Deliverable D4.4

“A report compiling the results employing a wireless sensor network in the field”

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1 Document purpose

The original short description of the deliverable as outlined in the proposal is:

> Wireless sensor networks will be first be tested in a lab environment, and then at the different sites chosen in pilots. We will assess how volunteers, during extreme events (temperature, humidity, rainfall) could allow their smart phones to act directly as sensors. We will monitor and discuss with stakeholders the need for maintenance, reliability and robustness and improvements needed for longer deployment, such as lifetime, battery time, and idle time between user access.

During the course of the project, some of the research questions and deliverable definitions had to be re-formulated due to different circumstances. It became obvious that the number of commercial sensors in the cities were pretty high and also increased during the project. The coverage was quite good and also the app development took a fast route to presentation and deployment among the pilots and resulted in a couple of conclusions: that the users of the app did not relate to the sensors nearby in a specific manner and they used the app to report weather data in various ambition levels.

Also, the Covid-19 pandemic situation during 2020 and 2021 prevented us from visiting elderly care centers nor could we travel to the extent we desired in order to maintain old sensors and install new sensors given the local restrictions. This resulted in a quite significant loss of data from the additional sensors installed by the project. The Covid-19 situation also prevented us from discussing with stakeholders to the extent desired, as we found out that meetings were required. It was hard to monitor and give instructions to the users from remote and attendance level was low in the meetings we called for.

However, as mentioned above, the coverage in the pilot cities through the open data is good. Therefore, in this report, we will discuss a couple of the networks deployed, but focus on the experimental Trondheim network and Norrköping.

2 Executive summary

During the project we deployed a set of sensors at different sites/cities and with different stakeholders and groups being active in reporting through the app. The success in deployment varied due to technical issues, maintenance issues during the Covid 19 crisis, and others. For some of the commercial sensors there were intermittent issues with lack of Wifi access, pulled power plugs, etc., and removal of equipment as well as theft. These issues are further described in D4.5.

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3 Background

In the project we deployed sensors in different ways: in (1) Rotterdam, we did not put any effort in installing new sensor stations, as the main focus here was on the app development. In (2) Porto, we relied on the already existing Porto Digital and Netatmo sensors. In (3) Trondheim, we did the same, used the already existing Netatmo and installed more advanced, professional equipment together with cheaper, commercially available products (for the home owners) and studied how they reported data and how well they correlated. In (4) Norrköping, we tried experimental sensor stations with different interaction schemes to test how we could build and interact with a sensor, but also installed commercial Netatmo modules with rain gauges to increase the density of precipitation measurement points.

Further on, we will use the terminology: "commercial sensors" to refer to sensor **stations** that the home owner typically would buy, like a Netatmo weather station, or similar. We will also use the terminology "LCS" as in low-cost sensor for those. With a professional sensor we refer to a dedicated weather station, research-graded, used for capturing elaborate weather data. With experimental sensors we refer to a sensor station that uses a hybrid of professional and cheaper, less accurate sensors, and various ways to communicate the data to the cloud. Further on, a sensor station, or node, typically employs a set of sensors (e.g. temperature, wind, etc.) but we will occasionally refer to the station as a "sensor" as a generic entity that measures and communicates the captured data.

3.1 Sensor stations in Trondheim, Norway, experimental site

The table below compiles the sensor stations and sensors installed at the Dragvoll site.

Sensor	Parameters	Comm.	Cloud platform	Data rate
Onset HOBO RX2100 CELL-4G	Temp, RH, Pressure, Rainfall, Wind speed, Gust speed, Wind direction	4G	hobolink.com	Delivered in 30 min. interval to a local FTP server maintained at NTNU
Libelium Waspmote Plug & Sense	Temp, RH, Pressure, Rainfall, Wind speed, Wind direction	LoraWan	www.thethingsnetwork.org	Real time (10 min cycle) imported to local InfluxDB, using Data API (MQTT) and Node.js

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Netatmo Smart Home Weather Station	Temp. RH, Rainfall, Wind strength, Gust strength, Wind direction	WiFi	www.netatmo.com	Real time (10 min cycle) imported to local InfluxDB, using Node.js

Table 1: The sensors (types, manufacturers, etc.) used in the Trondheim experimental setup.

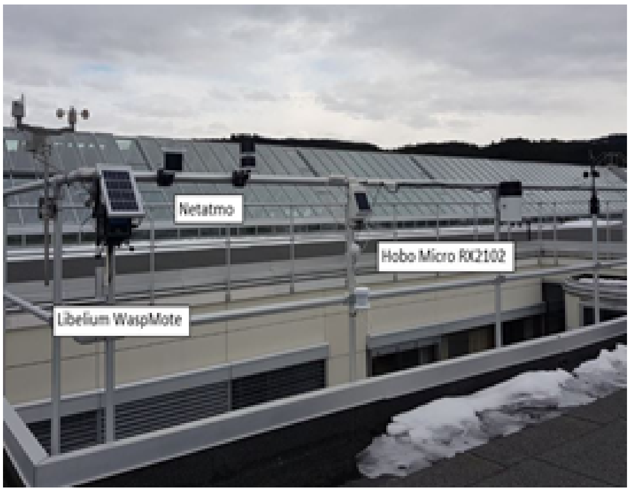

Figure 1: Installation site of citizen sensing sensors in Trondheim (left) and position of Voll weather station and citizen sensing sensors in Trondheim (right).

3.1 Sensor stations in Trondheim, Norway, Netatmos

Related to the campaigns performed in Trondheim, nine Netatmo stations (including rain gauges) were purchased and typically installed near blue spot areas in Trondheim. More on the campaigns and the findings are discussed in WP2. See figures below for the placement of Netatmo sensors in Trondheim.

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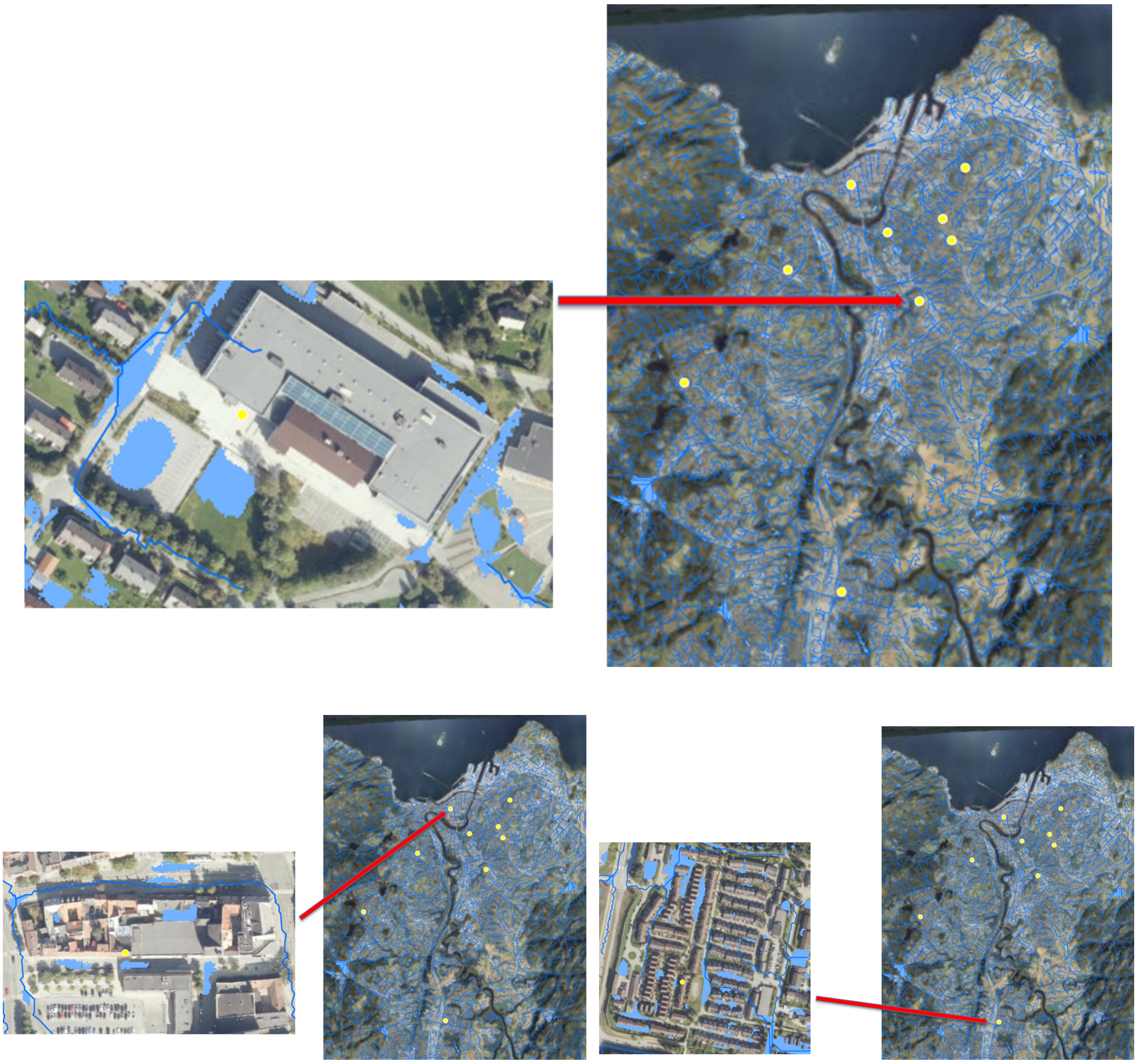

Figure 2: Installations of Netatmo sensors in Trondheim. Zoom-ins are shown illustrating blue spots.

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3.2 Sensor stations in Norrköping, Sweden

An overview of the locations of the Norrköping commercial as well as experimental sensors is shown in figure 3. The stations were deployed close to the operation of the pilot groups and campaigns as well as the university.

Rain gauges are not shipped with the Netatmo “starter kit”, and are also rather expensive. Thus the density of precipitation measurement data is quite low. A starter kit consists of an indoor sensor (temperature, noise, and CO2) and an outdoor sensor with temperature, pressure, and humidity. Therefore, in Norrköping we wanted to increase the density and installed more rain gauges. A total of some 6 rain gauges were installed in the range from Klockartorpet in western Norrköping to Åby and Kolmården (Krokek), northeast of Norrköping.

Besides the deficit in rain gauges, there is already quite good coverage in the city through the existing Netatmo network and their weather map application. The coverage also increased quite much during the span of the project. Further on, the Netatmo sensor station fulfilled the purpose of engaging the citizens. The sensors have a slick design, they have an already developed app, and data can be shared and commented on. Data is also available for download from their portal for the public.

Where it was possible, we had to extend the coverage with and connect to the cloud via local wifi or through 4G-hubs.

As mentioned, the four pilot cities offered four different ways of installing the sensor networks. In Norrköping, more focus was put on the development of different types of sensor hardware and the use of low-cost sensors and perhaps with a more educational and exploring purpose than in the other cities. These experiments are mainly covered in deliverable D4.3 and D4.5.

The experimental sensors consisted of units that could be logged on to via Bluetooth. This would enable citizens passing by a sensor to login to the device and download data, or read the current settings. We wanted to experiment with the active user, and not connect the sensor to any other existing network, like Wifi or GSM/similar. One idea was to consider for example geocaching as a way to collect information from the sensors. These sensors were described in previous deliverables. Due to low engagement and theft, these sensors did not report enough data to make them reliable enough. And more importantly, it was deemed that they could not compete with the commercially available Netatmo in terms of attractiveness, and “plug-and-play” fashion for the users. In D4.5, related to this work package, we further describe issues with the experimental sensors and their installations.

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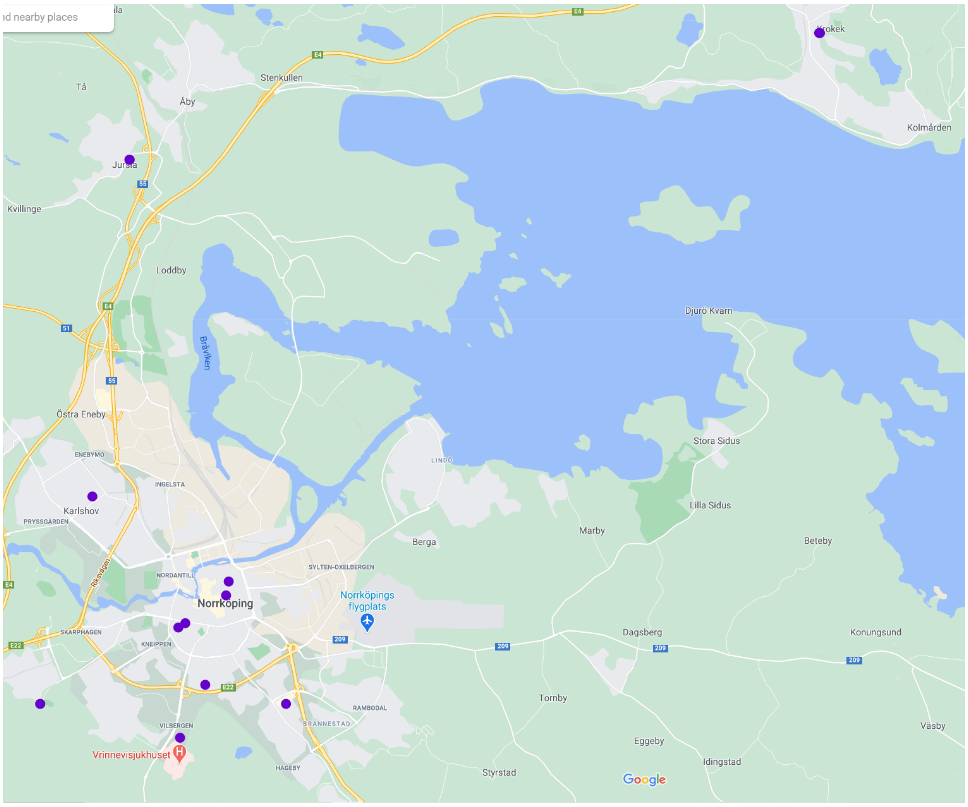

Figure 3: Distribution of the project's commercial Netatmo sensors in Norrköping.

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4 Method

In this deliverable we present information with respect to the calibration of sensor data captured mainly at the Trondheim research site. The method enables us to evaluate how accurate the sensors are and what means we have to employ to calibrate and evaluate the captured data.

4.1 Trondheim - Calibration of sensors

There are many studies that treat the data quality and reliability of LCSs (low-cost sensors). One general conclusion is that LCSs should be treated like any other measuring instrument in terms of assessing the quality and reliability of data. The quality of sensor data depends on many factors: assessment and analysis in the planning and purchasing phase, calibration, careful selection of the installation site, as well as maintenance and periodic quality control.

In general, there are two approaches to calibration:

- Calibration in the laboratory under controlled conditions and known measurement parameters.
    - This is more related to the technical properties of the sensor, response time, sensitivity threshold, linearity in a given temperature range, etc.
- Co-location method, by comparing the measuring sensor with a very precise reference sensor, both installed at the same location and under identical conditions.
    - This refers more to the measurement results themselves, without going into the technical characteristics of the sensors themselves.

The literature knows many methods of comparing data quality of sensors and correction of measured parameters. The most widely methods used are:

- Linear regression, LR
- Multi-linear regression, MLR
- Machine learning techniques using e.g. artificial neural networks, ANN.
- Root mean squared deviations (RMSD)

Root-mean squared deviations can be done once there is a series of data from a very accurate sensor. A series of data from other less accurate sensors could be compared with the most accurate series. For each data point

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(i.e. the temporal resolution used to slice the data) one takes the difference between the values, square the differences, sum all the squared differences, divide by the number of observations (that is number of values in the series) and finally take the root. This method was used for the Rotterdam case within the project [15]. WP4 leader, Rød, et al, found a warm bias in the Netatmo recordings and used RMSD to identify a quantity to which the temperature measured was calibrated with.

Further on, in Trondheim, we used the co-location method to calibrate the sensors and the simplest LR method to correct the data measured by the research-graded sensors. The sensors are installed in one place (within a meter): on the roof of NTNU University at Dragvoll in Trondheim. We were able to perform co-location calibration method in two ways:

- Use a Hobo station as a reference sensor (this is a research grade sensor and was purchased with the idea of using it as a reference sensor) and compare Libelium and Netatmo sensors with a HOBO sensor.
- Use Trondheim Voll meteorological station (part of the Norwegian national network of meteorological stations), which is only 800 m from the Dragvoll building, see Fig. 1b) as a reference sensor, so that all three sensors can be calibrated against Voll stations, including HOBO sensor .

Although the distance between Voll and Dragvoll is comparatively small, the local conditions and the position of the sensors are quite different. The Voll station is located in the open landscape and our sensors are located on the roof of the building that is heated and also affects wind conditions, etc. These conditions can significantly affect the measured values.

Further on, in our report we do not present an analysis of the entire time frame of the project. Instead, to illustrate and highlight the results, we present excerpts of various time periods. Some of this data could thus be biased due to say seasonal conditions.

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5 Results

5.1 Comparison of results from Trondheim

As can be seen in Fig. 2, there are periods when all our sensors follow the reference sensor well, and periods where all three of our sensors deviate significantly from the referenced Voll station. For the purpose of evaluating the LR method (see above), a three-week period, from 15.12.2020 to 05.01.2021, was used. The LR parameters for each sensor were calculated. These parameters were then used to correct the data for all other periods. The results of this correction for the randomly selected two-week period, from 12.01.2021 to 26.01.2021, are shown in Fig. 4. The results show that the Hobo temperature sensor corresponds best with the reference Voll station and Netatmo worst, which was to be expected considering the price of the sensor itself.

Figure 4: Registration of temperature data every 30 min using sensor data from the reference period 15.12.2020 to 05.01.2021.

From the results, we see that using the LR algorithm, bias (as in the systematic, built-in error) is best corrected, while it has little effect on the slope, or scatter R^2. The greatest R^2 is seen in the range of negative temperatures about -5C to -10C. This can be partly explained by the influence of various local factors (the distance between reference and measurement sensors is approximately 800m) and partly by the technical properties of the sensors themselves. The latter is confirmed by studying the correlation between the Libelium and Netatmo sensors against the Hobo sensor, Fig. 7, where the influences of various local factors

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are excluded since all sensors are installed in one place. LR analyses for calibration of Libelium and Netatmo sensors against HOBO sensors shown on Fig. 7 shows similar results. See the Rotterdam approach that further discusses this (section). The diagrams show that the quality of sensor data can be significantly improved by calibrating the sensor using simple LR methods.

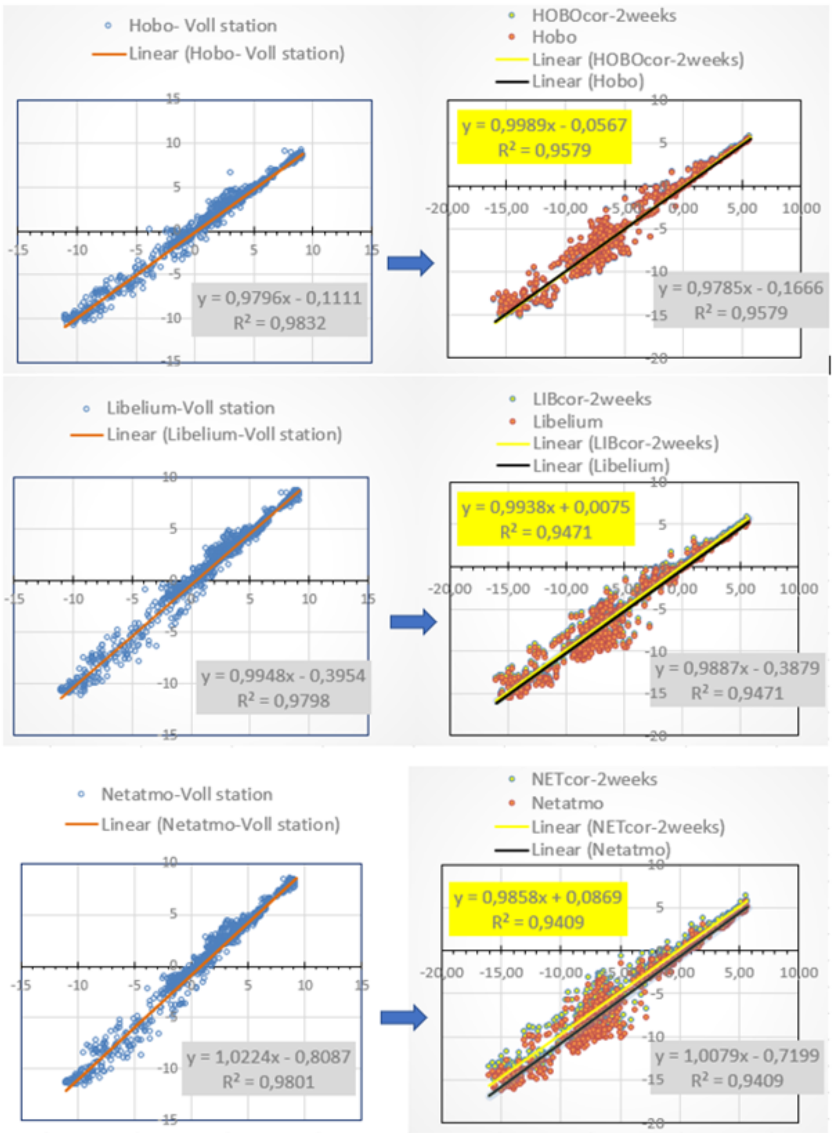

Figure 5: Correlation between CS sensors and Voll station; on the left, calculated LR parameters in period 15.12.2020-05.01.2021; on the right, applied correction for two weeks period 12.01.2021-26.01.2021, shows LR parameters for corrected and uncorrected values for each sensor.

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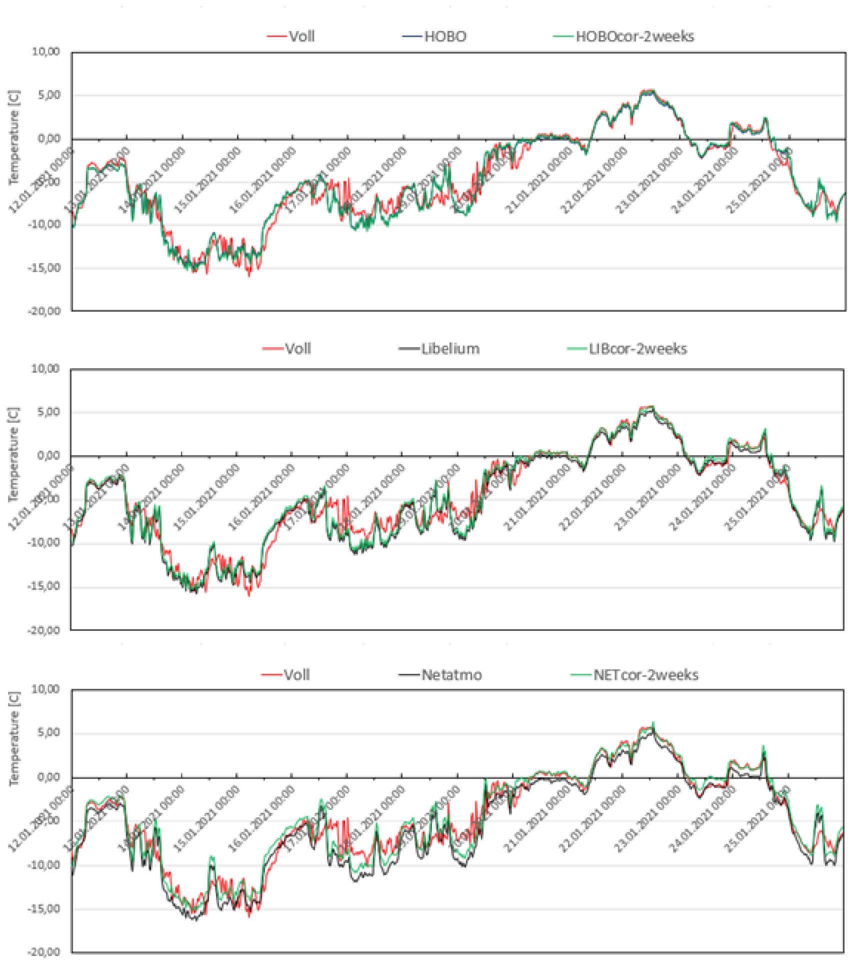

Figure 6: Registration of temperature data every 30 minutes, showing both corrected and uncorrected values for the test period 12.01.2021 - 26.01.2021.

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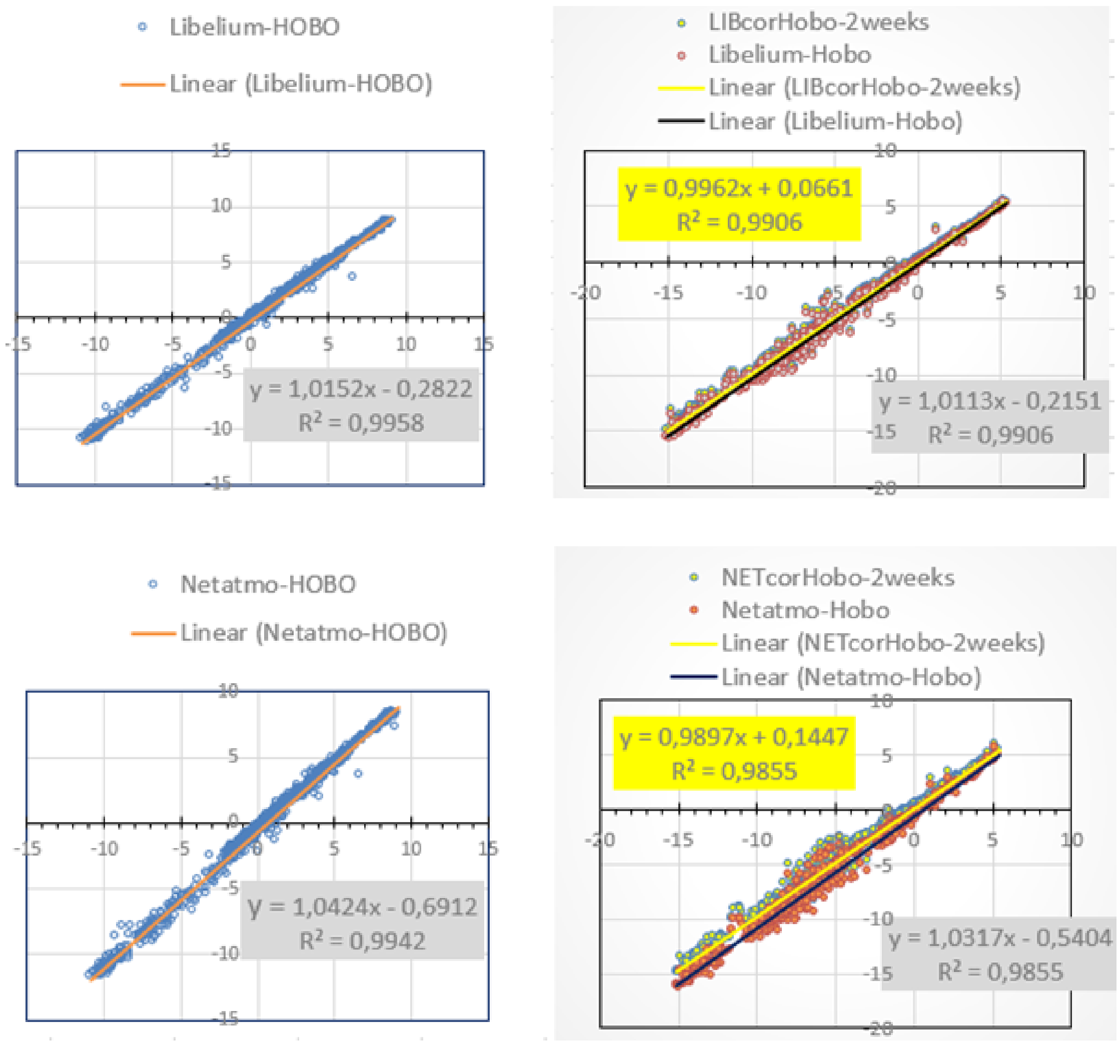

Figure 7: Correlation between Libelium and Netatmo senor against HOBO station; left, calculated LR parameters in period 15.12.2020-05.01.2021; right, applied correction for 2 weeks period 12.01.2021-26.01.2021, show LR parameters for corrected and uncorrected values for each sensor.

5.2 Netatmo vs weather map in the Netherlands

Heat waves are already appearing more often and longer due to climate change. As global warming continues, the numbers of heatwaves are expected to be more intense, more frequent and to last longer in Europe. The Mediterranean region is anticipated to be the most severely affected region and Northern Europe less severe. However, due to the urban heat island effect, a city such as Rotterdam can be up to 10 °C

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warmer than surrounding non-urban areas, and as Dutch cities are densely populated, also the Netherlands have a high potential for adverse impact of future heat waves. As demonstrated by several studies about the urban heat island effect, there is a considerable temperature gradient between rural areas and city centers. However, temperatures also vary within a city due to the heterogeneous nature of urban environments. Official measurement stations are unable to capture such local temperature variations since they use few measurement stations typically set up outside of urban areas. Indeed, classical observational networks are designed for detection of synoptic atmospheric conditions. The official measurement sensors are therefore typically set up outside urban areas to ensure precise and representative observation, not influenced by urban heat islands effects. As such, traditional meteorological measurements are at odds with crowdsourced data collection where absolute accuracy is sacrificed in pursuit of increased coverage which is obtainable by citizen sensing.

Using the heat wave in the Netherlands from July 22 to 27 as a case, we investigate the accuracy of temperature recordings from Netatmo weather stations, we assess whether Netatmo temperature recordings can be used to analyse the temperature variations among land use categories within a city, and finally, based on Netatmo recordings identify where the most heat exposed and heat vulnerable populations are.

We sliced the Netatmo readings into hourly intervals, calculated descriptive statistics, and excluded any observations that were more than three standard deviations from the mean of hourly observations. Regarding the accuracy of the remaining observations from 193 Netatmo weather stations in Rotterdam we find that, compared to official temperature measures, there is a warm bias at about 1.5 degrees Celsius. As more than 85 percent of the Netatmo weather stations are located in build up areas and very few or none in other land use categories, we are unable based on Netatmo recordings to infer whether some land use categories heat up more than others. Such inference should rather be based on satellite thermal imagery although they measure land surface temperatures and not air temperature as Netatmo and official weather stations. To identify the most heat exposed area within built up areas and to identify the most vulnerable population groups living there, we do find that Netatmo sensors are a valuable data source.

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6 Conclusions and future work

From the results at NTNU, we can conclude that the use of LCS to achieve better spatial resolution and to resolve local temporal variability seems to be very justified and encouraging. The above results also show that by using cheap sensors, one can get usable real-time data about consequences of climate changes.

Obtained data from LCS do not have the quality and reliability needed for scientific projects or official control and monitoring, but can be used in all projects aimed to raise awareness of climate changes, increase knowledge especially about local specific conditions and encourage society and individuals to become actively involved and help protect the environment and reduce the risk of the negative consequences of climate changes on the local community and population.

One can note that for negative temperatures, the scatter increases and additional methods could be evaluated, for example ANNs, in order to improve the compensation.

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