

## Master Thesis

# Improving the Availability of Contextual Data with Machine Learning-Based Interpolation

**Ian Maurice Buck**

---

ian.buck@studium.uni-hamburg.de  
Study Program Information Systems  
Matr.-Nr. 6911467

First Reviewer: Prof. Dr. Janick Edinger  
Second Reviewer: Philipp Kisters

Submission Deadline: 03.09.2023

A distributed system is one where the failure of some  
computer I've never heard of can keep me from getting my work done.  
– *Leslie Lamport*

# Abstract

Many science-based applications need continuous or gridded input data in order to work properly. This paper investigates how single data-points can be combined to create a continuous data layer, in which missing data points are interpolated. An example for such an application would be the prediction of temperatures coming from single sensors and weather-stations, that can be combined to detect Urban Heat Island (UHI)s. UHIs are weather phenomena that get amplified among other things by the ongoing densification of urban areas to create more living space, typically accompanied by the removal of green areas that can help with the dissipation of heat. These heat islands, in which the temperature is significantly higher than in surrounding areas, pose a threat to the health of the urban population, especially to the elderly, children and people with existing health conditions. Traditionally, UHIs are detected using Land Surface Temperatures (LST) captured by satellites, that usually have the downside of low spatial and temporal density. This paper proposes an alternative approach by creating a machine-learning model that is able to interpolate missing data between data-points coming from citizen-owned sensor networks that are combined with mobile sensors, which can be attached to rental bikes, buses or e-scooters, to gain temporary insights into otherwise unobserved areas. The model combines data streams of sensor readings with historic data and creates a fine-granular continuous data-layer, in this case for temperature, which allows for an accurate localization of UHIs.



# Table of Contents

<b>List of Figures</b>	<b>v</b>
<b>List of Tables</b>	<b>vii</b>
<b>List of Abbreviations</b>	<b>ix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Objective . . . . .	2
1.2 Structure of this work . . . . .	4
<b>2 Related Work</b>	<b>5</b>
2.1 Urban Heat Islands (UHI) . . . . .	5
2.1.1 UHI Classification . . . . .	5
2.1.2 Surface Urban Heat Island (SUHI) . . . . .	8
2.1.3 Canopy Urban Heat Island (CUHI) . . . . .	8
2.2 Smart Cities . . . . .	9
2.2.1 System Architecture . . . . .	10
2.2.2 Architecture Layers . . . . .	11
2.2.3 Smart City Case Studies . . . . .	13
2.3 Sensing Applications . . . . .	14
2.3.1 Remote Sensing . . . . .	14
2.4 Interpolation of Missing Data . . . . .	15
2.4.1 Regression Analysis in Statistics . . . . .	16
2.4.2 Interpolation in Geostatistics . . . . .	16
2.4.3 Applications for Machine-Learning . . . . .	16
<b>3 Machine Learning-based Interpolation</b>	<b>17</b>
3.1 Machine-Learning Application Areas in Air Temperarture Interpolation .	17
3.2 Model Selection Criteria . . . . .	18
3.3 Comparison of Machine Learning Algorithms . . . . .	22
3.3.1 (Multi) Linear Regression . . . . .	22
3.3.2 KNN Regression . . . . .	22
3.3.3 Regression Trees and Random Forests . . . . .	23
3.3.4 Support Vector Machine Regression . . . . .	24
3.3.5 Neural Networks . . . . .	25

---

3.4	Feature Engineering . . . . .	25
3.4.1	Spatial Autocorrelation . . . . .	26
3.4.2	Temporal Autocorrelation . . . . .	27
3.4.3	Temporal Cross Correlation . . . . .	27
3.4.4	Dealing with Correlation . . . . .	27
3.4.5	Dealing with Uncertainty . . . . .	27
3.4.6	Evaluation Metrics . . . . .	28
3.5	Model Selection . . . . .	28
3.6	Machine Learning in Geostatistics . . . . .	28
3.7	Additional Considerations . . . . .	29
<b>4</b>	<b>Preparation of Datasets</b>	<b>31</b>
4.1	Private Weather Station Network Providers . . . . .	32
4.1.1	Sensor.Community . . . . .	32
4.1.2	Netatmo . . . . .	34
4.1.3	Other Providers . . . . .	37
4.2	Reference Data Providers . . . . .	37
4.2.1	DWD . . . . .	38
4.2.2	Locally Operated Weather Stations . . . . .	39
4.3	Quality Control . . . . .	40
4.3.1	Quality Control for Sensor.Community . . . . .	41
4.4	Feature Engineering . . . . .	41
<b>5</b>	<b>Evaluation</b>	<b>47</b>
5.1	Identifying Sensors for Evaluation . . . . .	47
5.1.1	Stuttgart . . . . .	48
5.2	Geostatistical Interpolation Comparison . . . . .	48
5.3	Model Evaluation . . . . .	50
5.3.1	Model Validity . . . . .	50
5.4	Variable Importance . . . . .	50
5.5	Uncertainty Analysis . . . . .	50
<b>6</b>	<b>Conclusion</b>	<b>53</b>
6.1	Summary . . . . .	53
6.2	Future Outlook . . . . .	54
<b>Bibliography</b>		<b>xi</b>
<b>Sensor Community</b>		<b>xxi</b>
<b>Eidesstattliche Versicherung</b>		<b>xxv</b>

---

# List of Figures

2.1	Mesoscale view of the urban climate, redrawn from [Oke06] . . . . .	6
2.2	Localscale view of the urban climate, redrawn from [Oke06], (Todo finish)	6
2.3	Microscale view of the urban climate, redrawn from [Oke06], (Todo) . . .	7
2.4	In the data layer (left), a wide variety of environmental data is collected with the help of multiple sensors. These are connected to their citizen-owned local base stations, which manage access rights and forward collected data to subscribed services (right) via the decentralized publish-subscribe in the network layer (center). . . . .	11
4.1	Temperature map from Sensor Community for Hamburg, Germany, on 22.06.2023 12:51h with the DWD reference at 25°C . . . . .	33
4.2	Temperature outlier from Sensor Community for Hamburg, Germany, on 22.06.2023 12:51h with the DWD reference at 25°C . . . . .	33
4.3	Sensor locations of Sensor Community in Germany, as of 01.05.2023, of sensor type DHT22 (2590 sensors), BME280 (1558 sensors), BMP280 (100 sensors), BMP180 (72 sensors) . . . . .	34
4.4	Sensor locations of Netatmo in Hamburg, Germany, as of 28.06.2023 . . . .	36
4.5	Sensor locations of Netatmo in Stuttgart, Germany, as of 19.06.2023 . . . .	36
4.6	Temperature sensor locations from WOW, accessed on 05.07.2023 . . . .	37
4.7	DWD Weather Station Locations in Germany, <a href="https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/subdaily/standard_format/KL_Standardformate_Beschreibung_Stationen.txt">https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/subdaily/standard_format/KL_Standardformate_Beschreibung_Stationen.txt</a> , accessed 28.06.2023 . . . . .	39
4.8	QC Results for Sensor.Community Data for Germany, January 2023 . . . .	43
4.9	QC Results for Sensor.Community Data for Germany, June 2023 . . . . .	44
5.1	Locations for Sensor.Community around Stuttgart, Germany, June 2023 . .	51
5.2	Locations for Sensor.Community in Hamburg, Germany, June 2023 . . . .	51
5.3	Locations for Sensor.Community around Stuttgart, Germany, June 2023 . .	52
5.4	Daily Mean, Max, and Min Air Temperature at 2m in Stuttgart, Germany, June 2023, DWD Station 4931 . . . . .	52



# List of Tables

4.1	Netatmo Sensor Specifications (Vendor reported) . . . . .	35
4.2	Quality Control Steps of CrowdQC+ . . . . .	42



## List of Abbreviations

LST . . . . . Land Surface Temperatures

UHI . . . . . Urban Heat Island



# 1 Introduction

In 2023 56% of the human population already lives in urban areas with the number projected to continuously increase to 68% by 2050<sup>1</sup>. Combined with the ongoing climate change and urban densification due to the need for more and more living space, cities are facing many new challenges. With the removal of vegetation in favor of living space and the sealing of surfaces with heat-absorbing materials such as asphalt or concrete for streets and highways [GRGTDW20], rising temperatures lead to new phenomena that pose risks for the urban citizens. One especially critical phenomenon is the urban heat-island (UHI). A UHI is a local occurrence of higher temperatures than surrounding rural areas that pose health risks, especially for the elderly, children or citizen with prior health-issues [MBG15], pedestrians comfort, and other city-related topics such as water- and energy-management. The research topic of UHI's has seen a huge amount of contributions in the last two decades, but according to Steward, *controlled measurement* and *openness of method* are still two mayor areas of weakness [Ste11], that are related to difficulties in taking measurements in urban areas [Oke06] and a lack of rigorous methodology. There are two mayor approaches to measure the temperature of a city. The first approach is to use satellites to measure Land Surface Temperature (LST). While allowing for an analysis of large areas without the need of ground weather-stations, this approach comes with certain downsides, such as low temporal and spatial resolution and restrictions such as only being able to measure temperatures when no clouds interfere with the microwaves send from the measuring satellite [ZPL15]. The exact spatial and temporal resolution depends on the type of satellite used, with usual spatial resolutions ranging from 1km<sup>2</sup> to 5km<sup>2</sup> and usual temporal resolutions ranging from daily to monthly temperature values [GVP], however these resolutions are not enough to capture the micro-climate of a city [VS17].

In comparison, traditional meterological observation networks, such as the German Weather Service (DWD), offer a much higher temporal resolution at 10min intervals through the use of ground weather stations, however they are usually only available at very low spatial resolutions, as they are used to monitor the climate at a meso-scale level. Additionally, the placement of these stations is usually not optimized for the detection of UHI's, as they are commonly placed near to airports that are not located directly in the city center. They can however be used as reference stations to get an idea about the boundaries of the climate inside a city as they offer high quality data by using high quality reference

---

<sup>1</sup><https://ourworldindata.org/urbanization#by-2050-more-than-two-thirds-of-the-world-will-live-in-urban-areas>

sensors and follow WHO guidelines [Oke06].

Lastly, there is the possibility of deploying sensor networks to closely monitor the climate of the city. These sensor networks can either be deployed professionally by the city itself or research projects for a limited time period, in that case called testbeds, or they can be deployed by citizens themselves, in that case called citizen-owned sensor networks or private weather station networks (PWS) in the case of crowd-sensing meteorological data. Well-known examples of professionally setup testbeds include the Birmingham Urban Climate Laboratory (BUCL) [CMY<sup>+</sup>15] and the Helsinki Testbed [KPS<sup>+</sup>11] that usually focus on measuring meso-scale weather phenomena and are very costly to run and maintain. PWS networks can either be run by citizens themselves, such as the Sensor.Community<sup>2</sup> project, or by companies, such as Netatmo<sup>3</sup>, however citizens are always responsible for the placement and maintenance of the individual sensors. Due to the lack of quality control, the data quality of these networks is usually not as high as the data quality of professional networks and require special data quality control (QC) steps [FBD<sup>+</sup>21, MFG<sup>+</sup>17], however they offer a much higher spatial resolution and can be used to gain insights into the microclimate of a city. Recently, there have been efforts to combine the data from PWS networks, mainly from Netatmo, Wundermap, and Weather Underground, with data from national weather services, such as the DWD, to improve weather prediction quality. The main collaboration network in this area is EUMETNET which includes 31 european national meteorological services [HGMS<sup>+</sup>22].

While these different approaches offer different advantages and disadvantages of measuring air temperature (TA) on the ground, they all have one thing in common: they only offer point measurements of the temperature at the location of the sensor. To get an overview of the temperature distribution across a city, interpolation methods are needed to create a continuous data-layer from the point measurements.

## 1.1 Objective

As research realted activities commonly rely on continuous or gridded data fields, there needs to be a way to convert these single data points from the different sensors into a continuous data-layer.

In this paper, we propose a solution to this problem by training a machine learning regression model, that allows for the interpolation of missing data-points. Based on sensor readings, from the sensor networks and mobile sensors, of commonly collected weather information, such as temperature, humidity, rain, pressure, wind, and possibly other variables such as vegetation indexes [AR20], the model then creates a continuous data-layer that allows for a holistic view of the observed variable, in this case temperature.

---

<sup>2</sup><https://deutschland.maps.sensor.community/>

<sup>3</sup><https://weathermap.netatmo.com/>

current situation: abundance of data (data quality unknown), but different data sources at different places with different formats, making it hard to work with different sources at the same time - smart city example -> heat island detection - sensor networks (stationary + mobile) - LST satellite data (lack of spatiotemporal resolution, not suited for micro-climate) - vegetation indexes (in geoinformation systems/portals) - etc. - currently these sources are used independently from each other, but how can they be integrated? - hybrid approaches have shown that combining different approaches (smart city stationary + moving sensors) to give better prediction quality than singular approach (reasons: unobserved areas) - statistical models offer not enough flexibility/are too cumbersome to work with (and probabilities are not known) - ML is a good fit to analyse patterns and rules - but effort to retrain models for each application expensive - how can ML be used to integrate the different types of data? - how can data availability of contextual data be improved by leveraging ML approaches for different topics? - for the heat map detection, what you need is a fine-granular temperature map, that allows for outlier detection - either train your own model on a huge dataset - or access a temperature map -> this will be discussed, how to use ML for this and improve data availability by using interpolation - additional topics to briefly discuss (mainly apply by implementing ML models) - what work needs to be done before using the data in ML (preprocessing, transformation, outlier detection etc.) - one way of preparing data is to interpolate missing data to create continuous gridded features (focus of this work) - how ML can we improve the interpolation quality of features? -> turn sparse features into denser versions with interpolation, interpolation based on other features present

## Methodology

In order to validate these things, we need high quality data-sets with many different features, but there are not many available, even though for certain things (atmosphere etc.) there are OpenData sets available. Goal is: implement a temperature map based on ML that interpolates missing data based on historical and current data. Compare prediction quality of different type of models (DL, random forests etc.) based on cross-validation (simulate missing data by leaving data points out on purpose) -> experiment with different intervals, densities etc. -> could also compare to Kriging (as a typical geostatistical approach for temperature interpolation) Subgoal: In order to achieve this, we also need high quality data-sets to train and validate the model -> source them from OpenData platforms

Forschungsfragen: - Which machine learning-based interpolation methods are available and how do they differ from each other? - How can machine learning-based interpolation methods be used in the context of UHI detection and how do they perform compared to each other?

---

## 1.2 Structure of this work

Research methods:

- literature research as foundation
- heat island detection - smart cities -> sensor networks vs LST - what type of other data is available? geoinformation, vegetation, for micro-climate: shades of bigger buildings?
- - prototyping
- implement pipeline to pre-process different types of data
- feature extraction
- implement ML model
- deploy ML model
  
- create/search for fine granular data sets
- add new contextual data to existing data sets
- discuss different types of data (gridded vs continuous vs data points) and methods for each
- train ML models with different methods (deep learning, random forests etc.) and different features enabled
  
- cross validation of results
- discuss validation techniques and indicators (RMSE, MSE)

The rest of the thesis is structured as follows. Chapter 2 begins with an analysis of related work, where important literature is discussed, that forms the foundation of this research. In chapter 2.2.1, the focus lies on describing the service architecture, that shows how a machine learning model can be deployed in different contexts to improve data availability. Which machine learning approaches can be used to interpolate missing data and how they differ from each other is discussed in chapter 3. In Chapter 5, the different ML approaches are compared and cross validated with each other based on the different model that are trained on the obtained data-sets. Finally, chapter 6 discusses the findings of this thesis and gives an outlook into future work and research directions.

---

## 2 Related Work

Before we can start to investigate the usage of machine-learning based interpolation techniques in the context of urban climate data, we first need to understand what UHIs are and how they can be classified and detected in order to define requirements for the ML models later on. Especially in the context of smart cities with new possibilities such as sensor networks, we need to understand how urban climate data can be collected and what challenges arise such as spatial and temporal data availability, data quality and more. Due to the complexity of the urban climate [Oke06], special domain knowledge is needed to understand the data and the underlying processes. Finally, we need to get an understanding of existing interpolation techniques, traditionally in the form of regression analyses or in the context of climate data, geostatistical models, in order to define a baseline for the evaluation of ML-based models.

### 2.1 Urban Heat Islands (UHI)

UHIs have been the center of a lot of attention for quite some time in the scientific community. As early as 1833, with the research of Luke Howard in London which observed higher temperatures inside London than in surrounding areas [How33], UHIs have seen a steadily increase in scientific contributions. The term *Urban Heat Island* was first introduced in the 1940s [BP47]. The recording and investigation of UHIs has seen major steps since the begin of modern climatology, also known as the Sundborg's era beginning with Sundborg's 1951 classic heat island study of Uppsala [Sun51]. UHIs occur in many cities around the globe [PPC<sup>+</sup>12] in different climatic zones, during different times of day and in different intensities.

UHIs are so important, because heat related deaths are rising across the globe [KH08] and extreme heat waves are projected to occur more often and extreme with the ongoing climate change [LSF19]. Heat also has significant impact on human performance [KBF<sup>+</sup>16], mental health [OMPR18], or might disrupt sleep [OMMF17] and causes other issues such as overheating that causes urban infrastructure to fail, decreased air quality and low outdoor thermal comfort levels [SJVL<sup>+</sup>13].

#### 2.1.1 UHI Classification

UHIs can be classified in many different ways. Typically, there is a horizontal classification, defining the superficial extension of the UHI from micro-, to local- to meso-scale,

---

and a vertical classification, defining in which vertical layer of the urban area the heat island is observed. To better understand these scales and the anatomy of the planetary/urban boundary layer, figures 2.1, 2.2, and 2.3 show a detailed view of the meso-, local- and micro-scale of the urban climate respectively, as illustrated by Oke 2006 [Oke06].

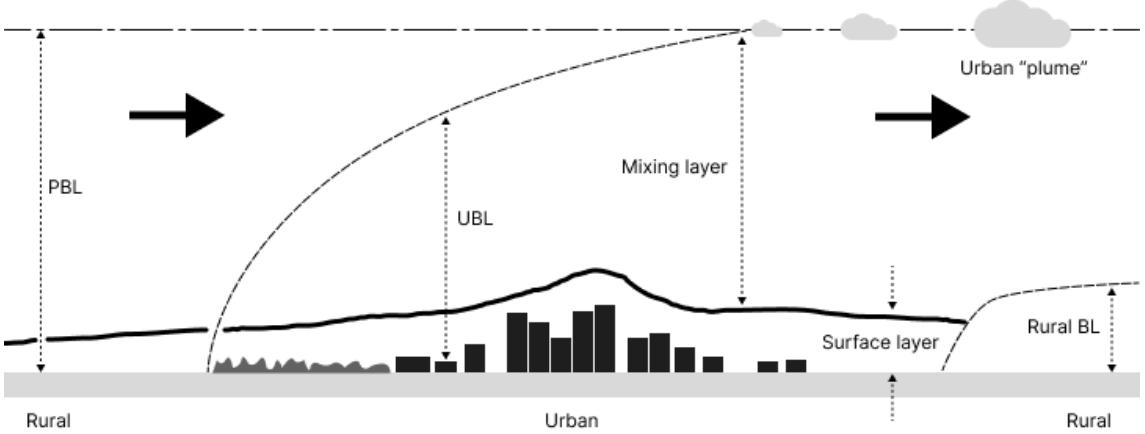


Figure 2.1: Mesoscale view of the urban climate, redrawn from [Oke06]

The mesoscale, as depicted in Fig 2.1, spans the whole urban environment of a city, typically tens of kilometres. There are several boundary layers, that comprise different scales. The planetary boundary layer (PBL) [Wyn85] is the lowest layer of the Earth's atmosphere and spans from the surface to a height of several hundred meters up to several kilometers. It is characterised by the turbulent mixing of air, forming wind currents, that are mainly influenced by the underlying surface.

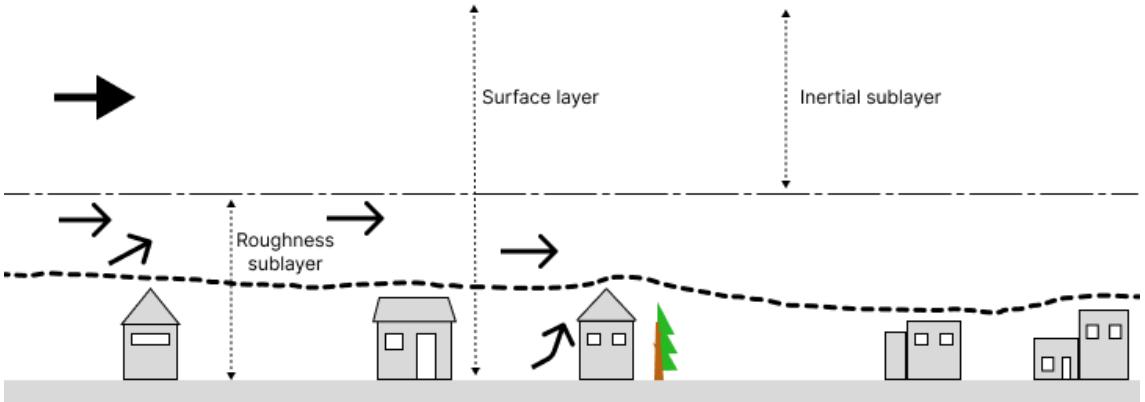


Figure 2.2: Localscale view of the urban climate, redrawn from [Oke06], (Todo finish)

The localscale is situated closer to the surface and contains landscape features such as topography, but does not yet include microscale effects. At this layer, the underlying microclimatic effects in form of fluxes mix together to form a more average and representative view of the source area, typically at the scale of one to several kilometers. This

layer is monitored by weather stations that are located at/or slightly above the canopy height.

### c) Microscale

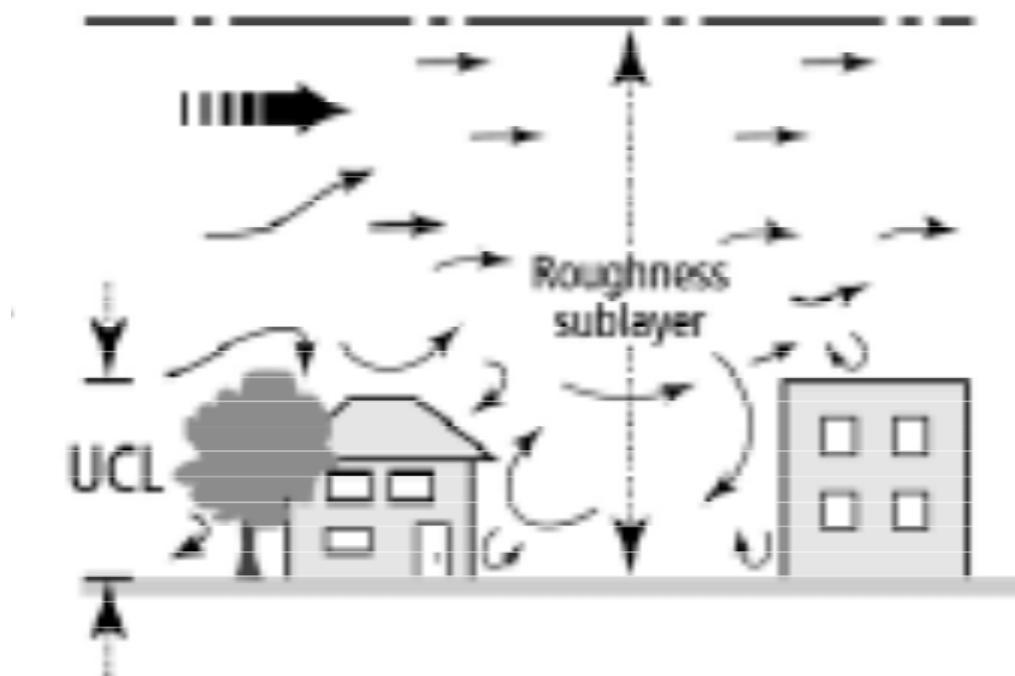


Figure 2.3: Microscale view of the urban climate, redrawn from [Oke06], (Todo)

The microscale usually ranges from a neighborhood scale to individual street canyons or even microclimates created by individual buildings. It is mainly influenced by the overall energy balance, which is influenced by cloud coverage, solar radiation and more. Single weather stations are not enough to capture the complex microscale [Oke04], therefore a dense network of sensors closer to the ground is needed to capture the microscale. Additionally, the microclimate is influenced by surface temperature (LST), however the correlation between air and surface temperature varies greatly based on other surrounding influences such as wind velocity or humidity [SB92], especially in cases of extreme temperatures [Goo16]. The closer the air temperature is measured to the surface, the more local the measurement, therefore air temperature of the canopy is usually measured at 2m height, so the different energy fluxes have enough time to mix together and form a more representative average for a bigger area.

Vertically UHIs can be divided based on these boundary layers into three major types [Oke76, OMCV17], namely Boundary Layer Heat Island (BLUHI), Canopy Urban Heat Island (CUHI) and Surface Urban Heat Islands (SUHI), corresponding to the boundary layer they can be measured in.

Another differentiating factor is the time of day at which UHIs get detected. For example Steward [Ste11] in his review focussed on night time UHIs, whereas Peng et al. [PPC<sup>+</sup>12] focussed on both day and night time UHIs.

### 2.1.2 Surface Urban Heat Island (SUHI)

The land surface temperature (LST) is measured directly at the surface of an object and is the main indicator of the surface urban heat island (SUHI). Surface temperature, in contrast to air temperature, is measured via remote sensing technologies via satellites. Well-known satellites include MODIS [Did21] (NASA), Sentinel 3 (ESA), Meteosat (EU-METSAT), Landsat, and more. The different satellite types carry different types of instruments and sensors, that are able to take various measurements. The used sensor has a major influence on the quality of data, e.g. resolution via pixel size, robustness against atmospheric influences, ability to handle clouds and more. In section 4.4 we discuss other features next to LST that are available via satellite data.

Through the use of satellites, the spatial coverage is great, but raster sizes usually range from one kilometer to a hundred, therefore the spatial resolution is not as high. Additionally, these satellites usually orbit earth to cover wide areas and are not geostationary, therefore only taking measurements a maximum of 1 to 2 times a day, up to every 16 days or even only once a month, depending on the orbit. As a result, the temporal resolution is quite low and especially in the case of UHI detection, this could mean that the satellite misses the peak of the UHI for a given day or even misses the UHI completely. Another downside is the general inability to take LST measurements through clouds, therefore even if the satellite passes over during a UHI, if there are clouds the UHI cannot be measured. To alleviate the problem there are new methods such as estimating LST based on emitted radiation from clouds [ZPL15], however they also have their limitations. Lastly, LST and air temperature are not the same and can vary greatly, especially in extreme heat events [Goo16].

To conclude, SUHI analysis can be a good indicator that there is a UHI phenomenon present in a city and can generally direct further research, however it lacks the temporal resolution to be used for real-time UHI detection and is not able to capture microscale effects of the UHI [VO03, VS17].

### 2.1.3 Canopy Urban Heat Island (CUHI)

The canopy UHI is measured in the canopy boundary layer several meters above ground slightly below or on the average roof layer of the surrounding buildings, as seen in fig. 2.3. The primary measurement in the canopy is air temperature, which is used to measure the urban heat island intensity (UHII) [Oke73], the most commonly used way of describing the heat island magnitude [KB21].

Since the beginning of modern climatology, major progress has been made in this research field, but methodologies and scientific rigor in CUHI research still seems to be

---

lacking, as discussed by Stewart in 2011 [Ste11]. Stewart found, that over 54% of CUHI research was lacking proper methodologies or had other shortcomings such as a lack of site descriptions, where sensors were placed, or the disregard of non-urban factors such as local weather phenomena. In response, progress has been made in recent years by improving methodologies and ensuring correct measurements of climate-related data and study design and execution through various guidelines [Oke06], especially in urban settings, that require special care due to the huge amount of possible influences on local recording sites.

Additionally, the UHII is highly related to other climatic factors such as wind, cloud cover, and precipitation and is tightly linked to the selection of the recording site [FHM<sup>+</sup>19], therefore such factors need to be taken into account when measuring the UHII.

Compared to LST, TA is measured *in situ* via weather station networks or other types of sensor networks.

### Shared UHI Challenges

Some shared challenges are: 1. Define what *urban* means in the context of UHIs [SO09]. The term urban is widely used to identify areas that are more densely populated than the surrounding rural areas. Having this distinction between urban and rural [Low77] helped researchers to better define the UHI magnitude (cite), but this simple distinction also lead to problems [Ste11]. The problem lies in the fact that there is no clear border between urban and rural areas, but a fluent transition. Especially for larger metropolitan areas, like Tokyo, the urban area could span 10s to 100s of kilometers, making the collection of reference rural temperatures hard. The reference rural temperature has a direct influence on the UHI magnitude, which is ‘the most widely recognized indicator of city climate modification in the environmental sciences’ [SO09]. As a solution, different classification into local climate zones were proposed [SO12, SO09], that classify areas based on surface roughness, building densities, building heights etc. 2. Measuring the influence of other local urban or meteorological phenomena on the temperatures collected. The urban climate is extremely complex, due to many different influences, such as anthropological energy,... (cite, todo find the influence factors). Additionally, the urban climate is also influenced by surrounding regional/meso-scale climate phenomena such as storms, valleys, mountains, large waterbodies, coastlines and more (cite).

## 2.2 Smart Cities

The most generalised architecture of a smart city consists of four layers, the sensing layer, transmission layer, data management, and application layer [SKH18]. In this work, we focus on the sensing layer, dealing with topics such as correct sensor placement and underlying sensor footprints, and the application layer, which accesses available data via data management services to provide additional services to the city and its citizens. For

---

the data transmission and data management layers, there already exist different technologies and service offerings, that aim at solving the underlying problems, e.g. network bandwidth, network availability, sensor discoverability, handling the massive amounts of data that is already or will be collected in the future, and many more. For the communication and discovery of sensor nodes, one solution could be SkipNet [HDJ<sup>+</sup>02], an overlay network focused on discoverability while also protecting privacy, with which the data transportation layer could be designed as a peer-to-peer (P2P) network. Other research focuses on the data accessibility and discoverability, by making data accessible for everyone, not only for economic partners in a closed-off system. Examples would be the Smart Networks For Urban Citizen Participation (SANE) initiative [BJK<sup>+</sup>19], which... Figure 2.4 shows the architecture of the SANE system.

### **UHI Detection in the Context of Smart Cities**

Smart Cities are ‘urban areas that exploit operational data [...] to optimize the operation of city services’ [HEH<sup>+</sup>10], by collecting near-real-time data from physical and virtual sensors, integrating those data sources into an enterprise computing platform and performing complex analytics on them. With current urbanization trends (60% of ppl living in cities 2060) and the ongoing global and urban warming (cite), research into smart cities has gotten a lot of attention recently (cite). One of the driving factors behind smart cities is next to progress in digitisation of cities the availability of cheap smart sensors (cite), that enable a good spatiotemporal surveillance of factors in a smart city.

- goals and pillars - architecture - challenges
- classification of UHI detection into the smart city framework
- In the context of UHI detection,
  - testbeds, sensor networks (citizen owned)
  - cross over to pollution detection

#### **2.2.1 System Architecture**

The main goal of this work is to apply ML-based interpolation techniques to the topic of UHI detection to improve data availability and compare different interpolation techniques that are based on traditional (statistical) and ML-based approaches. ML-based models first of all need a lot of data to be trained and validated with, and after deployment need access to relevant real-time data, if near real-time capabilities are desired. In the context of smart city, such ML-based interpolation models could be used to improve data availability by interpolating missing/unavailable data such as LST readings under cloudy conditions, and be incorporated into a service that other services, like a UHI detection service, could further rely on, without the need to implement interpolation techniques themselves. This could reduce costs to develop such depending services, as they no longer need to deal with missing data themselves while also improving interpolation

results with well-trained and designed models. First, we need to take a look at how such a service fits into existing smart city architectures.

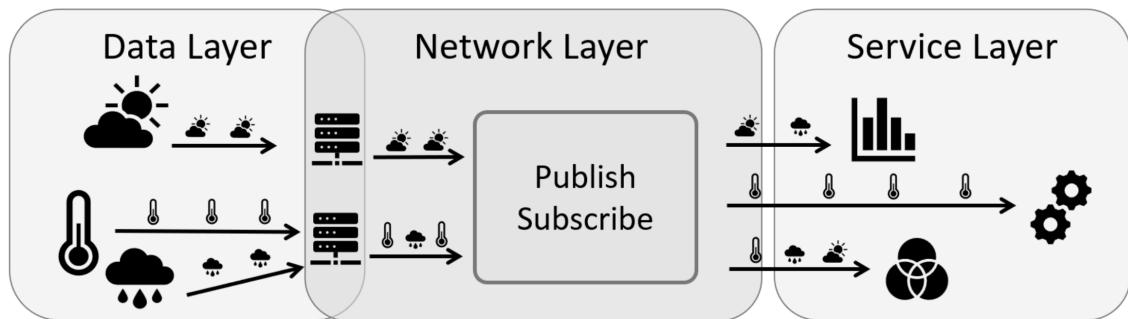


Figure 2.4: In the data layer (left), a wide variety of environmental data is collected with the help of multiple sensors. These are connected to their citizen-owned local base stations, which manage access rights and forward collected data to subscribed services (right) via the decentralized publish-subscribe in the network layer (center).

## 2.2.2 Architecture Layers

### Sensing Layer

The goal for the sensing layer is to monitor the surrounding environment and capture key data for further analysis and decision making. It consists of many different types of physical and virtual sensors. The first group of sensors are the physical sensors, which are placed directly inside the environment. Wireless sensor networks (WSN) [DP10] have seen a lot of attention for many different applications such as ‘military sensing, physical security, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing automation, distributed robotics, environment monitoring, and building and structures monitoring’ [CK03]. The challenges for WSNs primarily depend among other things on the deployment. An ad-hoc WSN has energy and bandwidth constraints due to the usage of batteries as power sources. In contrast, sensors that are permanently installed, either stationary or on a moving target, and connected to a constant power source don’t have this constraints. This approach could be used for smart cities to reduce waste and guarantee representative measurements via correct sensor placement. In the case of stationary sensor networks though, the initial deployment and following maintenance cost can be substantial [CMY<sup>+</sup>15].

In recent years, low-cost sensors (LCS) in combination with sensor networks have enabled fine-granular real-time monitoring of urban environments [Gri06, RGA<sup>+</sup>09], although the quality of individual low-cost sensors can be questionable [CDS<sup>+</sup>17]. In general, LCSs can improve data availability and support analysis, but do not substitute well-calibrated reference instrumentation [LPS18].

### Stationary Sensor Types

There are many different types of environmental features that can be measured directly inside an urban area. The types of measurements that can be observed are among others: air temperature, humidity, atmospheric pressure, reactive gaseous air pollutant (CO, NO<sub>x</sub>, O<sub>3</sub>, SO<sub>2</sub>), particulate matter (PM), greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>), precipitation, solar radiation, wind speed and direction, anthropogenic heat, noise, sky-view factor, heat fluxes and many more. Correlations between these features can vary greatly based on surrounding factors. In order to better understand these correlations, many empirical studies have studied the influence of meteorological factors on features such as PM [TMJ10]. Additionally, many fields of statistics have specialised on topics such as statistics in climatology [VSZ02], geostatistics [TYU86] and more.

All sensor readings that are taken by physical sensors are singular data points. Additionally to the type of measurement taken and the actual value observed, physical sensor readings include the physical location of the sensor, e.g. latitude, longitude and altitude, the type of sensor used to take the measurement, and the sampling rate. For air temperature, the sampling rate could be an average temperature measured over five minutes, whereas precipitation might be measured by collecting rain for certain periods of time and then measuring the amount of rain collected. The sensor type is important, as different types of sensors can produce different qualities of measurements, e.g. LCS compared to calibrated reference-grade high cost sensors, and perform better or worse based on the meteorological conditions, e.g. worse performance at low temperatures, high humidity etc. Due to the placement directly inside the environment, (near) real-time observation and high temporal resolution are generally possible, but might be influenced by factors such as network availability. The spatial resolution highly depends on the number of sensors deployed and the correct placement of the sensors. The correct placement has a direct influence on the footprint of the sensor [LF14] and the representativeness of the measurement taken for the underlying and surrounding area [Oke06].

One downside of the placement directly in the environment the sensors are observing, is the exposure to environmental influences such as heat, humidity, or pollution, that can decrease the lifetime of a sensor and may require more frequent maintenance or replacement.

- discussion premium vs low-cost sensors - discussion static data incorporation -> NDVI from geoportal via data management layer
- P2,5: highly depends on air flows - humidity: needs to be replaced more often due to pollution - temperature

### Mobile Sensor Types

- mobile Windmessungen mit einem SODAR - einem akustischen Windmesssystem -, Vergleichsmessungen an einer stationären Messstelle auf - Profilmessfahrten
-

### Modelling of the Sensing Layer

A model is an abstraction of the real world that helps us analyse and understand complex problems. In the context of UHI detection, we can use model climate on a bigger scale, or the micro-climate inside a city, to better understand and capture influences. In this work, we focus on ...

One major consideration in this context, what type of data is used to validate and train the ML models. The options in this case are either climate models which simulate data, or capturing/collecting real-world data. Due to the complexity and limitations of simulation, this work only focuses on collecting real-world data.

### Data Transportation Layer

### Data Management Layer

### Application Layer

The application layer contains services which utilize data provided by the data management layer to provide services for the city and its citizens. As part of this layer, services could be built that aggregate data streams coming from the data management layer and use ML to improve the data quality by detecting outliers, reducing bias, interpolating missing data etc. The improved data could then be published and other services that would otherwise rely on the raw data streams and potentially need to implement their own outlier detection or interpolation of missing data techniques, instead simply subscribe to the externally managed service. This could lower the barrier to entry for developers with less available resources, financially or domain-knowledge wise, and generally allow developers/service providers to allocate their resources to other areas like user experience (UX) and usability compared to the maintenance of complex ML-based services. In the context of this work, we focus on the topic of UHI detection. In this context, there could be a UHI detection service that ingests real-time data streams from the data management layer and notify citizens if an UHI is detected in or predicted for a particular urban area. As the main challenge for UHI detection lies, next to the definition of urban and rural reference areas, on the gathering of a comprehensive temperature map that allow UHI detection algorithms to work, in this work we primarily focus on creating and evaluating an air temperature map service, that enables the detection of CUHIs and could also be used as a foundation for other services in a smart city, like plant watering systems, smart healthcare and more.

### 2.2.3 Smart City Case Studies

Many European cities, like Amsterdam, Barcelona, London and Stockholm, have developed their own smart city strategies and platforms. In the following, we take a closer look at the steps each city has taken:

---

**Barcelona, Spain:** Barcelona operates the ‘Sentilo’ platform<sup>1</sup>, an open-source smart city platform that aims to break down informational silos inside the city to provide unified access to the data available. It currently contains more than 27.000 sensors<sup>2</sup>. It offers a modular and extensible architecture, high performance and scalability, alerts, stats, triggers, a simple REST API to send and receive sensor data, and is cross-platform by being built with Java, Redis and MongoDB.

**Amsterdam, Netherlands:** Amsterdam utilizes sensors to run an extensive smart lighting system, that

**London, England:** More infos

**Stockholm, Sweden:** More infos

More honorable mentions from outside the EU:

**Singapore:** more infos

**San Francisco, US:** more infos

## 2.3 Sensing Applications

### 2.3.1 Remote Sensing

In comparison to stationary sensors that are installed directly in the environment they are observing, remote sensing describes the process of observing a target environment from afar [CW11]. In climatology, remote sensing is used to collect meteorological data via satellites, planes or balloons by either capturing image data, that can be used to identify things like cloud and land coverage, by measuring passive radiation, or by actively sending out microwaves or using LIDAR to detect features such as surface temperature, e.g. LST data. Remote sensing comes with its own set of advantages and challenges.

The major upside of sensors moving way above ground is the high spatial coverage, that allows for meso- and planetary-scale analysis of weather phenomena. Another upside is the great data availability, as many satellite providers, such as ESA..., publish their satellite data. This creates many research opportunities, and many services directly rely on these measurements (todo list).

Remote sensing also comes with some downsides. The primary downside is the low

---

<sup>1</sup><http://www.sentilo.io/>

<sup>2</sup><http://connecta.bcn.cat/connecta-catalog-web/stats/> (Accessed: 23.03.2023)

spatio-temporal resolutions. Weather satellites usually are not orbit-stationary and move around earth on a predetermined orbit. As a consequence, satellites only pass over each individual area a couple times a day, making real-time applications for currently unobserved areas impossible. Additionally, the spatial resolution can be too low for micro-/local-scale analysis, with typical LST resolution spanning from 1 km<sup>2</sup> to tens or even hundreds of km<sup>2</sup> per data point/grid field. In the atmosphere, there is also a lot of environmental noise, like radiation, that can have a negative influence on the measurement accuracy. Another disturbing factor can be clouds or other types of particles like rain, that absorb radiation/microwaves sent from the sensors, traditionally making measuring under cloudy/rainy conditions either impossible (example) or less accurate (example), by instead relying on outgoing radiation from the surface. These restrictions highly depend on the sensor used, as different sensors use different sensors use different technologies, e.g. microwaves with different wave lengths or higher resolution sensors.

## 2.4 Interpolation of Missing Data

In the context of urban environments, there are many measurements such as surface temperature, which are measured by sensors that have certain weaknesses. In the case of LST data collection, clouds play a major part and prevent surface temperature to be measured. In many LST data-sets (ref), measurements for cloud areas are simply defined as having no value. As many applications and algorithms need continuous input data to work as expected, in this work we take a look on how interpolation, especially with the help of ML, can help solve this problem. In the context of LST data, this could mean interpolating the missing data either based on surrounding data (cite) or by integrating many different features such as air temperature, humidity, heat flux etc. in a ML model (cite).

- moving sensors for better spatial coverage into unobserved areas

### Interpolation vs. Extrapolation

In this work, we focus on interpolation of missing data. Interpolation is the process of calculating/guessing missing values between given values. This could be a missing value in a time-series or a missing cell in a data grid (cite). In contrast, extrapolation is the prediction of values based on previous values, like predicting values based on historic time-series data, as in the case of weather forecasting. Due to time constraints, we only focus on the interpolation part, tho extrapolation could also play an important role in smart cities by predicting UHIs and warning citizens about potential future heat-related risks.

---

### 2.4.1 Regression Analysis in Statistics

Fundamentaly, regression analysis has its roots in mathematics, more specifically in the field of statistics. todo: more

- foundation of other research fields, based in statistics/mathematics
- linear regression (least-squares) - multiple regression models - hierachical regression
- special cases - piecewise linear regression - inverse prediction - weighted least squares
- logistic regression - poisson regression

### 2.4.2 Interpolation in Geostatistics

- spatiotemporal (kriging) - time series prediction vs interpolation of missing data - based on GIS - pipeline: fit measured data points to grid, interpolate missing squares downside: cannot find local maximas/minimas

### 2.4.3 Applications for Machine-Learning

traditional interpolation techniques are simple and usually fast, but lack the ability to adapt to the specific problem at hand.

transition to ML based Interpolation

applications:

- all-in one solution (all features included) -> huge DL model with billions of parameters (ChaptGPT) - not feasible in this thesis
- pipeline solution (use ML models incrementally and build upon results) - similar to NLP - feasible for specific topics
- bottom-up approach (use ML to increase the amount of available data)
- types of ML utilisation - outlier detection - classification - regression - interpolation of missing data - prediction of future data

## 3 Machine Learning-based Interpolation

In recent times, the area of machine learning has seen big advancements in terms of model size and complexity. Especially in the area of generative AI, transformer-based neural networks have revolutionised text and image generation. Models such as OpenAI's *ChatGPT* [Ope23] or Google's *LaMDA* [TDFH<sup>+</sup>22] have generated significant hype for the possibility of use of AI. Additionally, statements like the universal approximation theorem, which states that a feed-forward network with a single hidden layer containing a finite number of neurons can approximate any continuous function [HSW89], emphasize the potential power of ML models. As a result, the question arises what benefits AI can bring to other areas of application, such as interpolation.

In this chapter, we will discuss the usage of ML in the context of data enrichment via interpolation, more precisely in the context of smart cities and urban air temperature interpolation. The ML model will be compared against traditional proven geostatistical model, e.g. Kriging, to outline and discover possible advantages and disadvantages. In general, the idea is to trade the explain- and interpretability of purely statistical-based approaches for model capabilities and accuracy, and the ability to capture more complex (non-linear) dependencies.

### AI vs. Machine Learning vs. Deep Learning

Before diving deeper into the applications of ML, we need to clarify what is meant by artificial intelligence (AI), machine learning (ML) and deep learning (DL). AI is a broad term that is used to describe the ability to perform tasks, that are usually associated with human intelligence. ML is a subfield of AI, that focuses on the ability of a system to learn from data without being explicitly programmed to do so. Finally, DL is a subfield of ML, that uses artificial neural networks, which imitate the structure of the human brain, to learn from data and perform various tasks.

### 3.1 Machine-Learning Application Areas in Air Temperarture Interpolation

As meteorological research and analysis activities are usually in need of gridded or continuous data [SKP<sup>+</sup>20], interpolation is a really important tool to convert the single data points from ground-based weather stations into continuous layers. Interpolation can also be applied to singular sensors in order to fill in missing data that are caused by network

---

outages or to increase the temporal resolution to turn hourly into sub-hourly readings. Especially with the capability to increase the temporal resolution, the question arises how this capability could be combined with moving sensors to increase the spatial coverage of a sensor network. In this work, we will discuss two approaches for the use of interpolation in urban air temperature sensing:

- ML-based interpolation for areas as a substitution for geostatistical methods, e.g. Kriging, to turn individual data points into a continuous grid, possibly with the ability to handle stationary and moving sensor data at the same time
- ML-based interpolation to simulate individual virtual sensors that are derived from either low-temporal resolution stationary sensors or moving sensors to increase the temporal resolution of individual sensors and the spatial coverage of sensor networks

Research suggests that for fine-granular spatio-temporal urban air temperature maps, a sensor density of at least 1 sensor per  $\text{km}^2$  is needed [VBEM20], however the denser the sensor network the better the prediction quality, as even inside a single street canyon air temperatures can easily vary by 2 to 3°C [SHN<sup>+</sup>08]. In order to achieve this sensor density as well as to gain insights into previously unobserved areas and to minimise prediction uncertainty for those areas, hybrid approaches combining stationary and moving sensors have shown to work better than purely stationary networks by covering more ground as well as reducing variability of purely mobile network setups in the context of urban temperature sensing [YBZ19]. The combination of reference grade stationary sensors and moving sensors also shows promise in other related applications, e.g. in the context of pollution island detection [IBA<sup>+</sup>22].

In the context of this work, we discuss both ML applications and set a focus on the ability to create virtual sensors from moving sensors in order to increase spatial coverage. In the following, we introduce several ML algorithms that can be used for regression tasks and discuss how they need to be adapted in order to solve interpolation tasks as well as the advantages and disadvantages of each model. Afterwards, we will decide on one model that will be implemented and evaluated in Chapter 5.

## 3.2 Model Selection Criteria

Before using the ML regression algorithms introduced in this section to solve the interpolation problem, the models need to be adapted to this specific use-case. This can happen either by adapting the input data and the types of features used or by adapting the model configuration. The following questions need to be answered:

- **How to model sensors?**: Do we want to model each sensor individually, do we want to model all sensors in the area, e.g. like a network, or do we want to model the whole area at once similar to image processing?
-

- **How to model stationary vs. non-stationary sensors?:** Do we model stationary and non-stationary sensors differently and can the model handle the possibly unsteadily data of moving sensors, e.g. different locations or different time intervals?
- **How to model the temporal correlation?:** Does the model allow to model temporal correlation between sensor readings and is it only short-term or also long-term correlation?
- **How to model the spatial correlation?:** Is spatial correlation directly incorporated in the model architecture or does it need to be modelled via features?

Next to the adaptations that need to be made in order to fit a regression algorithms to the interpolation problem, there are also non-functional requirements that need to be considered when selecting a model. The most important requirements are:

- **Model Assumptions:** The model assumptions need to be met by the features used in the input data. For example, linear regression assumes that the input features are independent from each other, as linear regression measures the amount the target variable is influenced by one feature changing while all other features stay the same. In case of correlation, this assumption is violated, as f.e. the amount of precipitation influences the humidity.
- **Accuracy and Reliability:** Creating an accurate and reliable model is really important to increase the trust for predicted values, however there are certain trade-offs to be made, as model performance or generalisation ability are also important factors to consider. The accuracy of the model is mainly determined how well the chosen model can fit the underlying data, e.g. a linear model cannot fit a non-linear function, and is measured by the evaluation metrics described in section 3.4.6. The reliability of the model is determined by the training data as well as the model architecture, as f.e. training data that is not representative of the underlying function can introduce bias into the model or can prevent the model from learning the correct function. Another important factor is the data quality, as more noise can result in worse model performance. Lastly, reliability of the model is also determined by the ability of the model to handle missing or sparse data as well as outliers. This is especially important in our context as we try to integrate moving sensors into the interpolation process, which sense data at different times and locations.
- **Extrapolation Capabilities:** One important factor to consider, especially when using a model with previously unseen data, is the ability to extrapolate data. Linear regression models f.e. try to fit a linear function that can be easily be used with data that is bigger/smaller than previously seen training data as the function is continuous. In comparison, regression trees by default do not allow for extrapolation. Also, Neural Networks (NNs) typically perform unpredictably on unseen data.

- **Amount of Training Data:** The amount of training data required to train the model is another important factor to consider, as some models require more training data than others. Especially neural networks tend to need more training data than other models, as they have lots of parameters that need to be tuned. In our context, the amount of data available is quite limited, therefore models that require less training data are preferred.
- **Handling of Missing Data:** If the model cannot handle missing data well, there might be additional data preprocessing steps that need to be done. One example for this would be how the model reacts to not a number (NaN) values which is a float number defined in the IEEE 754 floating-point standard [iee19]. Each multiplication with NaN results in NaN, which can therefore lead to a model where all weights turn into NaN when there is a single NaN value in the input data. This is especially important in the context of distributed sensors, as they might not sense every feature at all times. Common strategies to handle missing values involve dropping the complete feature if it has any NaN, drop any rows in the data that has NaN values or imputation, e.g. replace the missing value with a value such as the mean or median of the feature.
- **Handling of Sparse Data:** Similar to missing data, handling of sparse data is also really important to prevent problems such as the NaN problem mentioned previously. The main difference to missing data is that sparse data is not missing, but rather not available at all times. In our context, moving sensors would be an example for sparse data, as they only sense data at certain times and locations. The strategies to handle missing data are also similar to those of missing data, but imputation and interpolation are more common strategies to handle sparse data.
- **Model Performance:** The more complex a model is, generally speaking the more training data it needs to fine-tune all its weights and the longer it takes to train, either due to the amount of data or the amount of steps that need to be taken when updating weights in the training process. In the context of open-source and citizen participation less complex models are preferred, as they can be trained and deployed with less resources. However, a less complex model could have the downside of not being able to fit the underlying data as well as a more complex model, therefore there is a trade-off between model complexity and model performance.
- **Model Capabilities vs. Interpretability:** A common trade-off in ML models is between model capabilities and complexity and interpretability of the model as done by [ZKBK21], as ‘Neural network and deep learning approaches allow for large flexibility and predictive power but are harder to interpret than ensemble-based approaches which allow for the required flexibility, while still providing insights into the algorithms’ inner workings, e.g. via variable importance and prediction uncertainty estimation’.

- **Other:** Next to these main requirements, there are also other requirements, such as the ability to handle massive amounts of data, live retraining or sophisticated support via ML libraries such as *Tensor Flow*<sup>1</sup> for commercial use-cases. Due to the limited scope of this work, these requirements will be considered in less detail.

After introducing the requirements for model adaptions and selection, the next step is to introduce and compare the different ML regression algorithms. Generally speaking, ML algorithms can be categorised based on many different properties [Sar21], such as the type of learning, e.g. supervised, unsupervised, semi-supervised or reinforcement, or the type of problem they try to solve, e.g. classification, regression or clustering. The most important differentiation for this work is to distinguish algorithms based on the type of problem they try to solve. Because we focus on solving interpolation problems, in this work we will only consider algorithms that can be used to solve regression problems, as interpolation is a form of regression.

In regression analysis, the goal is to predict a (continuous) target variable  $y$  based on a set of input variables  $X$ , like it is the case for temperature interpolation. Generally speaking, this problem can be classified as a supervised learning problem, therefore the possible algorithm candidates are as follows:

- (Multi) Linear Regression (MLR)
- K-Nearest Neighbours (KNN) Regression
- Regression Trees and Forests
- Support Vector Regression
- (Deep) Neural Networks
  - Long-Short Term Memory (LSTM)
  - RNN

Each model has certain benefits but also comes with drawbacks or special assumptions for the input data to the model. First, we will discuss each model and then compare these assumptions with the data coming from the data-layer, to identify suitable models for the task of air temperature interpolation. These models will then later be implemented and compared in chapter 5.

Based on the domain, there already exist proposed best-practices for which algorithms to use for what applications. In the context of smart cities such recommendations for topics such as intelligent transportation systems, smart grids, smart city health care and more can be found in [UATMG20], which unfortunately does not cover interpolation.

---

<sup>1</sup><https://www.tensorflow.org/>

### 3.3 Comparison of Machine Learning Algorithms

#### 3.3.1 (Multi) Linear Regression

Linear regression [MPV21] is a comparatively simple, yet very powerful and widely used model for regression problems. The goal of this model is to predict a continuous dependent variable based on a number of independent variables. These independent variables can be either continuous or discrete. The model can be expressed as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \epsilon \quad (3.1)$$

where  $y$  is the dependent variable,  $x_1$  to  $x_n$  are the independent variables,  $\beta_0$  to  $\beta_n$  are the parameters of the model and  $\epsilon$  is the error term. The relationship between the parameters is assumed to be linear, while each variable must be independent of each other. Due to this independent assumption, there are special steps needed to make linear regression work for (geo-) spatial data, as these types of variables are usually correlated with each other. This is further discussed in 3.4.4.

Linear regression has the advantage, that it is a very simple model, therefore the majority of work needs to be done in the feature engineering process. The downside is that there is no inherent support for spatial or temporal correlation and the model cannot be used to fit non-linear functions. In order to fit non-linear functions, polynomial regression can be used, which can however lead to overfitting especially when the degree of the polynomial is high.

Linear models seem to perform worse in urban temperature related settings, as they are unable to capture non-linear effects [VS17].

#### 3.3.2 KNN Regression

K-Nearest Neighbours (KNN) is a simple algorithm that can be used for both classification [CH67] and regression problems [Alt92]. The main idea behind KNN is the assumption, that data points near each other are more similar than data points that are further away. As a result, the  $k$  nearest neighbours, either by number or by radius, of a data point are used to predict the target variable. The number of nearest neighbours is a hyperparameter that needs to be tuned in order to find the best trade off between bias and variance. The model can be expressed as follows:

$$\hat{y} = \frac{1}{k} \sum_{i=1}^k y_i \quad (3.2)$$

where  $\hat{y}$  is the predicted target variable,  $k$  is the number of nearest neighbours and  $y_i$  is the target variable of the  $i$ -th nearest neighbour.

KNN is part of the family of non-parametric models, meaning they do not make any strong assumptions about the underlying regression curve. KNN is a simple yet powerful

model, however the standard model does not have weights, e.g. all nearest neighbours have the same influence on the prediction, as well as each feature is weighted equally. In the context of correlated input features, this could introduce a bias into the model, if not handled properly in the feature engineering process.

### 3.3.3 Regression Trees and Random Forests

Tree predictors are used for a wide variety of classification and regression problems. Due to the fact that tree predictors are unstable, e.g. vary significantly given similar inputs, and tend to overfit, random forests were introduced as a counter measure. Random forests combine multiple tree predictors and train them on different features and sub-sets of data and either average their predictions in order to reduce the variance or use boosting methods to reduce the bias of a combined estimator [Bre01].

In the case of predicting a continuous target variable, regression trees can be used. The principle behind regression trees is to split the data into continuously smaller sub-sets, and organise the splitting points in a way that minimises the error. Compared to decision trees which try to minimise the entropy, regression trees try to minimise an error that is compatible with a continuous target variable such as mean squared error (MSE). The model can be expressed as follows:

$$\hat{y} = \sum_{m=1}^M c_m \mathbb{1}(x \in R_m) \quad (3.3)$$

Regression trees are comparatively easy to understand and interpret and offer certain benefits such as feature insensitivity, meaning that features do not need to be scaled before usage and can be used as is. In [ZKBK21] Zumwald et al. choose to use Quantile Regression Forests (QRF) [MR06] for mapping hyperlocal air temperature in Zurich, Switzerland, due to the flexibility and predictive power of ensemble-based approaches and the ability to still gain additional insights into the algorithms' inner workings via variable importance and prediction uncertainty estimation. They note however, that Neural Network and Deep Learning approaches allow for even larger flexibility and predictive power, but lack behind in other areas such as the aforementioned interpretability.

See: [AYDK22]

Related: Canada with Weather Undergorund (WoW) [HKS<sup>+</sup>14] -> RMSE = 2.31 °C

### Bagging Methods

In order to decrease the variance of a single tree predictor, bagging is used to introduce randomization into the training process. There are several different bagging methods:

- **Pasting:** Splitting the data into different subsets and training a tree predictor on each subset [Bre99]
- **Bagging:** Splitting the data into different subsets but with replacement [Bre96]

- **Random Subspaces:** Splitting the data into different subsets of features [Ho98]
- **Random Patches:** Splitting both samples and features into different subsets [LG12]

There are a couple of studies that use regression trees for temperature interpolation. In [VBEM20] the authors achieve an average RMSE of 0.52 °C ( $R^2 = 0.5$ ), 1.85 °C ( $R^2 = 0.05$ ) and 1.46 °C ( $R^2 = 0.33$ ) for annual mean, daily maximum and minimum air temperature respectively for the city of Oslo, Norway by combining 20 features from satellite data and PWS from the Netatmo network. However, they do not discuss the downsides of regression trees to extrapolate data.

In [ZKBK21] the authors used the quantile regression forest algorithm to use regression trees to predict the daily maximum and minimum air temperature for the city of Zurich, Switzerland. They achieve an average RMSE of 1.5 °C ( $R^2 = 0.7$ ) and 1.4 °C ( $R^2 = 0.7$ ) for the daily maximum and minimum air temperature respectively by combining 20 features from satellite data and PWS from the Netatmo network.

In [HKS<sup>+</sup>14]... - good for reference stations - worse for WOW stations + stations close to the ocean

These studies show that regression trees can be used to predict air temperature with a high accuracy on a daily and annual basis for minimum and maximum air temperature with a high spatial resolution, but do not explore the ability to predict actual air temperature for low time resolutions, e.g. hourly or sub-hourly.

Due to the downside of the inability to extrapolate data which is especially critical in the detection of CUHIs, e.g. air temperature maximas, we do not use regression trees in this work. However, other findings such as station density and features used can be used in this work.

There is a systematic bias to underestimate high temperatures and overestimate low temperatures [ZKBK21, ZL12]

### 3.3.4 Support Vector Machine Regression

Support Vector Machines (SVM) are typically used in classification problems, however they can be also used for regression problems, called Support Vector Regression (SVR). SVMs transform the input data into a higher dimensional space and try to find a hyperplane that separates the data into two classes. This approach is similar to linear regression, however SVMs are more robust to outliers and can be used for non-linear problems. Depending on the Kernel function used, e.g. Linear, Polynomial, Radial Basis Function (RBF) or Sigmoid, the model can suffer from the same problems as linear regression when dealing with correlated spatial data. As a result, appropriate counter measures need to

be taken, such as using the Mahalanobis distance instead of the Euclidean distance for RBF kernels [KA06], which converts correlated features into uncorrelated features.

### 3.3.5 Neural Networks

- trade off between interpretability and model capabilities - more data needed to train the network, because there are more weights to train

Neural networks

#### Deep Neural Networks

- approximation theorem - special form of neural networks with hidden layers  
- overparametrization

## 3.4 Feature Engineering

Next to the model, the most important thing for a machine learning algorithm is the data. Even when the model is perfectly suited for the task at hand, if the data is not suitable, e.g. not enough data, wrong quality, wrongly prepared or formatted etc., the model will not be able to perform well. In the following, we take a look at the data coming from the data-layer and discuss important assumptions such as spatial and temporal autocorrelation. These correlations are important to consider, as they could invalidate models as f.e. Linear Regression 3.3.1 assumes uncorrelated input variables.

First of all, the data-layer exposes a variety of single data-points for various features for different locations for current and past points in time. Features other than air temperature could further improve the predecicition quality, like how [AR20] suggests that in their study the Normalized Difference Vegetation Index (NDVI) and Modified Normalized Difference Water Index (MNDWI) have a strong impact on their estimation model. Therefore, we discuss how additional features can be included in the model.

This model should then be deployed inside the *service-layer* and act as a building block for further temperature related research and analysis, as air temperature is an important variable for research in agronomy, meteorology, hydrology, ecology and many other fields of application and could be used for UHI detection in the context of smart cities. The general idea and architecture behind the model should not only be applicable for air temperature, but also other types of output features, even tho potentially significant domain knowledge, like in geostatistical analysis and statistics, is required to select and prepare the input features.

Generally, there are different types of input features. Firstly, there are discrete measurements that capture the underlying continuous geological process as a specific value at a certain point in time. Examples for this are the measurements from sensors which might be deployed in an urban environment to capture air temperature, humidity and more.

---

Important to note here is the interval, the values are captured. For example, a sensor might capture the air temperature as the average over five minutes, whereas a rain sensor might capture the absolute amount of rain in a specific time interval. Secondly, there are calculated features, which might be derived from the discrete measurements or the location of a measurement. For example, the distance to the closest body of water with a minimum size of  $x^2$  meters might be an important information for the air temperature. Lastly, ...

In the following chapter, we discuss how different types of correlation between measurements can be taken into account to improve the model and gain additional insights into local (meteological) dynamics.

### 3.4.1 Spatial Autocorrelation

As discussed in chapter 2, there is a dependency between air temperature and other meteological features and the location of the sensors. The closer a sensor is to another sensor, the more correlated the sensor readings should be. In geo-statistics, this is called spatial autocorrelation and can be defined traditionally with the Moran's I index [Mor48] or the Geary's coefficient [Gea54].

This relationship is however greatly influenced by the type of feature and the location of a sensor. As explained in [Oke06], the sensor placement in the urban environment is a complex task, as the urban environment is highly dynamic and sensors can be influenced by highly local phenomena, such as air temperarture by heat vents or solar radiation by buildings and surface materials. For this model, we assume that the sensors are placed in a way that the sensor readings are representative for the area they are placed in, even tho in practice this assumption might not hold up, especially for sensors placed by non-experts.

Each sensor reading from the data-layer has a location associated with it in the form of longitude, latitude and altitude (if available). This information can be used to calculate the distance between sensors and subsequently the correlation between sensor readings. However, how exactly the distance between two locations is calculated is not trivial. As the earth is a sphere, the distance between two points on the surface is not a straight line. Depending on the application, different distance metrics can be used. For a small area, such as the city of Hamburg, the euclidean distance could be sufficient, as the curvature of the earth for a small distance is negligible. However, for larger areas the geodesic (harvesine) distance might be more appropriate. In this work, we are focussing on a single city including it's surrounding area, therefore the euclidean distance should have a sufficient accuracy while also simplifying the calculation. As the city of Hamburg does not have big differences in elevation, the altitude is not considered in the distance calculation.

The location data can be incorporated into the input data in several ways. The most straight forward way would be to just include the longitude and latitude as input fea-

tures. Depending on the type of model used, these values might need to be normalised. For example, tree-based models do not require normalisation (cite), as they are not sensitive to the scale of the input features. However, neural networks are very sensitive to the scale of the input features and therefore require normalisation (cite). This approach has the downside, that the distance between sensors is not directly encoded in the input data. If this information is important for the model, it could be included by precalculating the distances between all sensors, however this would increase the complexity of the model especially for large amounts of sensors, as this would result in a quadratic number of input features.

The next approach would be to convert the

- area  $n \times m$  grid of data points, each grid cell with  $n \times n$  size (depending on the resolution), 4D space with location as x and y coordinates (euclidean distance -> but only for smaller areas such as city of Hamburg and surroundings), time as z coordinate and feature values as w coordinate.

### 3.4.2 Temporal Autocorrelation

- trends -> expect normally distributed temperature curve -> temporal lag (e.g. temperature of yesterday has influence on temperature of today)

Either explicitly model

### 3.4.3 Temporal Cross Correlation

### 3.4.4 Dealing with Correlation

Todo: Techniques to turn correlated variables into uncorrelated ones - principal component analysis (PCA) - ...

variance inflation factor (VIF)

-> over 10 = invalid model[MPV21] -> others more moderate with max 3 [ZIE10]

### 3.4.5 Dealing with Uncertainty

- The model has a lot of uncertainty - model uncertainty in input data? (depending on sensor type, sensor age, placement...)
- dealing with bias - dealing with variance -> problem of over-fitting

## Neural Network Models

input layer -> hidden layers -> output

- The advantages of Multi-layer Perceptron are:
- Capability to learn non-linear models.
- Capability to learn models in real-time (on-line learning) using `partial_fit`.

The disadvantages of Multi-layer Perceptron (MLP) include:

- MLP with hidden layers have a non-convex loss function where there exists more than one local minimum. Therefore different random weight initializations can lead to different validation accuracy.
- MLP requires tuning a number of hyperparameters such as the number of hidden neurons, layers, and iterations.
- MLP is sensitive to feature scaling.

- Loss functions/optimizers: Stochastic Gradient Descend, Adam, L-BFGS
- random forest regression ...

### 3.4.6 Evaluation Metrics

- Mean absolute error, mean absolute relative, mean squared error, r-squared, root mean squared error (RMSE)

## 3.5 Model Selection

Question: do we want to model each sensor individually, do we want to model all sensors at once or do we want to model the whole area? Do we model stationary and non-stationary sensors differently?

Options:

- linear regression - needs independent variables -> PCA
- KNN regression - needs independent variables -> PCA
- Neural Network - try without independent variables - LSTM -> temporal correlation - CNN -> spatial correlation, temperature map

After listing the selection criteria, the next step is to discuss the possible model candidates and evaluate them based on the selection criteria. The following models are considered:

- linear regression - knn regression - neural networks - deep learning - sequential model
- recurrent neural network (RNN) - long short-term memory (LSTM) - convolutional neural network (CNN)

## 3.6 Machine Learning in Geostatistics

Idea/Hypothesis: ML outperforms traditional geostatistical models (in certain scenarios) as it is able to capture more complex interdependencies between features and isn't necessarily bound to the (mathematical) assumptions of geostatistical models.

An important point to mention, is that different meteorological features have different interpolation techniques, as they have different (physical) properties. For example, temperature is a scalar value, while wind speed and direction are vector values. Relative humidity on the other hand is a relative value that is bound between 0 and 1. For precipitation it gets even more complex, as rainfall is highly connected to cloud coverage and movements. In the following, we will take a look at commonly used existing interpolation techniques for different meteorological features and discuss data preprocessing steps.

---

- Dealing with sparse data - Dealing with extreme weather events (e.g. heat waves, blizzards, etc.) - how can a ML model be trained if no such data exists for a given area?  
-> transfer learning

### Temperature Interpolation

- difference between air and surface temperature
  - surface temperature -> solar radiation, surface roughness, emissivity, soil moisture, soil temperature, vegetation cover, snow cover, and surface slope
  - air temperature -> surface temperature

### Wind Speed and Direction Interpolation

prob not easily archivable with ML -> depends on high/low pressure areas

### Relative Humidity Interpolation

Data preprocessing: scale to [0, 1] does not seem to work well with kriging, maybe just nearest neighbor approach/linear, or the input values are just not accurate

### Precipitation Interpolation

DeepLearning Lecture - sequence modeling design criteria - handle variable-length sequences - track long term dependencies - maintain information about order - share parameters across the sequence

- The model is implemented following advice from [RABW23]...
- Additonal ideas: - types of geological features (vectors, rasters) -> distance, containment, intersection, etc.

## 3.7 Additional Considerations

### ML Model Deployment

Deployed as a service. Input ingested -> continous data map as output all 5 min or so (could also be smaller depending on use-case -> trade-off between cost and accuracy)

### ML Model Retraing

Need to retrain model from time to time, e.g. if the accuracy drops below a certain threshold.

---



## 4 Preparation of Datasets

Next to the ML model selected, the data used to train and evaluate the model has a major influence on its performance. If the data is not representative or information is missing about the underlying process that the model should be fitted to, there can be errors, bias or an inability to generalize well to new data. In this chapter, we take a look at potential features for air temperature, at data sources for these features, and discuss the construction process of the datasets used in this work.

In the field of natural language processing (NLP) and computer vision (CV), there is an abundance of large available datasets which have a big contribution to the advancements in the field, like annotated datasets as provided by Google Research<sup>1</sup>. In comparison in the field of climate research, there are also many datasets, including satellite data, weather station data, and climate model data, however they are highly distributed or often not openly available. Platforms such as Google Earth Engine [GHD<sup>+</sup>17] try to address this issue, however the dataset catalog<sup>2</sup> is still limited and does not include datasets offered by local authorities or other research institutions, such as universities.

For the specific use case of temperature interpolation in urban areas, an optimal dataset would contain high spatial and temporal resolution sensor data, e.g. a high sensor density and a low time interval of f.e. five to ten minutes. Additionally, the sensor placement and sensor quality have a high influence on the accuracy of the sensor readings [Oke06], therefore the correct placement and calibration of the sensors needs to be guaranteed. Such requirements are not met by traditional weather station networks as the spatial coverage is too low, as a single weather station is not enough to capture the urban microclimate [OMCV17]. The weather station locations of the DWD are shown in figure 4.7, which shows that usually at most one weather station is available per city. The weather stations however offer a high temporal resolution in addition to very high quality sensors, which is why they can be used as reference stations for quality control of other sensors, as discussed in section 4.3.

A solution to the problem of low spatial coverage is the usage of sensor networks. There are several projects that run dense urban-climate monitoring networks [MCG<sup>+</sup>13] such as the Helsinki Testbed [KPS<sup>+</sup>11] or the Birmingham Urban Climate Laboratory [WYC<sup>+</sup>16], however access to those datasets is limited, for example due to outdated links or the need to request access. Due to the high cost of running such dense sensor networks with high sensor and maintenance costs, professionally run sensor networks are rare and are often

---

<sup>1</sup><https://research.google/resources/datasets/>, last accessed: 05.08.2023

<sup>2</sup><https://developers.google.com/earth-engine/datasets>, last accessed: 05.08.2023

only run for a limited time period until project funds run out.

As an alternative, sensor networks can also be crowdsourced and run by citizens, distributing the cost of individual sensors as well as maintenance costs among many. Especially with advances in sensor technologies, lost cost and compact sensors are more affordable than ever while still providing good data quality [Gri06, RGA<sup>+</sup>09]. In the context of meteorological data, such such sensor networks are often referred to as citizen weather station (CWS) [MFG<sup>+</sup>17] or personal weather station (PWS) [HGMS<sup>+</sup>22] networks. In this work, we use the term PWS.

The main downside of this approach is the lack of quality control and meta data, as the sensors are usually placed by non-professionals in suboptimal locations, e.g. in direct sunlight or too close to walls, leading to incorrect readings or bias in the data. A lack in meta data can also lead to issues, if for example exact positions of the sensors are not known and information about the height of the sensor above ground is missing. However, other concerns such as data privacy also need to be accounted for, as such weather stations are often placed on private property.

In this work, data from PWS networks is used to create datasets for the training and evaluation of ML models for air temperature interpolation. In the following sections, we take a look at available PWS providers and their data, look at potential features for air temperature interpolation, discuss additonal pre-processing steps such as quality control or sensor height correction, and finally discuss the construction of the datasets used in this work.

## 4.1 Private Weather Station Network Providers

PWS providers offer a platform for users to upload their sensor data and either sell weather stations and sensors themselves such as Netatmo, or provide guides to allow users to connect their own sensors to the platform such as Sensor.Community. Netatmo data in particular has been used in several studies [MFG<sup>+</sup>17, HGMS<sup>+</sup>22, VBEM20, ZKBK21] and has seen complementary studies for example discussing QC processes [FBD<sup>+</sup>21], later seen in Section 4.3. There are also other PWS network providers such as Sensor.Community or Weather Underground (WOW) that have been used in several studies [HKS<sup>+</sup>14]. In order to find out which provider best fits our needs in this work, the following section compares the different providers and their data.

### 4.1.1 Sensor.Community

Sensor Community<sup>3</sup> is a contributers driven global sensor community that creates Open Environmental Data, and has an archive<sup>4</sup> of their historical sensor data world wide. There are no quality measures recorded for each sensor, but as crowd-sourced sensor data

---

<sup>3</sup><https://sensor.community/en/>, last accessed: 05.08.2023

<sup>4</sup><https://archive.sensor.community/>, last accessed: 05.08.2023

tends to have a lower quality than professionally setup sensors, e.g. sensor placement by non-professionals, we need to explore how the data quality looks like. In Figure 4.1, where we see the greater Hamburg area with a currently reported temperature of 25°C by the DWD Fuhlsbüttel station, there are multiple sensors that report a temperature of 30°C and above, which could be either due to the sensor being placed in direct sunlight or due to the sensor being faulty. An outlier near Pinneberg is shown in Figure 4.2, where one sensor reports 25°C, as currently expected, and one sensor reporting 50°C, which is clearly an outlier. This data quality issue needs to be addressed in the data pre-processing step and can result in a significant reduction of available data. This was also an issue discussed in [MFG<sup>+</sup>17], as “erroneous metadata, failure of data collection, and unsuitable exposure of sensors lead to a reduction of data availability by 53 %”. From a meta-data perspective, there is no information on the sensor height above ground as well as no quality measures for each sensor, or information on the sensor location accuracy.

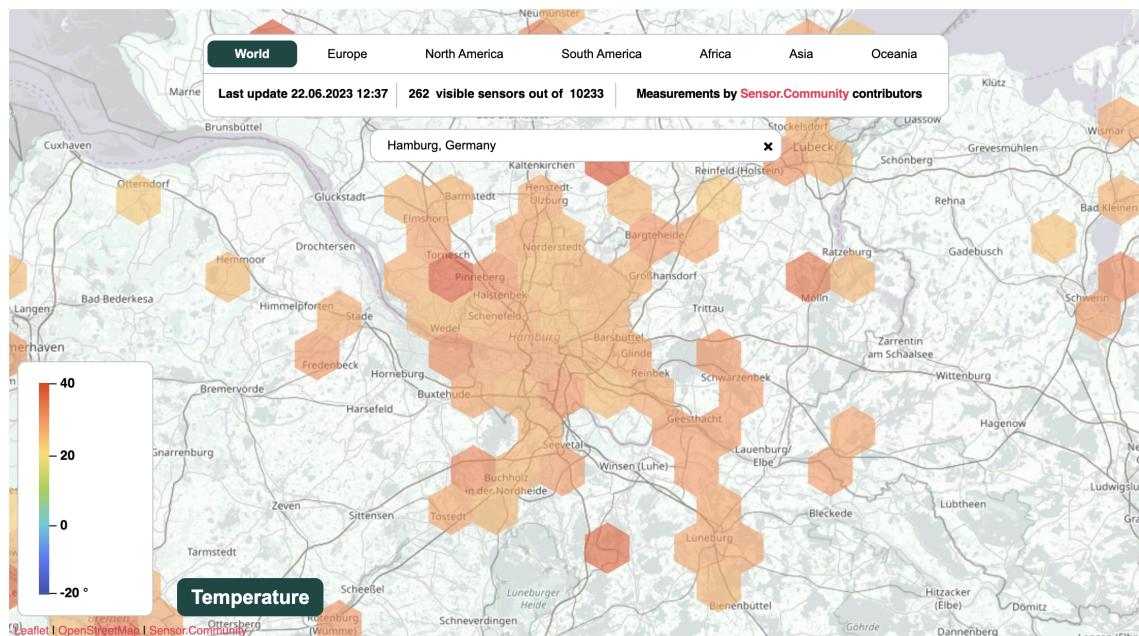


Figure 4.1: Temperature map from Sensor Community for Hamburg, Germany, on 22.06.2023 12:51h with the DWD reference at 25°C

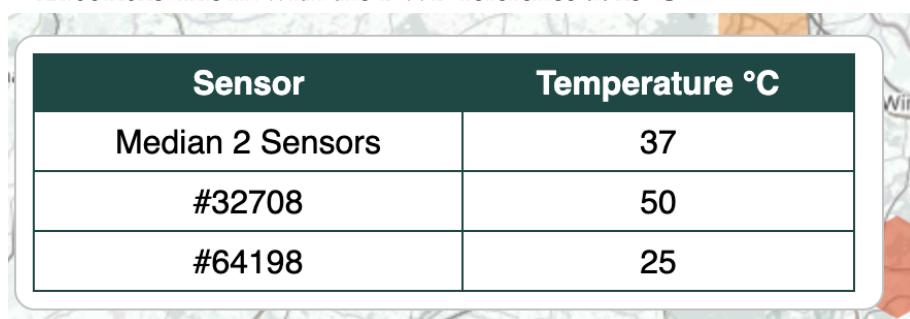


Figure 4.2: Temperature outlier from Sensor Community for Hamburg, Germany, on 22.06.2023 12:51h with the DWD reference at 25°C

Overall, there are around 11.738 active sensors<sup>5</sup>. Of these sensors, many are located in Germany, as seen in Appendix 1, and almost half of them are of type BME 280, which is a low-cost Bosch sensor which can measure temperature, pressure and humidity. The sensor locations as of May 2023 are shown in 4.3. DHT22 sensors can measure temperature and humidity, BMP280 and BMP180 sensors can measure temperature and pressure, and BME280 sensors can measure temperature, pressure and humidity.

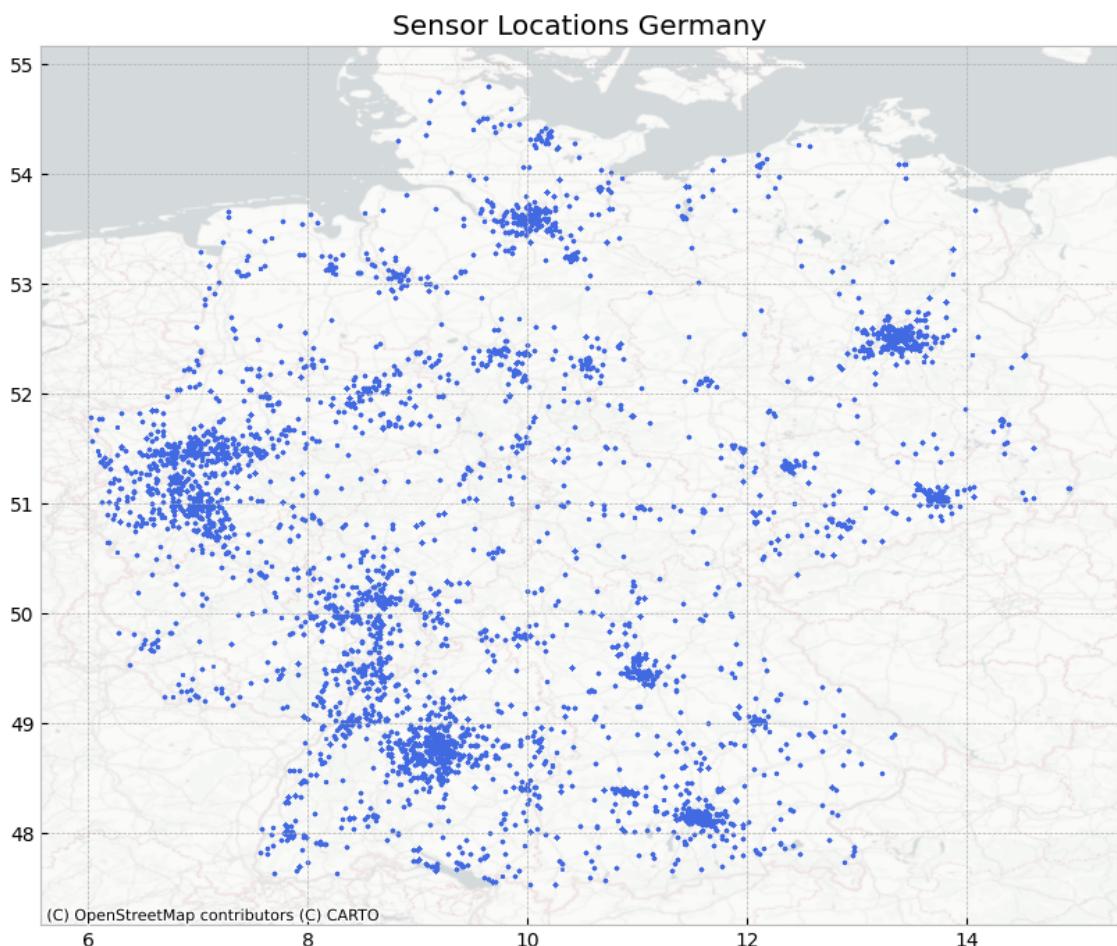


Figure 4.3: Sensor locations of Sensor Community in Germany, as of 01.05.2023, of sensor type DHT22 (2590 sensors), BME280 (1558 sensors), BMP280 (100 sensors), BMP180 (72 sensors)

#### 4.1.2 Netatmo

Netatmo<sup>6</sup> is a French company that sells smart-home devices including outdoor weather stations, indoor sensors for air quality, as well as other products such as smart cameras. They host a weather map<sup>7</sup> where customers can share their outdoor weather station

<sup>5</sup>as of 24.06.2023

<sup>6</sup><https://www.netatmo.com/en-eu>

<sup>7</sup><https://weathermap.netatmo.com/>, last accessed: 06.08.2023

Measurement	Unit	Measurement Range	Precision	Recording Frequency
Temperature	°C	-40°C to 65°C	0.3°C	averaged over 5 min
Humidity	% (RH)	0 to 100%	3%	-
Air Pressure	mbar	260 to 1160 mbar	1mbar	-
Noise	dB	35 to 120 dB	-	-
Wind Speed	m/s	0 to 45 m/s (160 km/h)	0.5 m/s	every 6 sec, averaged over 5 min
Wind Direction	°	0 to 359°	5°	every 6 sec, averaged over 5 min
Rainfall	mm/h	0.2 to 150 mm/h	1mm/h	every 5 min (bucket is emptied)

Table 4.1: Netatmo Sensor Specifications (Vendor reported)

data. They provide an API to access current weather station data as well historic data from individual outdoor sensors and modules. They provide their historical and current weather data for commercial partners or partners in the research and education sector. They are part of the EUMETNET project <sup>8</sup> which is a network of 31 European meteorological and hydrological services (NMHSs). The project aims to facilitate the exchange of weather data and to improve the quality of weather forecasts, especially in the context of PWS [HGMS<sup>+</sup>22]. There are currently no openly historical datasets available from Netatmo data, only private datasets <sup>9</sup> that are only available for partners such as EUMETNET members. They offer an educational program <sup>10</sup> to access temporally and spatially limited amounts of data that is usually only available to commercial partners.

In the context of collecting meteorological data, the smart weather products are of particular interest. These include a smart outdoor weather station that collects air temperature, humidity and air pressure, an anemometer that collects wind speed and direction, and a rain gauge. The sensor specifications, as reported by the vendor himself, is reported in Table 4.1.

In this work, data from Netatmo stations is used as Netatmo offers a large amount of sensors in Germany in urban areas, exemplified by Figure 4.4 for the region of Hamburg, and by Figure 4.5 for the region of Stuttgart. The developer portal <sup>11</sup> offers a way to programmatically access all public sensor measurements via a REST API, however each request has a limit on the spatial extend of the requested area for the current weather data. For historic data, the limit per request per sensor is 1024 data points. The API has a tight rate limit per application. For applications below 100 users, the rate limit is 2000 requests every hour and 200 requests every 10 seconds across all users, and 500 requests every hour and 50 requests every 10 seconds per user <sup>12</sup>. In this work, we use the REST API to collect sensor data from Netatmo sensors.

<sup>8</sup><https://www.eumetnet.eu/>, last accessed: 06.08.2023

<sup>9</sup><https://catalogue.ceda.ac.uk/uuid/e8793d74a651426692faa100e3b2acd3>, last accessed: 06.08.2023

<sup>10</sup><https://www.netatmo.com/en-eu/weather-with-netatmo>

<sup>11</sup><https://dev.netatmo.com/apidocumentation>

<sup>12</sup><https://dev.netatmo.com/guideline#rate-limits>, last accessed: 06.08.2023

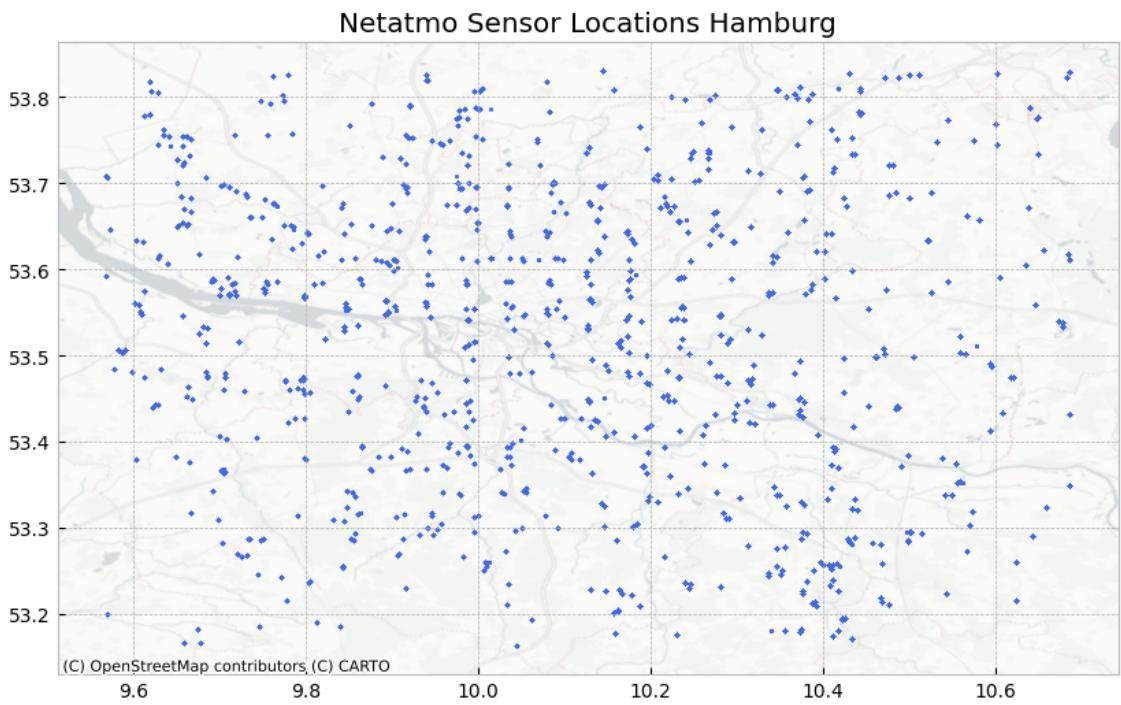


Figure 4.4: Sensor locations of Netatmo in Hamburg, Germany, as of 28.06.2023

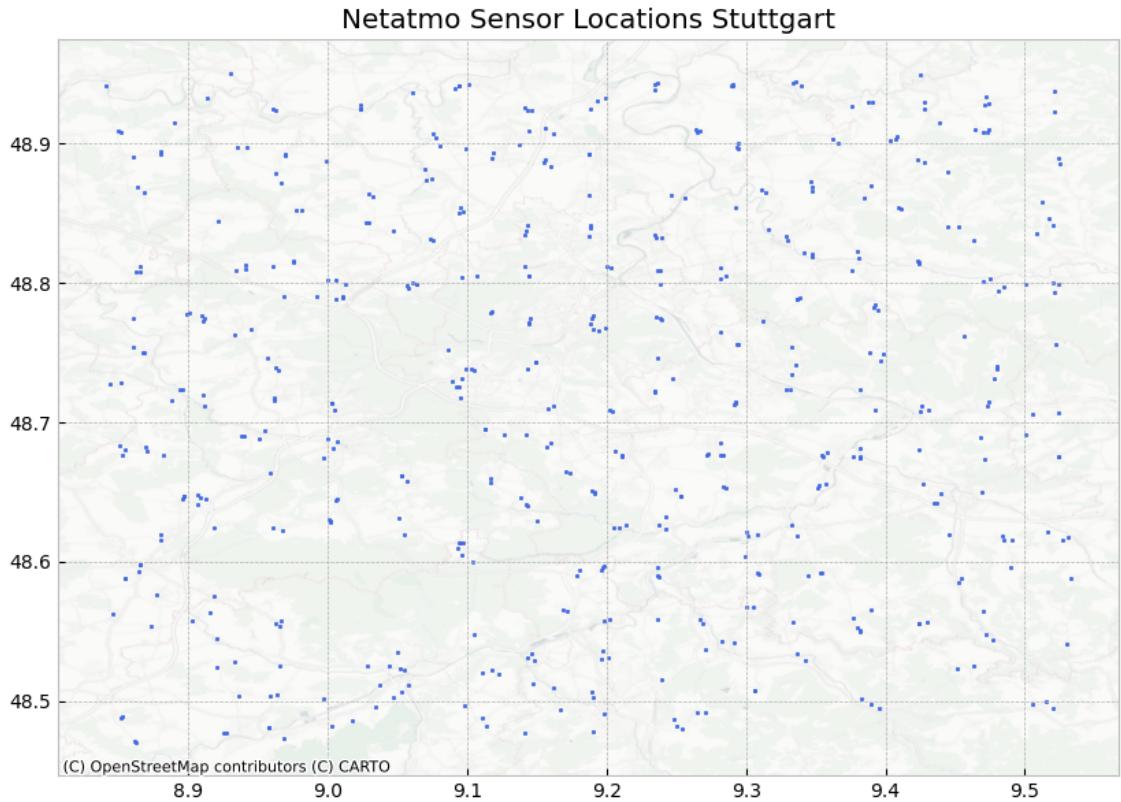


Figure 4.5: Sensor locations of Netatmo in Stuttgart, Germany, as of 19.06.2023

---

## Quality Considerations

Netatmo sensors have a good measurement accuracy, however due to the compact design, an aluminium housing, poor ventilation due to the small case, no dedicated radiation screen resulting in a proneness to radiative errors, and therefore overall slow sensor-response time [MFG<sup>+</sup>17, Büc18], Netatmo weather stations have a systematic bias that influences data quality. Due to the uniformity of Netatmo sensors, e.g. all sensors are built in the same way, this bias could be corrected in the QC step, however this is not further explored in this work.

### 4.1.3 Other Providers

Other sources for crowdsourced weather station data include WeatherObservationsWebsite (WOW)<sup>13</sup> and Weather Underground<sup>14</sup>. WOW is a platform run by the UK Met Office, which is the UK's national weather service, and has a dense sensor coverage in the UK and the Netherlands as seen in figure 4.6. Weather Underground is a commercial weather service which also provides a crowdsourced weather station network. Unfortunately, Weather Underground only provides an API for users with a registered weather station or other bulk download options for historical data. The website would allow for manual download of historical data, but this is not feasible for the amount of data needed for this work.

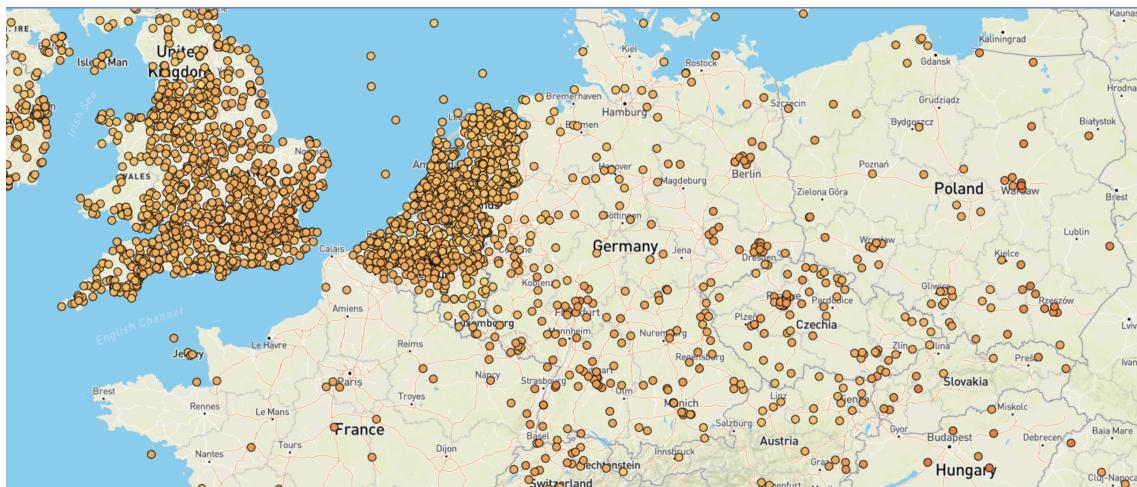


Figure 4.6: Temperature sensor locations from WOW, accessed on 05.07.2023

## 4.2 Reference Data Providers

In order to add additional validation to crowdsourced weather data, reference data from (official) weather stations can be used. These weather stations should be setup according

<sup>13</sup><https://wow.metoffice.gov.uk/>

<sup>14</sup><https://www.wunderground.com/>

to current World Meterological Organization (WMO) guidelines [WMO18] in order to ensure high data quality. These standards are either achived by offical weather services, or by institutions such as universities whose sensors are maintained by experts.

#### 4.2.1 DWD

The official german weather service (DWD) has many objectives, that are defined by the DWD-law in Germany. Its tasks include meterological and climatological monitoring of the atmosphere, meterologically securing the airspace for civil aviation, monitoring the maritim climate, and more. The DWD operates a large monitoring network and publishes most of it's data via its OpenData portal<sup>15</sup>.

The main advantages of the DWD data are high data quality through reference instruments and proper setup according to WMO guidelines [WMO18]. The main disadvantage is the low spatial coverage of the data, as stations are sparsely distributed to measure the overall mesoscale climate, as seen in Figure 4.7. Additionally, a lot of the public weather stations are located close to airports, which are usually located outside of cities, and therefore not suitable for measuring urban microclimates.

#### Urban Climate Stations

Next to the official weather stations, the DWD also operates urban weather stations, however there are currently only four stations in the following cities:

- Berlin-Alexanderplatz, Berlin, Berlin
- Freiburg-Mitte, Freiburg, Baden-Württemberg
- Hannover-Nordstadt, Hannover, Niedersachsen
- Dresden-Neustadt, Dresden, Sachsen

The number of urban weather stations is planned to be gradually extended to reach 10 stations with the locations being primarily determined by the measurement objectives such as determining a city's maximum UHI intensity<sup>16</sup>. Due to the low number of weather stations, their data is not used in this work.

#### Weather Radar

The DWD also operates a network of weather radars<sup>17</sup> that are used to measure precipitation and wind speed. This data could be interesting in the context of air interpolation

<sup>15</sup><https://opendata.dwd.de/>, last accessed 13.07.2023

<sup>16</sup>[https://www.dwd.de/EN/climate\\_environment/climateresearch/climate\\_impact/urbanism/urban\\_heat\\_island/urbanheatisland\\_node.html](https://www.dwd.de/EN/climate_environment/climateresearch/climate_impact/urbanism/urban_heat_island/urbanheatisland_node.html), last accessed 12.07.2023

<sup>17</sup><https://www.dwd.de/DE/leistungen/radarprodukte/radarprodukte.html>, last accessed 12.07.2023, not available in english

---

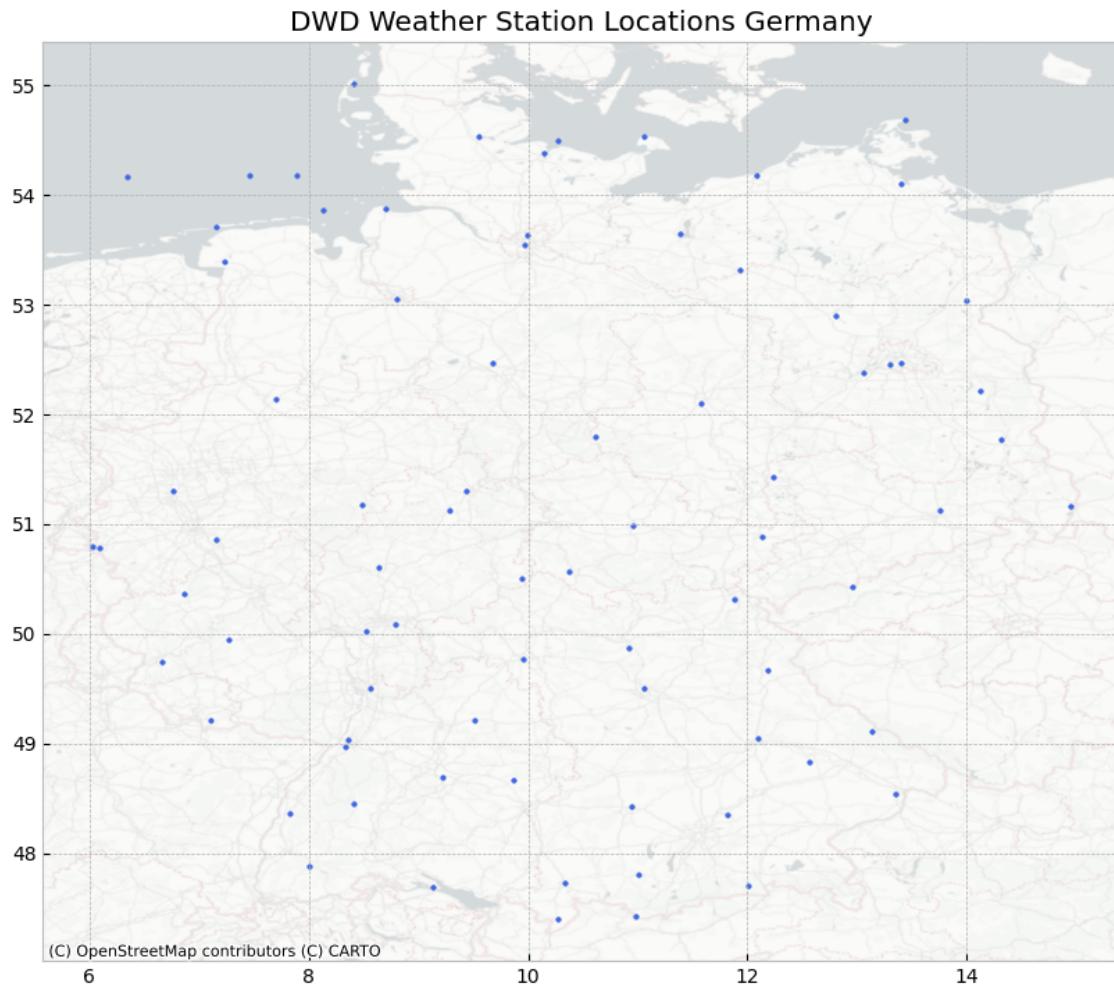


Figure 4.7: DWD Weather Station Locations in Germany, [https://opendata.dwd.de/climate\\_environment/CDC/observations\\_germany/climate/subdaily/standard\\_format/KL\\_Standardformat Beschreibung\\_Stationen.txt](https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/subdaily/standard_format/KL_Standardformat Beschreibung_Stationen.txt), accessed 28.06.2023

in order to detect precipitation events that have a major influence on humidity and temperature or to detect wind speeds that also play an important factor in dissipating heat and transporting it away from urban areas. Due to the limited scope of this work, this data is currently not used.

### 4.2.2 Locally Operated Weather Stations

Next to official weather services, many public and private institutions operate weather stations.

#### University of Hamburg – Meteorological Institute

- address local climate concerns and support decision making

**City of Stuttgart – Office for Environmental Protection**

- climate analysis and monitoring

### 4.3 Quality Control

Quality control (QC) is an essential step in the process of data analysis and preparation. The goal is to identify and remove outliers in the data that are due to placement errors of sensors, sensor malfunctions, sensor inaccuracies or other errors. In the context of PWS, weather stations are placed and maintained by non-professionals, making QC even more important. One of the main challenges in the context of (hyper-) local urban air temperature data is to not flag data as outliers that is representative of the local climate in case of extreme temperature, e.g. heat islands, and at the same time identify erroneous or wrongly placed sensors, e.g. too close to walls, in direct sunlight, indoors, etc. Additionally, current PWS networks do not track sufficient metadata on the sensor placement, e.g. sensor height, which also plays an important role in protecting the privacy of citizens and not exposing too accurate sensor locations.

Due to the popularity of Netatmo weather station data in research due to high spatio-temporal resolution, there are several software libraries available that help simplify and automate the QC process. These tools were primarily developed for Netatmo temperature data, however CrowdQC and TITAN can also be used for other nearly-normally distributed data sources [HGMS<sup>+</sup>22]. The following tools are available:

- CrowdQC (R package <sup>[18](#)</sup>)
- CrowdQC+ [FBD<sup>+</sup>21] (R package <sup>[19](#)</sup>)
- TITAN (R package <sup>[20](#)</sup>)
- NetatmoQC (Python 3 package <sup>[21](#)</sup>)

In this work, CrowdQC+ is used for QC as it offers improvements and bug fixes compared to CrowdQC. It's an open-source software library written in R, a popular programming language for statistical applications. The data needs to be in the following format:

- *p\_id*: The unique ID of the station
- *time*: The time of the measurement
- *ta*: The air temperature in degree Celsius
- *lon*: The longitude of the station

<sup>18</sup><https://doi.org/10.14279/depositonce-6740.3>

<sup>19</sup><https://github.com/dafenner/CrowdQCplus>

<sup>20</sup><https://github.com/mtno/TITAN>

<sup>21</sup><https://source.coderefinery.org/iOBS/wp2/task-2-3/netatmoqc>

- *lat*: The latitude of the station
- *z*: The height of the station in meters, optional

The CrowdQC+ library implements the following required steps of QC: Metadata Check, Distribution Check, Data Validity, Temporal Correlation, Spatial Buddy Check. There are also the following optional steps available, that are currently not used: Temporal Interpolation, Daily Validity, Validity in Time Period, and Correction for Time Constant. The steps used in this work are shown and explained in Table 4.3.1, including the number of data and stations available after each step.

In their own study, CrowdQC+ kept 47.1% and 69.2% of data after steps m1-5, and only 20.7% and 29.5% after steps o1-o3, for the cities Amsterdam and Toulouse respectively [FBD<sup>+</sup>21], given default parameters. In that setting, CrowdQC kept more data with 41.0% in Amsterdam and 54.9% in Toulouse. In this work, CrowdQC+ is used with default parameters excluding height validation, as this data was not available for almost all sensors. Additionally, only the first 5 required steps are used, as the optional steps are not needed for the interpolation. The input data for CrowdQC+ also needs have the same temporal resolution and intervals.

In this study, we use a 10 min interval to have a high temporal resolution and use the default parameters except excluding the height check due to the missing values. Important to note here, that in the following, only the air temperature is validated and not other measurements such as pressure or humidity. CrowdQC+ could be used for other approximately normally distributed features, however there hasn't been more specific research in this direction. We assume that a station that seems to be setup correctly and produces good air temperature measurements, also captures the other measurements correctly for simplicity reasons.

### 4.3.1 Quality Control for Sensor Community

Interesting findings: - way less data does not pass m4 in june compared to january 2023 - more data passes m5 if combined file is used (due to more stations being available)

-> we will use combined data (as both BME280 and DHT22 are good low cost sensors) that passed m5 -> we will not validate humidity, pressure for now

Here comes more data

#### Handling of Moving Sensors

Another question arises about the ability to handle hybrid sensor network data...

## 4.4 Feature Engineering

The goal of feature engineering is to create features from the available data that can be used as input for the machine learning models. The process includes the selection of fea-

Table 4.2: Quality Control Steps of CrowdQC+

Required	<b>Id</b>	<b>Name of Step</b>	<b>Functionality</b>	<b>% of Data</b>	<b>Num Stations</b>	<b>Num Values</b>
	m1	Metadata Check	Validates longitude and latitude values and removes stations with identical values. Mainly aims to remove stations with default values from locations from IP addresses due to improper configuration by the end-user	97.40%	1077	2.082.283
	m2	Distribution Check	Primarily targets radiative error that lead to unrealistic high ta values and sensors installed indoors	86.50%	1041	1.849.247
	m3	Data Validity	Checks values of stations that did not pass m2. If more than 20% of data didn't pass the check, the station is considered to be faulty and is removed	85.20%	845	1.821.479
	m4	Temporal Correlation	Checks the temporal correlation between each station and the median of all stations for a specified period of time, default 1 month. Targets indoor stations that have weak temporal correlation to the median of all stations.	79.90%	829	1.708.061
	m5	Spatial Buddy Check	Neighbourhood-based check to identify outliers within a specific area. Primarily targets radiation errors with too high ta values. Defaults to radius of 3000m and 5 neighbours.	31.53%	466	674.004
Optional	o1	Temporal Interpolation	Step to interpolate missing values in the time-series of each station to increase data availability	-	-	-
	o2	Daily Validity	Verifies robust calculations of daily values	-	-	-
	o3	Validity in Time Period	Checks if enough values are available in a given time frame Sensors have different times that they respond to ta changes.	-	-	-
	o4	Correction for Time Constant	Due to Netatmo design flaws, a constant correction for all stations can be applied.	-	-	-

This table shows the QC steps used in this work from the CrowdQC+ library, including the % of data available after each step, the number of stations available and the number of values left after each step. Optional steps are currently not used.

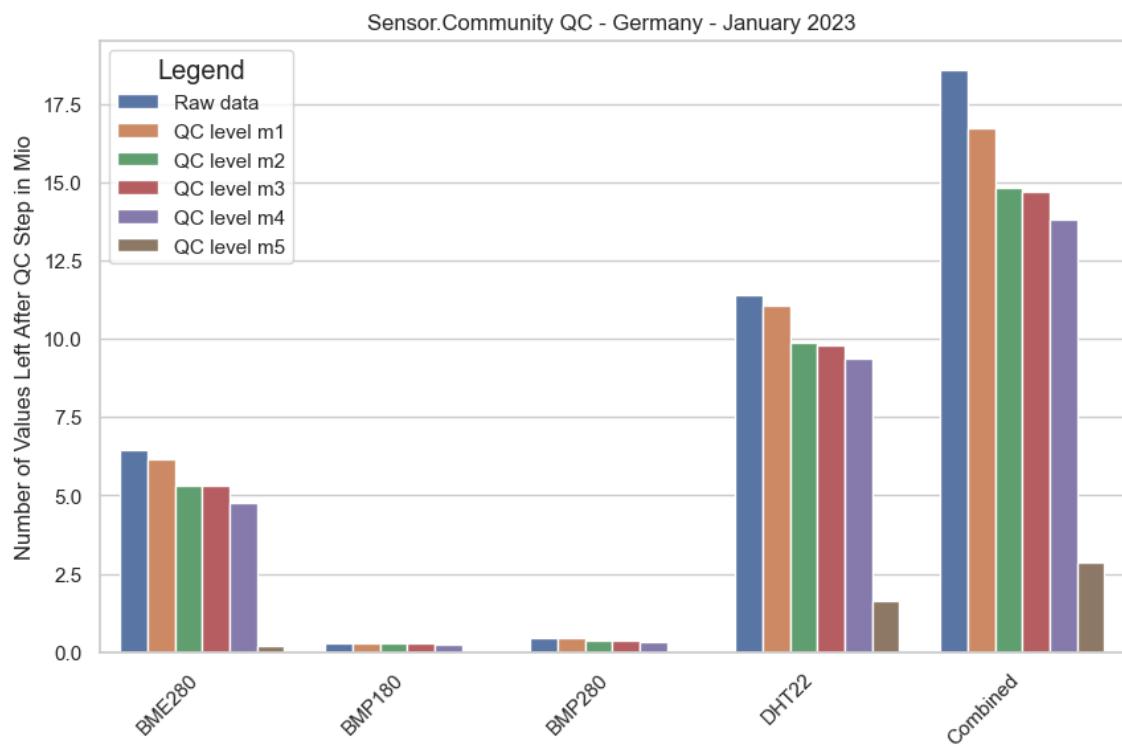


Figure 4.8: QC Results for Sensor.Community Data for Germany, January 2023

tures, the extraction of features from the raw data, and the transformation of features into a format that can be used by the machine learning models. The target feature in this work is the air temperature at 2m height. The input features are a combination of sensor readings from weather stations, sensor networks such as Sensor Community and Netatmo, as well as additional meta data such as soil conditions, zoning plans, vegetation health, and satellite data.

- target variable: air temperature
- input features:
  - weather station measurements (air temperature, humidity, wind speed, wind direction, precipitation)
  - satellite data (surface temperature, surface roughness, soil temperature, land coverage indexes, sky view factor, ...)

Need to separate between reference grade data (weather station calibrated), and low-cost sensors without placement information

- additional goals:
  - collect multiple datasets (many features, fine-granular spatiotemporal)
  - enhance datasets with additional information (soil conditions, zoning plans, vegetation health)

Next to sensor readings captured for a given area, there are also other types of information that could be useful for ML applications. Alonso and Renard [AR20] used these additional indexes to predict air temperature:

- Vegetation Index

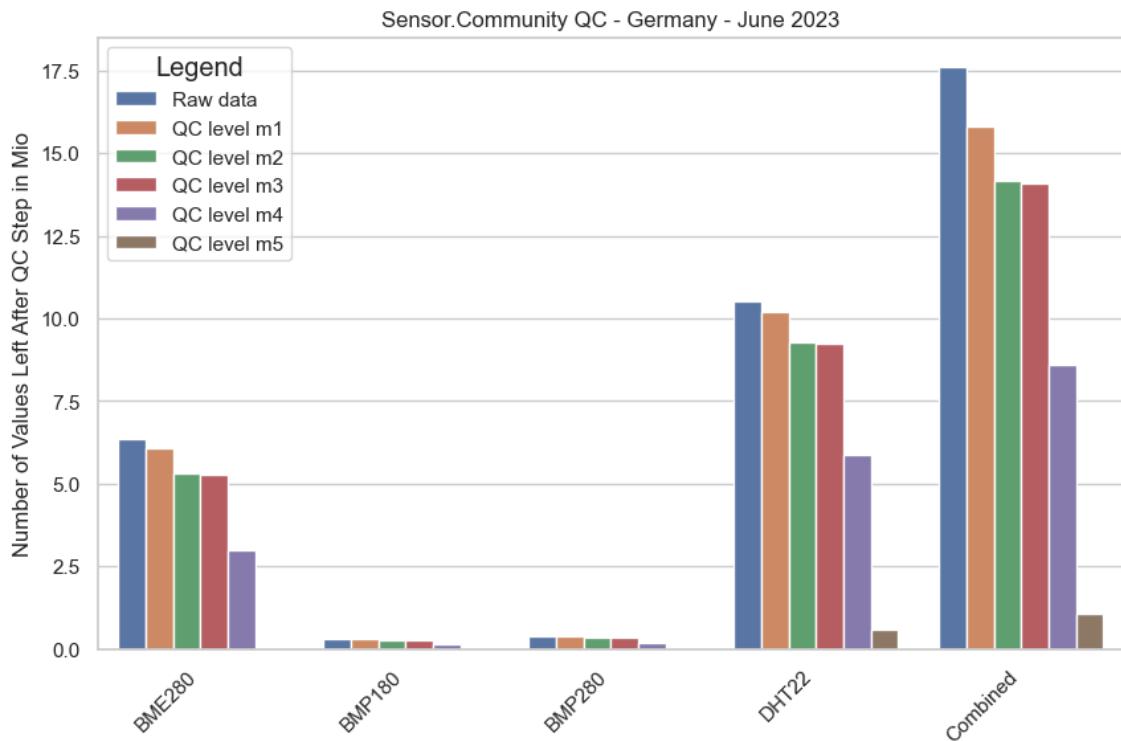


Figure 4.9: QC Results for Sensor.Community Data for Germany, June 2023

- Normalized Difference Vegetation Index (NDVI)
- Soil Adjusted Vegetation Index (SAVI)
- Enhanced Vegetation Index (EVI)
- Tasseled Cap Transformation greenness (GVI)
- Density of low vegetation
- Density of medium vegetation
- Density of high vegetation
- Water Presence Index
  - Modified Normalized Difference Water Index (MNDWI)
  - Normalized Difference Water Index (NDWI)
- Moisture Index
  - Tasseled cap Transformation Wetness
  - Normalized Difference Moisture Index (NDMI)
- Bare Soil Index
  - Normalized Difference Bareness Index (NDBal)
  - Bare Soil Index (BI)

- Enhanced Build-Up and Bareness Index (EBBI)
- Density of bare soil
- Radiation Index
  - Spectral radiance
  - Emissivity
  - Tasseled Cap Transformation Brightness
- Building Index
  - Normalized Difference Build-Up Index (NDBI)
  - Urban Index (UI)
  - Index-based Build-Up Index (IBI)
  - Building Density
- Topographic
  - Slope ( $^{\circ}$ )
  - Exposure
  - Curvature
- Urban morphology
  - Sky View Factor
  - Standard Deviation (STD) of Building Height (building height variation)
- Land use
  - Distance to railway tracks
  - Distance to points of tourist interest
  - Distance to subway entrances
  - Distances to fountains
  - Water area

These types of data can be sourced either directly via satellites like LiDAR or Landsat 8, or via geoportals that publish such data, like the State Office for Geoinformation and Surveying Hamburg<sup>22</sup> on a regional basis or the EU Inspire Geoportal<sup>23</sup> on a continental basis.

ref to google earth engine [GHD<sup>+17</sup>]

Features: - completed: - ndvi, evi (modis) -> 500m, 16 days - todo: - lai, nb

---

<sup>22</sup><https://geoportal-hamburg.de/geo-online/>

<sup>23</sup><https://inspire-geoportal.ec.europa.eu/>

Hyperlocal Mapping in Oslo: Red Landsat 7, 8 and Sentinel 2 Open source L: 30 m, S: 10 m Green Blue Near infrared Short-wave infrared 1 L: 30 m, S: 20 m Short-wave infrared 2 NDVI L: 30 m, S: 10 m IBI L: 30 m, S: 20 m Land surface temperature Landsat 7, 8 30 m Elevation above sea STRM 30 m Terrain aspect Terrain slope Terrain ruggedness CHM LiDAR Closed source 1m CHM slope CHM aspect CHM shadow/SVI Building height LiDAR + building footprint Building height sd 1–4m Building height sd 4–20 m Building height sd 20–100 m Fractional tree cover LiDAR + orthophoto Tree height Distance to coast Global water occurrence Open source 30 m Distance to fresh water

Hamburg ICDC overview: - atmospheric data - air temperature - pressure - wind - precipitation - clouds - aerosols - humidity - radiation - climate indices - ocean - water temperature - wave height (SSH) - salt content - tide - ocean color (e.g. plankton etc.) - climatology - ocean currents - ice/snow - sea ice coverage - sea ice thickness - sea ice type - snow thickness (ice) - snow water equivalent (SWE) - land snow cover - glacier thickness - melting ponds - land - albedo - surface temperature - vegetation - soil moisture - topography - short-wave radiation - perma-frost - society - social science parameters

---

## 5 Evaluation

TODO First compare only air temperature for stations that are near a reference station and have enough buddies for sensor community - only for june 2023 from sensor community, not january as heat islands are not as important in winter (which depends on the context ofc if the goal is f.e. to save heating costs, could be a factor)

Steps in the evaluation: - find sensor community stations near reference stations that passed m5 QC step - Compare different interpolation approaches - linear, forests, KNN, NNNetwork - with different amounts of data available (99% -> 1%) and see how RSME evolves

1. Data Collection and rough analysis
  - 1.1. Get data from Sensor.Community
  - 1.2. Get data from DWD
  - 1.3. Get data from satellites via Google Earth Engine
  - 1.4. Get data from Netatmo (Hamburg, try to get Stuttgart as reference with historical data via API)
2. QC steps (TA first)
  - 2.1. Try to remove indoor stations and stations with irregular data
  - 2.2. Remove stations based on buddy check (removes a lot of sensor community stations due to lower density)
  - 2.3. Reference station has high quality data already, but can be used as a reference (interesting the comparison from 2m TA to 5cm TA)
  - 2.4. Discuss QA for other parameters (Humidity, Pressure etc.)
3. Comparison of models
  - 3.1. Simple models with only coordinates as input features and TA as target feature
  - 3.2. Add additional features (land coverage (NDVI, EVI)) and see how they improve the model
    - 3.2.1. For land coverage etc. compare different satellites and resolutions
    - 3.2.2. For coordinates/distances, compare different ways of calculating distances or modelling them in the model
    - 3.2.3. Compare influence of normalization
  - 3.3. Try to create a more complex NN model to show capabilities of NNs and try out LSTM for time series
  - 3.4. Compare different loss functions and metrics (MSE, MAE, RMSE)
  - 3.5. Choose final candidate that seems the most promising and compare with reference approach
4. Comparison with reference approaches
  - 4.1. Compare with simple Ordinary Kriging approach (with different kernels)
  - 4.2. Discuss problem of not being able to extrapolate

### 5.1 Identifying Sensors for Evaluation

- find locations that are:  
- somewhat near reference stations for comparison  
- high station density  
- interesting features (e.g. parks, water, ...)

- locations in Germany for Sensor.Community are:  
- Stuttgart (birthplace of Sensor.Community) with high station density + one reference station somewhat close - Hamburg with lower

---

sensor density, but 2 reference stations (interesting to see changes between those over relatively short distances) and close to water/river (Elbe) - other candidates (but with way fewer sensor and no reference stations): Cologne, Munich, Freiburg (interesting that they have an airport but no reference station), Lüneburg - interesting to note, that Berlin did not have any sensor stations that passed the QC step

- we choose stations from Stuttgart and Hamburg for the evaluation -> identify stations with high mean daily temperature difference to reference station (to see if they are in a heat island)

### 5.1.1 Stuttgart

Station Locations:

DWD Reference location: 48.6883;9.2235 -> DWD id: 4931, Daily Max, Mean and Min values for June 2023

Steps: - deterministic approaches - "naive" approach with nearest neighbor -> show high error rate - probabilistic approaches - reference approach with geostatistical methods (ordinary kriging, empirical bayesian kriging, EBK with regression) -> still high error rate, especially with lower density of weather stations/bad support for irregularly spaced data - ordinary kriging: - temperature semivariogram first - add additional features (e.g. soil temperature, land coverage, sky view factor, ...) as semivariograms and use cokriging to combine them - empirical bayesian kriging: - not implemented out of the box (pykrige)

- semivariogram: <https://pro.arcgis.com/en/pro-app/latest/help/analysis/geostatistical-analyst/understanding-a-semivariogram-the-range-sill-and-nugget.htm>

- deep learning approach with neural networks -> iteratively improve model by adding additional features, compare with reference approach

## 5.2 Geostatistical Interpolation Comparison

In order to evaluate the performance of the ML model, we need to first get a better understanding of the interpolation quality of existing interpolation techniques. Next to simpler deterministic interpolation methods, such as inverse weight distance (IWD) or k-nearest neighbours (KNN) that are easy and performant, but struggle to capture more complex interdependencies, there are also more complex methods available. The most common geostatistical method for interpolation is Kriging, which is based on a gaussian process and uses a covariance function to model the spatial correlation between data points. The covariance function is a measure of the similarity between two data points, which is used

---

to calculate the weight of the data point in the interpolation process. There are different types of Kriging methods available, each suited for different use cases, including:

1. Simple Kriging: the simplest form of Kriging, that assumes that the mean of the measured values is known and constant
2. Ordinary Kriging: same as Simple Kriging, but the mean is an unknown constant
3. Universal Kriging: instead of assuming a constant mean, the mean is modeled as a deterministic function
4. Indicator Kriging: same as Ordinary Kriging, but for categorical data
5. Probability Kriging: same as Indicator Kriging, but assumes two types of random errors that can be each auto-correlated and cross-correlated to each other
6. Disjunctive Kriging: same as Ordinary Kriging, but tries to improve the prediction quality by using an unknown constant and approximating an arbitrary function. It requires the bivariate normality assumption and is difficult to verify and solutions might be mathematically and computationally complicated
7. Cokriging: offers methods for the previous Kriging methods, but uses information on several variable types. This could improve the prediction quality, but might increase the variance of the prediction, as more estimation is required

In the context of geostatistical analysis, there are different types of Kriging methods available that combine the aforementioned methods with other techniques, such as regression analysis. The following list is the geostatistical methods offered by ArcGIS Pro as part of the Geostatistical Analyst toolbox<sup>1</sup>:

1. Empirical Bayesian Kriging (EBK)
2. Empirical Bayesian Kriging 3D (EBK3D)
3. EBK Regression Prediction (EBKRP): Empirical Bayesian Kriging with regression prediction
4. Global Polynominal Interpolation
5. Kernel Interpolation with Barriers
6. Moving Window Kriging
7. Radial Basis Function

---

<sup>1</sup><https://pro.arcgis.com/en/pro-app/latest/tool-reference/geostatistical-analyst/an-overview-of-the-geostatistical-analyst-toolbox.htm>

In the scope of this work, we unfortunately cannot compare all of these methods with each other and therefore need to focus on a subset of methods. EBK and EBKRP are one of the most commonly used methods for temperature interpolation (cite). According to [NAEB23], EBKRP continuously outperforms EBK in different weather station density scenarios, therefore we will use EBKRP as a baseline for our comparison.

In the following, the machine learning fundamentals for this work are explained and the different ML regression model types are introduced.

## 5.3 Model Evaluation

TODO

### 5.3.1 Model Validity

Use 70% of data for training, 30% for test. cross-validation

## 5.4 Variable Importance

## 5.5 Uncertainty Analysis

measurement uncertainty, contextual uncertainty, prediction uncertainty

1. Data Collection and rough analysis
  - 1.1. Get data from Sensor.Community
  - 1.2. Get data from DWD
  - 1.3. Get data from satellites via Google Earth Engine
  - 1.4. Get data from Netatmo (Hamburg, try to get Stuttgart as reference with historical data via API)
2. QC steps (TA first)
  - 2.1. Try to remove indoor stations and stations with irregular data
  - 2.2. Remove stations based on buddy check (removes a lot of sensor community stations due to lower density)
  - 2.3. Reference station has high quality data already, but can be used as a reference (interesting the comparison from 2m TA to 5cm TA)
  - 2.4. Discuss QA for other parameters (Humidity, Pressure etc.)
3. Comparison of models
  - 3.1. Simple models with only coordinates as input features and TA as target feature
  - 3.2. Add additional features (land coverage (NDVI, EVI)) and see how they improve the model
    - 3.2.1. For land coverage etc. compare different satellites and resolutions
    - 3.2.2. For coordinates/distances, compare different ways of calculating distances or modelling them in the model
    - 3.2.3. Compare influence of normalization
  - 3.3. Try to create a more complex NN model to show capabilities of NNs and try out LSTM for time series
  - 3.4. Choose final candidate that seems the most promising and compare with reference approach
4. Comparison with reference approaches
  - 4.1. Compare with simple Ordinary Kriging approach (with different kernels)
  - 4.2. Discuss problem of not being able to extrapolate

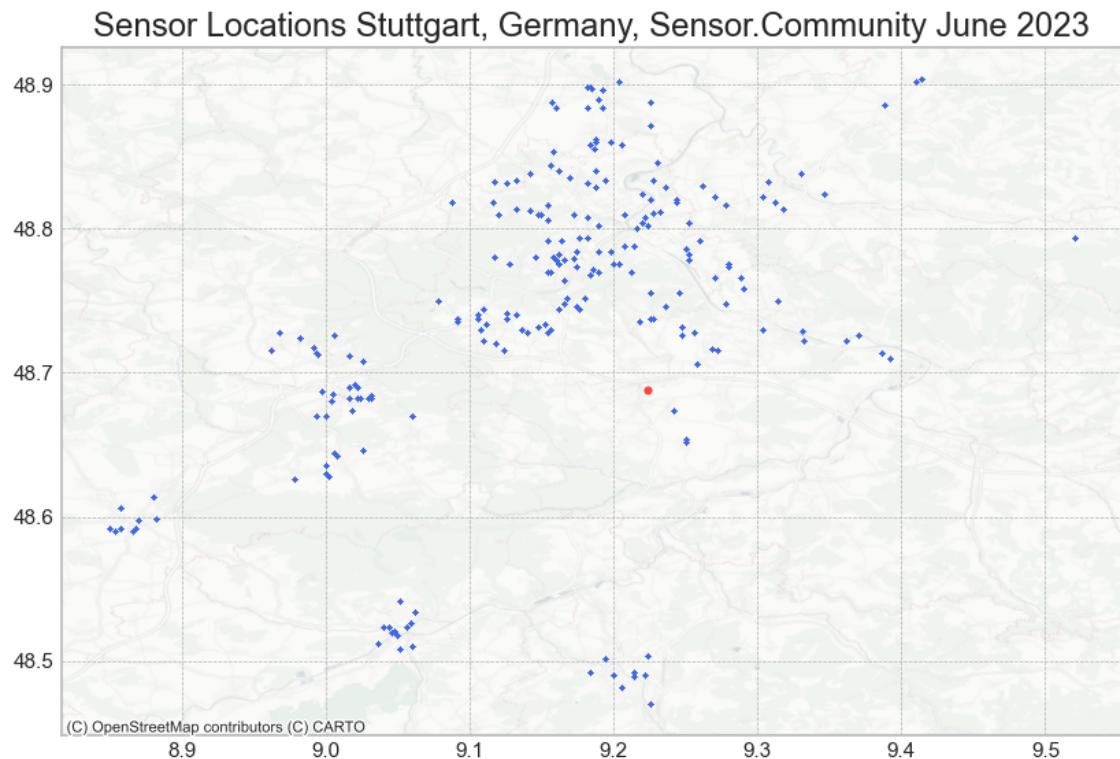


Figure 5.1: Locations for Sensor.Community around Stuttgart, Germany, June 2023

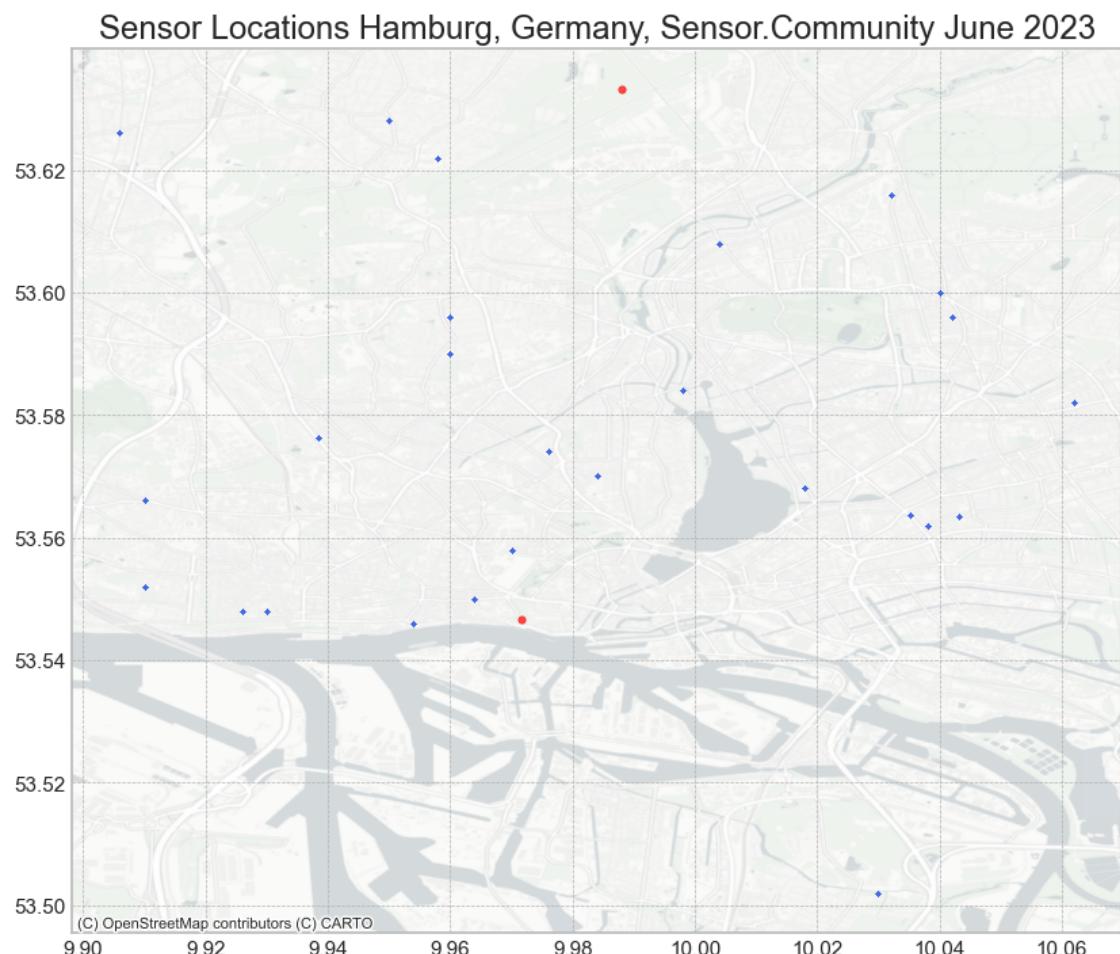


Figure 5.2: Locations for Sensor.Community in Hamburg, Germany, June 2023

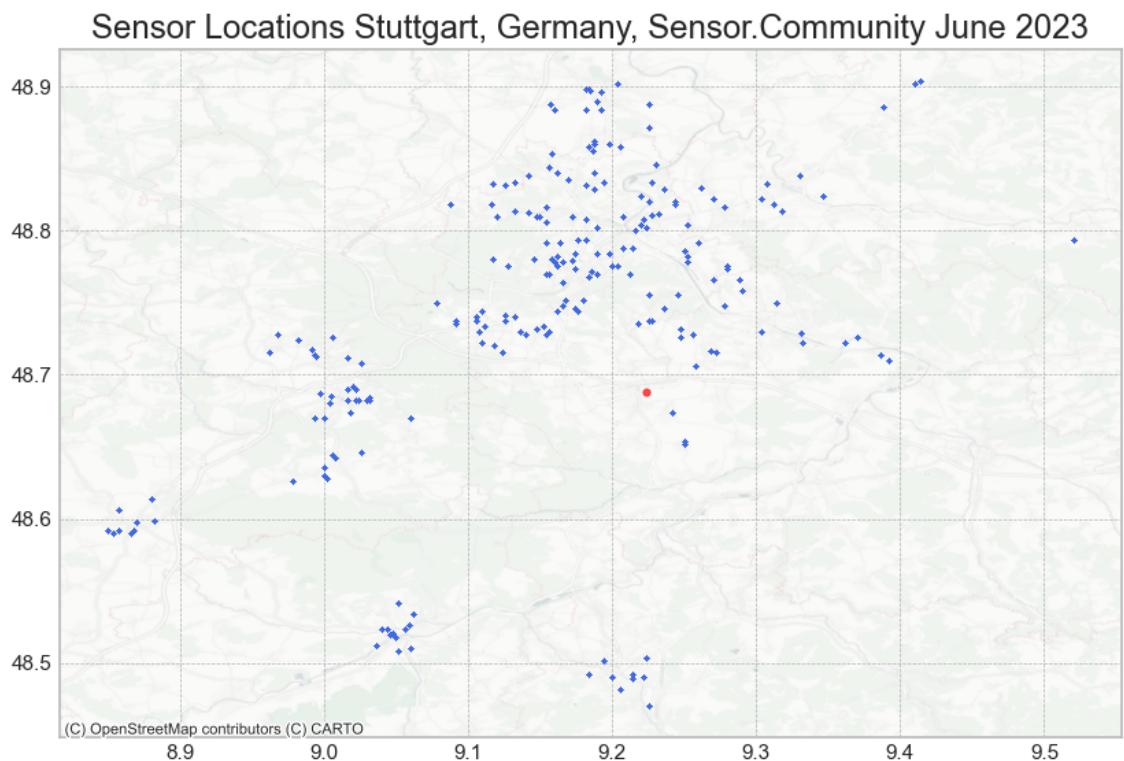


Figure 5.3: Locations for Sensor.Community around Stuttgart, Germany, June 2023

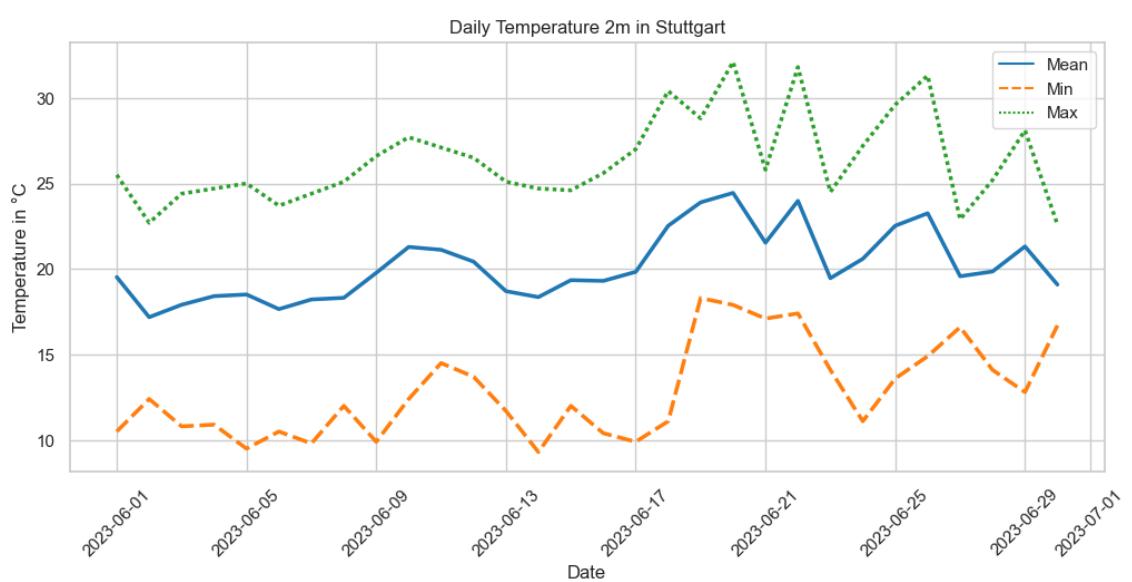


Figure 5.4: Daily Mean, Max, and Min Air Temperature at 2m in Stuttgart, Germany, June 2023, DWD Station 4931

# 6 Conclusion

## 6.1 Summary

- discuss low amount of parameters and curse of dimensionality

TODO: Rewrite once Evaluation done

With the growing need to analyze microclimates of cities in order to protect them against new phenomena like UHIs, this paper proposes the use of citizen-owned sensor networks that offer a higher spatial and temporal resolution of data points in comparison to traditional approaches such as relying on LST data. This approach also comes with challenges such as observing areas without stationary sensors and identifying poor quality data-points from broken or incorrectly installed sensors. With the obtained data, we create a temperature interpolation service that predicts temperature data between data points using a regression model that can act as a building block for further temperature-based analysis by abstracting the underlying single data-points in the data-layer away. In order to improve the quality of temperature predictions for unobserved areas, we investigate how temporary sensor readings, f.e. by attaching sensors to buses, bikes or e-scooters, can be used to capture temporary local meteorological snapshots, and how these snapshots can be incorporated into the interpolation process. We also evaluate which features need to be captured to generate the most accurate predictions, if machine-learning is a suitable approach, and how it compares to more traditional geostatistical approaches.

Possible improvements: - QC -> use different time intervals, investigate different qc processes for other variables, how it looks with reference stations, combining more data, bias of specific sensors etc., not default parameters, e.g 3000m radius too big?

Support for existing findings: - harder to interpolate when it's hotter/air temperature is more variable - harder to interpolate when there is less data - surface temperature/temperature near the ground way more variable and less useful in predicting UHIs

Other options (not yet shown): (harder to interpolate closer to water/big rivers)

New findings: - SensorCommunity data cannot substitute Netatmo data due to low sensor density, and data quality an issue, however data availability is comandable

---

## 6.2 Future Outlook

TODO

# Bibliography

- [Alt92] ALTMAN, Naomi S.: An introduction to kernel and nearest-neighbor non-parametric regression. In: *The American Statistician* 46 (1992), Nr. 3, S. 175–185
- [AR20] ALONSO, Lucille ; RENARD, Florent: A new approach for understanding urban microclimate by integrating complementary predictors at different scales in regression and machine learning models. In: *Remote Sensing* 12 (2020), Nr. 15, S. 2434
- [AYDK22] APAYDIN, Merve ; YUMUŞ, Mehmetan ; DEĞIRMENCI, Ali ; KARAL, Ömer: Evaluation of air temperature with machine learning regression methods using Seoul City meteorological data. In: *Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi* 28 (2022), Nr. 5, S. 737–747
- [BJK<sup>+</sup>19] BORNHOLDT, Heiko ; JOST, David ; KISTERS, Philipp ; ROTTLEUTHNER, Michel ; BADE, Dirk ; LAMERSDORF, Winfried ; SCHMIDT, Thomas C. ; FISCHER, Mathias: SANE: Smart networks for urban citizen participation. In: *2019 26th International Conference on Telecommunications (ICT)* IEEE, 2019, S. 496–500
- [BP47] BALCHIN, William George V. ; PYE, Norman: A micro-climatological investigation of bath and the surrounding district. In: *Quarterly Journal of the Royal Meteorological Society* 73 (1947), Nr. 317-318, S. 297–323
- [Bre96] BREIMAN, Leo: Bagging predictors. In: *Machine learning* 24 (1996), S. 123–140
- [Bre99] BREIMAN, Leo: Pasting small votes for classification in large databases and on-line. In: *Machine learning* 36 (1999), S. 85–103
- [Bre01] BREIMAN, Leo: Random forests. In: *Machine learning* 45 (2001), S. 5–32
- [Büc18] BÜCHAU, Yann G.: *Modelling Shield Temperature Sensors: An Assessment of the Netatmo Citizen Weather Station*, Universität Hamburg, Diss., 2018
- [CDS<sup>+</sup>17] CASTELL, Nuria ; DAUGE, Franck R. ; SCHNEIDER, Philipp ; VOGL, Matthias ; LERNER, Uri ; FISHBAIN, Barak ; BRODAY, David ;

- BARTONOVA, Alena: Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? In: *Environment international* 99 (2017), S. 293–302
- [CH67] COVER, Thomas ; HART, Peter: Nearest neighbor pattern classification. In: *IEEE transactions on information theory* 13 (1967), Nr. 1, S. 21–27
- [CK03] CHONG, Chee-Yee ; KUMAR, Srikanta P.: Sensor networks: evolution, opportunities, and challenges. In: *Proceedings of the IEEE* 91 (2003), Nr. 8, S. 1247–1256
- [CMY<sup>+</sup>15] CHAPMAN, Lee ; MULLER, Catherine L. ; YOUNG, Duick T. ; WARREN, Elliott L. ; GRIMMOND, C Sue B. ; CAI, Xiao-Ming ; FERRANTI, Emma J.: The Birmingham urban climate laboratory: an open meteorological test bed and challenges of the smart city. In: *Bulletin of the American Meteorological Society* 96 (2015), Nr. 9, S. 1545–1560
- [CW11] CAMPBELL, James B. ; WYNNE, Randolph H.: *Introduction to remote sensing*. Guilford Press, 2011
- [Did21] DIDAN, K: MODIS/Terra vegetation indices 16-day L3 global 1 km SIN grid V061 [data set]. In: *NASA EOSDIS Land Processes DAAC*. Available online: <https://lpdaac.usgs.gov/products/mod13a2v061/> (accessed on 1 August 2023) (2021). <http://dx.doi.org/10.5067/MODIS/MOD13A2.061> – DOI 10.5067/MODIS/MOD13A2.061
- [DP10] DARGIE, Waltenebus ; POELLABAUER, Christian: *Fundamentals of wireless sensor networks: theory and practice*. John Wiley & Sons, 2010
- [FBD<sup>+</sup>21] FENNER, Daniel ; BECHTEL, Benjamin ; DEMUZERE, Matthias ; KITTNER, Jonas ; MEIER, Fred: CrowdQC+—a quality-control for crowdsourced air-temperature observations enabling world-wide urban climate applications. In: *Frontiers in Environmental Science* 9 (2021), S. 553
- [FHM<sup>+</sup>19] FENNER, Daniel ; HOLTMANN, Achim ; MEIER, Fred ; LANGER, Ines ; SCHERER, Dieter: Contrasting changes of urban heat island intensity during hot weather episodes. In: *Environmental Research Letters* 14 (2019), Nr. 12, S. 124013
- [Gea54] GEARY, Robert C.: The contiguity ratio and statistical mapping. In: *The incorporated statistician* 5 (1954), Nr. 3, S. 115–146
- [GHD<sup>+</sup>17] GORELICK, Noel ; HANCHER, Matt ; DIXON, Mike ; ILYUSHCHENKO, Simon ; THAU, David ; MOORE, Rebecca: Google Earth Engine: Planetary-scale geospatial analysis for everyone. In: *Remote sensing of Environment* 202 (2017), S. 18–27

- [Goo16] GOOD, Elizabeth J.: An in situ-based analysis of the relationship between land surface “skin” and screen-level air temperatures. In: *Journal of Geophysical Research: Atmospheres* 121 (2016), Nr. 15, S. 8801–8819
- [GRGTDW20] GRÊT-REGAMEY, Adrienne ; GALLEGUILLOS-TORRES, Marcelo ; DISSEGNA, Angela ; WEIBEL, Bettina: How urban densification influences ecosystem services—a comparison between a temperate and a tropical city. In: *Environmental Research Letters* 15 (2020), Nr. 7, S. 075001
- [Gri06] GRIMMOND, CSB: Progress in measuring and observing the urban atmosphere. In: *Theoretical and Applied Climatology* 84 (2006), S. 3–22
- [GVP] GHENT, D. ; VEAL, K. ; PERRY, M.: *ESA Land Surface Temperature Climate Change Initiative (LST\_cci): Multisensor Infra-Red (IR) Low Earth Orbit (LEO) land surface temperature (LST) time series level 3 supercollated (L3S) global product (1995-2020), version 2.00.* <http://dx.doi.org/10.5285/ef8ce37b6af24469a2a4bdc31d3db27d>
- [HDJ<sup>+</sup>02] HARVEY, Nicholas J. ; DUNAGAN, John ; JONES, Mike ; SAROIU, Stefan ; THEIMER, Marvin ; WOLMAN, Alec: Skipnet: A scalable overlay network with practical locality properties. (2002)
- [HEH<sup>+</sup>10] HARRISON, Colin ; ECKMAN, Barbara ; HAMILTON, Rick ; HARTSWICK, Perry ; KALAGNANAM, Jayant ; PARASZCZAK, Jurij ; WILLIAMS, Peter: Foundations for smarter cities. In: *IBM Journal of research and development* 54 (2010), Nr. 4, S. 1–16
- [HGMS<sup>+</sup>22] HAHN, Claudia ; GARCIA-MARTI, Irene ; SUGIER, Jacqueline ; EMSLEY, Fiona ; BEAULANT, Anne-Lise ; ORAM, Louise ; STRANDBERG, Eva ; LINDGREN, Elisa ; SUNTER, Martyn ; ZISKA, Franziska: Observations from Personal Weather Stations—EUMETNET Interests and Experience. In: *Climate* 10 (2022), Nr. 12, S. 192
- [HKS<sup>+</sup>14] HO, Hung C. ; KNUDBY, Anders ; SIROVYAK, Paul ; XU, Yongming ; HODUL, Matus ; HENDERSON, Sarah B.: Mapping maximum urban air temperature on hot summer days. In: *Remote Sensing of Environment* 154 (2014), S. 38–45
- [Ho98] HO, Tin K.: The random subspace method for constructing decision forests. In: *IEEE transactions on pattern analysis and machine intelligence* 20 (1998), Nr. 8, S. 832–844
- [How33] HOWARD, Luke: *The climate of London: deduced from meteorological observations made in the metropolis and at various places around it.* Bd. 3. Harvey and

- Darton, J. and A. Arch, Longman, Hatchard, S. Highley [and] R. Hunter, 1833
- [HSW89] HORNIK, Kurt ; STINCHCOMBE, Maxwell ; WHITE, Halbert: Multilayer feedforward networks are universal approximators. In: *Neural networks* 2 (1989), Nr. 5, S. 359–366
- [IBA<sup>+</sup>22] IYER, Shiva R. ; BALASHANKAR, Ananth ; AEBERHARD, William H. ; BHATTACHARYYA, Sujoy ; RUSCONI, Giuditta ; JOSE, Lejo ; SOANS, Nita ; SUDARSHAN, Anant ; PANDE, Rohini ; SUBRAMANIAN, Lakshminarayanan: Modeling fine-grained spatio-temporal pollution maps with low-cost sensors. In: *npj Climate and Atmospheric Science* 5 (2022), Nr. 1, S. 76
- [iee19] IEEE Standard for Floating-Point Arithmetic. In: *IEEE Std 754-2019 (Revision of IEEE 754-2008)* (2019), S. 1–84. <http://dx.doi.org/10.1109/IEEESTD.2019.8766229>. – DOI 10.1109/IEEESTD.2019.8766229
- [KA06] KAMADA, Yuya ; ABE, Shigeo: Support vector regression using mahalanobis kernels. In: *Artificial Neural Networks in Pattern Recognition: Second IAPR Workshop, ANNPR 2006, Ulm, Germany, August 31-September 2, 2006. Proceedings* 2 Springer, 2006, S. 144–152
- [KB21] KIM, Se W. ; BROWN, Robert D.: Urban heat island (UHI) intensity and magnitude estimations: A systematic literature review. In: *Science of the Total Environment* 779 (2021), S. 146389
- [KBF<sup>+</sup>16] KJELLSTROM, Tord ; BRIGGS, David ; FREYBERG, Chris ; LEMKE, Bruno ; OTTO, Matthias ; HYATT, Olivia: Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts. In: *Annual review of public health* 37 (2016), S. 97–112
- [KH08] KOVATS, R S. ; HAJAT, Shakoor: Heat stress and public health: a critical review. In: *Annu. Rev. Public Health* 29 (2008), S. 41–55
- [KPS<sup>+</sup>11] KOSKINEN, Jarkko T. ; POUTIAINEN, Jani ; SCHULTZ, David M. ; JOFFRE, Sylvain ; KOISTINEN, Jarmo ; SALTIKOFF, Elena ; GREGOW, Erik ; TURTIAINEN, Heikki ; DABBERDT, Walter F. ; DAMSKI, Juhani u. a.: The Helsinki Testbed: a mesoscale measurement, research, and service platform. In: *Bulletin of the American Meteorological Society* 92 (2011), Nr. 3, S. 325–342
- [LF14] LECLERC, Monique Y. ; FOKEN, Thomas: *Footprints in micrometeorology and ecology*. Bd. 239. Springer, 2014

- [LG12] LOUPPE, Gilles ; GEURTS, Pierre: Ensembles on random patches. In: *Machine Learning and Knowledge Discovery in Databases: European Conference, ECML PKDD 2012, Bristol, UK, September 24-28, 2012. Proceedings, Part I* 23 Springer, 2012, S. 346–361
- [Low77] LOWRY, William P.: Empirical estimation of urban effects on climate: a problem analysis. In: *Journal of Applied Meteorology and Climatology* 16 (1977), Nr. 2, S. 129–135
- [LPS18] LEWIS, Alastair ; PELTIER, W R. ; SCHNEIDEMESSER, Erika von: Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications. (2018)
- [LSF19] LORENZ, Ruth ; STALHANDSKE, Zélie ; FISCHER, Erich M.: Detection of a climate change signal in extreme heat, heat stress, and cold in Europe from observations. In: *Geophysical Research Letters* 46 (2019), Nr. 14, S. 8363–8374
- [MBG15] MARTIN, Philippe ; BAUDOUIN, Yves ; GACHON, Philippe: An alternative method to characterize the surface urban heat island. In: *International journal of biometeorology* 59 (2015), S. 849–861
- [MCG<sup>+</sup>13] MULLER, Catherine L. ; CHAPMAN, Lee ; GRIMMOND, CSB ; YOUNG, Duick T. ; CAI, Xiaoming: Sensors and the city: a review of urban meteorological networks. In: *International Journal of Climatology* 33 (2013), Nr. 7, S. 1585–1600
- [MFG<sup>+</sup>17] MEIER, Fred ; FENNER, Daniel ; GRASSMANN, Tom ; OTTO, Marco ; SCHERER, Dieter: Crowdsourcing air temperature from citizen weather stations for urban climate research. In: *Urban Climate* 19 (2017), S. 170–191
- [Mor48] MORAN, Patrick A.: The interpretation of statistical maps. In: *Journal of the Royal Statistical Society. Series B (Methodological)* 10 (1948), Nr. 2, S. 243–251
- [MPV21] MONTGOMERY, Douglas C. ; PECK, Elizabeth A. ; VINING, G G.: *Introduction to linear regression analysis*. John Wiley & Sons, 2021
- [MR06] MEINSHAUSEN, Nicolai ; RIDGEWAY, Greg: Quantile regression forests. In: *Journal of machine learning research* 7 (2006), Nr. 6
- [NAEB23] NJOKU, Elijah A. ; AKPAN, Patrick E. ; EFFIONG, Augustine E. ; BABATUNDE, Isaac O.: The effects of station density in geostatistical prediction of air temperatures in Sweden: A comparison of two interpolation techniques. In: *Resources, Environment and Sustainability* 11 (2023), S. 100092

- [Oke73] OKE, Tim R.: City size and the urban heat island. In: *Atmospheric Environment* (1967) 7 (1973), Nr. 8, S. 769–779
- [Oke76] OKE, Timothy R.: The distinction between canopy and boundary-layer urban heat islands. In: *Atmosphere* 14 (1976), Nr. 4, S. 268–277
- [Oke04] OKE, TR: *Siting and exposure of meteorological instruments at urban sites.* 27th NATO/CCMS Int Tech Meeting on Air Pollution Modelling and Application. 2004
- [Oke06] OKE, Timothy R.: Initial guidance to obtain representative meteorological observations at urban sites. (2006), 01, S. 51
- [OMCV17] OKE, Timothy R. ; MILLS, Gerald ; CHRISTEN, Andreas ; VOOGT, James A.: *Urban climates.* Cambridge University Press, 2017
- [OMMF17] OBRADOVICH, Nick ; MIGLIORINI, Robyn ; MEDNICK, Sara C. ; FOWLER, James H.: Nighttime temperature and human sleep loss in a changing climate. In: *Science advances* 3 (2017), Nr. 5, S. e1601555
- [OMPR18] OBRADOVICH, Nick ; MIGLIORINI, Robyn ; PAULUS, Martin P. ; RAHWAN, Iyad: Empirical evidence of mental health risks posed by climate change. In: *Proceedings of the National Academy of Sciences* 115 (2018), Nr. 43, S. 10953–10958
- [Ope23] OPENAI: *GPT-4 Technical Report.* 2023
- [PPC<sup>+</sup>12] PENG, Shushi ; PIAO, Shilong ; CIAIS, Philippe ; FRIEDLINGSTEIN, Pierre ; OTTLE, Catherine ; BRÉON, François-Marie ; NAN, Huijuan ; ZHOU, Liming ; MYNENI, Ranga B.: Surface urban heat island across 419 global big cities. In: *Environmental science & technology* 46 (2012), Nr. 2, S. 696–703
- [RABW23] REY, Sergio ; ARRIBAS-BEL, Dani ; WOLF, Levi J.: *Geographic data science with python.* CRC Press, 2023
- [RGA<sup>+</sup>09] RUNDEL, Philip W. ; GRAHAM, Eric A. ; ALLEN, Michael F. ; FISHER, Jason C. ; HARMON, Thomas C.: Environmental sensor networks in ecological research. In: *New Phytologist* 182 (2009), Nr. 3, S. 589–607
- [Sar21] SARKER, Iqbal H.: Machine learning: Algorithms, real-world applications and research directions. In: *SN computer science* 2 (2021), Nr. 3, S. 160
- [SB92] STOLL, Matthew J. ; BRAZEL, Anthony J.: Surface-air temperature relationships in the urban environment of Phoenix, Arizona. In: *Physical Geography* 13 (1992), Nr. 2, S. 160–179

- [SHN<sup>+</sup>08] SUGAWARA, Hirofumi ; HAGISHIMA, Aya ; NARITA, Ken-ichi ; OGAWA, Hiroko ; YAMANO, Mitsuo: Temperature and wind distribution in an EW-oriented urban street canyon. In: *SOLA* 4 (2008), S. 53–56
- [SJVL<sup>+</sup>13] STONE JR, Brian ; VARGO, Jason ; LIU, Peng ; HU, Yongtao ; RUSSELL, Armistead: Climate change adaptation through urban heat management in Atlanta, Georgia. In: *Environmental science & technology* 47 (2013), Nr. 14, S. 7780–7786
- [SKH18] SILVA, Bhagya N. ; KHAN, Murad ; HAN, Kijun: Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities. In: *Sustainable cities and society* 38 (2018), S. 697–713
- [SKP<sup>+</sup>20] SEKULIĆ, Aleksandar ; KLIBARDA, Milan ; PROTIĆ, Dragutin ; TADIĆ, Melita P. ; BAJAT, Branislav: Spatio-temporal regression kriging model of mean daily temperature for Croatia. In: *Theoretical and Applied Climatology* 140 (2020), S. 101–114
- [SO09] STEWART, Iain ; OKE, TR: Newly developed “thermal climate zones” for defining and measuring urban heat island magnitude in the canopy layer. In: *Eighth Symposium on Urban Environment, Phoenix, AZ*, 2009
- [SO12] STEWART, Ian D. ; OKE, Tim R.: Local climate zones for urban temperature studies. In: *Bulletin of the American Meteorological Society* 93 (2012), Nr. 12, S. 1879–1900
- [Ste11] STEWART, Iain D.: A systematic review and scientific critique of methodology in modern urban heat island literature. In: *International Journal of Climatology* 31 (2011), Nr. 2, S. 200–217
- [Sun51] SUNDBORG, Åke: *Climatological studies in Uppsala: With special regard to the temperature conditions in the urban area.* 1951
- [TDFH<sup>+</sup>22] THOPPILAN, Romal ; DE FREITAS, Daniel ; HALL, Jamie ; SHAZEEER, Noam ; KULSHRESHTHA, Apoorv ; CHENG, Heng-Tze ; JIN, Alicia ; BOS, Taylor ; BAKER, Leslie ; DU, Yu u. a.: Lamda: Language models for dialog applications. In: *arXiv preprint arXiv:2201.08239* (2022)
- [TMJ10] TAI, Amos P. ; MICKLEY, Loretta J. ; JACOB, Daniel J.: Correlations between fine particulate matter (PM2.5) and meteorological variables in the United States: Implications for the sensitivity of PM2.5 to climate change. In: *Atmospheric environment* 44 (2010), Nr. 32, S. 3976–3984

- [TYU86] TRANGMAR, Bruce B. ; YOST, Russel S. ; UEHARA, Goro: Application of geostatistics to spatial studies of soil properties. In: *Advances in agronomy* 38 (1986), S. 45–94
- [UATMG20] ULLAH, Zaib ; AL-TURJMAN, Fadi ; MOSTARDA, Leonardo ; GAGLIARDI, Roberto: Applications of artificial intelligence and machine learning in smart cities. In: *Computer Communications* 154 (2020), S. 313–323
- [VBEM20] VENTER, Zander S. ; BROUSSE, Oscar ; ESAU, Igor ; MEIER, Fred: Hyper-local mapping of urban air temperature using remote sensing and crowd-sourced weather data. In: *Remote Sensing of Environment* 242 (2020), S. 111791
- [VO03] VOOGT, James A. ; OKE, Tim R.: Thermal remote sensing of urban climates. In: *Remote sensing of environment* 86 (2003), Nr. 3, S. 370–384
- [VS17] VOELKEL, Jackson ; SHANDAS, Vivek: Towards systematic prediction of urban heat islands: Grounding measurements, assessing modeling techniques. In: *Climate* 5 (2017), Nr. 2, S. 41
- [VSZ02] VON STORCH, Hans ; ZWIERS, Francis W.: *Statistical analysis in climate research*. Cambridge university press, 2002
- [WMO18] WMO, WMO: Guide to instruments and methods of observation. In: *World Meteorological Organization WMO, URL https://library.wmo.int/index.php* (2018)
- [WYC<sup>+</sup>16] WARREN, Elliott L. ; YOUNG, Duick T. ; CHAPMAN, Lee ; MULLER, Catherine ; GRIMMOND, CSB ; CAI, Xiao-Ming: The Birmingham Urban Climate Laboratory—A high density, urban meteorological dataset, from 2012–2014. In: *Scientific data* 3 (2016), Nr. 1, S. 1–8
- [Wyn85] WYNGAARD, John C.: Structure of the planetary boundary layer and implications for its modeling. In: *Journal of Applied Meteorology and Climatology* 24 (1985), Nr. 11, S. 1131–1142
- [YBZ19] YANG, Jiachuan ; BOU-ZEID, Elie: Designing sensor networks to resolve spatio-temporal urban temperature variations: fixed, mobile or hybrid? In: *Environmental Research Letters* 14 (2019), Nr. 7, S. 074022
- [ZIE10] ZUUR, Alain F. ; IENO, Elena N. ; ELPHICK, Chris S.: A protocol for data exploration to avoid common statistical problems. In: *Methods in ecology and evolution* 1 (2010), Nr. 1, S. 3–14
- [ZKBK21] ZUMWALD, Marius ; KNÜSEL, Benedikt ; BRESCH, David N. ; KNUTTI, Reto: Mapping urban temperature using crowd-sensing data and machine learning. In: *Urban Climate* 35 (2021), S. 100739

- [ZL12] ZHANG, Guoyi ; LU, Yan: Bias-corrected random forests in regression. In: *Journal of Applied Statistics* 39 (2012), Nr. 1, S. 151–160
- [ZPL15] ZHANG, Xiaoyu ; PANG, Jing ; LI, Lingling: Estimation of land surface temperature under cloudy skies using combined diurnal solar radiation and surface temperature evolution. In: *Remote Sensing* 7 (2015), Nr. 1, S. 905–921



# Sensor Community

Listing 1: Sensor Distribution by Country

```

1  {
2      "2023-06-24": {
3          "bme280": {
4              "WORLD": "5006",
5              "DE": "1558"
6          },
7          "bmp180": {
8              "WORLD": "159",
9              "DE": "72"
10         },
11         "bmp280": {
12             "WORLD": "254",
13             "DE": "100"
14         },
15         "dht22": {
16             "WORLD": "5292",
17             "DE": "2590"
18         },
19         "ds18b20": {
20             "WORLD": "29",
21             "DE": "11"
22         },
23         "hpm": {
24             "WORLD": "6",
25             "DE": "1"
26         },
27         "htu21d": {
28             "WORLD": "105",
29             "DE": "14"
30         },
31         "laerm": {
32             "WORLD": "233",
33             "DE": "117"
34         },
35         "nextpm": {
36             "WORLD": "1",

```

```
37         "DE": "1"
38     },
39     "pms1003": {
40         "WORLD": "7",
41         "DE": "2"
42     },
43     "pms3003": {
44         "WORLD": "7"
45     },
46     "pms5003": {
47         "WORLD": "255",
48         "DE": "16"
49     },
50     "pms6003": {
51         "WORLD": "1",
52         "DE": "1"
53     },
54     "pms7003": {
55         "WORLD": "206",
56         "DE": "8"
57     },
58     "ppd42ns": {
59         "WORLD": "2",
60         "DE": "1"
61     },
62     "radiation_sbm-19": {
63         "WORLD": "3"
64     },
65     "radiation_sbm-20": {
66         "WORLD": "7"
67     },
68     "radiation_si22g": {
69         "WORLD": "71",
70         "DE": "54"
71     },
72     "scd30": {
73         "WORLD": "2"
74     },
75     "sds011": {
76         "WORLD": "12199",
77         "DE": "4964"
78     },
79     "sht15": {
80         "WORLD": "1",
81         "DE": "1"
82 }
```

```
83     "sht30": {
84         "WORLD": "130",
85         "DE": "17"
86     },
87     "sht31": {
88         "WORLD": "259",
89         "DE": "57"
90     },
91     "sht35": {
92         "WORLD": "11",
93         "DE": "5"
94     },
95     "sht85": {
96         "WORLD": "2",
97         "DE": "2"
98     },
99     "sps30": {
100        "WORLD": "279",
101        "DE": "53"
102    }
103 }
104 }
```



# **Eidesstattliche Versicherung**

Hiermit versichere ich an Eides statt, dass ich die vorliegende Arbeit im Studiengang XXX selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel – insbesondere keine im Quellenverzeichnis nicht benannten Internet-Quellen – benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus Veröffentlichungen entnommen wurden, sind als solche kenntlich gemacht. Ich versichere weiterhin, dass ich die Arbeit vorher nicht in einem anderen Prüfungsverfahren eingereicht habe und die eingereichte schriftliche Fassung der auf dem elektronischen Speichermedium entspricht.

Hamburg, den \_\_\_\_\_ Unterschrift: \_\_\_\_\_

# **Veröffentlichung**

Ich stimme der Einstellung der Arbeit in die Bibliothek des Fachbereichs Informatik zu.

Hamburg, den \_\_\_\_\_ Unterschrift: \_\_\_\_\_