A Satellite-derived Heating- and Cooling-Degrees Geospatial Dataset: Results for Antwerp

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Abstract—In the context of developing a low-carbon economy by 2050, the European Union (EU) member states have committed to improve energy efficiency by at least 27% by 2030. To empower municipalities and local authorities addressing this goal, the H2020 PLANHEAT research project develops an open-source software tool for developing economically sustainable energy plans for low-carbon heating and cooling. To take into account the Urban Heat Island (UHI) effect on energy demand, the PLANHEAT software tool uses a geospatial dataset of hourly 1 km Heating and Cooling Degrees that is derived from satellite thermal data and information from weather models. This article describes the methodology used for producing this dataset and presents the first results for the city of Antwerp in Belgium. The PLANHEAT tool will be released as a QGIS plugin in June 2019.

Keywords—urban heat islands, heating degrees, cooling degrees, energy assessment, thermal remote sensing, cities, SEVIRI, PLANHEAT

I. INTRODUCTION

Urban areas are warmer than their surrounding rural areas [1]. This effect is known as the Urban Heat Island (UHI) and it is observable in all urban areas irrespectively of their size. The intensity of the UHI varies within a city as a function of land cover and land use and also with time-of-day and season. UHIs impact the health and wellbeing of the urban population [2] and affect the energy demand of buildings [3], [4]. This is because UHIs increase the need for cooling in summer and reduce the need for heating in winter [5]. These effects have a major impact in the energy consumption of cities, as Santamouris et al. [6] showed for the centre of Athens in Greece.

Presently, buildings account for 30% of the global energy consumption [7], which is satisfied mostly by fossil fuels. In the context of developing a low-carbon economy by 2050, the European Union (EU) member states have set to improve energy efficiency by at least 27% by 2030 [7]. This implies that significant improvements in the energy performance of the building sector are required, and that municipalities and local authorities play a key role in achieving this goal. In this context the PLANHEAT project (<http://planheat.eu/>), which is funded by the Horizon 2020 research programme of the

European Commission, aims to develop an integrated, easy-to-use and open-source tool so as to empower local authorities in the development of economically sustainable plans for low-carbon heating and cooling. The PLANHEAT integrated tool will be available as a QGIS version 3 plugin in June 2019 and will consist of three interconnected modules: (i) the Mapping Module for mapping and quantifying the current heating and cooling (H&C) energy demand and the local energy sources potential; (ii) the Planning Module for identifying sustainable and feasible H&C scenarios according to energy planning criteria; and (iii) the Simulation Module for analyzing the technical feasibility of the developed scenarios.

The Mapping Module consists of two sub-modules: the City Mapping Module (CMM) and the District Mapping Module (DMM) [7]. The former is for disaggregating annual final energy consumption data over the entire city; while the latter for mapping, quantifying and storing the georeferenced current thermal energy demand of each building at the district level [7]. To take into account the UHI effects, PLANHEAT's Mapping Module is accompanied by a dynamic geospatial dataset of 1 km / 1 h Heating and Cooling Degree data (HD and CD, respectively) that cover an entire year. These data are energy demand proxies that are defined relative to a base outdoor air temperature, below or above which a building is assumed to need heating or cooling [8], [9].

In PLANHEAT project the HD and CD energy demand proxies are derived from 1 km air temperature image data that are retrieved from geostationary satellite thermal images and information from weather models. This article describes the workflow for producing PLANHEAT's HD and CD geospatial dataset and presents the derived data for the city of Antwerp in Belgium, which is one of the three validation cities of PLANHEAT. Following this introduction, the employed data and methods are discussed in Section 2 and the temporally aggregated HD and CD maps for Antwerp are presented in Section 3. The final section of this article corresponds to the conclusions.

II. DATA & METHODS

The methodology for producing PLANHEAT's geospatial dataset is based on satellite thermal image data acquired with very high frequency by sensors on geostationary orbits. In particular, the satellite data employed are from the Meteosat Second Generation-Spinning Enhanced Visible and Infrared Imager (MSG-SEVIRI). SEVIRI acquires image data over Europe and Africa every 15 min in 12 spectral bands: four located in the 0.4 – 1.6 μm spectral region and eight in the 3.9 – 13.4 μm (the pixel size ranges from 4 km at 35°N to 6 km at 50°N) [10]. The latter cover thermal infrared (TIR) wavelengths and measure radiation emitted by the Earth's surface and atmosphere, which can be used for monitoring the diurnal cycle of surface temperatures.

The devised methodology is presented in Fig. 1 and comprises four key stages. The first stage is the retrieval of a multi-year time series of outdoor 2 m above ground air temperatures (TA) from SEVIRI TIR data. The second stage is the pixelwise modeling of the climatological diurnal and annual temperature cycles of the employed TA time series. The third stage is the use of these models so as to generate a modelled TA dataset, where the impact of short-term weather effects is reduced; while the fourth and final stage is the calculation of the 1 km / 1 h HD and CD data from the

modelled TA data.

A. Retrieval of TA

The retrieval of the TA is performed using the nowcasting service [11] of the Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing of the National Observatory of Athens (IAASARS/NOA) [12]. The workflow of this service is described in detail in [11] and starts with the real-time acquisition and preprocessing of the SEVIRI data. The preprocessing includes the decompression and radiometric correction of the data, the masking of the clouds (as discussed in [13]), and the extraction of the image sections that cover each area-of-interest. The next operation of the IAASARS/NOA service is the retrieval of a collocated vertical profile of Numerical Weather Predictions (NWP) from the Global Forecasting System (GFS) [15]. This profile covers the 0.1–1013.3 hPa range and is input in an iteration scheme (i.e. SAFNWC's SEVIRI Physical Retrieval algorithm [14]) that modifies it in a controlled manner until its radiative transfer properties fit the satellite observations and in particular the measured SEVIRI 6.2, 7.3, 10.8, 12.0 and 13.4 μm brightness temperatures (BTs) [14]. The TA is then retrieved from the updated air temperature profile by vertically interpolating or extrapolating the air temperature at a height of 2 m above ground. This process requires information about the surface elevation, which is obtained from the Shuttle Radar Topography Mission Digital

Fig. 1. The workflow for producing PLANHEAT's geospatial dataset of HD, CD, HDH and CDH.

Elevation Model (SRTM DEM) [15]. To avoid image gaps, the TA of cloud-contaminated pixels is retrieved directly from the NWP profiles (after appropriate temporal interpolation), without using any information from the SEVIRI data [11]. The final operation of the IAASARS/NOA nowcasting service is the spatial enhancement of the 4-5 km TA image data to 1 km using a statistical downscaling technic similar to [16].

B. Modelling the Diurnal and Annual TA Cycle

The TA retrieval runs iteratively every 1 h in real-time (as shown in Fig. 1) until a multi-year 1 km / 1h TA time series is obtained that is representative of the surface thermal patterns. The next stage for producing PLANHEAT's geospatial dataset is the use of this time series for modelling the diurnal and annual TA cycles of each pixel. This is done by grouping the TA data into 24 groups (based on their acquisition time, t) and then retrieving the Annual Cycle Parameters (ACP) [17], [18] of each group, as done in [19]. The result is 24 sets of ACP data, namely the mean annual TA (M , in $^{\circ}\text{C}$) at t ; the yearly TA amplitude (Y , in $^{\circ}\text{C}$) at t ; and the phase shift from the spring equinox (T , in days) at t [17]. These ACP data are then used as input in Eq. 1 so as to produce a one-year time series of climatological 1 km / 1 h TA data ($\widehat{TA}$), where the impact of short-term weather effects is mitigated. The x and y in Eq. 1 are the image coordinates of each pixel and d the day-of-cycle.

$$\widehat{TA}(x, y, d, t) = M(x, y, t) + Y(x, y, t) \sin\left(\frac{2\pi}{365}d + T(x, y, t)\right) \quad (1)$$

C. Calculation of HD and CD

The last stage of the devised methodology is the calculation of the HD and CD (in $^{\circ}\text{C}$) for each pixel. This is done using Eqs. 2 and 3:

$$HD_{i,j} = (TA_{b,H} - \widehat{TA}_{i,j})_{((TA_{b,H} - \widehat{TA}_{i,j}) > 0)} \quad (2)$$

$$CD_{i,j} = (\widehat{TA}_{i,j} - TA_{b,C})_{((\widehat{TA}_{i,j} - TA_{b,C}) > 0)} \quad (3)$$

In these equations j is the day-of-year, i the time-of-day and TA_b the base outdoor temperature relative to which the HD and CD are calculated. In PLANHEAT the HD are calculated for two base temperatures ($TA_{b,H}$), namely 15.5°C and 18.0°C , as done in [8], [9]; while the CD using a base temperature ($TA_{b,C}$) of 22.0°C [9]. The subscripts $((TA_{b,H} - \widehat{TA}_{i,j}) > 0)$ and $((\widehat{TA}_{i,j} - TA_{b,C}) > 0)$ in the above equations denote that only positive values are considered.

The HD and CD data utilized in PLANHEAT's DMM are retrieved from Eqs. 2 and 3 using as input a times series of 1 km / 1 h $\widehat{TA}$ that covers an entire year (8760 value in total) [7]. However, the use of the HD and CD in PLANHEAT's CMM requires the reduction of the temporal detail. This is achieved using the following two temporal aggregation schemes:

1) for each pixel the sum of the hourly HD or CD is calculated for a whole year; and

2) for each pixel the number of hours where the $\widehat{TA}_{i,j}$ is lower than $TA_{b,H}$ or higher than $TA_{b,C}$ is calculated for a

whole year. This approach results to the annual HD Hours (HDH) and CD Hours (CDH), respectively.

III. RESULTS FOR THE CITY OF ANTEWRP

Antwerp is the most populous municipality in Belgium and one of the largest ports in Europe. Its climate is sub-oceanic, humid and rainy with cold winters and cool summers. The core of the city is highly urbanized and as the distance from the city centre increases the imperviousness fraction decreases. The Antwerp metropolitan area is surrounded by croplands, water bodies and forest areas but also of several smaller towns/villages. A prominent landscape feature is the river Scheldt that runs through the city and is connected with Antwerp's port area.

Figures 2a and 2b present the annual HDH and CDH data for the city of Antwerp, respectively. These data are from PLANHEAT's geospatial dataset (version 2017-2) and show that the need for heating is stronger for the city districts of Berchem (BE in Fig. 2), Hoboken (HO), Wilrijk (WI) and Deurne (DE) and weaker for Borgerhout (BO), Merksem (ME) and Antwerp (AN). Moreover they also suggest that

Fig. 2. The PLANHEAT annual (a) HDH and (b) CDH data for the city districts of Antwerp in Belgium. The diagonal strip pattern corresponds to the port area.

the need for cooling is strongest at the city centre. This intra-urban variability of the HDH and CDH data is strongly related to the intra-urban intensity of the UHI effect and also to the presence of the river Scheldt.

To assess the accuracy of PLANHEAT's geospatial dataset, the satellite-derived TA, which are the basis for the calculation of the HD and CD data, have been compared with in-situ TA observations retrieved from the National Oceanic and Atmospheric Administration (NOAA) archive of weather stations. For the city of Antwerp, the nearby stations of Deurne and Sint Katelijne-Waver were used and a dataset of corresponding pairs of satellite-derived and in-situ TA for 2016-2017 was derived. The evaluation results are given in Table 1 are based on several descriptive statistical measures, i.e. the mean difference, the standard deviation (SD), the Root-Mean-Square-Error (RMSE) and Pearson's Correlation Coefficient. Overall, the accuracy assessment showed that the RMSE of the satellite-derived TA data is less than 2°C and Pearson's Correlation Coefficient is 96%.

TABLE I. TA ACCURACY ASSESSMENT FOR ANTWERP.

Statistical Measure	Evaluation Sites for Antwerp	
	Deurne station	Sint Katelijne-Waver
Lat./Lon.	51.189°N/4.460°E	51.083°N/4.517°E
Mean Difference	0.0°C	0.2°C
Standard Deviation	1.8°C	1.9°C
RMSE	1.8°C	1.9°C
Correlation Coef.	96.4%	96.0%
Observations used	8481	7058

IV. CONCLUDING REMARKS

HD and CD maps provide proxy information about the intra-urban variations of energy demand. This article describes the methodology that has been designed in the context of the PLANHEAT project so as to produce a geospatial dataset of 1 km / hourly HD and CD using as a basis geostationary satellite thermal image data. The derived dataset is a key part of PLANHEAT's Mapping module and is used so as to take into account the UHI effects when mapping and quantifying the current H&C energy demand of a city's buildings. The PLANHEAT integrated software tool aims to help municipalities develop economically sustainable plans for low-carbon heating and cooling and thus progress the EU goal to move to a competitive low-carbon economy by 2050. PLANHEAT will be released as a QGIS version 3 plugin in June 2019.

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