hr mean values of $T_a$, $T_{mrt}$, PET and wind speed v. $T_a$ and v reached values, which are typical of hot summer days in Central European cities. Interesting is the behaviour of $T_{mrt}$ and PET in contrast to $T_a$ around noon. Whereas $T_a$ still increased, the direct sun radiation did not receive the mirco-site within this street canyon due to shading effects by the adjacent building. Therefore, $T_{mrt}$ and PET were clearly reduced for some hours. This result leads to the hypothesis that the urban heat island indicated by $T_a$ does not agree with a human thermal discomfort island. This hypothesis is not only confirmed by the results in Fig. 24. It was also confirmed by previous urban bioclimate maps (Jendritzky and Nübler, 1981)

## 5. CONCLUSION

The joint research project KLIMES is focused on analyses of human thermal comfort in different quarters in Central European cities. Results of regional climate simulations require these analyses. They are the basis for a better understanding and consideration of human-biometeorological aspects in urban planning, which has as one of the main tasks the maintenance of thermal comfort for citizens even if the thermal background conditions are changing to a pronounced heat load in Central Europe in the future.

## 6. ACKNOWLEDGEMENT


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- Environmental Modelling Group of the Institute for Geography, University of Mainz (Michael Bruse), KLIMES JGUM,
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