Next Generation City Climate Services Using Advanced Weather Models And Emerging Data Sources

Optimized Full Prototype of Data Processors for City Weather Model

Deliverable 5.4

An overview on the engines behind CityCLIM's observational data...

September 2024

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No *101036814*

Foreword

Welcome to the CityCLIM project. Europe's metropolitan areas are increasingly suffering from the effects of climate change. Prolonged heat waves pose a threat to the health of the population. To counter this threat, it is important to understand its causes and identify suitable countermeasures in good time. For this reason, the EU funded the project "Next Generation City Climate Services Using Advanced Weather Models and Emerging Data Sources", or CityCLIM for short (2021-2024), as part of its Horizon 2020 programme. The aim of the project was to develop a cloud-based platform which provide various weather and climate services specifically for metropolitan areas based on data from weather models, Earth observation and ground measurements.

Heat waves are a major problem for densely populated areas

As a result of climate change, heat waves are occurring with increasing frequency. Especially densely populated areas are strongly affected by high temperatures, as the heat usually lasts longer and temperatures hardly drop even at night. For this reason, the health burden caused by heat is significantly higher in cities than in surrounding areas. This is why the CityCLIM project aimed to develop a weather forecast model tailored to the needs of large cities. Unlike conventional forecast models, which resolution are usually in the range of several kilometres, the new weather model has a resolution of one hundred by one hundred meters. In addition, the model combines data from satellites with measurements from in-situ sensors and information provided by the population itself.

Weather and climate services for citizens and city administrations

The improved weather model and Earth observation data are the basis for deriving a suite of City Climate Services for combating some of the negative effects of climate change in cities, namely:

- Climate Information Services: Heat Wave Information and Warning, Pollution Information, historical Climate Information Service
- Citizen Weather Sensation Service
- Identification Services: Heat Island, City Air Flow and Pollution Area
- Simulation and Mitigation Strategies Services: Heat-Island, City Air flow and Pollution

These services are made available to the general public, specifically addressing citizens, city councils and other authorities. The services make it possible, among other things, to examine the effects of urban planning measures on urban heat or air flow.

Implementation by a European consortium

Several European companies were involved in implementing the CityCLIM project. OHB System AG was acting as the project coordinator and was responsible for processing and providing the satellite Earth observation data and services. OHB Digital Connect developed an airborne system to validate the calculated model predictions with thermal infrared measurement data. OHB Digital Services developed the cloud-based platform storing and processing the data and hosting the City Climate Services (CCS). OHB Digital Solutions from Austria was responsible for the integration of in-situ data from the pilot cities and the exchange with the pilot cities. Other industrial partners include the Institut für angewandte Systemtechnik Bremen GmbH (ATB), which was responsible for the technical coordination of the project together with OHB and was also supporting the development of the cloud-based data platform. At Meteologix AG, a subsidiary of Kachelmann GmbH, the high-resolution weather model providing the precise weather forecasts was developed. Scientific partners were the Global Change Unit of the University of Valencia, which contributed novel processing methods for thermal spaceborne data for the examination of urban heat islands. Finally, the Helmholtz Centre for Environmental Research from Leipzig developed methods to incorporate data collected by the population in the scope of citizen science.

Four European pilot cities as partners

In order to develop the City Climate Services as application-oriented as possible, the CityCLIM project was carried out in close cooperation with four pilot cities which are spaced out across Europe to represent its climatic diversity. These are Karlsruhe in Germany, the city of Luxembourg, Valencia in Spain and Thessaloniki in Greece. The cities were contributing to the project by defining their specific needs towards the City Climate Services and the data platform, by supporting the provision of data and by enabling the project results to be validated in a real environment.

Data Processors for the City Weather Model

This document outlines the development and optimization of the Full Prototype (FP) of data processors, which serve as the foundation for generating and preparing data used in various urban climate services. The optimized In-Situ, Airborne, and Spaceborne Data Processors handle diverse datasets, including city sensor data, airborne campaign information, and satellite-derived products like high-resolution land surface temperature (LST). Notably, the Spaceborne Data Processor powers the EO-Based Heat Island Identification Service for LST and heat analysis, as well as the EO-Based Heat Island Simulation and Mitigation Strategies Service, which evaluates the impact of land cover changes on heat. This deliverable highlights improvements in performance, scalability, and accuracy across the processors, supporting advanced urban climate analysis.

Table of Contents

1 Introduction

This document presents the development and optimization of the Full Prototype (FP) of data processors, a key deliverable that enables the efficient generation and preparation of data for the services offered by the project. This milestone introduces the optimized versions of the In-Situ Data Processor, Airborne Data Processor, and Spaceborne Data Processor, each designed to handle and process diverse data types essential for urban climate analysis.

Within the overall CityCLIM ecosystem (see Figure 1), WP5 covers the specification, implementation, and optimization of data processors for the City Weather Model, which includes the building of a reference dataset of in-situ measurements, the acquisition of high-resolution imagery from airborne sensors, and the development of data processors for satellite data on urban agglomerations. The work inside all WP5 tasks is structured according to a development lifecycle, with a gradual refinement of developments from specification, the development of the early prototype (EP, TRL4-5), to the implementation of the full prototype (FP, TRL6-7). Each step is documented in a dedicated project-internal deliverable (D5.1-D5.3). Finally, the full prototype implementations are optimized according to the feedback from validation and field testing with end users (D7.7). This public deliverable, D5.4, at the final M36 of the CityCLIM project, documents the Optimized Full Prototypes (OP) of the Data Processors for the City Weather Model as a summary of the achievements of the final developments within all tasks of WP5.

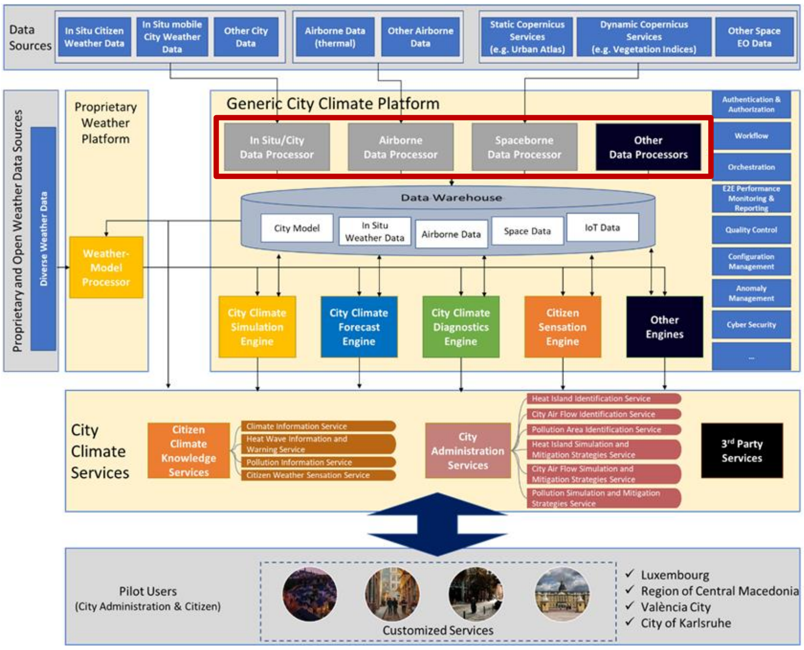


Figure 1. The components of WP5 “Data Processors for City Weather Model” (red box) within the CityCLIM architecture.

2 Optimized Prototypes of Data Processors for City Weather Model

The three processors form the backbone of the project’s data infrastructure, transforming raw inputs from multiple sources—such as in-situ sensors, airborne campaigns, and satellite observations—into valuable datasets ready for integration into the project's services. These services include near real time monitoring, predictive urban heat analysis, and long-term urban planning tools aimed at city planners and administrators.

Each processor has undergone significant enhancements to optimize performance, scalability, and accuracy. The In-Situ Data Processor ensures smooth handling of data from various city platforms and sensor networks. The Airborne Data Processor transforms airborne sensor data into detailed surface-level information, such as LST and land-leaving radiance.

The Spaceborne Data Processor plays a particularly critical role, not only generating satellite-derived products, such as high-resolution land surface temperature (LST) and heat-related indices, but also providing the engines that power key project services. These include the EO-Based Heat Island Identification Service, which allows users to analyse LST, heat maps, and time series, and the EO-Based Heat Island Simulation and Mitigation Strategies Service, which assesses the impact of land cover changes on urban heat.

2.1 In-Situ Data Processor

The **In Situ/City Data Processor (ISDP)** serves as a central data hub and communication bridge between terrestrial sensors and the Data Warehouse. Developed in Python, the ISDP operates within the GCCP and connects to external API endpoints using REST protocols.

Tables

Number of tables	15
Number of entities	11.14 M
Total data stored	47.36 GiB

Figure 2: Summary of Data Stored in the project.

Data Sources:

The data collected by the ISDP originates from three primary sources:

- **MeteoTracker Data:** A portable weather sensor, MeteoTracker uploads its data following each recording session.
- **Bresser Wi-Fi Stations:** Civilian-targeted weather sensors distributed across each pilot city to capture localized climate data.
- **Valencia Sensor Network:** Valencia’s pre-existing sensor network provides a wealth of environmental data. This network includes sensors mounted on buses, pollution sensors, and traditional weather monitoring devices.

The ISDP constantly communicates with the API endpoints of these platforms, organizing and storing the data in the Data Warehouse across multiple structured tables.

Key features:

- The ISDP connects to sensor platforms or third-party intermediaries via RESTful interfaces. Data transfer occurs through either **POST** requests sent by the sensor platforms or **GET** requests initiated by the ISDP to retrieve data.
- Once received, the data undergoes validation and parsing to ensure consistency in format across all sensors. Due to the variety of sensor types involved, pre-processing steps—such

as unit conversions and restructuring—may be required to align the data with the requirements of the weather model.
- Consolidated data is stored in the Data Warehouse, where it becomes accessible to the pilot cities and other project services through REST APIs. This centralized access is critical for both real-time urban climate analysis and city-specific weather models.

Methodology

The methodology for data acquisition varies slightly across sensor types:

- **MeteoTracker** and **Valencia Network Sensors** upload data directly to their respective platforms. The ISDP retrieves, processes, and stores this data in the Data Warehouse.
- **Bresser Wi-Fi Stations** rely on users to upload data via a third-party platform. The ISDP then accesses this platform, processes the data, and stores it in the central repository.

Although the ISDP primarily functions as a communication conduit between sensors and the GCCP, its role is pivotal in ensuring that data from diverse sources is processed and made available for downstream applications, including weather modeling and analysis.

Application potential

The ISDP's primary function is to secure and centralize weather data for integration into weather models or other forms of analysis. It can easily be adapted to other projects of similar scope and scale, particularly those aimed at enhancing the liveability of urban environments by leveraging in-situ sensor data.

Main achievements

The ISDP has successfully centralized sensor data from multiple sources, making it readily accessible for weather models and other project services. Its scalability is a key advantage: the infrastructure allows for the seamless addition of new sensors of the same type, while introducing new sensor types requires minimal effort and implementation time.

2.2 Airborne Data Processor

CityCLIM brings together and operationalizes climate-related data from real and simulated data sources in the form of in-situ and spaceborne data on one hand and simulated weather model outputs on the other. These data sources fuel the services developed in the scope of the project. However, while spaceborne and weather model data provide comprehensive and up-to-date layers, they lack in resolution to account for finer urban features. In-situ data are timelier and are collected specifically in selected locations of significance for daily life, feeding also into weather modelling to ensure that solutions cannot diverge from observations. Yet, they are not spatially resolved.

Airborne data bridges this by providing land surface temperature (LST) readings at variable resolutions significantly below spaceborne data. As airborne data can be collected only for specific points in time, it is not intended for operational use during the project. However, there are numerous unique uses to this data source. First, it can aid verification and validation of LST readings by other data sources or by algorithmic super-resolution. Second, future commercial and institutional satellite missions provide improved resolutions, allowing the use of airborne data to mimic them as of now unavailable data products and enables devising usecases that are not feasible with current spaceborne resolutions.

Further, stakeholder feedback collected as part of the CityCLIM workshops revealed a strong stand-alone interest in this type of data for different reasons, raising even the question whether future concepts could pursue operationalisation in an on demand-fashion, e.g. by utilizing drones as sensor carrier platform. For instance, albeit they are in principle superseded by the operational CityCLIM services, snapshot/scenario type climate analyses are still the go-to tool of choice for urban planners to incorporate climate metrics into their processes. An unresolved point of discussion among stakeholders was the reliability of these high-resolution simulations, and in general trust in observations was higher than in simulations.

Figure 3: Aircraft and airborne system prior to take-off for the Valencia campaign (Summer 2024).

Key features:

- **Thermal infrared processing chain**: Computing useful LST data from thermal infrared measurements requires the synthesis of various primary and secondary sensor data, as well as careful calibration and correction steps. This is facilitated by the custom thermal infrared processing chain set up for CityCLIM, which replicates the key processing steps performed also in spaceborne systems. All processing steps were verified using laboratory experiments and flight campaign data.
- **Airborne data acquisition system**: Although the airborne data acquisition system is carried by a manually flown aircraft, it operates autonomously, recording and cataloguing all relevant primary and secondary data required for subsequent data analysis.
- **Flight campaigns**: During CityCLIM, two airborne campaigns were conducted. The first campaign (Summer 2023) aimed at verification of the airborne system and processing chain. The second campaign (Summer 2024) was conducted at the pilot city Valencia and was accompanied by an extensive field campaign providing ground measurements. Figure 3 shows the airborne system prior to take-off during the Valencia campaign.

Methodology

Retrieval of LST and related quantities requires specialized sensors. These sensors operate in the LWIR (long-wave infrared) part of the electromagnetic spectrum, based on the principle that each material emits a spectrum of thermal radiation dependent on its temperature. For an ideal emitter, the emission spectrum is described by Planck's law. The shape of this spectrum as well as the wavelength at which the emission is strongest, shift with the maximum temperature according to Wien's displacement law. Cooler bodies emit less energetic, long wavelength radiation whereas hot bodies emit radiation with a shorter wavelength, eventually even shifting into the visible spectrum. Bodies with a temperature near the ambient 20 °C (293.15 K) emit LWIR (Long-Wave Infrared) radiation with a wavelength near 10 µm, motivating the selection of spectral bands selected for LWIR sensing within CityCLIM.

Generally, remote sensing of absolute radiative quantities is difficult because the radiation collected by a sensor consists of contributions from different sources and is further modulated by the atmosphere. Contributions include the desired emission of the targeted object and radiation from other sources, including reflected solar radiation, self-emissions from the atmosphere and even from the optics and casing of the employed sensor. These contributions, down- and upwelling, are modulated based on atmospheric transmissivity. Within the LWIR regime, the latter effects are diminished because of the infrared atmospheric window, an absorbance minimum cantered around 10 µm which allows thermal radiation in this region to pass through the atmosphere with minimal dampening, making remote sensing of ambient thermal radiation possible.

The primary sensor employed in the airborne system is the custom three-band LWIR sensor RAVEN (Remote Airborne Variable Emissivity and Temperature Sensor) which records LWIR radiation in three spectral bands using three separate, temperature-stabilized thermal cameras equipped with suitable bandpass filters. Figure 4 shows the band specification of RAVEN and its integration into the airborne system. It is complemented by a high-resolution RGB camera and secondary sensors for position and location.

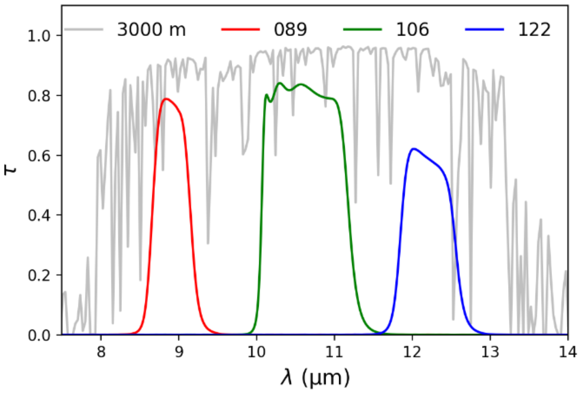


Figure 4: Spectral bands of the sensor "RAVEN" and simulated atmospheric transmittance (left). RAVEN and high-resolution RGB camera as integrated in the airborne system.

The data processing pipeline established to work with RAVEN or similar sensors has to primary objectives. First, based on information on position and location of the sensor relative to Earth's surface, and utilizing further calibration data on how the lens distorts the imagery, image data are converted to geo-referenced information describing points on the surface rather than image pixels. Second, based on a series of radiometric corrections, any non-ideal effects stemming e.g. from the atmosphere are removed, enabling accurate sensing of the LWIR radiation emitted by the surface.

Whereas single- and broadband sensors struggle to disentangle contributions to emitted radiation stemming from emitter material and actual temperature, employing a calibrated multi-band sensor enables application of the Temperature Emissivity Separation (TES) method, which performs well at estimating the unknown surface properties along the adjusted Land Surface Temperature. For

CityCLIM, TES was re-implemented, verified using satellite imagery and finally adjusted to the employed airborne sensor.

Application potential

- **Verification / validation activities:** The primary strength of airborne data lies in its improved resolution, which is unmatched by any current satellite mission and can be adjusted via operating altitude. By obtaining more fine-grained information, fewer mixed pixels (pixels receiving radiation from different materials) are expected, making airborne data acquisition the preferred tool for developing or verifying models for sharpening simulating lower-resolution data.
- **Novel insights into the urban ecosystem:** Although limited to singular points in time, high-resolution data provides a novel qualitative and quantitative view on the urban area, revealing features, effects and dynamics not accessible in other spectral channels or at coarse resolution.
- **Infrastructure inspection:** The high resolution enables inspection of infrastructures, e.g. for leakage detection in district heating pipes.
- **Irrigation management & water body health:** In principle, airborne LST data can be used for usecases that can be performed for extended regions using spaceborne data. While the data collection effort using a piloted aircraft is too high to enable regular revisits, the autonomous operation of the airborne data acquisition system prepares future operation e.g. as part of an Unmanned Aerial System (UAS).

Main achievements

We have successfully prepared a system for collecting, processing, and evaluating Long-Wave Infrared data. The system components showed excellent performance in laboratory verification tests, and could be validated during two flight campaigns, the latter carried out on 10.09.2024 and 11.09.2024 in the pilot city Valencia. Figure 5 and Figure 6 show exemplary LST maps overlayed on RGB imagery of selected regions in Valencia.

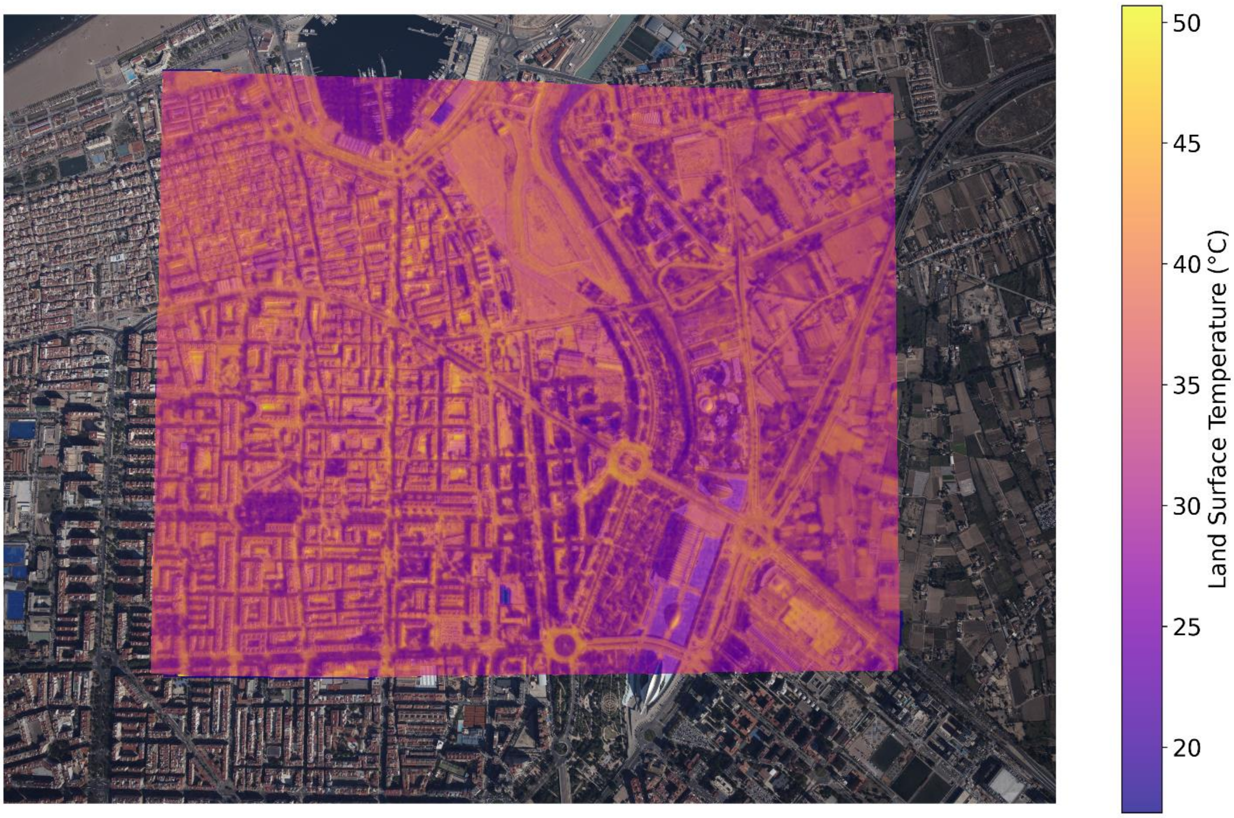


Figure 5: Land surface temperature retrieved via airborne measurements (Near Valencia harbour, 2024-09-10 14:54 UTC).

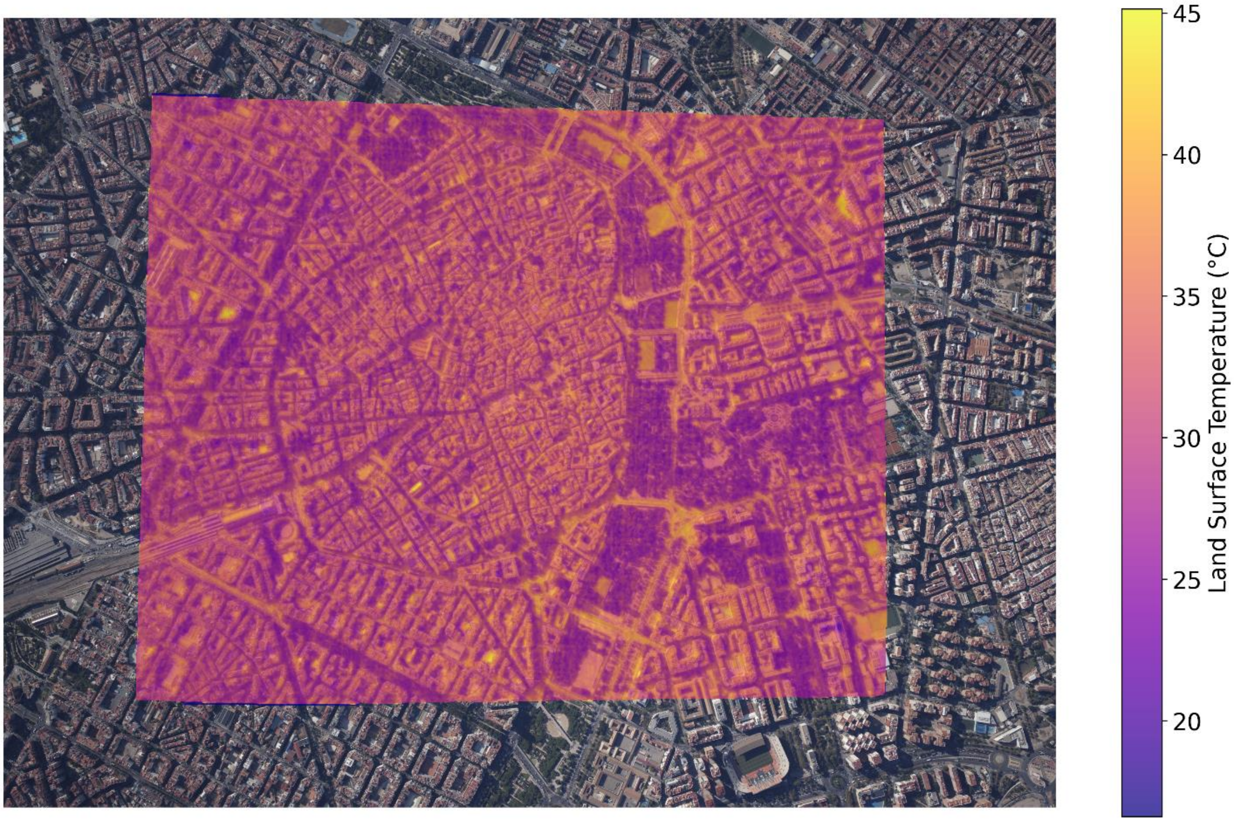


Figure 6: Land surface temperature retrieved via airborne measurements (Valencia center & Jardins del Real, 2024-09-10 15:30 UTC).

2.3 Spaceborne Data Processor

The **Spaceborne Data Processor** is a core component of the project, responsible for handling and transforming Earth observation data to support urban heat analysis and simulation. It is divided into four distinct yet interconnected components, each playing a crucial role in converting raw satellite data into valuable insights for urban planners and city administrations.

First, the **Spaceborne Data Preprocessor** is tasked with acquiring and preparing the satellite data. It automates the downloading and preprocessing steps, such as resampling and mosaicking, to ensure that data from multiple satellite sources are harmonized and ready for further analysis. After all the preprocessing steps, the data is stored in the CityCLIM Data warehouse and made available for other components through a STAC catalogue.

Next, the **Thermal Sharpener** enhances the spatial and temporal resolution of land surface temperature (LST) data by fusing two complementary datasets: Sentinel-3, which provides coarse but frequent observations, and the Sentinel-2 and Landsat series, which offers fine but less frequent data. The result is an improved LST product with a resolution of 30 meters and a bi-daily temporal frequency, allowing for more precise monitoring of urban heat patterns.

Following the sharpening process, the **Index Calculator** computes several urban heat indices derived from the enhanced LST data. These indices provide critical metrics to assess the thermal behaviour of urban environments, offering key insights into heat stress, heat island intensity, and other urban climate factors.

Finally, the **EO-Based Heat Island Simulation and Mitigation Strategies Service (HISMSS) engine** enables users to simulate the impact of land cover changes on LST. This engine contains the models necessary for assessing how modifications to the urban landscape—such as increased vegetation or changes in building materials—affect urban heat dynamics, providing valuable guidance for city planners aiming to mitigate heat island effects.

2.3.1 Spaceborne Data Preprocessor

The **Spaceborne Data Preprocessor**'s objective is the collection, preliminary processing and harmonization of different types of satellite-based earth observation data, ensuring compatibility and uniformity across data from multiple sources.

Data Sources:

- **Sentinel-3 LST:** Provides frequent (2 to 4 images per day) but coarse (1km resolution) LST data.
- **Landsat 8 and 9 LST:** Offers higher spatial resolution (30m) but is less frequently available (every 16 days each satellite)
- **Sentinel-2 Optical Data:** Used to calculate Normalized Difference Built-up Index and Normalized Difference Vegetation index, both of which contribute to the fusion process.
- **ESA Worldcover:** Global land cover classification product provided annually on 10m spatial resolution. Basis for the calculation of distance layers (distance to water, distance to vegetation) for including the cooling effect of water and vegetation.
- **Digital elevation models:** Information on a city's height structure most often existing as proprietary datasets is used to derive indicators on the 3D urban morphology (e.g., building height index, building roof index).

Key features:

- **AOI Management for Data Collection**: Dedicated Rest API for creating, reading, updating, deleting, querying AOIs for data collection.
- **Automated Data Collection from Multiple Data Providers**: Copernicus Data Space Ecosystem, Terrascope, Planetary Computer.

- **Data Preprocessing**: Crop, scale, reproject/resample, mosaic the data product tiles and convert to cloud optimized data formats

- **Statistics and STAC Compliant Metadata**: Compute statistics of the collected and pre-processed data, consolidate metadata in STAC format, catalogue metadata and data in a STAC catalogue accessible via some STAC API.

- **Data Visualizations**: Generate RGB data visualizations such as low-resolution previews and hight resolution overviews.

Methodology

- **Automated Data Collection from Multiple Data Providers**: Access via standards APIs provided by the data providers, e.g. STAC API.

- **Data Preprocessing and Data Visualization**: Established geo-processing libraries such as GDAL, Rasterio and Titiler.

- **AOI Management for Data Collection, Statistics and STAC Compliant Metadata**: Provision of a STAC API via the Stac-FastAPI library.

Application potential

- **Support for Other Services**: As support for other services via providing analysis ready satellite-based earth observation data.

Main achievements

- **Access to Pre-processed Data**: Successful provision of pre-processed satellite-based each observation data for other CityCLIM components such as the Thermal Sharpener and the EO-based Heat Island Simulation and Mitigation Strategies Service Engine.

2.3.2 Thermal Sharpener

The **Thermal Sharpener** is a critical component of the Spaceborne Data Processor, responsible for fusing satellite data to produce enhanced Land Surface Temperature (LST) products. Its primary goal is to merge coarse but frequent LST data from Sentinel-3 (1 km resolution) with the finer but less frequent LST data from Landsat 8 and 9 (30 m resolution). By combining these datasets, the sharpener generates bi-daily LST products at a significantly improved spatial resolution of 30 meters, providing more detailed insights into urban heat dynamics.

Data Sources:

The Thermal Sharpener relies on three key satellite datasets:

- **Sentinel-3 LST:** Provides frequent (2 to 4 images per day) but coarse (1km resolution) LST data.
- **Landsat 8 and 9 LST:** Offers higher spatial resolution (30m) but is less frequently available (every 16 days each satellite)
- **Sentinel-2 Optical Data:** Used to calculate Normalized Difference Built-up Index and Normalized Difference Vegetation index, both of which contribute to the fusion process.

Key features:

- **Enhanced Spatial Resolution:** Combines Sentinel-3 and Landsat data to produce bi-daily LST products at a 30-meter resolution.
- **Daytime Fusion (ubESTARFM):** Uses high-resolution Landsat data to sharpen coarser Sentinel-3 data during the day, improving spatial and temporal resolution.

- **Nighttime Fusion (Area-to-Point Regression Kriging):** Enhances Sentinel-3 data at night using statistical techniques to approximate fine-resolution temperature data without Landsat observations.

Methodology

- **Daytime Fusion:** The ubESTARFM method integrates Landsat's high-resolution data with Sentinel-3's coarser data to refine LST measurements.
- **Nighttime Fusion:** The Area-to-Point Regression Kriging method estimates finer-resolution LST data by leveraging statistical relationships, compensating for the lack of Landsat data during nighttime.

Application potential

- **CityCLIM Services:** The enhanced LST products goes to the EO-Based Heat Island Identification Service. This service uses sharpened LST data for heat map visualization, time series analysis, offering valuable insights for urban planning and management.
- **Beyond the CityCLIM services:** The enhanced LST products from the Thermal Sharpener offer broad applications including climate change research, where they support urban heat island studies and long-term climate monitoring. They are valuable for environmental management by tracking heat stress impacts and ecosystem health. In agriculture and land use planning, the data aids precision agriculture and informs land development decisions. For disaster management, it helps predict and manage heatwaves and assess wildfire risks. In infrastructure development, it supports urban design and energy efficiency improvements. Public health applications include developing heat-related health alerts and studying temperature impacts on health. Lastly, it assists in policy development and climate action planning by providing crucial data for regulatory and strategic decision-making.

Validation and Key Metrics:

- **Performance Evaluation:** Assessed using metrics like Root Mean Square Error (RMSE), Bias, and R^2.
- **High Accuracy:** Valencia and Thessaloniki exhibit RMSE values around 1.83 K and 1.89 K, with R^2 values of 0.78 and 0.73, respectively.
- **Regional Variations:** Luxembourg and Karlsruhe show slightly higher RMSE values (around 2.20 K and 2.18 K), suggesting some limitations in downscaling accuracy in these areas.

Main achievements

- **High-Resolution Data Generation:** Successfully combines frequent and fine-grained satellite data to produce accurate, high-resolution LST products (See Figure 7).
- **Validation Success:** Demonstrates significant improvements in temperature data enhancement, particularly in regions with low cloud coverage, proving its effectiveness as a scalable and reliable solution for urban heat analysis.

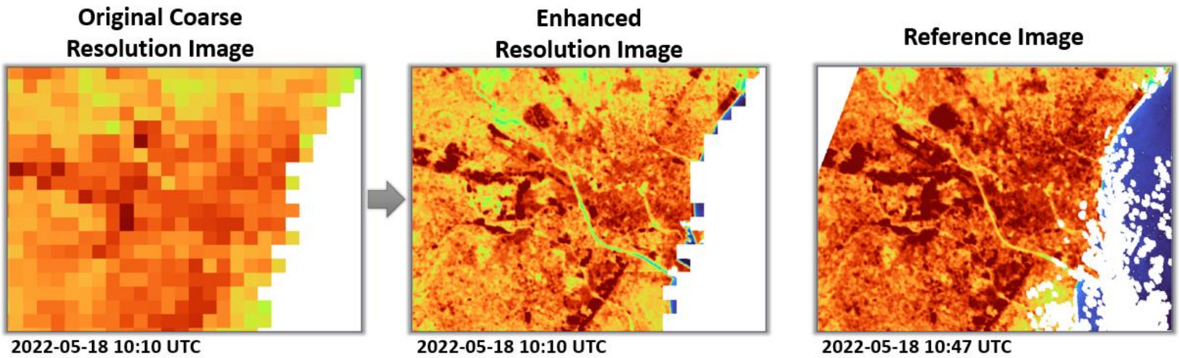


Figure 7. Example of a Sharpened Image

2.3.3 Index Calculator

The **Index Calculator** is designed to generate a variety of urban heat-related indices based on the enhanced Land Surface Temperature (LST) data produced by the Thermal Sharpener. These indices provide valuable insights into the thermal behavior of cities, allowing for detailed assessments of urban heat patterns, thermal discomfort, and the urban heat island effect. The output of the Index Calculator serves as an essential tool for urban planners and decision-makers aiming to mitigate the effects of urban heat on local environments.

Data Sources:

The Index Calculator relies on multiple datasets to generate the required indices:

- **Sharpened LST:** Produced by the Thermal Sharpener at 30 m resolution, this dataset forms the core input for calculating the various heat-related indices.
- **Urban Areas:** Provided by users or calculated from WorldCover data, these define the areas of interest for urban heat analysis.
- **Relative humidity:** Sourced from the ERA5 land reanalysis dataset, this is used in combination with LST to calculate the Discomfort Index.

Key features:

The Index Calculator offers the following key features:

- **Multiple heat indices**: The component computes a range of indices that address various aspects of urban heat, including human discomfort, thermal heterogeneity, and the intensity of the urban heat island effect.
- **Customizable analysis areas**: Users can input bounding boxes for specific areas of interest, allowing for tailored analysis within specific urban or regional boundaries.
- **Integration with reanalysis data**: By incorporating relative humidity data, the Index Calculator provides a more nuanced understanding of thermal comfort and environmental conditions.

Methodology

The Index Calculator processes the input data to calculate the following key indices:

- **Discomfort Index (DI):** This index is computed using a combination of surface temperature and relative humidity. It quantifies the impact of both heat and humidity on human comfort, with higher values indicating greater discomfort.
- **Surface Urban Heat Island (SUHI)**: The SUHI index measures the temperature difference between urban and rural areas. It is calculated by comparing LST values within urban

bounding boxes with those in surrounding rural areas, revealing how urbanization impacts surface temperatures.

- **Urban Thermal Field Variance Index (UTFVI)**: This index assesses the variability of surface temperatures within urban areas. It highlights the thermal heterogeneity caused by different land uses and surface materials, providing a spatially detailed view of heat distribution within cities.
- **Urban Heat Island Intensity Index (UHIII)**: The UHIII measures the intensity of the urban heat island effect by calculating the temperature difference between urban cores and rural peripheries. This index helps identify areas most affected by urban heat and informs potential mitigation strategies.
- **Urban Hot Spots (UHS):** This index identifies specific areas within cities that exhibit significantly higher surface temperatures compared to their surroundings. These "hot spots" are often linked to high levels of impervious surfaces, limited vegetation, and concentrated human activities. Identifying such zones is critical for targeted interventions.
- **Surface Temperature (LST):** Although LST is used as an input, it is also provided as a direct output to offer a comprehensive view of the thermal state of various surfaces, such as vegetation, water bodies, and urban areas.

Application potential

The Index Calculator is a valuable tool for urban planners, environmental agencies, and researchers interested in understanding and mitigating the effects of urban heat. The calculated indices are applicable in a variety of contexts:

- **Urban heat mitigation**: By identifying heat islands and hot spots, city planners can design targeted interventions, such as increasing vegetation or improving urban design to reduce surface temperatures.
- **Climate resilience**: The ability to monitor and quantify heat patterns enables cities to develop strategies to cope with rising temperatures, improving overall climate resilience.
- **Public health**: The Discomfort Index helps identify areas where extreme heat may pose a risk to human health, guiding public health responses during heatwaves.

Main achievements

Successful calculation of multiple heat-related indices across the entire sharpened LST data time series stored in the data warehouse. These indices provide valuable insights for decision-makers and the general public, enabling them to make informed decisions regarding urban heat management and mitigation. The generated indices offer a comprehensive understanding of urban thermal dynamics, supporting actions to reduce the impacts of heat on city environments and improve overall liveability.

2.3.4 EO-based Heat Island Simulation and Mitigation Strategies Service Engine

The “EO-based Heat Island Simulation and Mitigation Strategies Service” offers a simulation tool to estimate and visualize the impact of changes in the urban landscape on urban heat patterns as indicated by the land surface temperature (LST). The tool is able to provide a fast and initial overview of the direct effects of future construction projects before they are realized. Multiple options can easily be evaluated as it is needed by city administrations or the interested public. Since the tool is based on EO data only, its advantages are a short runtime and a low effort of implementation for any city worldwide. This is in contrary to the simulation tool applying the UltraHD weather model simulations (UHD Heat Island Simulation Service, see D3.4).

Data sources:

- **Landsat 8 and 9 land surface temperature products:** LST acquired on 100m and delivered as product on 30m spatial resolution. Available every 8 days.
- **Sentinel-2 optical data:** High spatial resolution and high quality multispectral data used to calculate Normalized Difference Built-up Index and Normalized Difference Vegetation index.

The indices are indicators for the degree of sealed surface and the vegetation greenness and used to describe the urban landscape. Available every 10 days.

- **ESA Worldcover:** Global land cover classification product provided annually on 10m spatial resolution. Basis for the calculation of distance layers (distance to water, distance to vegetation) for including the cooling effect of water and vegetation.
- **Digital elevation models:** Information on a city's height structure most often existing as proprietary datasets is used to derive indicators on the 3D urban morphology (e.g., building height index, building roof index).

Key features:

- Evaluation of user-defined changes in urban heat upon changes in urban configuration under average and extreme summer day conditions of the last years (2021-2024)
- Possible land uses: built-up (when 3D information is included also building heights), vegetation, water
- Immediate prediction of LST for new configuration

Methodology

The input data for this tool were pre-processed by the Spaceborne Data Pre-Processor and are available on the GCCP Data Warehouse. Within the tool, an additional mask for the city centre is applied. The EO-HISMSS engine is only run for **specific points in time**: (1) a **typical summer day** representing average summer conditions (selected based on the median LST value among the available summer month LST data), and (2) an **extreme summer day** to represent extreme hot weather conditions within a city (selected based on the maximum scene mean LST value among the available data). These two options are considered for each year of 2021-2024. For each dataset, a machine learning model is set up linking the satellite LST measurements to a number of layers characterizing the urban land surface which are derived from optical satellite data (vegetation and built-up indices, distances to vegetation and water) and the 3D structure of the city when available. We use a fully connected neural network. The model is calibrated for he typical/extreme summer days and stored along with the datasets on the GCCP Data Warehouse. When a user draws and submits a scenario, the layers describing the urban land surface are modified according to the user-defined changes (e.g., average vegetation index is assigned upon change to vegetation, height or dimension of buildings is modified) and the calibrated prediction models are used to calculate a new LST layer. For output, the predicted LST layer is resampled to 30m spatial resolution and the results are depicted in the service GUI. The workflow of this engine underlining the "EO-based Heat Island Simulation and Mitigation Strategies Service" from a users' perspective is presented step by step in D6.4.

Application potential

- The engine and service were developed to support practitioners, i.e. city administrations, in assessing and implementing urban heat mitigation options (e.g. planting trees, building constructions). The tool can also be valuable for the interested public as information and to enhance the understanding of urban heat patterns and the immediate effects of changes in the urban landscape on the urban heat distribution.
- The engine is an easy-to-use tool answering requests within seconds to minutes. Its requirements for data storage and processing are low. The usage of standard EO data allows for an easy transfer to new cities.
- From a methodological point of view, the engine can be extended by including further layers which describe the urban landscape and have a relationship with urban heat and by extending the options within the engine (e.g., separate consideration of grass and tree vegetation).

Validation and key metrics:

- **Performance evaluation:** Assessed using metrics like the correlation coefficient (R^2) specifying the ability of the model to predict LST from urban characteristics and the Root Mean Square Error (RMSE) specifying the mean deviation of predicted from observed LST values.
- **Accuracy:** For three of CityCLIM's pilot cities and multiple observation times, the performance of the engine is very stable. Average R^2 is about 0.68 and RMSE around 0.56 K.
- **Regional Variations:** The models developed to simulate Land Surface Temperature (LST) changes for the Central Macedonia region showed lower performance, with R^2 values ranging from 0.34 to 0.46 and RMSE between 0.73 and 0.82 K. This lower accuracy is primarily due to the presence of certain areas where the temperature behaves in ways that differ from the expected patterns, such as artificial soccer fields, which tend to have unusual temperature dynamics. These areas skew the model's predictions, reducing overall performance.

Main achievements

We successfully created a modelling workflow predicting LST from urban optical satellite data which is of sufficient quality to be used in an operational service. The service which is based on this is an easy-to-use tool for assessing the effect of changes in the urban configuration on urban heat intended to be used by practitioners from city administrations and the interested public. It can be used to simulate an unlimited number of scenarios. Figure illustrates an example for Valencia and Figure for the CityCLIM pilot Karlsruhe. Because it applies EO data in combination with machine learning, its computational demand is low and it is suited to be transferred to other cities with a low effort.

Figure 8. Example for performance of the EO-based Heat Island Simulation and Mitigation Strategies Service Engine. Sealing the municipal park Jardins del Real in Valencia, Spain, leads to an increase of about 4.4 °C over the modified areas. The simulation was done for the extreme summer day of 2023 (model R^2 of 0.57, RMSE of 0.66K).

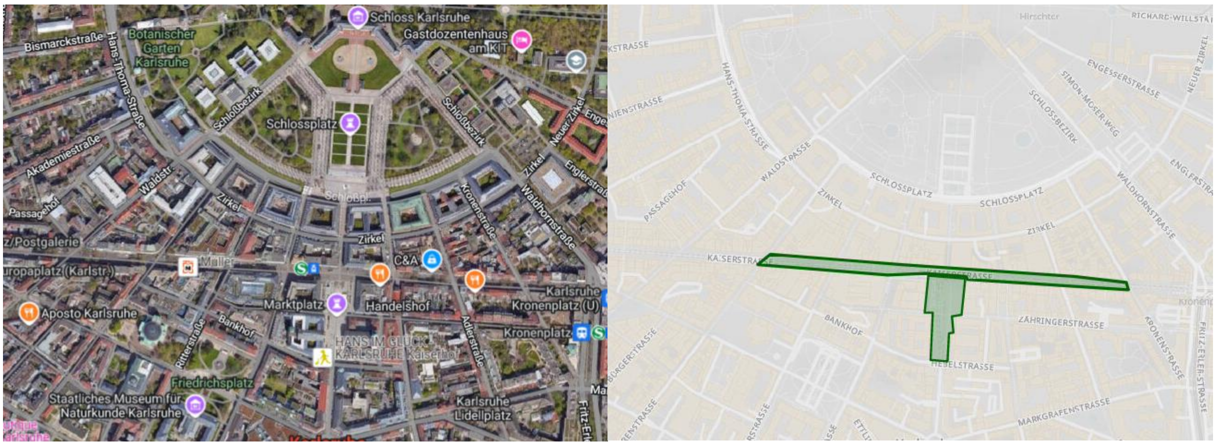


Figure 9. Example for performance of the EO-based Heat Island Simulation and Mitigation Strategies Service Engine. Greening the pedestrian zones at Marktplatz and Kaiserallee in Karlsruhe, Germany, as very hot areas within the city area would reduce the LST in these areas by more than 4°C over the modified areas. The simulation was done for the extreme summer day of 2023 (model R^2 of 0.67, RMSE of 0.58K).

3 Conclusions

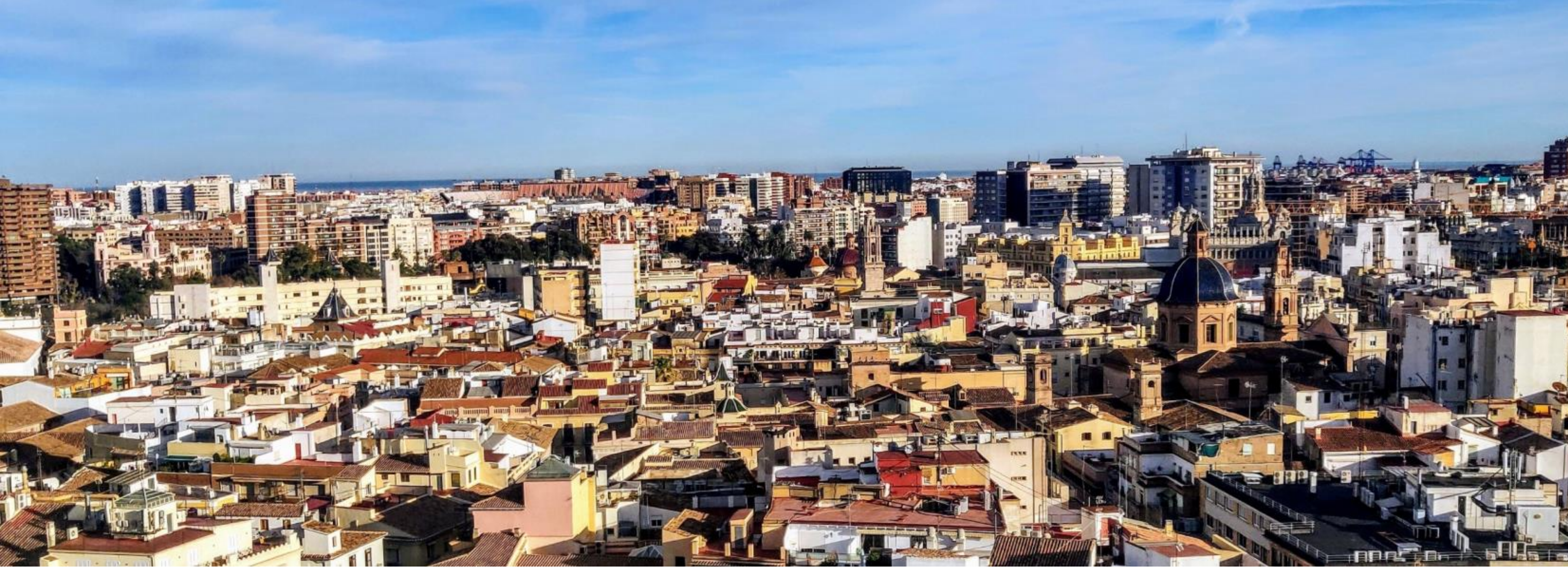
This deliverable demonstrates the successful development and integration of key data processing components that form the backbone of CityCLIM's urban heat monitoring and mitigation services. The combined infrastructure enables accurate, reliable, and scalable urban heat analyses that can support city administrations and decision-makers in developing data-driven strategies for mitigating the effects of urban heat islands.

The **In-Situ Data Processor** has effectively streamlined the collection, validation, and standardization of data from various terrestrial sensor networks and portable weather stations across pilot cities. This ensures that environmental and atmospheric data are continuously available, serving as a foundation for further analysis, including weather models and other applications within the CityCLIM platform. Its design facilitates seamless communication between in-situ sensors and the Data Warehouse, ensuring the timely and consistent storage of high-quality data.

The **Airborne Data Processor** plays a crucial role in preparing thermal and optical imagery captured by aerial platforms equipped with multiband radiometric cameras. This processor executes all necessary steps, from georeferencing and orthorectification to radiometric processing using a Temperature Emissivity Separation (TES) algorithm, which enables the generation of accurate Land Surface Temperature (LST) mosaics from airborne data. This allows for high-resolution mapping of temperature variations at a finer scale than what is achievable through satellite-based systems, making it particularly valuable for detailed urban heat studies.

The **Spaceborne Data Processor** integrates several components to handle satellite data efficiently, transforming raw satellite observations into actionable information. This includes the preprocessing of Sentinel and Landsat data, the Thermal Sharpener, which enhances the spatial and temporal resolution of satellite-derived LST, and the Index Calculator, which computes several key heat-related indices such as the Discomfort Index (DI), Surface Urban Heat Island (SUHI), and Urban Hot Spots. These indices provide critical insights into the thermal dynamics of urban environments and support urban planners and decision-makers in making informed choices about heat mitigation strategies. Finally, the EO-Based Heat Island Simulation and Mitigation Strategies Service (EO-HISMSS) Engine leverages these data to simulate the impact of urban planning decisions on future temperature patterns, offering an accessible tool for scenario-based evaluations of urban heat management strategies.

Together, these processors form a comprehensive and integrated data framework that enhances the CityCLIM platform's capability to assess, monitor, and simulate urban heat phenomena. The system's scalability and transferability ensure that it can be adapted for use in a wide variety of cities with minimal effort, making it a valuable tool for urban climate resilience planning worldwide. By providing high-quality, timely, and actionable data, CityCLIM's data processing infrastructure enables city administrations to effectively address the challenges posed by rising urban temperatures and climate change.



About CityCLIM

The strategic objective of CityCLIM is to significantly contribute to delivering the next-generation of City Climate Services based on advanced weather forecast models enhanced with data both from existing, but insufficiently used, sources and emerging data sources, such as satellite data (e.g., Copernicus data) or data generated by Citizens Science approaches for Urban Climate Monitoring etc. For City Climate Services, data products of interest related to land surface properties, atmospheric properties (e.g., aerosol optical thickness), geometry etc. For all of those, information of interest concerns e.g., Copernicus data products and services that are already existing (e.g., based on Sentinel-3/OLCI, PROBA-V, SPOT, Sentinel-1, MetopASCAT data), will exist in the near future (based on already flying satellites such as Sentinel-2), or will exist in the mid-term (based on satellites currently under development) and long-term (based on satellites soon starting concept phase) future. The project will establish; (i) an open platform allowing for efficient building of services based on access to diverse data; (ii) enhanced weather models based on data from diverse existing and emerging sources; (iii) a set of City Climate Services customizable to specific needs of users in cities; and (iv) a generic Framework for building next generation of Urban Climate Services. CityCLIM will be driven by 4 Pilots addressing diverse climate regions in Europe (Luxembourg, Thessaloniki, Valencia, Karlsruhe) which will define requirements upon the tools to be developed, support specification and testing of the services and serve as demonstrators of the selected approaches and the developed technologies. The consortium will elaborate business plan to assure sustainability of the platform and services.

Funded by the Horizon 2020 Framework Programme of the European Union