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LAND SURFACE TEMPERATURE IN ŁÓDŹ OBTAINED FROM LANDSAT 5TM

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Abstract. The main aim of this paper is to present the spatial differentiation of Land Surface Temperature LST in Łódź based on Landsat 5 Thematic Mapper (L5TM) images. Analysis was performed for all L5TM images from 2011, with clear sky over Łódź. Land surface temperature (LST) play an important role in determination of weather conditions in boundary layer of atmosphere, especially connected with convection. Environmental satellites from Landsat series delivers the high resolution images of Earth's surface and according to the estimations made on the ground of it are precise. LST depends widely on surface emissivity. In this paper the emissivity was estimated from MODIS sensor as well as NDVI index, then both method were compared. The processed images allowed to determine the warmest and the coldest areas in the administrative boundaries of Łódź. The highest LST values has been found in industrial areas and the in the heart of the city. However, there are some places lying in city outskirts, where the LST values are as high, for instance Lodz Airport. On the contrary the lowest LST values occur mostly in terrains covered with vegetation i.e. forests or city parks.

Keywords:. Land Surface Temperature, Landsat 5 TM, Remote sensing, emissivity, NDVI

Introduction

Nowadays when nearly half of a human population live in urban areas and we are facing with climate change, the knowledge about urban climate and its peculiarity play a vital role in climatological researches. Very important issue is bounded to spatial variability of the Land Surface Temperature (LST). As the great amount of the artificial materials, with different from natural characteristics, (i.e. heat capacity) covering the surface in the cities results in higher temperature than in rural areas, what is commonly known as Urban Heat Island (UHI). Furthermore rapid changes in the surface cover, that can be found for instance in the neighborhood of more "natural" areas like parks etc, results in greater contrast in LST between adjacent areas. The information on the thermal conditions in the cities could be helpful not only for ordinary people but for the spatial-policy makers as well.

The UHI studies are mainly based on in situ measurements of temperature at 2 m (i.e. Fortuniak 2003), however, there are many different ways of investigating this phenomenon. Temperature sensors could be installed on car (Kłysik, Fortuniak 1999) or even bicycles. Such measurement could be expensive, especially when one is going to do measurements simultaneously at many sites. The advantage of the remote sensing is the availability to provide high resolution data. The satellites images has been successfully applied to UHI or LST investigation in many cities, hence many different types of sensors has been used. Strathopoulou and Cartalis (2007) investigated the intensity of daytime UHI at major cities in Greece, using LANDSAT 7 ETM+ (L7ETM+). UHI effect in major Asian "mega" cities were investigated with L7ETM+ and MODIS (Hunt et. al 2006). In Poland the spatial differentiation of LST has been examinated e.g.. in Kraków based on the LANDSAT 5 TM (L5TM) and L7ETM+ images (Walawender 2009).

The main aim of this study is to present the spatial distribution of LST in Łódź and to determine the areas that represent "hot spots" and "cold spots". The second important goal is the comparison of the LST derived from L5TM with two different methods of the emissivity determination.

Study area

Łódź is city located in Central Poland with the population about 740 000. It is geographically situated on longitude 19°19'16" East - 19°38'35" East and latitude 51°41'10" North - 51°51'40". Western part of the city is elevated to 180 m, while the eastern part rises up to 235 m.

In general the land uses in Łódź is a mixture of residential and industrial areas (Fig. 1). The most eastern and western parts of the city are agricultural areas. In the north east of Łódź the „Łagiewniki" forest is situated. As the remaining of natural forests it is one of the largest forested area lying in the administrative boundary of the city in Europe.

Łódź has very regular streets pattern. The buildings in most central part were built about 100 yr ago. The average buildings height varies here from 15 to 20 m. The greatest space of the city is occupied with blocks of flats districts with predominance of 15 m high buildings. In some areas the 35 m high blocks of flats could be found. In the outskirts the detached and residential houses are located, often they coexists with gardens (Kłysik, Fortuniak 1999). The remains of industrial history of Łódź are clearly visible in the districts with domination of big production plants. They are mainly situated east, north-west and south to the central of the city (Fig. 1).

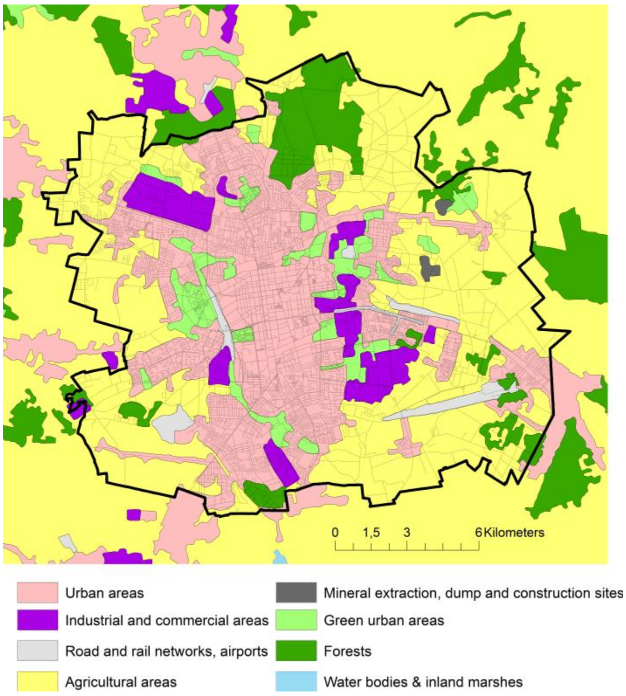

Fig 1. Land use / land cover in Łódź based on Corine Land Cover database.

Data and Methods

In this study dataset of LANDSAT 5 TM and MODIS Terra has been used. The former included six terrain corrected (L1T) images acquired in the 2011, that covered the Łódź area (see Table 1). The latter contained six MODIS Land Surface Temperature and Emissivity Daily L3 Global 1 km Grid SIN products from corresponding days.

MODIS products has been obtained from NASA's Earth Observing System Data and Information System via REVERB ECHO (http://reverb.echo.nasa.gov), while LANDSAT images from USGS Earth Resource Observation and Science (EROS) Center via GLOVIS (http://glovis.usgs.gov/)

Unfortunately there are not many L5TM images covering Łódź throughout a calendar. This result mainly from the characteristics of mentioned satellite orbit, as the revisit time is 16 days. Even if the image is acquired, the cloud cover occurrence could prevent to use such scene to any investigations that include land surface.

Table 1. Landsat 5 TM images used in this study.

Day of the Year (DOY)	Data	Acquisition time (GMT)
093	03.04.2011	9 :28
150	30.05.2011	9 :21
157	06.06.2011	9 :27
230	08.18.2011	9 :20
269	26.09.2011	9 :26
310	06.11.2011	9 :20

Thematic Mapper sensor has spatial resolution of 30 m for six reflectance bands (1-5, 7) and 120 m for thermal band (6). The latest satellite of Landsat (Landsat 7 Enchanced Thematic Mapper Plus) series has thermal band with resolution of 60 m, however, the malfunction of scan line corrector in 2003 resulted in lacks of data on images acquired after 2003. As a result those images have not been used in this study. The resolution of MODIS LST and Emissivity product is about 1 km. This dataset was resampled to spatial resolution corresponing to L5TM.

As the L5TM data set, that is available for download is just geometrically corrected, the radiometric calibration and two more corrections (atmospheric and solar) need to be done before further processing of the images.

The sattelite sensors are able to measure the Top of Amosphere (TOA) radiance. In order to obtain the radiance from land surface the atmospheric correction of the image must be performed. In this study the analyzed L5TM images (bands 1-5 and 7) were corrected by the means of the image-based COST method (Chavez 1996). After the image correction the LST could be estimated.

At first radiometric calibration consisting of coversion from raw digital number (*DN*) to units of absolute radiance (L_S) must be done.

$$L_S = \left(\frac{L_{\max} - L_{\min}}{255} \right) \cdot DN + L_{\min} \qquad (1)$$

L_{max} and L_{min} are the maximal and minimal values of spectral at-sensor radiance [$W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$]. Those parameters could be found in metadata file, that is provided with the image in GeoTiff format or for instance in Chander et al. (2009).

The spectral at-sensor radiance could be converted into the brightness temperature *BT* as follows:

$$BT = \frac{K_2}{\ln\left(\frac{K_1}{L_s}+1\right)} \quad (2)$$

K_2 and K_1 are constants applied for L5TM. The former equals 1260.56 K, while the latter 607.76 $W\cdot m^{-2}\cdot sr^{-1}\cdot\mu m^{-1}$. Since brightness temperature from equation 2 refers to black body with emissivity ε equal 1, the temperature of real surface would be different. If the emissivity is known the LST could be determined from simple formula (Lillesand, Kiefer 2004):

$$LST = \frac{BT}{\varepsilon^{0,25}} \quad (3)$$

Both *BT* and *LST* are expressed in Kelvins.

Most of the emissivity estimation is based on Normalized Difference Vegetation Index (NDVI):

$$NDVI = \frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + \rho_R} \quad (4)$$

where ρ_{NIR} and ρ_R are reflectance and near infrared (L5TM band 4) and red (L5TM band 3) part of electromagnetic radiation spectrum.

In this study the method of emissivity estimation from the NDVI by Sobrino et al. (2004) and Sobrino et al. (2008) has been applied.

$$\varepsilon = \begin{cases} 0.979 - 0.035\rho_R & NDVI < 0.2 \\ 0.986 + 0.004P_V & 0.2 \le NDVI \le 0.5 \\ 0.99 & NDVI > 0.5 \end{cases} \quad (5)$$

In this method pixels are divided into three groups according to the NDVI value. If NDVI exceeds 0,5 then pixel is assumed to be entirely covered by vegetation. In such cases the ε equal 0.99 is assigned to them. For the pixels where NDVI ranges from 0.2 to 0.5 the Fractional Vegetation Cover (P_V) is calculated (eq.6).

$$P_V = \left(\frac{NDVI - NDVI_S}{NDVI_V - NDVI_S}\right)^2 \quad (6)$$

where $NDVI_S$ = 0.2 - value for pure soil pixel and $NDVI_V$ = 0.5 - value for pure vegetation pixel.

Finally the ε is obtained from simple linear regression using P_V values (eq. 5). In case of pixels with NDVI lower than 0.2 the ε is calculated from reflectance in red band (eq. 5).

As the ρ_R and P_V values are positive this method has a disadvantage (eq. 5). In other words any pixel could not be assigned with emissivity ranging from 0.979 to 0.986.

The emissivity from Terra MODIS band 31 and 32 has been used to make comparison with method mentioned before, as their spectral range nearly cover the thermal band of L5TM. The MODIS emissivity has been used with assumption that 1 km pixel of this product consists of different heterogeneous surfaces and represent the mean emissivity from that area.

$$\varepsilon = \frac{\varepsilon_{31} + \varepsilon_{32}}{2} \quad (7)$$

Table 2 presents the results of emissivity estimation from both methods. Estimation made upon NDVI in general results in lower values of ε than MODIS product. This mainly result from different spatial resolution of L5TM and MODIS images. As the NDVI changes corresponds with alternations of vegetation cover, the ε changes as well.

Table 2. Emissivity estimated from MODIS and with NDVI.

DOY	NDVI			
	Min	Mean	Max	Std. Dev.
093	0.937	0.985	0.990	0.005
150	0.956	0.989	0.990	0.003
157	0.953	0.989	0.990	0.003
230	0.957	0.989	0.990	0.003
269	0.959	0.989	0.990	0.003
310	0.969	0.987	0.990	0.003
DOY	MODIS			
	Min	Mean	Max	Std. Dev.
093	0.973	0.978	0.991	0.004
150	0.973	0.977	0.986	0.004
157	0.973	0.977	0.986	0.004
230	0.973	0.978	0.986	0.004
269	0.973	0.978	0.986	0.004
310	0.973	0.978	0.986	0.004

In order to determine hot and cold spots, the average LST from six images were calculated for each pixels. Afterwards mean and standard deviation of pixel values on that image were obtained. The pixel were incorporated to “cold spots” group if its value were lower than mean minus one standard deviation. On the other hand pixels, which values were higher than mean plus one standard deviation were assigned to “hot spots” group.

Results

In case of all considered days the high pressure systems prevailed during the acqusition of the L5TM images. Such circulation patterns are preferable as low cloudiness connected with them, allows to obtain the accurates LST estimates. In general the LST_{NDVI}

calculated with the emissivity estimated with NDVI corresponds to LST_{MOD} based on MODIS emissivity.

Table 3 contain list of minimum, mean, maximum and standard deviation LST results for all considerable days in both emissivity cases - NDVI and MODIS. In DOY093 the difference between maximum and minimum LST was 17.26°C in case of LST_{NDVI} and 17.38°C in case of LST_{MOD}. Such a signifcant difference between the warmest and the coolest areas is especially interesting in comparison to greatest intensity of UHI (12°C) ever measured in Łódź (Kłysik, Fortuniak 1999). During the image acquisition the temperature at 2 m measured in the city centre was about 13°C and wind direction was SSE.

Table 3. LST [°C] derived with emissivity estimated from MODIS and with NDVI.

DOY	NDVI			
	Min	Mean	Max	Std. Dev.
093	11.69	17.80	28.95	1.55
150	18.89	24.87	42.56	2.91
157	21.43	27.47	43.17	2.75
230	18.44	23.48	39.67	2.42
269	15.69	20.77	32.41	1.77
310	4.85	9.97	16.17	0.79
DOY	MODIS			
	Min	Mean	Max	Std. Dev.
093	11.53	18.35	28.91	1.52
150	19.18	25.73	42.58	2.97
157	22.11	28.32	43.34	2.77
230	19.03	24.32	39.87	2.42
269	16.13	21.60	32.59	1.70
310	5.02	10.64	16.48	0.82

Spatial differentiation of LST in that day was relatively small (Fig. 2a), which is indicated by low values of standard deviation (Table 3). Both LST_{NDVI} and LST_{MOD} presents simillar pattern of spatial distribution (Fig. 2a). Relatively higher LST values (more than 22°C) occured in the central part of Łódź, however, the highest were found in industrial ares north-west and east of the city centre. The lowest LST valuese in DOY093 could be found in the western part of Łagiweniki forest and in nort-west of the city. The rest of anylezd terrain was characterized by LST ranging from 14 to 18°C.

The second of considered L5TM images indicates greater spatial variability of LST values (Fig. 2b). In DOY150 the range of measured LST values was even higher than in DAY093 – 23,67°C (LST_{NDVI}) and 23,4°C (LST_{MOD}) (see Table 3). The most densely built-up areas are characterized by LST higher than 32°C (Fig. 2b). The Lodz Airport is another place with high LST values. In case of DAY150 some places where LST exceeds 40°C can be clearly seen. They are mainly related to large plant buildings located in industrial districts, however, there are some exceptions, for instance Manufaktura emporium. Even though, it is not situated in industrial zone, its genesis is connected with the textile industry. The surface in Manufaktura and nearest neighborhood is covered with concrete and asphalt. This result in great heat storage, what in turn increase LST. In case of more "natural" surface the LST is relatively low, and varies between 14 to 22°C.

Image from DOY157 show very similar spatial distribution of LST in Łódź (Fig. 2c). However, there is slightly smaller variations of surface temperature (Table 3). This is indicated by lower diference (about 21.5°C), than in previous considered day. between the warmest and the coldest pixel in anylezd image.

Mean LST in image aquired on DOY230 was 23.48°C in case of LST_{NDVI} and 24.32°C in case of LST_{MOD} (Table 3). The location of the warmest and coldest pixels in that day as well as in DOY269 is comparable to the previous days(Fig. 3a,b). In general the LST in city centre was higher than 28°C, while in forests, parks etc. the LST did not exceed 22°C.

During DOY269 the LST characeterized less spatial differentiation, but still it was significant. The difference between maximum and minimum LST value was nearly 16.5°C (Table 3).

DOY310 stands out from images considered before . In that case the spatial differentiation was the lowest, as the standard deviation of LST value was about 0.8°C (Table 3, Fig 3c). Even the mean LST in that day reached the lowest value from all considered cases. During that and previous days the high pressure system developed over central Europe. This in turn resulted in appearence of fog over mentioned region. The solar radiation were not able to heat the surface for long time, so the maximum LST reachead only 16°C. The spatial differentiaton of the LST in that day is also relatively low (Fig. 3c). On averege the LST values ranged from 8 to 10°C. Still the location of hot pixels is similar to previous images, however the coldest pixels were not related with parks or forests area. Both LST_{NDVI} and LST_{MOD} indicate that the most north-western part of Łódź is the warmest. The fog faded away south-easternward so the considered part of city absorbed more solar radiation than the residual areas.

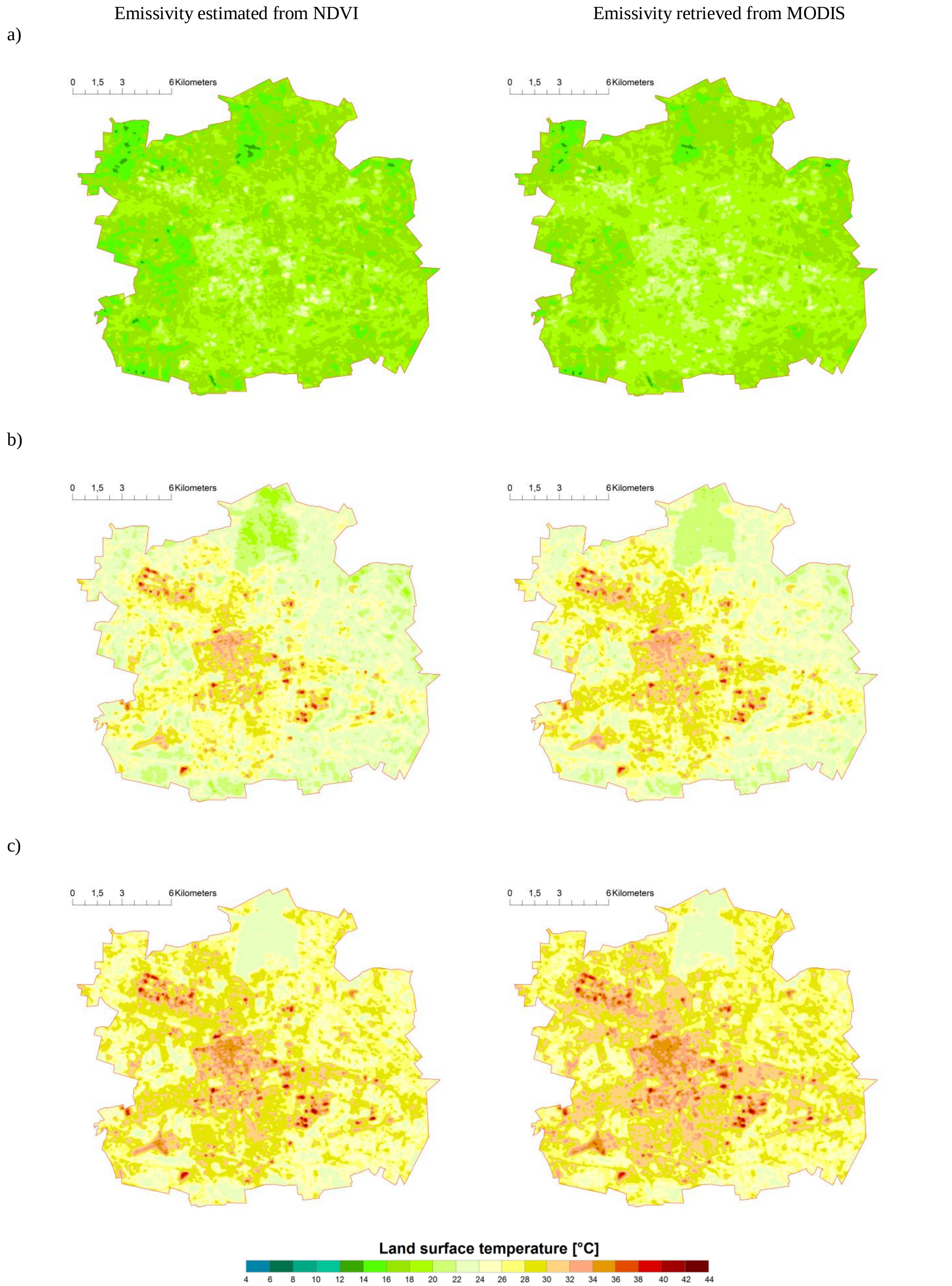

Fig 2. Land Surface Temperature in Łódź derived with emissivity estimated with NDVI and retrieved from MODIS for: a) DOY093 b) DOY150 c) DOY157

Emissivity estimated from NDVI | Emissivity retrieved from MODIS

a)

b)

c)

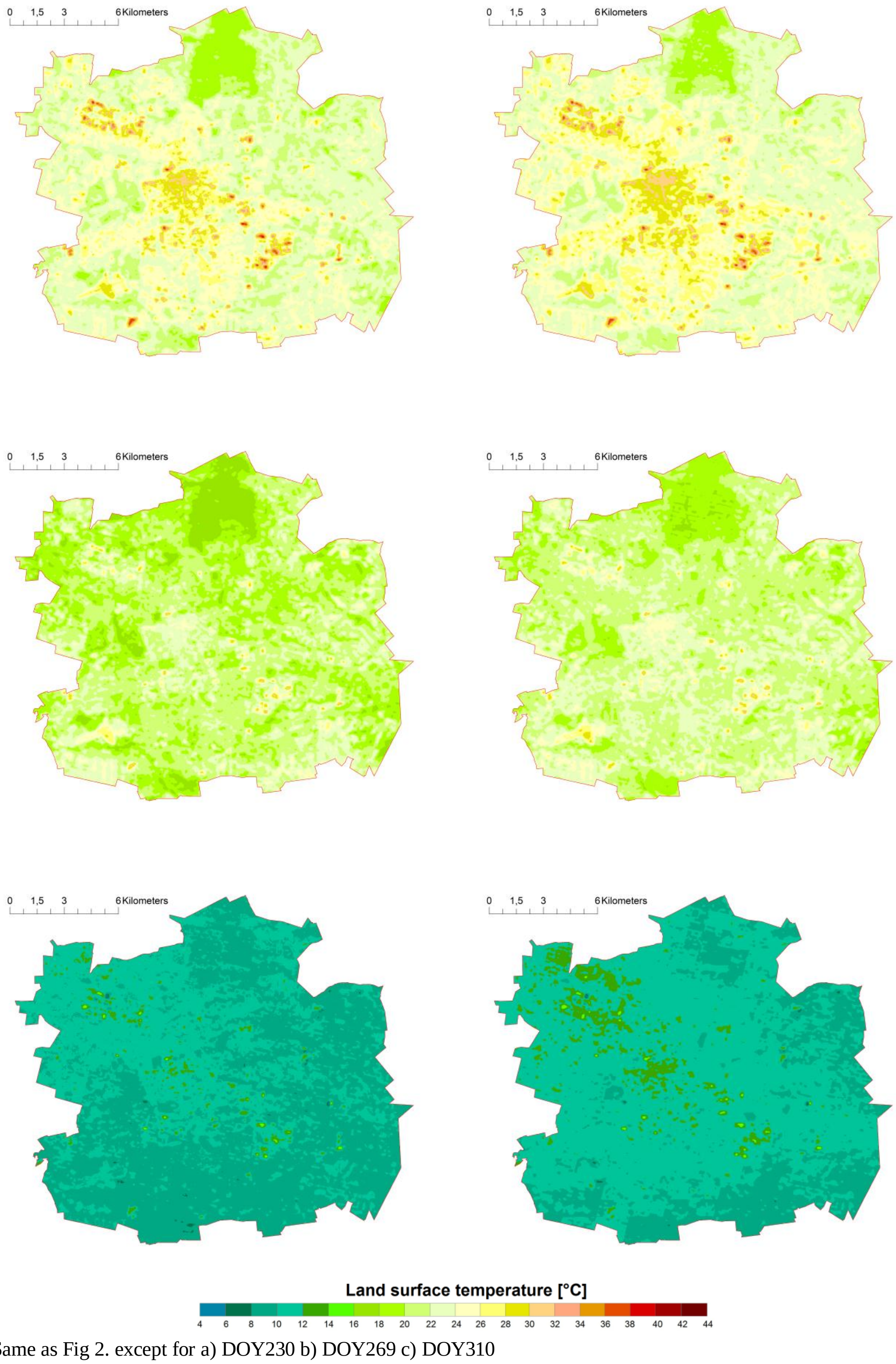

Fig. 3 Same as Fig 2. except for a) DOY230 b) DOY269 c) DOY310

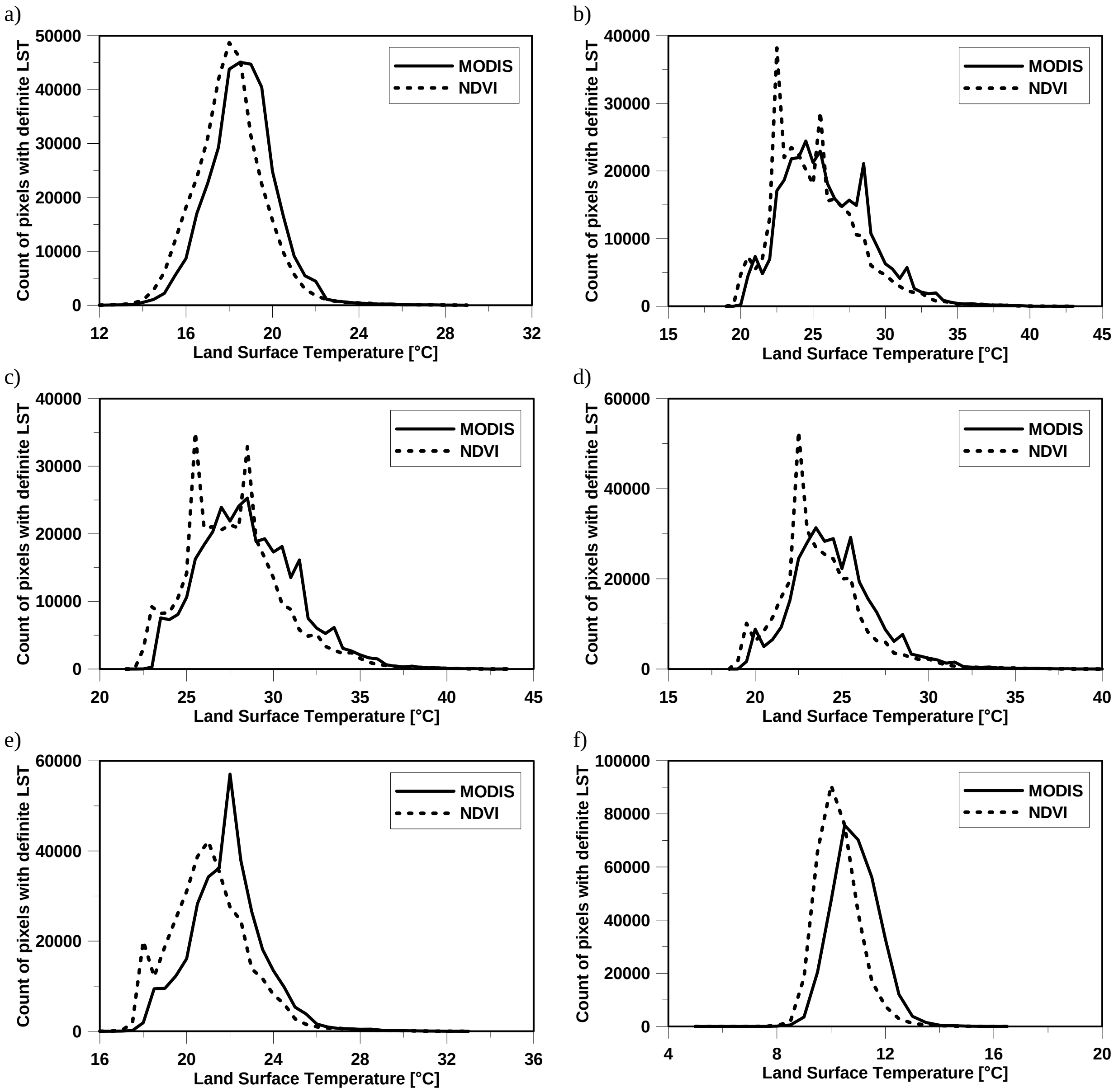

Fig 4. The distribution of pixels with definite LST determined with emissivity estimated with NDVI and retrieved from MODIS. a) DOY093 b) DOY150 c) DOY157 d) DOY230 e) DOY269 c) DOY310

The difference between LST estimated from MODIS and from NDVI is clearly visible in Figure 4a-f. The occurence frequency of pixels with definite LST is very simillar for both methods, however, LST_{MOD} is in general higher than LST_{NDVI}. In DOY093 (Fig. 4a) the histogram of LST is close to normal distribution.. Furhtermore it shows relatively small variety in comparison with the rests of analyzed days, except for DOY310 (Fig. 4f). In DOY150 two maximums in histograms could be seen (Fig. 4b). In case of LST_{NDVI} it occurs close to 22°C and 26°C, while in case of LST_{MOD} they can be found about 24°C and 28°C. In the following considered day (DOY157) the LST_{NDVI} histogram shows two spikes about 26°C and 28°C (Fig. 4c). The LST_{MOD} shows just one spike about 28°C. During the DOY230 (Fig. 4d). the most predominant LST_{NDVI} values were about 22°C. LST estimated on MODIS emissivity do not indicated such value, as LST between 22°C and 27°C occured nearly in the same amount of pixels. In the DOY269 the maximum frequency occurence of pixels with definite LST, in case of LST_{MOD} was about 23°C, while in case of LST_{NDVI} about 21°C (Fig. 4e).

The distribution of relatively warm (hot spots) and cold (cold spots) areas in Łódź is distincly related to type of land use/land cover (Fig. 5). The greatest area of low LST values is the „Łagiewniki" forest in the north of analyzed city. The second large cold spot is located in the south were another forest occur. The rest of cold spots are also related with zones covered with vegetation like parks in the west of city centre.

For hot spots the largest area of relatively high LST occurs in the central part of Łódź. This is the most densely built-up region in the whole city. High LST results mainly from domination of artificial surfaces in that area. For instance dark tarred roofs, that covers old tenement houes absorb more heat than natural surface. Two more hot spots are related to industrial areas. The first is located in the north-west of city centre, while second is situated in the east of the city centre. The noticeable fact, is that not all of industrial districts are characterized by high LST values, what could be clearly seen in the example of southhern part of Łódź (sede Fig. 1 and Fig. 5). Another area, that could be included to hot spots is the Lodz Airport situated in the south-west.

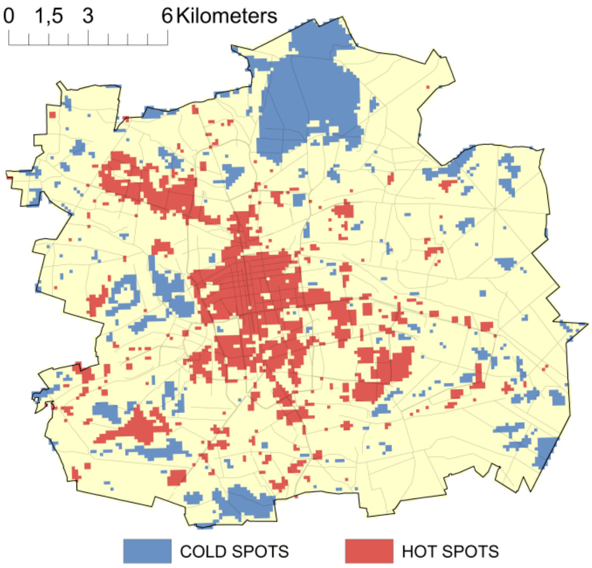

Fig 5. Hot and cold spots in Łódź.

Conclusions

The LANDSAT satellite images are applicable as a source of knowledge about the land surface temperature estimates. Nevertheless, the exact estimates of surface emissivity are substantial in order to derivation of precise LST values. This paper attempted to compare the LST values derived with emissivity estimated by means of method using the NDVI with that from MODIS. Either methods yields valuable information on LST in areas covered with vegetation. Difference between LST mainly results from the different resolution of L5TM and MODIS images as well as different algorithms used to obtain emissivity.

Due to analyze of few L5TM images acquired for different seasons, some general patterns of spatial LST distribution could be obtained. In Łódź the highest LST values have been found in the most densely built-up areas in city centre, as well as in the most industrialized one. Furthermore the Lodz Airport is also the area of high LST. In view of all considered L5TM images, the hottest surface seems to be located in Manufaktura trade center. As opposed to, the lowest LST is bounded to natural areas like „Łagiewniki" forest or urban parks. The land use/land cover is distinctly related with LST values.

This study has shown that the spatial differentiation of surface temperature increases with increasing solar angle. The most varied LST in Łódź occurred in images acquired for May, June, and August. On the other hand when the sun angle is low the amount of absorbed solar energy is low as well. In turn, this result in relatively low differences between LST of natural and artificial surfaces.

Acknowledgments

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Abstrakt

Głównym celem tego opracowania było oszacowanie temperatury powierzchni Ziemi w Łodzi, na podstawie obrazów satelitarnych pochodzących z satelity Landsat 5 Thematic Mapper (L5TM). Analizę wykonane dla obrazów wszystkich dostępnych obrazów z 2011 roku, na których zachmurzenie nie wystąpiło nad obszarem Łodzi. Temperatura powierzchni Ziemi odgrywa istotną rolę w kształtowaniu warunków pogodowych w warstwie granicznej, szczególnie związanych z konwekcją. Satelity środowiskowe z serii Landsat dostarczają obrazów w dużej rozdzielczości, dzięki czemu pozwalają na stosunkowo dokładne oszacowanie tego parametru. Wielkość temperatury w dużym stopniu zależy od emisyjności danej powierzchni. W niniejszym opracowaniu porównano temperaturę powierzchniową obliczoną dla emisyjności wyznaczonej z danych spektrometru MODIS, umieszczonego na satelicie Terra, jak również dla emisyjności oszacowanej przy wykorzystaniu wskaźnika NDVI obliczonego z danych L5TM. Opracowane obrazy satelitarne pozwoliły na wyznaczenie obszarów w Łodzi, cechujących się najwyższymi i najniższymi wartościami temperatury powierzchniowej. Najwyższe wartości LST na obszarze Łodzi występują w obszarach przemysłowych, jak również w najbardziej centralnej części miasta. Niekiedy jednakże obszary o podwyższonych wartościach LST spotykane są na przedmieściach, czego przykładem może łódzki port lotniczy. Z drugiej strony najniższe wartości LST występują w obszarach, na których występuje roślinność, przy czym dotyczy to głównie obszarów leśnych oraz parków śródmiejskich.

Słowa kluczowe: temperatura powierzchni Ziemi, LANDSAT 5TM, obrazowanie satelitarne, emisyjność, NDVI