NIGHT-TIME SURFACE URBAN HEAT ISLAND
IN THE CITY OF KRAKOW (POLAND)
DETERMINED WITH THE USE OF NOAA/AVHRR DATA

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Abstract

Determination of surface urban heat island (SUHI) is possible by estimating land surface temperature (LST) with the use of thermal infrared satellite remote sensing. In this study 26 NOAA/AVHRR images of the study area were selected and processed. The images were recorded at cloudless nights (between 1 and 2 UTC) from April to September 2003-2005. The study area was the city of Krakow (Poland) and its vicinity. In order to estimate LST values the Ulivieri et al. (1994) split-window algorithm was applied. Land surface emissivity (LSE) included in the algorithm was estimated by Normalised Difference Vegetation Index Thresholds Method (NDVI). NDVI values were calculated on the basis of day-time NOAA/AVHRR images recorded at 11-12 UTC in April-September 2003-2005. The average NDVI maps for three vegetation seasons (spring, summer and autumn) were prepared for further estimation of seasonal LSE. After estimating LST for 26 selected satellite images the average night-time LST map was created and analysed. Thermal contrast (difference between minimum and maximum LST values) of 6.6 °C was noted. The greatest LST values were observed in the city centre and in the industrial area. The average LST map was compared with the 1 km land use/land cover (LULC) data. Higher LST values were identified when the percentage share of artificial surfaces exceeded 50%. Lower LST values were observed for greater percentage share of agricultural areas. Each night-time LST map was confronted with air temperature (AT) observations from two weather stations (located in the green urban area and in the suburbs). The LST pixels corresponding to each station location were used. Linear relationship of minimum AT and LST was defined for both station locations (R² determination coefficients of 0.97 and 0.93).

INTRODUCTION

One of the most important anthropogenic modifications of the local climate is urban heat island (UHI) effect (Oke, 1987). UHI phenomenon is defined as the occurrence of higher air temperature (AT) in built-up areas in cities in comparison to more vegetated surrounding areas. Satellite remote sensing in thermal infrared (TIR) spectral range enables observations of surface urban heat island (SUHI) (Tomlinson et al., 2011; Voogt and Oke, 2003; Weng, 2009). SUHI is determined on the basis of land surface temperature (LST). It is assumed that at night AT and LST distribution observed over an area characterised by various land use/land cover (LULC) are similar (Voogt, 2000), so the thermal contrast of AT and LST may be comparable. This is especially significant because the UHI intensity is the highest at night (Reducing…, 2008).

This study applied NOAA/AVHRR data to multi-year investigations of night-time SUHI. The relationship between LST and LULC was analysed. An attempt of defining correlations between AT and LST night-time observations was also made.
Figure 1: Location of the study area over the hypsometric map of Poland

Figure 2: Simplified land use/land cover (LULC) map of the study area (on the basis of CORINE Land Cover 2006 database) and location of weather stations used in the study (1 – Botanical Garden, 2 – Airport)
STUDY AREA
The study area (1521 km$^2$) is located in southern Poland (Fig. 1) and includes the city of Krakow (50° N, 20° E) and its vicinity. Terrain of the study area is diversified. Land use/land cover (LULC) structure (Fig. 2) is dominated by agricultural areas (76.9 %). Artificial surfaces cover 13.7 % of the study area, forest and semi-natural areas 8.5 %, and water bodies 0.9 %. Krakow is the second largest city of Poland in terms of its area (327 km$^2$ within administrative border) and population (over 759 thousand permanent residents) (Tab. 1).

<table>
<thead>
<tr>
<th>No.</th>
<th>City name</th>
<th>Area [km$^2$]</th>
<th>Population [thousand]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Warszawa</td>
<td>517</td>
<td>1708.5</td>
</tr>
<tr>
<td>2</td>
<td>Kraków</td>
<td>327</td>
<td>759.1</td>
</tr>
<tr>
<td>3</td>
<td>Łódź</td>
<td>293</td>
<td>725.1</td>
</tr>
<tr>
<td>4</td>
<td>Wrocław</td>
<td>293</td>
<td>631.2</td>
</tr>
<tr>
<td>5</td>
<td>Poznań</td>
<td>262</td>
<td>553.6</td>
</tr>
<tr>
<td>6</td>
<td>Gdańsk</td>
<td>262</td>
<td>460.5</td>
</tr>
<tr>
<td>7</td>
<td>Szczecin</td>
<td>301</td>
<td>409.6</td>
</tr>
<tr>
<td>8</td>
<td>Bydgoszcz</td>
<td>176</td>
<td>363.0</td>
</tr>
<tr>
<td>9</td>
<td>Lublin</td>
<td>147</td>
<td>348.6</td>
</tr>
<tr>
<td>10</td>
<td>Katowice</td>
<td>165</td>
<td>309.3</td>
</tr>
<tr>
<td>11</td>
<td>Białystok</td>
<td>102</td>
<td>294.3</td>
</tr>
</tbody>
</table>

Table 1: The largest Polish cities listed by population (Statistical Yearbook..., 2012)

DATA & METHODS
Land Surface Temperature (LST) retrieval
In order to estimate night-time LST pattern, 26 cloudless and mostly windless NOAA/AVHRR satellite images of the study area were selected and processed. The selected images were recorded at about 1-2 UTC between April and September 2003-2005. Only images acquired with small scanning angle (up to 20°) were included. Consequently all selected images had a sub-satellite spatial resolution close to 1 km.

Geometric correction and radiometric calibration of thermal infrared (TIR) NOAA/AVHRR data (channels 4 and 5) were made with the use of VCS 2Met! software.

Equivalent blackbody temperature, also referred to as brightness temperature ($T_\lambda$) was obtained on the basis of Planck’s law according to:

$$ T_\lambda = \frac{c_2}{\lambda \ln \left( \frac{c_1}{\lambda^5 L_\lambda} + 1 \right)} $$

where $c_1$ and $c_2$ are the Planck’s radiation constants ($c_1 = 1.19104 \cdot 10^8$ W $\cdot$ μm$^4 \cdot$ m$^{-2} \cdot$ sr$^{-1}$ and $c_2 = 1.43877 \cdot 10^4$ μm $\cdot$ K), $\lambda$ is effective wavelength of TIR channel (4 or 5), $L_\lambda$ is Earth view radiance computed using nonlinearity correction (NOAA KLM..., 2013).

LST was calculated with the use of $T_\lambda$ values derived from NOAA/AVHRR TIR images through application of the split-window algorithm proposed by Ulivieri et al. (1994) and recommended by the other authors (Pozo Vázquez et al., 1997; Qin et al., 2004):

$$ LST = T_\lambda + 1.8(T_{\lambda i} - T_{\lambda j}) + 48(1 - \varepsilon) - 75\Delta \varepsilon $$

where $i$ and $j$ are NOAA/AVHRR TIR channels 4 and 5, $\varepsilon$ is land surface emissivity (LSE) which means the average value for NOAA/AVHRR TIR channels: $\varepsilon = (\varepsilon_{\lambda i} + \varepsilon_{\lambda j})/2$ and $\Delta \varepsilon = \varepsilon_{\lambda i} - \varepsilon_{\lambda j}$.

The split-window method incorporates correction of atmospheric effects.

LSE ($\varepsilon_j$) for TIR channels of NOAA/AVHRR was estimated by Normalized Difference Vegetation Index Thresholds Method (NDVI$^{\text{THM}}$). NDVI was calculated according to:
\[ NDVI = \frac{\rho_{NIR} - \rho_{VIS}}{\rho_{AIR} + \rho_{VIS}} \]

where \( \rho_{VIS} \) and \( \rho_{NIR} \) are reflectivity values of visible and near infrared channels (for NOAA/AVHRR channels 2 and 1).

NDVI_TIRM uses certain NDVI values (thresholds) to distinguish between bare soil pixels (NDVI < NDVI_L), full vegetation pixels (NDVI > NDVI_L) and mixed (soil and vegetation) pixels (NDVI_L ≤ NDVI ≤ NDVI_V) (Sobrino et al., 2008). In this study values of NDVI_L = 0.2 and NDVI_V = 0.5 were applied. Emissivity of soil pixels (NDVI < 0.2) was set as \( \varepsilon_{\lambda} = \varepsilon_{\lambda_s} \), assuming bare soil emissivity (\( \varepsilon_{\lambda_s} \)) 0.95 for NOAA/AVHRR channel 4, and 0.96 for NOAA/AVHRR channel 5. Emissivity of full vegetation pixels (NDVI > 0.5) for both TIR channels was set to 0.99 according to equation \( \varepsilon_{\lambda} = \varepsilon_{\lambda_v} + C_{\lambda} \), assuming typical full vegetation emissivity (\( \varepsilon_{\lambda_v} \)) 0.985 and correcting by \( C_{\lambda} \) (a term taking into account cavity effect due to surface roughness) which was set as 0.005. Emissivity of mixed pixels was estimated according to: \( \varepsilon_{\lambda} = \varepsilon_{\lambda_v} \cdot P_{\lambda} + \varepsilon_{\lambda_s} \cdot (1 - P_{\lambda}) + C_{\lambda} \) where: \( P_{\lambda} \) is a proportion of vegetation (fractional vegetation cover) derived from NDVI (Carlson and Ripley, 1997):

\[ P_{\lambda} = \left( \frac{NDVI - NDVI_L}{NDVI_V - NDVI_L} \right)^2 \]

Day-time NOAA/AVHRR images recorded at 11-12 UTC in April-September 2003-2005 were used for preparing average NDVI maps representing three different vegetation seasons (spring, summer and autumn). The NDVI maps were used to calculate LSE which was further applied for LST estimation. Average night-time land surface temperature pattern was evaluated on the basis of 26 LST maps for selected NOAA overpasses.

**Land Use/Land Cover (LULC) data processing**

CORINE Land Cover 2006 (CLC2006) vector database (EEA Data and Maps…) was used in order to prepare gridded LULC map with spatial resolution of 1 km. For each grid cell percentage share of four generalised LULC classes was calculated. The output LULC dataset was used for calculations of basic zonal statistics of LST values within different LULC classes.

**Comparison of Land Surface Temperature and Air Temperature**

For each night-time satellite image air temperature (AT) observations from two weather stations (WS) were collected. The first station (WS1) was located in the green urban area (Botanical Garden), the second one (WS2) in the suburbs, at the airport (Tab. 2, Fig. 2). The values of minimum AT were compared with the averaged values of LST from four pixels closest to the location of particular WS. The parallel AT and LST values were set together in the scatter plots. Scatter plots were also drawn to collate minimum AT differences between WS1 and WS2 with corresponding LST differences.

<table>
<thead>
<tr>
<th>WS</th>
<th>Name</th>
<th>Coordinates</th>
<th>Altitude [m a.s.l.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Botanical Garden</td>
<td>50° 03' 50&quot; N, 19° 57' 31&quot; E</td>
<td>206</td>
</tr>
<tr>
<td>2</td>
<td>Airport</td>
<td>50° 04' 40&quot; N, 19° 47' 41&quot; E</td>
<td>237</td>
</tr>
</tbody>
</table>

*Table 2: Location of the weather stations (WS) used in the study*

**RESULTS**

**Night-time Surface Urban Heat Island**

The average night-time LST map was presented (Fig. 3). Difference between minimum and maximum LST values was 6.6 °C. The highest LST values were observed over the city centre and over the steelworks. The lowest LST values were recognised mainly in agricultural areas. Greater LST values in rural areas were mostly related to forest and semi-natural areas.
Land Surface Temperature dependence on Land Use/Land Cover
LST zonal means for different ranges of percentage share of four generalised LULC classes were compared with each other (Fig. 4). It was observed that LST mean values distinctly increased while percentage share of artificial surfaces were above 50%. Decreasing LST values were proportional to increasing percentage share of agricultural areas. LST mean values were slightly higher with the increase of percentage share of forest and semi-natural areas. Tendency of zonal mean LST for water bodies was not clear. Relationships mentioned were also recognised in scatter plots (Fig. 5). However, dispersion of the LST values was large.

![Figure 4: Land surface temperature (LST) mean values for different percentage shares of four generalised land use/land cover (LULC) classes](image-url)
Correlations between Land Surface Temperature and Air Temperature

Linear relationship of minimum AT and LST was observed (Fig. 6). Determination coefficients ($R^2$) were about 0.97 in case of urban weather station (WS1) and about 0.93 in case of suburban weather station (WS2). Minimum AT differences and LST differences between the locations of the weather

**Figure 5:** Scatter plots of land use/land cover (LULC) classes percentage shares and land surface temperature (LST)

**Figure 6:** Relationship between: a) minimum air temperature and land surface temperature; b) minimum air temperature differences and land surface temperature differences between WS1 and WS2 weather stations
stations were not clearly correlated. Tendency was difficult to determine because of dispersion of the values.

CONCLUSIONS
Lower spatial resolution of NOAA/AVHRR data compared to the other thermal infrared satellite data, e.g. Landsat/TM (ETM+) or Terra/ASTER, is undoubtedly a disadvantage for investigation of LST spatial distribution in urban areas. Additional inconvenience is the changing scanning angle typical for radiometers installed aboard polar orbiting satellites. On the other hand, high temporal resolution (several images per day) and long data series (over 25 years) of NOAA/AVHRR make these data valuable for all types of climate studies including urban climate applications. The surface structure of urban heat island in the city of Krakow observed in this study and the previous ones (Hajto et al., 2012a, 2012b; Walawender and Hajto, 2009; Walawender et al., 2013) was characterised by the greatest LST values in the city centre and in the industrial area. Average night-time thermal contrast in the study area exceeded 6 °C.

Land surface temperature dependence on land use/land cover was confirmed. In particular, higher LST values were identified when the percentage share of artificial surfaces exceeded 50 % whereas lower LST values were observed for greater percentage share of agricultural areas. During selected cloudless nights air temperature clearly correlated with land surface temperature. It was concluded that No clear correlation of AT differences between two weather stations and corresponding LST differences resulted from factors such as relief, soil type, land use/land cover, vegetation cycle, air circulation or anthropogenic conditions.

Acknowledgements
NOAA/AVHRR data were taken from the archives of the IMGW-PIB Satellite Receiving Station in Krakow. Authors would like to thank the satellite receiving station staff for their help in data preparation. Air temperature data was derived from the weather stations operated by Jagiellonian University (Botanical Garden) and IMGW-PIB (Airport). ESRI ArcGIS Desktop 10 software was used for spatial analyses and creation of output maps.

REFERENCES


