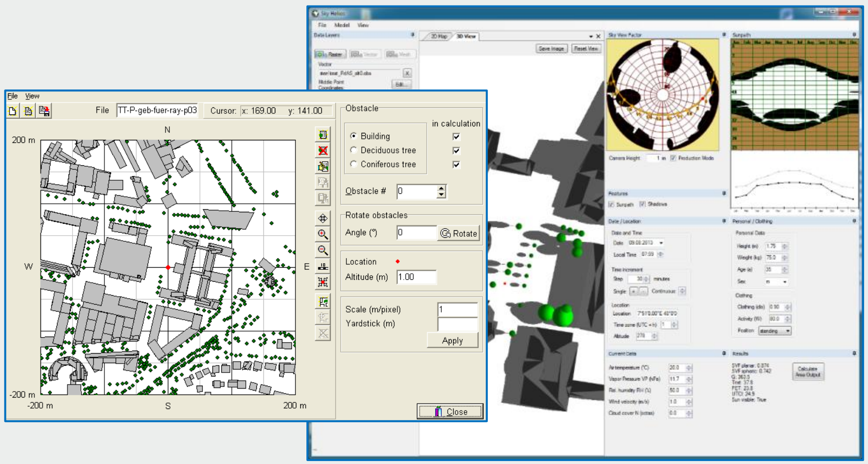
Developments and applications of thermal indices in urban structures by RayMan and SkyHelios model



Andreas Matzarakis, Yung-Chang Chen, Dominik Fröhlich, Marcel Gangwisch, Christine Ketterer

Albert-Ludwigs-Universität Freiburg

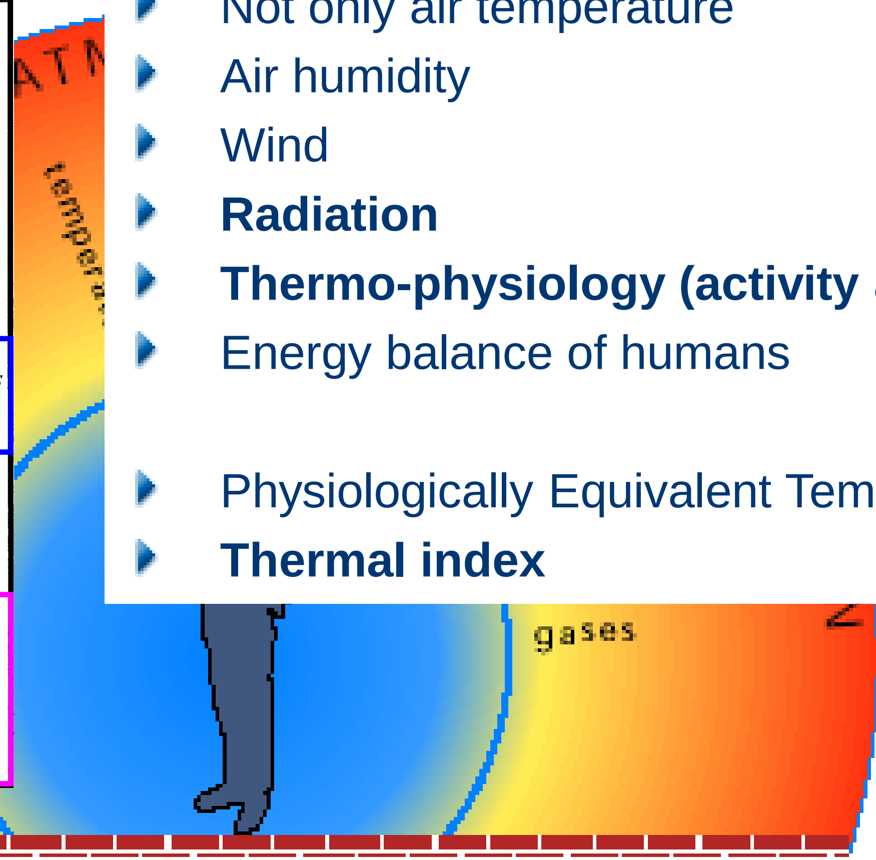
Effect of the thermal atmosphere on humans

PET	Thermal Sensitivity	Grade of Physiological Stress
	very cold	extreme cold stress
4 °C		
	cold	strong cold stress
8 °C		
	cool	moderate cold stress
13 °C		
	slightly cool	slight cold stress
18 °C		
	neutral (comfortable)	*no thermal stress*
23 °C		
	slightly warm	slight heat stress
29 °C		
	warm	moderate heat stress
35 °C		
	hot	strong heat stress
41 °C		
	very hot	extreme heat stress

Assessment of effects of climate

- Not only air temperature
- Air humidity
- Wind
- **Radiation**
- **Thermo-physiology (activity and clothing)**
- Energy balance of humans

- Physiologically Equivalent Temperature
- **Thermal index**



(Matzarakis, 2007)

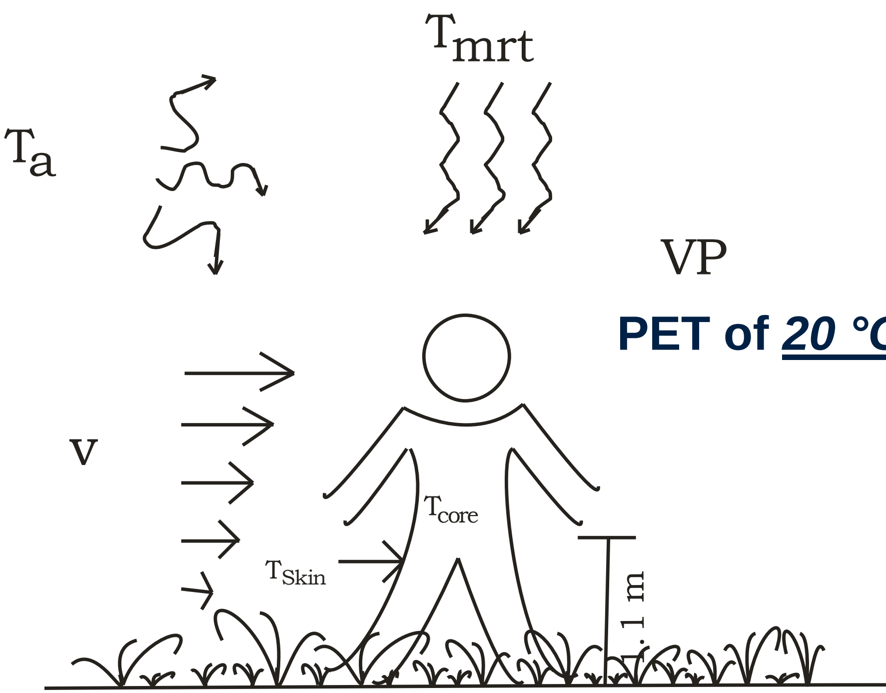
Modern Thermal Indices

(derived thermal indices: PMV, PET, SET*, PT, UTCI)

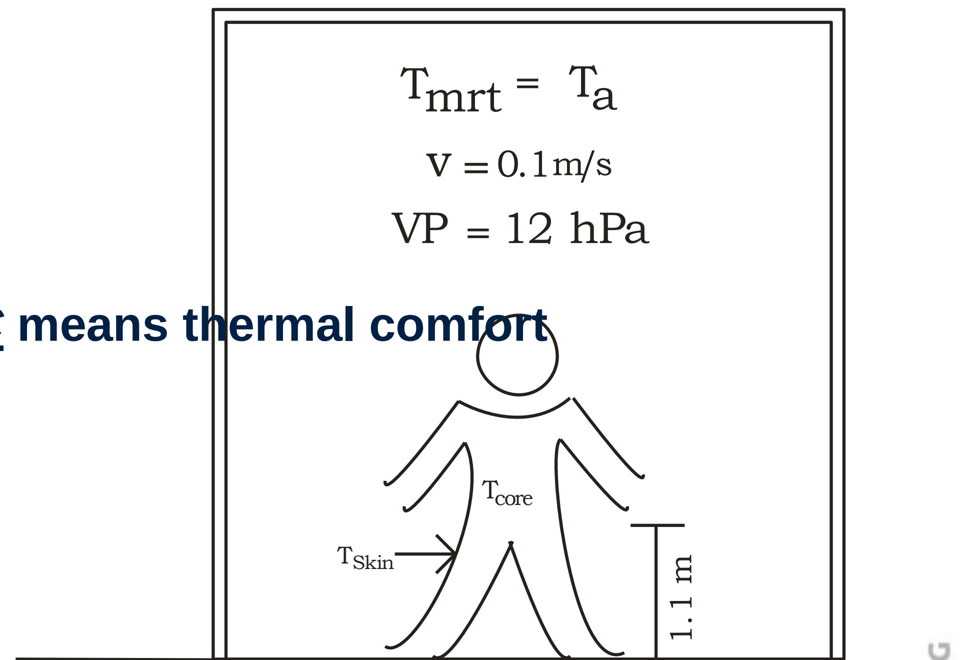
Physiologically Equivalent Temperature (PET):

Definition:

M_{work} = 80 W
I_{cl} = 0.9 clo



PET of *20 °C* means thermal comfort



Thermal perception and stress

PET	Thermal Sensitivity	Grade of Physiological Stress
	very cold	extreme cold stress
4 °C		
	cold	strong cold stress
8 °C		
	cool	moderate cold stress
13 °C		
	slightly cool	slight cold stress
18 °C		
	neutral (comfortable)	*no thermal stress*
23 °C		
	slightly warm	slight heat stress
29 °C		
	warm	moderate heat stress
35 °C		
	hot	strong heat stress
41 °C		
	very hot	extreme heat stress

Thermal indices (PMV, PET),
Thermal perception,
Physiological stresss

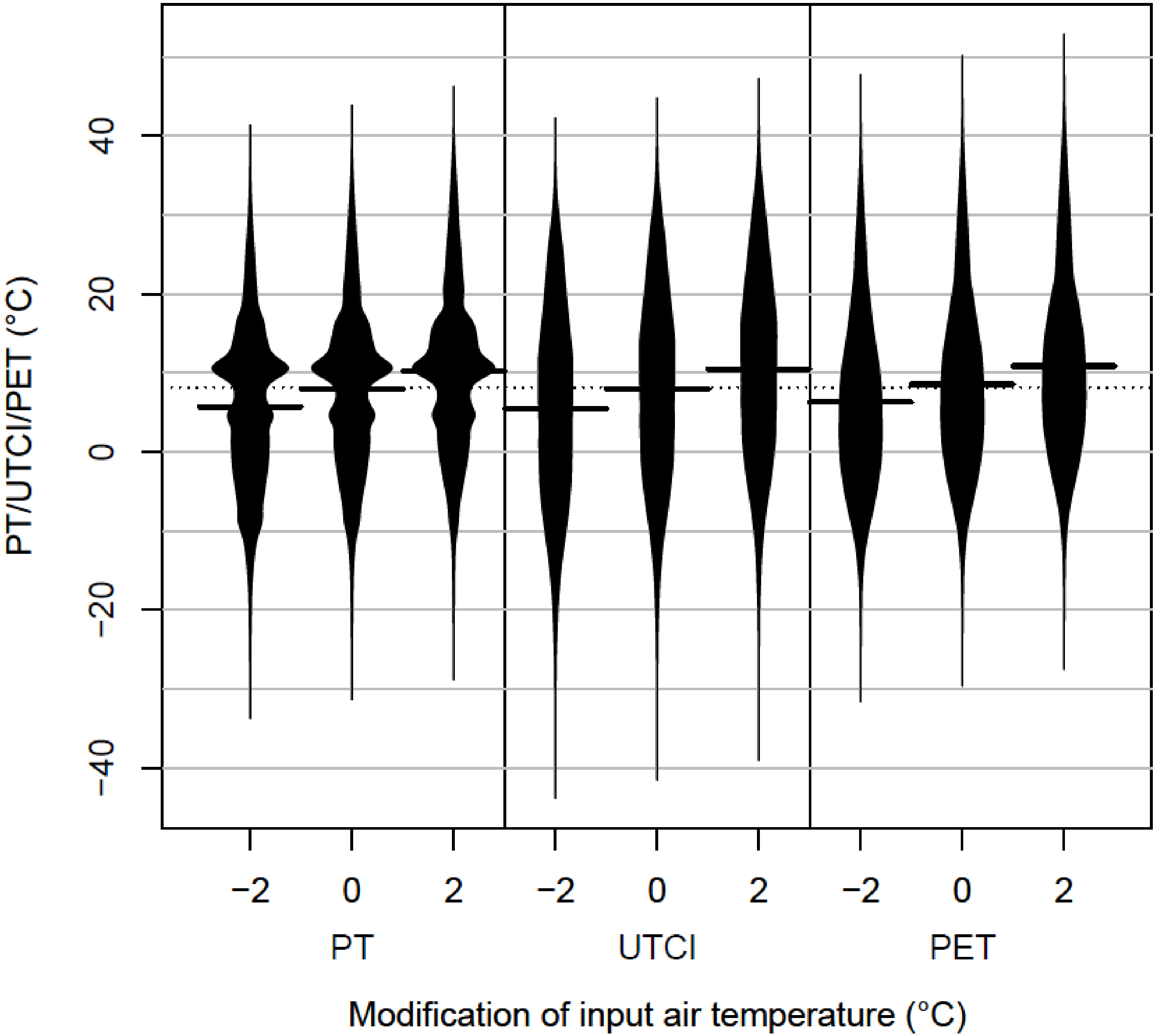
Threshold values of thermal indices PMV and PET for different grades of thermal sensitivity of human beings and physiological stress on human beings

(according to Matzarakis and Mayer, 1996)

Adjustment of the assessment scale:

Taiwan, (Nigeria), Israel, Greece, Hungary, Tansania, …

Sensibility study: thermal indices



Fröhlich and Matzarakis, 2015

Dilemma/Input – Difficulties in estimation

	Input parameters					
	Thermo-physiology		Meteorology			
	clo	Met/act	T_a (°C)	RH (%)	v (m/s)	T_{mrt} (°C)
Index				*	**	***
PMV	var	M var (W/m²)	1.1 m	1.1 m	1.1 m	1.1 m
PET	0.9	act 80 (W)	1.1 m	1.1 m	1.1 m	1.1 m
SET*	0.6	M 1.2 (W/m²)	1.1 m	1.1 m	1.1 m	1.1 m
PT	adapt	M (W)	1.1 m	1.1 m	1.1 m	1.1 m
UTCI	Model T_a	2.3 M (W/m²)	1.1 m	1.1 m	10 m	1.1 m
mPET	Var/auto	var Act	1.1 m	1.1 m	1.1 m	1.1 m

*	RH	Vapour pressure (hPa), appropriate parameter for thermal indices
**	v	Justification (wind profile, wind direction, roughness, micro climate)
***	T_{mrt}	Measurement based (T_g, 6-Direction), Semi-modelling (G, clouds, SVF, T_s, Albedo, …) Modelling (SVFs, T_s, Shade, SW, LW, Albedo, Emm., fabrics), res. Morphol.

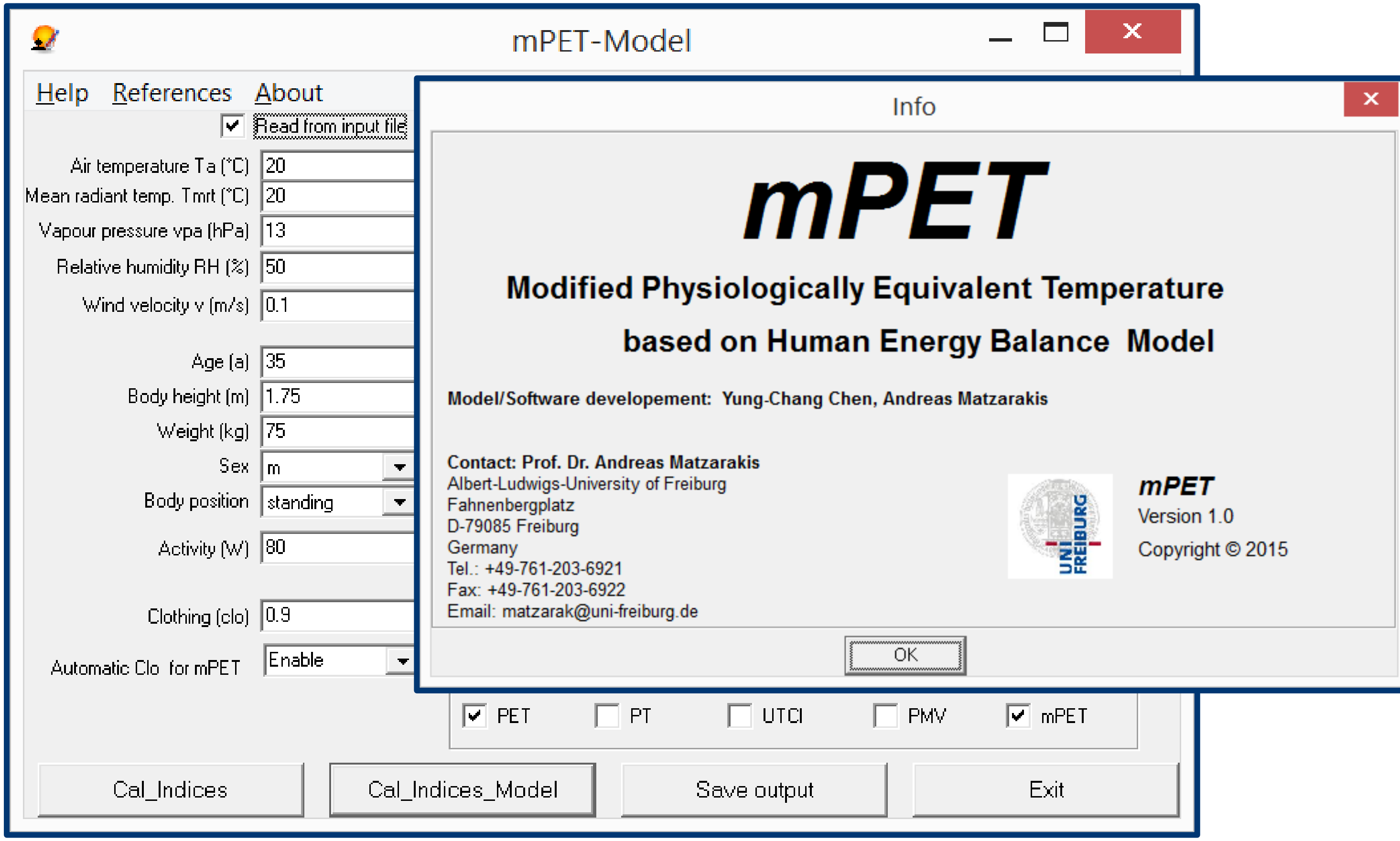
Differences between PET and mPET.

	mPET	PET
Body model	15 nodes – 25 nodes + 1 blood pool	2 nodes
Clothing model	1 layer – 3 layers	1 node
Vapor resistance of clothing	Yes	Not real, only applied for potential sweating over clothing
Sweating evaporation through clothing	Depend on vapor resistance of clothing, VPa, VPsk and VPcl	Indentified by water vapor permeability factor, potential sweating
Vapor diffusion trough nude skin	Calculated with sweating evaporation	Depend on T_{sk}, Vpa and skin wettedness
Vapor diffusion through clothing	Limited by vapor resistance of clothing	No vapor diffusion
Auto changing clo	clo = 0.3 - 2.5	No variance

Comparison of PET, mPET and UTCI

	PET	mPET	UTCI
T_a	major and essential influence	essential influence but slightly essential influence by low T_a due to auto clo working	major and essential influence
RH	tiny influence of RH on PET	moderate influence of RH on mPET, while T_a is over 15 °C	violent influence of RH on UTCI, while T_a is over 5 °C
T_{mrt}	strong influence of T_{mrt} on PET	moderate influence of T_{mrt} on mPET	slight influence of T_{mrt} on UTCI, while T_a is high or low
Velocity	slight influence of velocity on PET	moderate influence of velocity on mPET	violent influence of velocity on UTCI, while T_a is low
clo	no effect	increasing influence of clo on mPET, while T_a is low	no effect
activity	Default (80 W)	Default or variable	2.3 Met (133 watt)

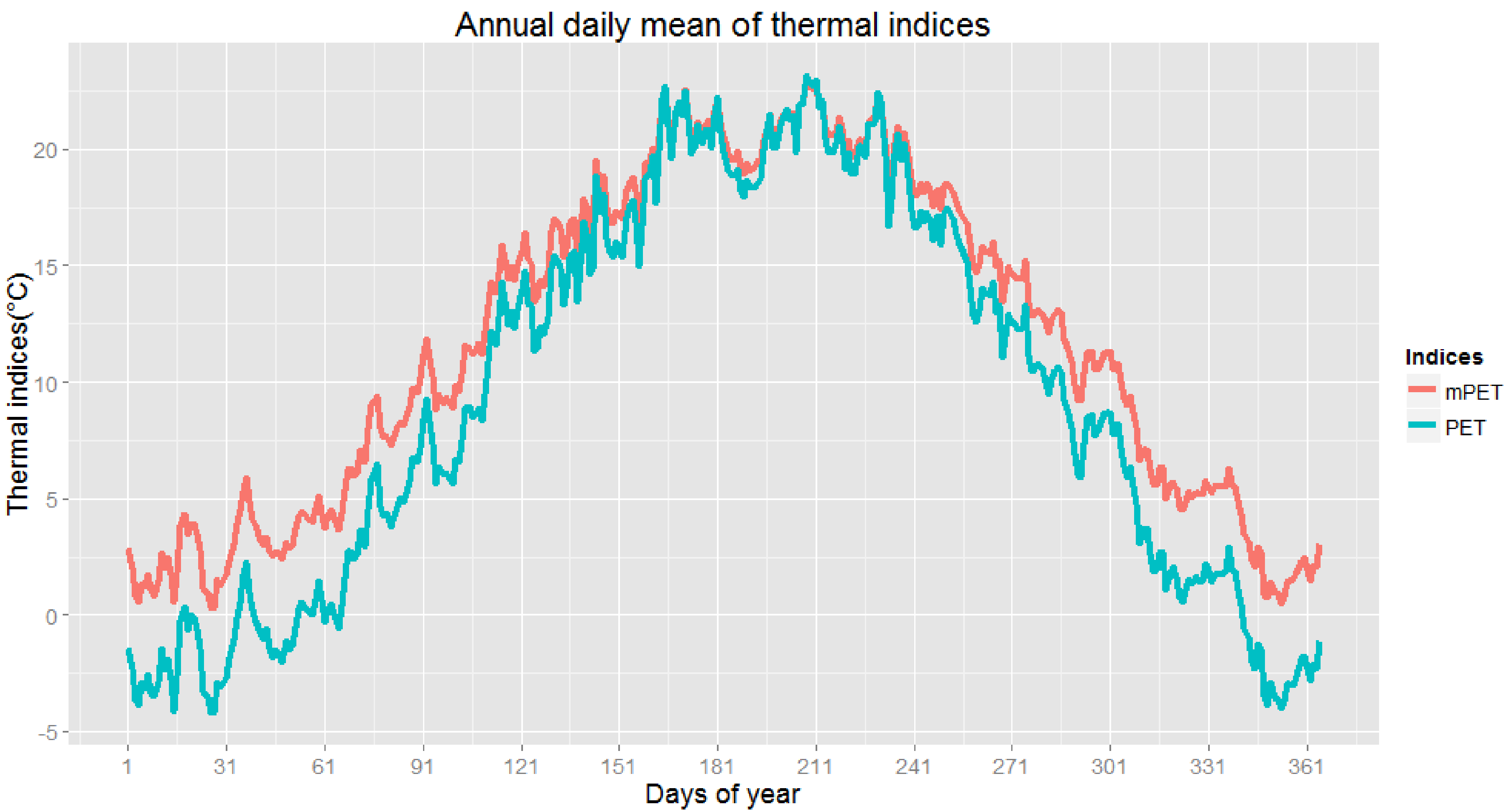
mPET, PET



- **PET**
- **mPET**
- **EB fluxes**
- **Effect of single parameters**

- **Implementation in RayMan/SkyHelios and stand alone**

Pattern of PET, mPET



Chen and Matzarakis, 2015

Modified physiologically equivalent temperature for application in urban climate studies

Yung-Chang Chen and Andreas Matzarakis

Introduction

An universal thermal index is necessary for objective comparisons in different climatic zones for the research of human-biometeorology (e.g. for environmental evaluations, climate assessment for tourists, as well as assessments of climate change). Universal Thermal Comfort Index (UTCI) has been developed to fulfill these requirements. However, UTCI was an operative statistical function based on investigations in Europe and Russia. Hence, UTCI shows limitations in its applicability in the other climatic zones, such as tropic and dry climates. Physiologically Equivalent Temperature (PET) is another thermal index which is at the beginning developed to evaluate the outdoor thermal conditions in temperate climates. It has been proved to effectively evaluate the impact of the air temperature, mean radiant temperature and wind speed on thermal comfort, but variations in air humidity and clothing insulation show weak influence on PET. Thus, this study aims to develop a thermal index for universal applications in all climate zones based on a modified PET (mPET).

mPET and mPET-model

mPET has two major adjustments on PET: (1) physiological thermoregulation is improved to a simple multi-segment body model including a blood pool element and a bio-heat transfer principle; and (2) a multi-layer clothing model with clothing insulation and vapour resistance is implemented. Due to those two adjustments, PET has been improved to effectively evaluate of the impact of vapour pressure and clothing insulation on thermal conditions and mPET can be applied in all climatic zones. Fig. 1 shows the calculating concept of mPET-model to predict mPET.

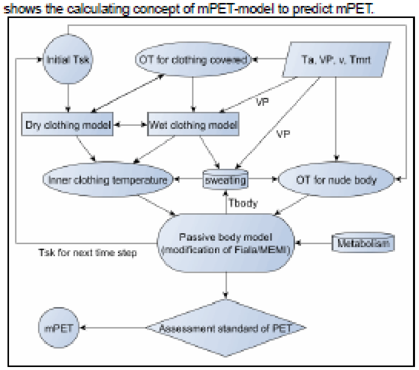


Fig. 1: The calculating principle and flow chart of mPET-model.

Differences between PET and mPET

The differences, such as thermoregulation, clothing model and evaporative heat transfer, between PET and mPET are listed in table 1.

Table 1: List of differences between PET and mPET.

	mPET	PET
Body model	15 nodes – 25 nodes + 1 blood pool	2 nodes
Clothing model	1 layer – 3 layers	1 node
Vapor resistance of clothing	Yes	Not real, only applied for potential sweating over clothing
Sweating evaporation through clothing	Depend on vapor resistance of clothing, VPa, VPsk and VPcl	Indentified by water vapor permeability factor, potential sweating
Vapor diffusion trough nude skin	Calculated with sweating evaporation	Depend on T_{sk}, Vpa and skin wettedness
Vapor diffusion through clothing	Limited by vapor resistance of clothing	No vapor diffusion
Auto changing clo	clo = 0.3 - 2.5	No variance

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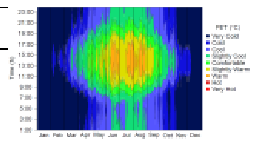
Results

Table 2: Thermal classification of PET for Western- and Central European and thermal classification of UTCI (Source: Matzarakis and Mayer (1996); Bröde et al. (2012))

Thermal sensation	PET range for Western- & Central Europe (°C)	UTCI range
Very cold	< 4	< -27
Cold	4 ~ 8	-27 ~ -13
Cool	8 ~ 13	-13 ~ 0
Slightly cool	13 ~ 18	0 ~ 9
Neutral	18 ~ 23	9 ~ 26
Slightly warm	23 ~ 29	26 ~ 32
Warm	29 ~ 35	32 ~ 38
Hot	35 ~ 41	38 ~ 46
Very hot	41 <	46 <



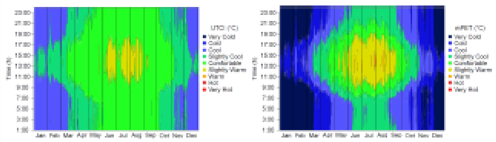


Fig. 2: Annual and diurnal distributions of PET (top-right), mPET (bottom-right) and UTCI (bottom-left) to analyze the human thermal condition in hourly data at Freiburg during 1999 to 2010.

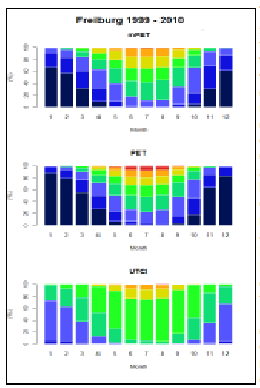


Fig. 3: Histograms of PET, mPET and UTCI to analyze the human thermal condition in hourly data at Freiburg during 1999 to 2010.

The three thermal indices displayed significantly different evaluations on thermal conditions in Freiburg during winter. Applying PET leads to more than 80 % probability of occurrence of extreme cold conditions. Concurrently, mPET evaluated only 60 % incidence of extreme cold events. Furthermore, extreme cold events occurred even during May, June, and September according to the assessment of PET but did not happen at the same time depending on the evaluations of mPET. UTCI shows quiet less cold and no very cold evaluations than PET and mPET.

For the estimation of extreme hot events in Freiburg during summer, there were also differences between PET, mPET and UTCI. Almost no extreme hot events were given by the estimations of mPET and only moderate hot stress occurred. On the contrary, PET has given a regularly occurrence of extreme hot stress. UTCI carried only few hot stress in August and evaluated almost no heat stress.

Conclusions and discussions

1. In temperate regions, mPET rates the climate as less extremely hot and extremely cold thermal conditions than PET.
2. mPET doesn't underestimate during summer or overestimate during winter the thermal conditions alike UTCI.
3. The applicable thermal classification of mPET is necessary to be furthermore investigated.
4. In summary, mPET is a more realistic, reasonable and universally applicable thermal index than the other two.

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Modified physiologically equivalent temperature for application in urban climate studies

Yung-Chang Chen and Andreas Matzarakis

Poster 20: BPH/ID – Human perception of comfort, and multicriteria evaluation

UNI FREIBURG

RayMan Pro - A Tool for Applied Climatology

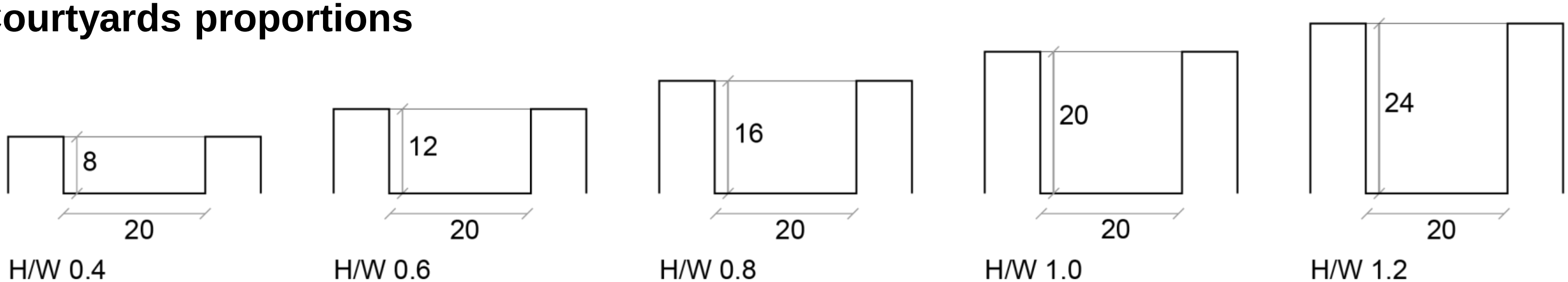
(urban climatology, human-biometeorology, tourism climatology, …)

- Sunshine duration
- Sun paths
- Shadow
- Global radiation
- Mean radiant temperature
- Predicted Mean Vote (PMV)
- Phys. Equiv. Temp. (PET)
- Stand. Effec. Temp. (SET*)
- Universal Thermal Climate Index (UTCI)
- Perceived Temperature (pT)
- new: mPET

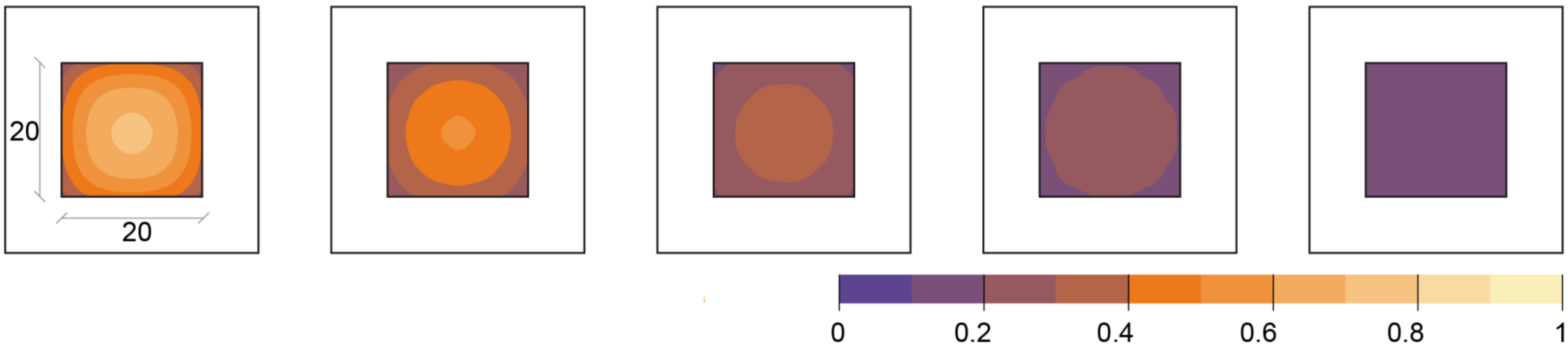
- Simple environments
- Complex environments
- Topography
- Fish-Eye
- Hemisph. input/SVF
- Meteo data
- Climate data
- ....

Long-term analysis - Courtyard typologies

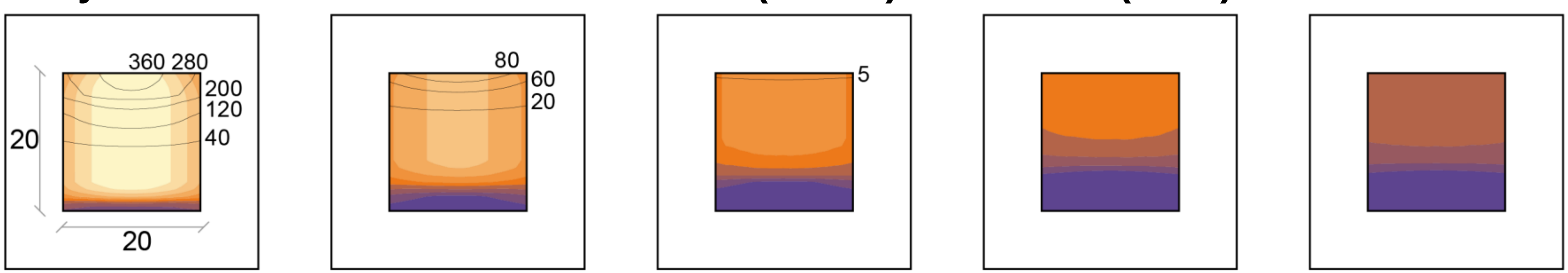
Courtyards proportions

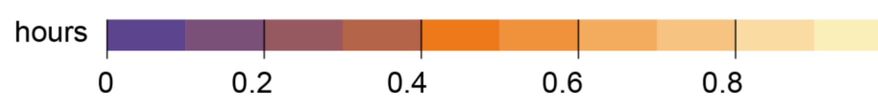


Courtyards Sky View Factor



Courtyards sunshine duration in summer (colors) and winter (lines)





Martinelli, Matzarakis, 2015

UNI FREIBURG

Influence of different urban configurations on human thermal conditions in a pypical Subtropical Coast City – Case of Santos, São Paulo

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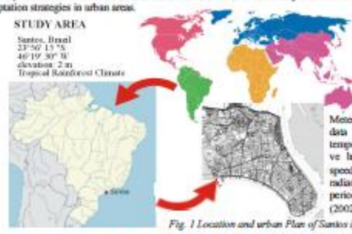
INTRODUCTION

Urban design features as orientation of streets, height of buildings, width of street, influences directly on thermal comfort and contribute to increase urban heat island (UHI). The study of different urban configuration using long term data to calculate mean radiant (Tmrt) and physiologically equivalent temperature (PET) helps to develop urban design guidelines to adapt urban climate change (Abreu-Harbich et al. 2014a, Abreu-Harbich et al., 2014b). This paper aims to quantify the human thermal conditions on human thermal conditions at pedestrian level and develop adaptation strategies in urban areas.

STUDY AREA

Santos, Brazil
23°56' 13"S
46°19' 30" W
elevation: 2 m
Tropical Rainforest Climate



Meteorological data used: air temperature, relative humidity, wind speed, and solar radiation for a period of 10 years (2002-2012).

Fig. 1 Location and urban Plan of Santos in 2011

Santos is a coast city, partially located on the island of São Vicente, and was founded in 1546. In 1899, notorious sanitarian Engineer and modern urban planner, Saturnino de Brito, remodeled the city plan and landscape through draining canals in open air in 1910 a long urban park in front the seaside built in 1935 (Arruda and Sá, 2006), fig 1. Urban sprawl caused by socio-economic made changes on urban design and it became a very dense city because the legislation of city eliminated the requirement for maximum height of new projects since 1998.

H/W	FEATURES	STREET VIEW	SVF
0,5	Building Height: 1-2 floors Street: 20 m		SVF=0.6
1,0	Building Height: 6-12 floors Street /Canal: 50 m		SVF=0.5
1,5	Building Height: 3-6 floors Street: 20 m		SVF=0.34
2,0	Building Height: 12-22 floors Street/Canal: 50 m		SVF=0.08
2,5	Building Height: 6-12 floors Street: 20 m		SVF=0.28
3,0	Building Height: 22-35 floors Street/Canal: 50 m	Future Modifications due to new Urban Planning	SVF=0.26
5,0	Building Height: 12-22 floors Street: 20 m		SVF=0.21
7,5	Building Height: 22-35 floors Street: 20 m	Future Modifications due to new Urban Planning	FVC=0.07
5,0	Building Height: 12-22 floors Street: 20 m		SVF=0.16
	Building Height: 22-35 floors Street: 20 m		SVF=0.17
	Building Height: 12-22 floors Street: 20 m		SVF=0.86

Fig. 2 Urban Configuration of Santos, Brazil

The scheme of Santos urban design of Santos was develop based on urban configuration: typical urban street, a long urban park in front the seaside and forestry canal. Fig. 2 shows aspect ration (H/W) of typical street or canal varies between 0.5 to 5, with or without trees.

METHODOLOGY

The simulations are conducted using the RayMan model (Matzarakis et al. 2007; 2010). The main primary input parameters for RayMan in the present study are air temperature, air humidity, wind speed and total solar radiation. The following configurations and setups used are: the model canyon are 500 m in length, with values for the width – 10 m, 30 m, 50 m, 100 m, 150 m – and its height adopted was 20 (street) and 50 m (Canal) (Fig. 3).

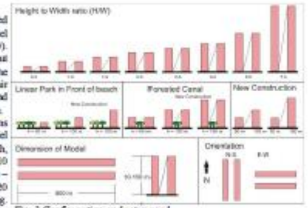


Fig. 3 Configuration and setup used

RESULTS

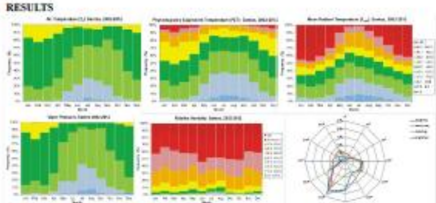


Fig. 4 Monthly frequency distribution of Ta, PET, Tmrt, vapor pressure, relative humidity and wind and direction of wind at urban climate station of Santos for the period January 1st, 2002 to December 31st, 2012

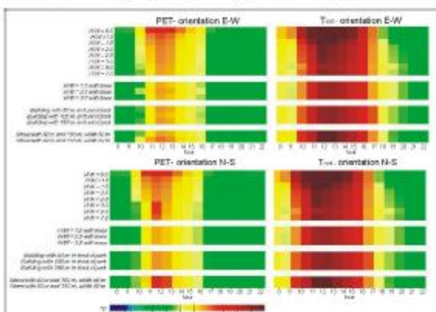


Fig. 6 Diurnal courses of PET (oC) for typical urban configuration and future modifications, north-south, east-west orientations, based on data from climate station for the period January 1st, 2002 to December 31st, 2012

CONCLUSION

The findings show that east-west orientation and the H/W ratio between 2.0 and 3.0 can improve thermal comfort, but H/W ratio above 3.0 requires additional measures such as planting vertical gardens to control the heat fluxes in the street canyon. The findings suggest that trees can improve thermal comfort of tropical cities, and it confirms results of Abreu-Harbich et al. (2015). Not only shading provided by buildings but also trees can improve thermal comfort in summer of tropical cities (Lin et al. 2010). In additional, to alleviate the negative effects of high-density cities, the wind can infiltrate in the city and improve thermal comfort, particularly at midday, the most warm day hour. The presented methods and results can be applied for architecture and urban planning interested in performing sustainable cities. The strategically city management need to develop urban guidelines and making intervention in the existing city. Study of influence of urban obstacles on microclimate and also the energy balance of materials of pavement and buildings are necessary.

ACKNOWLEDGMENT
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The influence of urban geometry on thermal comfort of public open spaces for Italian climate zones

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Introduction

The relationship between urban morphology and microclimate is a relevant topic for both urban planning and urban climatology, as it significantly influences the thermal comfort of individuals. Urban morphology and height-width proportions (H/W) have a discordant seasonal effect on thermal comfort, with a demand for compactness in summer, to secure protection from the sun, and openness in winter, to provide solar access. Due to minor mixing of air with the exterior, open spaces of historical city centres, surrounded by buildings and located in medium-high compact urban fabric, are strongly affected by height-width proportions.
We present a long-term numerical study on the effect of urban morphology on the thermal comfort of public open spaces in Italian climate zones. As Italy, with its long extension on the North-South and its complex orography, comprise several climates of the temperate zone, the results can have a wider significance in other countries with similar climates.

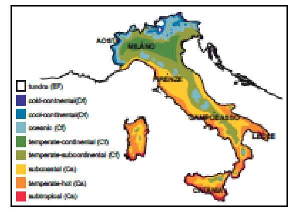
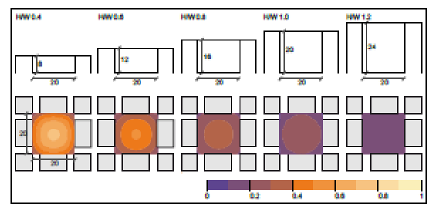


Fig. 1 (left): *Italian climate zones, according to Blasi and Michetti (2005).*

Fig. 2 (below): *H/W proportions and corresponding Sky View Factor for the five open spaces taken into account.*



Methodology

According to a detailed version of Köppen-Geiger classification (Blasi & Michetti, 2005), 6 Italian cities were selected for each Italian climate zone: Aosta, Milano, Campobasso, Firenze, Lecce, Catania.
The study takes into account five open spaces with a square shape of 20x20 m and different height of 8 m, 12 m, 16 m, 20 m, and 24 m. A no building scenario depicts the reference conditions for each climate zone.
We described the urban geometry and solar access using the sunshine duration, which is the annual or monthly duration of direct solar radiation in hours for a given location, and the sky view factor (SVF), which can be defined as the portion of sky visible from a specific point (Oke, 1978), estimated with the SkyHelios model (Matzarakis and Matuschek, 2011).
The assessment of thermal comfort is based on the Physiologically Equivalent Temperature (PET) index (Mayer and Höppe, 1987, Höppe, 1993, 1999), calculated with the RayMan model (Matzarakis 2007, 2010). The input are 30 years data on air temperature, vapour pressure, air velocity and cloud cover, with 3-hours resolution, obtained from the meteorological station of each city.

Results

The results give an overview of the annual trend of PET.
The first result is represented by the median PET for every day of the year for the different open spaces for each climate, calculated during daytime (Fig. 3) and at 15:00 LST, which exemplifies extreme hot conditions in summer, when people in Italy use public spaces most frequently.

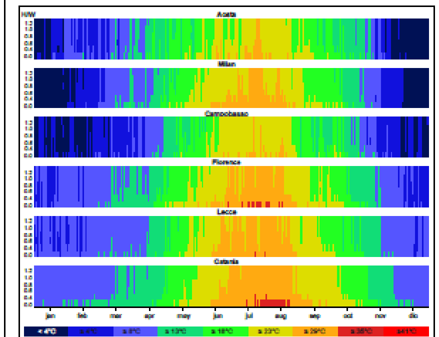


Fig. 3 (above): *Median of PET for each day of the year for the five open spaces for the different Italian climate zones, calculated during daytime for different H/W.*

The second result is the frequency of occurrence of PET values during daytime for the 3-hour resolution timesteps over the 30 years interval considered, calculated for summer (June, July, August) and winter (December, January, February) periods (Fig. 4).

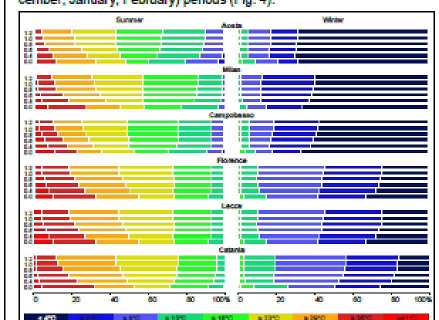


Fig. 4 (above): *Frequency analysis of daily PET values for summer (June, July, August) and winter (December, January, February) or different H/W.*

Discussion and Conclusions

The results indicate that aspect ratio appears to have a stabilizing effect over thermal comfort, more conspicuous in summer than in winter. This effect depends on the diminution of sunshine duration provided by low SVF, which moderates the variable influence of direct sunshine.
The results also point out how the influence of courtyards proportions is linked to specific climatic conditions and is affected by small-medium variations in the meteorological factors, such as the ones depicted by Italian climatic subdivision.

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Poster 2: UCD – Impact of urban forms on comfort and ventilation

- Sun paths
- Sun duration/diagram
- Shade
- Sky view factor(s)
- Roughness
- Global radiation
- Mean radiant temperature
- Wind speed and direction
- PET, (mPET) and UTCI

- Vector and grid data
- Google Earth implementation
- Interfaces and outputs for RayMan
- Interface/Output for Climate Mapping Tool

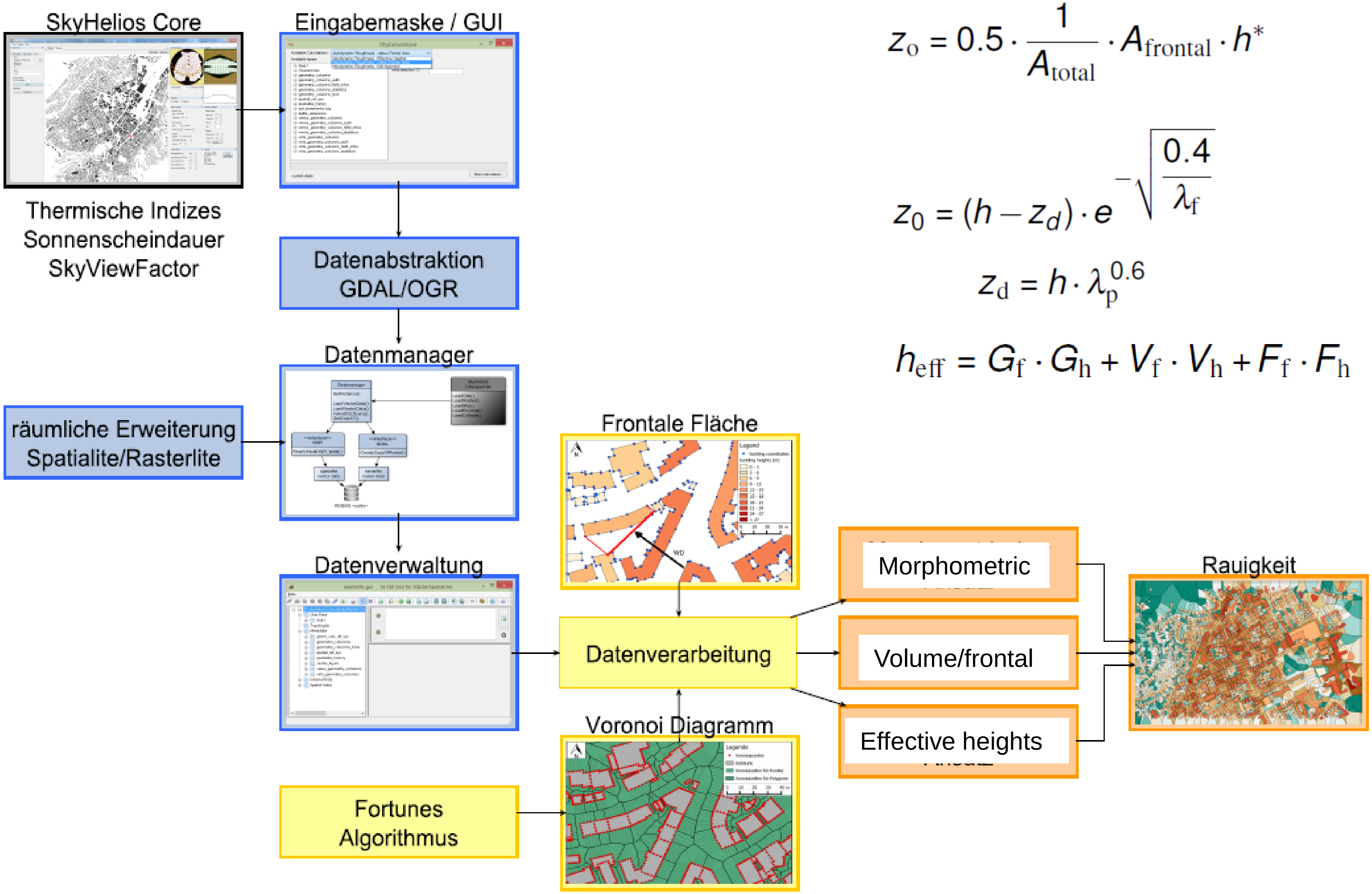
SkyHelios – Roughness

$$z_0 = 0.5 \cdot \frac{1}{A_{\mathrm{total}}} \cdot A_{\mathrm{frontal}} \cdot h^*$$

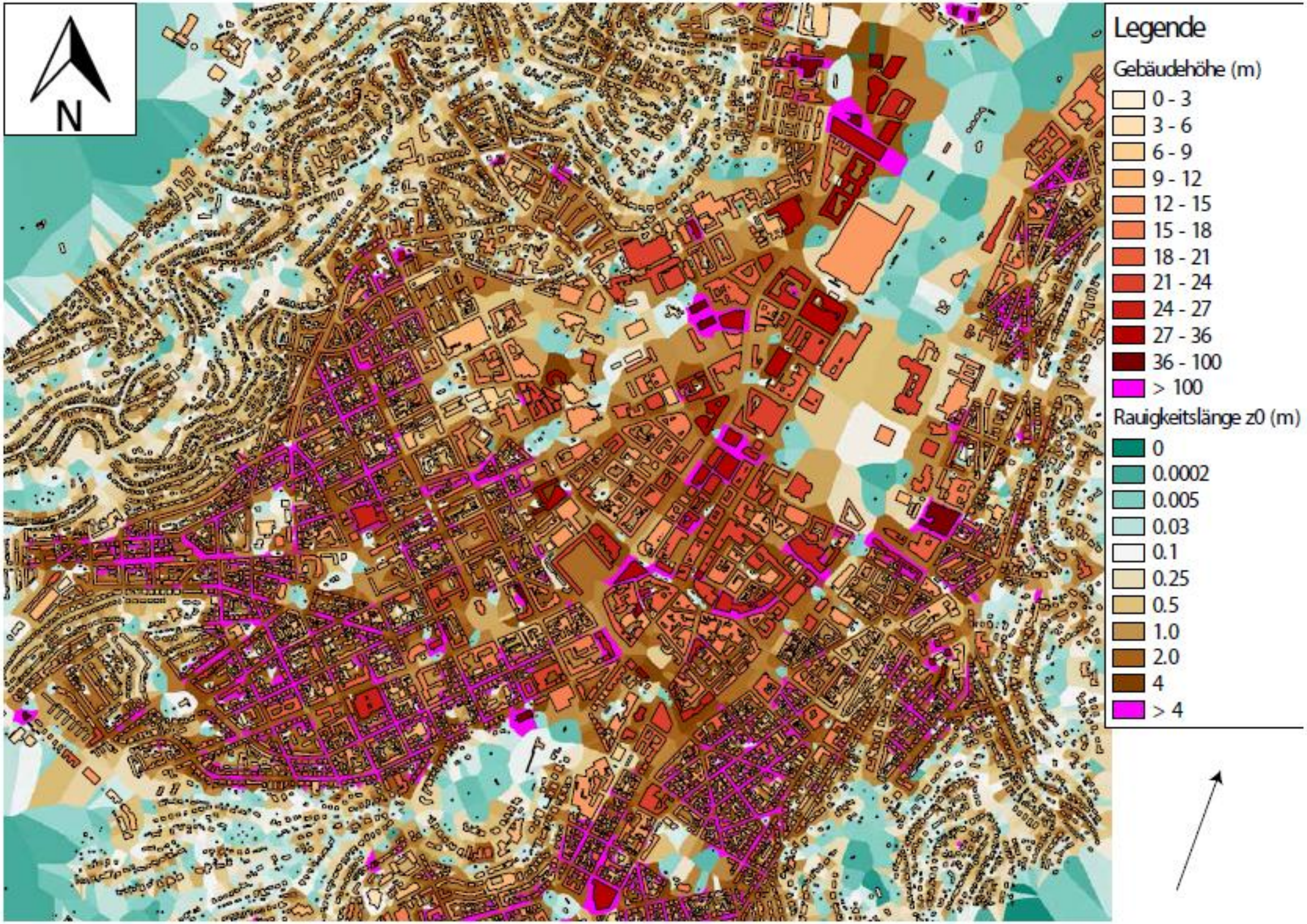
$$z_0 = (h - z_d) \cdot e^{-\sqrt{\frac{0.4}{\lambda_{\mathrm{f}}}}}$$

$$z_{\mathrm{d}} = h \cdot \lambda_{\mathrm{p}}^{0.6}$$

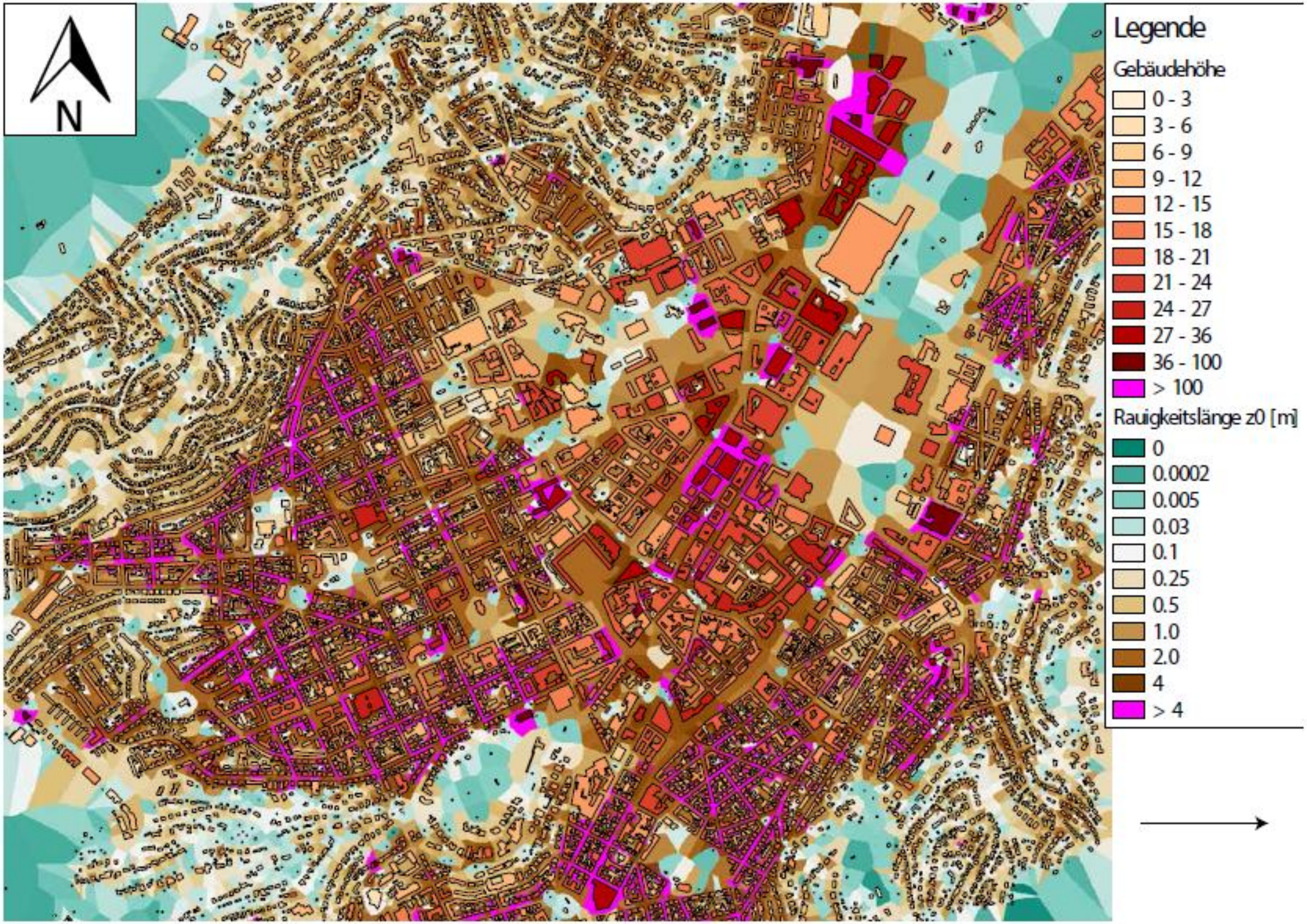
$$h_{\mathrm{eff}} = G_{\mathrm{f}} \cdot G_{\mathrm{h}} + V_{\mathrm{f}} \cdot V_{\mathrm{h}} + F_{\mathrm{f}} \cdot F_{\mathrm{h}}$$



SkyHelios – Roughness, wind direction = 20°



SkyHelios – Roughness, wind direction = 270°



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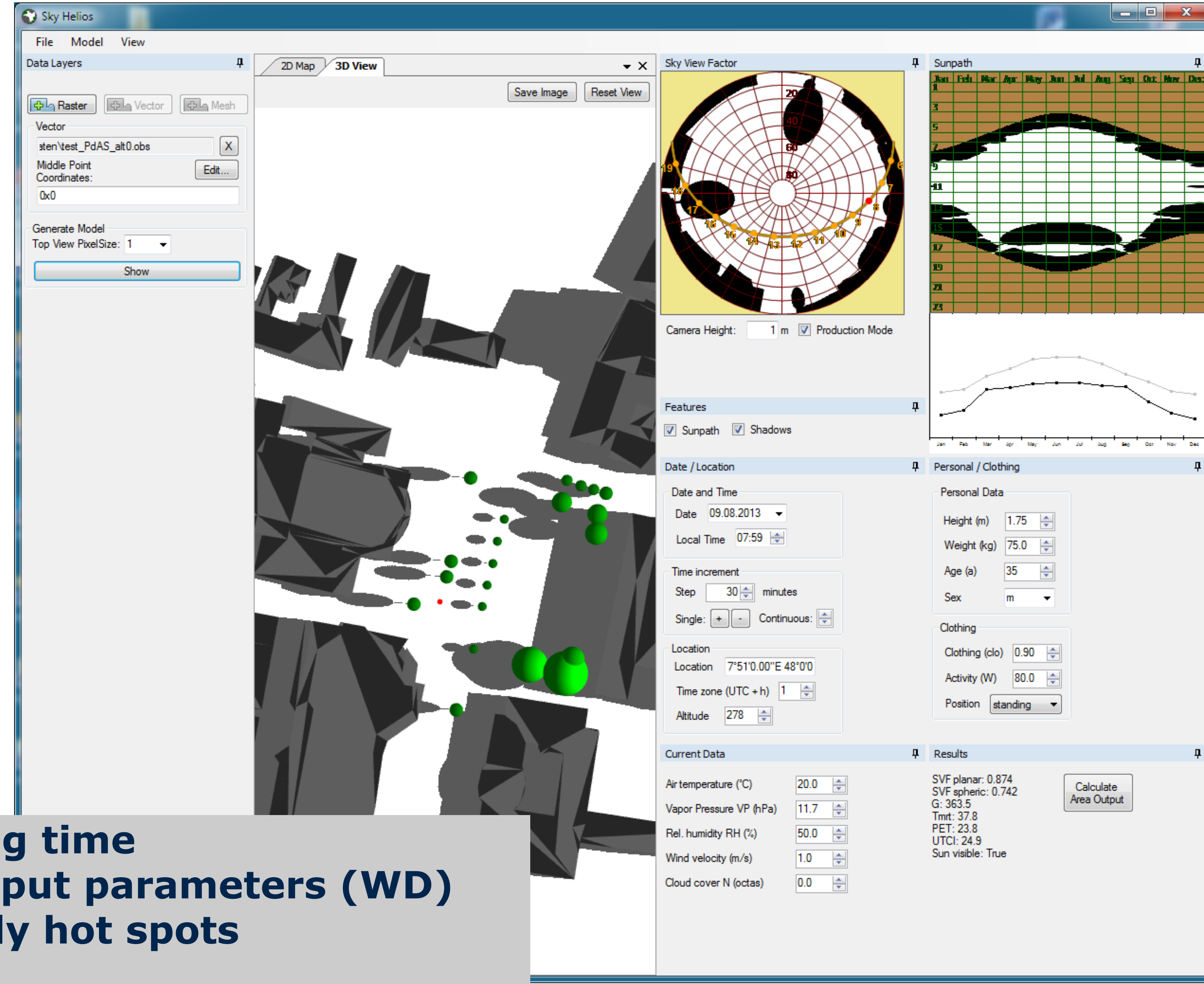
Diagnostic models: + Thermal indices



- Running time
- Add. input parameters (WD)
- Not only hot spots
- …

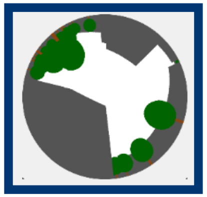
Interfaces

RayMan	Obs can be imported in SkyHelios
SkyHelios	SVF – Save and import in RayMan
SkyHelios	Conversion of shp files in obs files
SkyHelios	Import (New) Collada - Google Earth
SkyHelios	ENVI-met surface files
TIC-ENVI-met	Running PET/UTCI based on ENVI-met

- Free tools

RayMan Pro
http://www.urbanclimate.net/rayman

SkyHelios
http://www.urbanclimate.net/skyhelios



Statements

- Models deliver good and important results
- Recommendations to users of models
  - Validation
  - Consider possibilities and limitation – aim of development

  - PLEASE: read/consider manual

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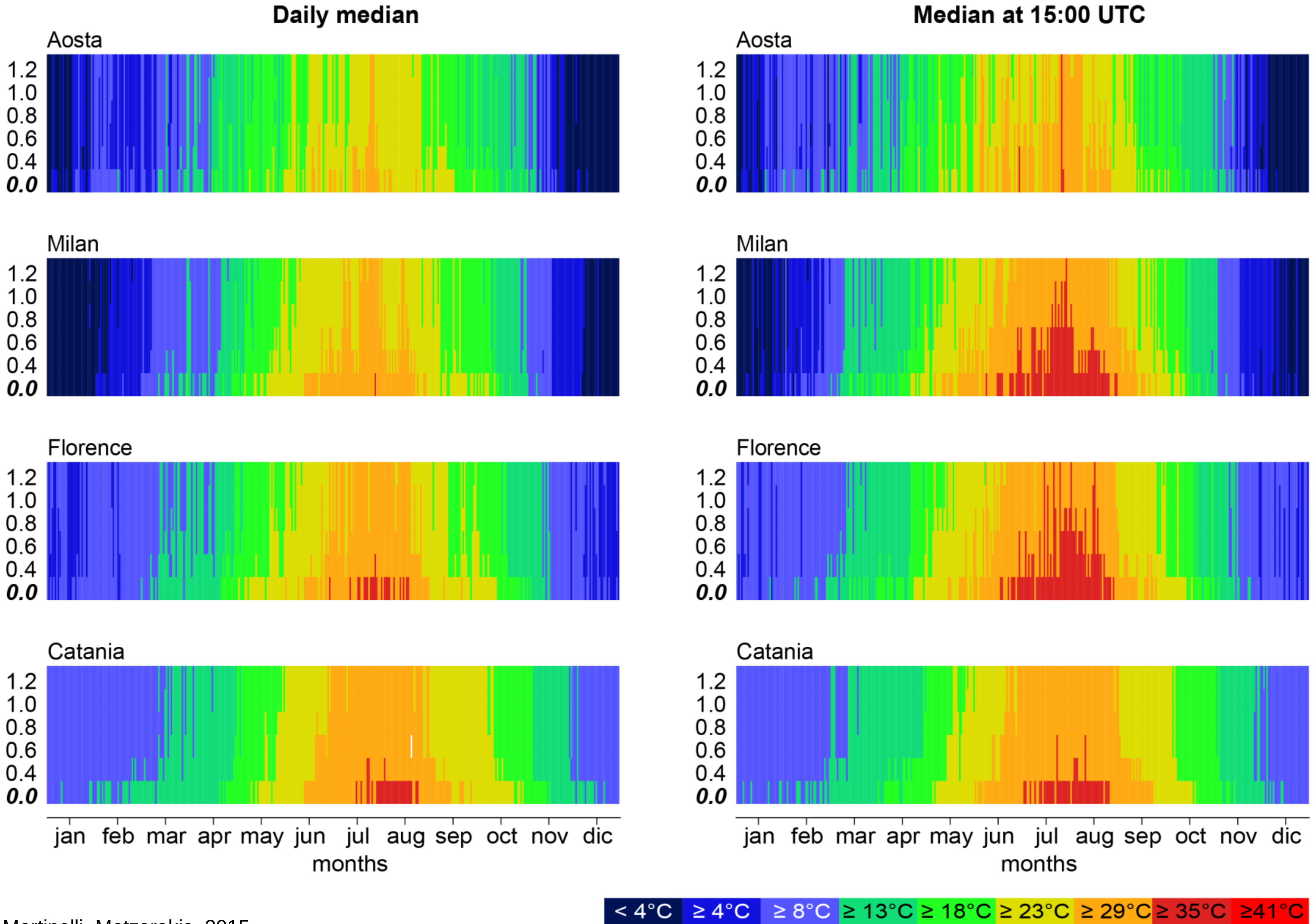
Long-term analysis - Results

Daily median of PET and median of PET at 15:00 LST over the year for four exemplar cities



Martinelli, Matzarakis, 2015