Strategies to mitigate the effects of future extreme heat waves - a new method for mapping

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Abstract. Global warming is increasingly causing extreme weather events, such as heat waves. One-way heat waves are problematic in society, particularly in urban areas, is because of their negative impact on vulnerable groups including elderly people and children. Organizations such as municipalities that are responsible for local schools, day care centres and/or elderly homes, may struggle to provide the necessary care and function during extreme heat waves. This work explores how remote sensing images providing historical data of land surface temperatures (LST) can be used to create summer urban heat island maps and heat wave intensity, and in the longer run, how such information could be used by municipalities and other actors to mitigate effects of future heat waves. The method presented in this study was used to detect the “hot spots” in two participating Swedish municipalities and identify the municipal services located within these spots based on MODIS (1 km) and Landsat (30 m) LST datasets. Furthermore, this study showed that urban heat island phenomenon existed in the two participating municipalities.

In general, this methodology can be applicable at both local and regional scale, although it might require additional site-specific data.

1. Introduction

In the European Union over 75% of the population lives in urban areas and in Sweden over 85% of the population lives in urban areas [1], [2]. Therefore, cities are particularly vulnerable to extreme weather impacts. In recent decades, several heat wave events have been recorded worldwide. During the 2018 heat wave, temperatures far above the long-term average were recorded in the Northern Hemisphere [3]. In Sweden, where this work is conducted, the Swedish Meteorological and Hydrological Institute (SMHI) issued class 2 warnings, for extreme heat (the highest level of heat warnings) for many regions in the country [4]. Predicted consequences of global warming of 1.5°C show that climate change disproportionately affects children and elderly and can increase gender inequality [5]. Additionally, this change could be responsible for additional annual deaths of 38000 people from heat stress, particularly among the elderly, and 48000 from diarrhea, 60000 from malaria and 95000 from childhood malnutrition worldwide [6].

The urban heat island (UHI) effect is a daytime elevation in the outdoor urban air temperature that results in part from the replacement of trees and other vegetation with buildings, roads and other heat-absorbing infrastructure [7]. The causes can be urban surface properties and human activity; and consequences can be increased energy use, impaired air quality and illness. During heat waves, the response of urban and its surroundings temperature are likely to be different. Therefore, it is necessary to quantify the pattern of UHIs so that their effect on urban environments can be alleviated to increase the sustainability of cities and improve living conditions of their residents, particularly vulnerable...
groups such as children and elderly people [8]. Confronting the issues of UHI can contribute to adaptive capacities of local authorities and mitigate the impacts of climate change. Thus, such studies address the UNs Sustainable Development Goals (SDGs), particularly on “climate action” and “sustainable cities and communities”. Health inequalities are expected to grow with lack of green spaces and with impacts from climate change, thus affecting people’s equal chances to create healthy and prosperous lives [9]. Such green spaces can contribute the UNs SDGs, particularly on “good health and well-being” and “reduce inequalities”.

Sweden is one of the few countries designing its cities as green and blue as possible which helps the cities to be cooler via air circulation and evaporation of surface moisture. Although the impact of heat waves is not as severe in Sweden as in, for instance, southern Europe, there are temperature differences between urban areas and its surroundings. Additionally, the number of very extreme heat waves in Northern Europe will likely increase [10]. On average, the heat wave events which are currently occurring in Sweden every twenty years is expected to occur every three to five years by the end of this century [11]. Furthermore, taking the demographics of Sweden, with an increasing number of elderly people, the preparedness in Sweden may be lower than in many countries already accustomed to higher temperatures which makes UHI effects in Sweden comparatively more serious.

The impact of increasing temperatures and heat waves can be studied by remote sensing images to monitor the most vulnerable areas. Thermal remote sensing can capture the spatial variability in urban heating. Satellite thermal remote sensing provides a mechanism for observing the surface temperature of an area and gives an excellent spatial picture of the urban landscape for a snapshot in time allowing a comparative analysis of areas of high surface temperatures [12].

This study is a part of a larger project which aims at contributing to the preparedness and adaptability of the society towards future extreme weather conditions and increasing temperatures. Within the project, decision support strategies will be developed in collaboration with two participating municipalities to mitigate the severe effects of heat waves based on both quantitative and qualitative data with a focus on the vulnerable groups, elderly and children. This project has a clear focus on the following four SDGs: Sustainable cities and communities, climate action, good health and well-being and reduce inequalities. This study covers the quantitative data analysis part of this larger project. The outcome will be used in the qualitative data analysis which is planned to be conducted in spring 2020 and it will be described briefly in future work section (5.1.).

The first objective of this study is to find the “hot spots” and identify the municipal services, such as schools, day cares and elderly homes, which are located in these spots during cool, average and warm years based on MODIS and Landsat temperature datasets. The second objective is to observe UHI effect in the study area whether it exists based on Landsat dataset.

2. Materials

2.1. Study Area

The study area encompassed Lerum and Trelleborg municipalities in Sweden. Lerum situates on the west coast, 20 kilometers from Gothenburg and Trelleborg is the southernmost town in Sweden (Figure 1). Both municipalities experienced very high temperatures above average and great problems during the 2018 summer heat wave at their schools, day care centres and elderly homes. Furthermore, these two municipalities have identified that the heat wave events have had an impact on the health and comfort of children at schools and people who are living in day care centres run by the municipality. Table 1 presents the county, population, area, elevation, and forest, water and farmland cover information from the municipalities. Average temperature presented in the table was calculated based on MODIS temperature dataset for all study years from June to August.
### Table 1. County, population, area, elevation, and forest, water and farmland cover information from Lerum and Trelleborg municipalities. Pop. is population. Avg. Temp. is average temperature.

| County        | Pop. total | Pop. density | Area | Elevation | Forest Cover | Water Cover | Farmland Cover | Avg. Temp. |
|---------------|------------|--------------|------|-----------|--------------|-------------|----------------|------------|
| Lerum Västra Götaland | 41510 | 2909/14.27 km² | 14.27 km² | 100 m | 61 % | 17 % | 6 % | 20.7°C |
| Trelleborg Skåne | 44854 | 3284/13.66 km² | 13.66 km² | 29 m | 3 % | 1 % | 81 % | 24.1°C |

2.2. **SMHI Data**

SMHI distributes various types of data as open data. Daily maximum and minimum temperatures (two times per day, at 06 and 18) for five stations (Göteborg, Landvetter Flygplats, Falsterbo, Strurup and Malmö) were obtained from [https://opendata-download.metobs.smhi.se/api/version/1.0/parameter/27.atom](https://opendata-download.metobs.smhi.se/api/version/1.0/parameter/27.atom). The average year for the study sites was calculated based on the average of 1989-2018.

In Sweden, SMHI defines a heat wave as a continuous period when the highest temperature of the day exceeds 25°C for at least five days in a row [13]. According to SMHI's warning criteria, high temperature announcements are issued if the forecast shows maximum temperatures of at least 26°C for three consecutive days. Warning Class 1 for very high temperatures is issued if the forecast shows maximum temperatures of 30°C or more for three consecutive days. Warning Class 2 for extremely high temperatures is issued if the forecast shows maximum temperatures of 30°C or more for five consecutive days, alternatively 33°C or more for three consecutive days [13]. SMHI uses these thresholds based on an earlier project, which showed that the daily mortality increased by about ten percent if the temperature reached 26°C or more three days in a row, and that it increased by another ten percent if the temperature reached 30°C or more three days in a row [14]. According to SMHI, 2002, 2006, 2014 and 2018 were the hottest years of the century in Sweden [13].

2.3. **MODIS Data**

MODIS temperature (MOD11A1) data with 1 km spatial resolution were downloaded for 2002, 2006, 2009, 2010, 2012, 2014, 2017 and 2018 from June to August from [https://search.earthdata.nasa.gov/search](https://search.earthdata.nasa.gov/search). The revisit time of the satellite is around 11:30 everyday. The data were masked based on the provided data to use only the pixels of good quality.

2.4. **Landsat Data**

Landsat does not provide temperature data globally, but it can be retrieved. Therefore, Landsat Level 1 (Thermal band) and Level 2 (Red and NIR bands) data were obtained for 2009, 2017 and 2018 from June to August from [https://earthexplorer.usgs.gov/](https://earthexplorer.usgs.gov/). The list of the downloaded data can be found in Table 2. The data were masked based on the provided data to use only the pixels of good quality. Landsat passes over the study area around every 15th day at 10 a.m. Cloud conditions could naturally limit the number of good quality images during a given study period.
Table 2. Downloaded Landsat data

| Landsat | TIRS Band (Level 1) (resampled to 30m) | Red Band (Level 2) (30m) | Nir Band (Level 2) (30m) | Days Lerum | Days Trelleborg |
|---------|--------------------------------------|--------------------------|--------------------------|------------|-----------------|
| 5       | 10.40-12.50μm, 120m                  | 0.63-0.69μm              | 0.76-0.90μm              | 2009-0601, 0626, 0820 | 2009-0806      |
| 7       | 10.40-12.50μm, 60m                   | 0.63-0.69μm              | 0.76-0.90μm              | 2009-0625, 20170701; 2018-0602, 0704 | 2009-0823; 20170829; 2018-0604, 0807 |
| 8       | 10.6-11.19μm, 100m                   | 0.64-0.67μm              | 0.85-0.88μm              | 2017-0709, 0718; 2018-0603, 0721, 0610, 0626, 0712, 0813 | 2017-0609, 0711; 2018-0605, 0628, 0723 |

2.5. Other Data
There are other data required to contact the analysis. The temperature response of different land use and land cover is different. In order to show this difference, the land use land cover (LULC) map of the study area was used. The map was obtained from Swedish Environmental Protection Agency, https://www.naturvardsverket.se/Sa-mar-miljon/Kartor/Nationella-Marktackedata-NMD/Ladda-ned/. Additionally, municipalities provided the data of the location of day-cares, schools, elderly.

3. Methods
The method employed in this study was used to find the “hot spots” and identify any municipal services located in these spots, based on the MODIS and Landsat LST during summer periods under different heat intensity conditions in Lerum and Trelleborg. Municipal services here refer to schools, day care centres and/or elderly homes that are managed by the municipality in question. MODIS LST images with higher temporal and lower spatial resolution are appropriate for studying the temporal variations of temperature, whereas Landsat LST images with lower temporal and higher spatial resolution are effective for investigating the spatial variation of temperature. Pre-processing of data from both satellites were carried including conversion of the projection, extracting the region of interest, masking out the bad pixels and atmospheric correction (except for Landsat Level 1 data, others were provided as atmospherically corrected). The results from the sections (3.1, 3.2.1, and 3.2.2.) below were combined by summing up the final results from the mentioned sections to find the “hot spots”.

3.1. Heat wave Intensity Calculations Based on MODIS Data
Heat wave intensity was calculated based on the heat wave definitions of SMHI (see in 2.2.). For each study year, the total number of occurrences were calculated based on these definitions (ex. How many times it occurred that the temperature exceeded 25°C more than 5 days in a row during a summer period in a given year). Then each pixel was ranked based on these occurrences from 1 to 6 (got 1, if over 25°C min 5 days in a row occurred at least one time; got 2, if over 26°C min 3 days in a row occurred at least one time; got 3, if over 30°C min 3 days in a row occurred at least one time; got 4, if over 30°C min 5 days in a row or over 33°C min 3 days in a row occurred once; got 5, if over 30°C min 5 days in a row or over 33°C min 3 days in a row occurred twice; got 6, if over 30°C min 5 days in a row or over 33°C min 3 days in a row occurred three times).

3.2. Landsat
Temperature data is not provided by Landsat. In the literature, there are various methods to calculate LST and Li et al. made a thorough literature review on the available methods [15]. In this study, we adopted a single-channel algorithm and the details of LST derivation algorithm can be found in Walawender et al. [16]. Additionally, the images were normalised based on maximum and minimum LST of the same image in order to make them comparable from different years and these images range between 0 to 1 which represents lowest LST to highest LST respectively.
3.2.1. Categorisation of LST Values. For each study year, the LST values for municipal services were categorised from 0 to 4 (When LST was lower than 25°C, it got 0; when LST was higher than 25°C, it got 1; when LST was higher than 26°C, it got 2; when LST was higher than 30°C, it got 3; when LST was higher than 33°C, it got 4;). Then results of all years were summed up.

3.2.2. Distance Analysis. The intersection was calculated for two normalised and classified (from 1 to 10) LST images from 2017 (cool year) and 2018 (warm year) to find the common areas. Then the distance between each class and the municipal services was calculated. Finally, inverse distance weighing method was used based on the distance values and the classes to find the proximity of municipal services to all classes.

3.2.3. Landsat Urban Heat Island Effect Analysis. Built-up areas are warmer than their surroundings, and vegetation and water cool down the surrounding temperature. To address this UHI phenomenon, the average LST was calculated for each LULC class (green space, water and buildings) and in the buffer zone of 30 m outside of these classes.

4. Results

4.1. Ranking Municipal Services

The results of municipal services ranking are presented in Figure 2. The higher the rank, the warmer the area (shown by red). The services with higher rank were predominately located in the built-up areas. The lower rank services were located mostly outside of the city centre or in the suburbs.

![Figure 2](image_url)

**Figure 2.** Normalised ranking of municipal services in Lerum (left (1a), overlaid with normalised LST from 20180603) and Trelleborg (right (2a), overlaid with normalised LST from 20180628). The red colour represents the warmer areas and blue cooler for both the services and the maps. 1b represents the normalised LST from 20170701 and 2b from 20170711.

4.2. Normalised LST Images

Figure 2 shows that 2018 was warmer than 2017 in both municipalities (see the differences between 1a & 1b and 2a & 2b). It was even warmer in Trelleborg mainly due to the LULC differences (see the difference between 1a & 2a). The green space and water in Lerum helped to prevent higher temperatures compared to farmland areas in Trelleborg. In general, there was a similar pattern, such as built-up areas (red and orange) were warmer than the surrounding areas (yellow and blue) regardless of whether it was a warm or cool year.

Figure 3 shows an example from three LULC classes: green space, lake and built-up area (industry in this example). Built-up area was warmer than green space which was warmer than lake.
4.3. Landsat Urban Heat Island Effect Analysis

Figure 4 shows an averaged LST for all green spaces, water and built-up areas and a buffer zone of 30 m outside of these areas in Lerum and Trelleborg. The green space and water warmed up in the buffer zone and the built-up area cooled down which shows that the previous was cooler than its environment and the latter was warmer. The temperature difference between 2017 and 2018 for the two municipalities can also be observed in the graphs, there is around 10°C difference in Trelleborg and 3°C in Lerum. On the other hand, the temperature difference between the classes and respective buffer zone is bigger in Lerum (around 2°C) than Trelleborg (around 1°C). There were also differences within municipalities between different urban areas. Less inhabited areas were cooler than more inhabited areas. Additionally, the temperature difference was smaller during 2018 heat wave because long lasting heat waves contributed to increase the temperature in general.

5. Discussion

Urban areas are prone to local extreme heat events due to climate change which causes risks for particularly elderly people and children. Therefore, it is important for local authorities to comprehend the overall picture of their urban land use model and urban planning. Additionally, to the knowledge of the authors, there are not many studies regarding spaceborne thermal remote sensing analysis of heat wave and UHI effect at a larger scale in Sweden. Therefore, this study has been innovative in a sense that it used a method to find the “hot spots” in the study areas and to identify municipal services which located in these spots by combining MODIS and Landsat LST datasets, and to present UHI by using Landsat LST dataset at a municipal scale in Sweden based on multiple years.

This study presented a method to combine various datasets to identify and rank the municipal services based on how much they were impacted by a heat wave situation or UHI. The method includes calculating the heat wave intensity based on SMHI’s heat wave definitions and MODIS LST dataset, categorisation of LST values and calculating the distance between normalised LST classes and the municipal services based on Landsat LST dataset. Furthermore, this study showed that both municipalities have experienced a detectable UHI phenomenon. For all study years, there were similar trends in both municipalities. During different types of years (cool, average and warm), built-up areas (industrial zones and residential neighbourhoods) were experiencing higher temperatures compared to their surroundings in both municipalities. During a warm year, the difference between an urban area and a non-urban area was smaller and the non-urban area was impacted more by an extreme heat in Trelleborg compared to Lerum. These observations can be explained by two reasons. The first one is the LULC differences. In Lerum, there is more green space and water which helped cooling down in...
In general, whereas in Trelleborg, agricultural lands are more common compared to forest and water areas which caused higher temperatures in general. This LULC difference was also the reason of bigger temperature differences in between the LULC classes and their buffer zones in Lerum. The second reason is the geographical location and elevation. Trelleborg is located by the see with lower elevation in the southern part of the country, while Lerum is located inland with a higher elevation and around 300 km north of Trelleborg.

The results of this study aligned with other published studies. For instance, there are studies showing that the high LST areas were generally distributed in built-up areas, while the low LST areas were distributed in land surfaces covered with vegetation and water [17]–[19]. Therefore, larger and contiguous heat sink patches, including green spaces and water, can contribute to optimising the diversity of urban landscape spatial configurations and significantly decreasing the magnitude of LST [17].

The method used in this study was tested in two municipalities in Sweden; however, it is not site specific. Therefore, the method could be extended to other regions and climate zones. However, it might be required to collect additional data from the local area such as LULC maps, the information about the cool, average and warm years, the city borders and locations of the municipal services whether it is a topic of interest. Finally, it is important to highlight a limitation with the study. Since the MODIS satellite provided enough images during the given period but with lower resolution, and the Landsat satellite provided details about the location but generated fewer images (which were dependent on clear weather conditions as well), we had to include both data sets in our analysis. Therefore, for future uses, it is worth noting that long time series data could not be obtained by Landsat, but by MODIS.

5.1. Future Work

As a next step, qualitative interviews will be conducted during spring 2020 with personnel working at the identified schools, day care centres and elderly homes in respective municipality. The interviews will among other things explore past experiences of dealing with heat waves (primarily during the summer 2018), and existing as well as lacking routines, strategies and resources necessary for mitigating future heat waves. Based on the quantitative data analysis from step one (presented here) in combination with the qualitative data analysis of the interviews, the last step of the project will be to work out decision support strategies together with the two participating municipalities.

6. Conclusions

This study was the first step of a larger project and had two objectives. Firstly, different datasets obtained from MODIS and Landsat LST images were combined to find “hot spots” and identify and rank municipal services located within these spots. Secondly, Landsat LST images were used to find out whether there was a UHI effect in study areas. The results did not only reveal the information about the municipal services but also the difference between the two municipalities, and within each municipality regarding their geographical specifications and LULC distribution under different types of summer seasons, cool, average and warm. The method can be extended to larger regions, although additional data from the study area might be required such as the LULC maps and the locations of municipal services. As a part of the larger project, this study had a clear focus on the following four SDGs: Sustainable cities and communities, climate action, good health and well-being and reduce inequalities.

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