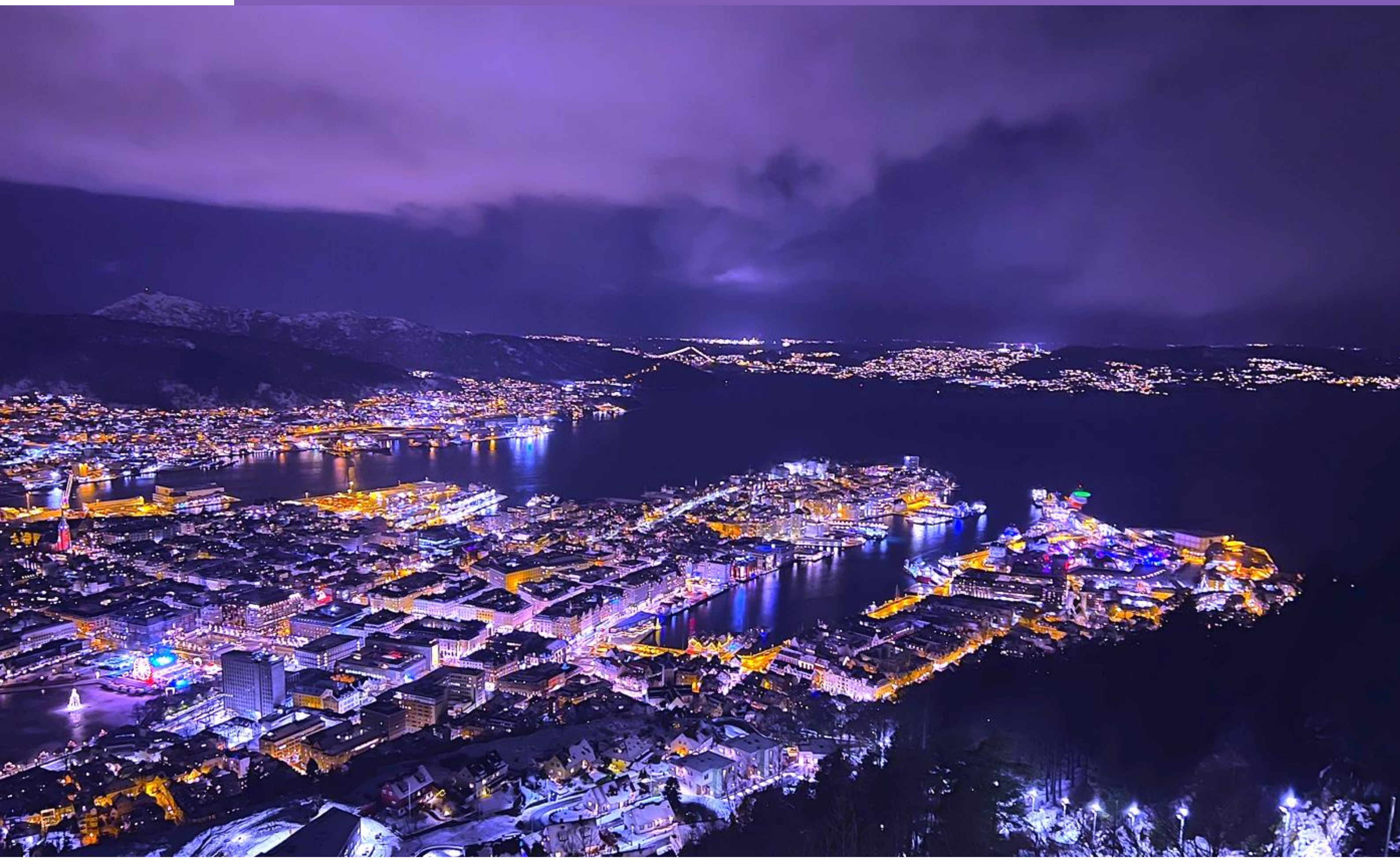
Urban Air Quality and Thermal Comfort: A Case Study in Bergen



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Norway grants

T A C R

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Introduction

The TURBAN project, funded by the Norway Grants and the Technology Agency of the Czech Republic (TA CR), aimed to enhance tools and methods for assessing urban atmosphere and supporting measures to mitigate thermal stress and air pollution. Collaborating partners from both the Czech Republic and Norway worked on improving urban environment quality assessment and modeling, sharing joint approaches to modeling and data analysis. Validation of model tools in both Prague and Bergen ensured the generalizability, applicability, and reliability of methodologies and instruments.

The project achieved several significant milestones:

1. Collected, processed, and published an extensive set of diverse atmospheric observations, including data from specific observation campaigns.
2. Advanced knowledge and capabilities for managing urban climate and air quality, enabling foresight into the impacts of policy actions and socio-economic decisions.
3. Contributed to the scientific understanding of complex atmospheric flow and energy exchanges within the urban canopy, crucial for developing advanced tools for assessing urban thermal comfort and air quality.

In this report, we will be discussing the results of our observations and modeling techniques for certain urban areas in Bergen. Furthermore, we will be exploring the possible mitigation options and ways to communicate and disseminate these results. By conducting specific urban studies in collaboration with relevant city authorities, our project has obtained data and analyses that can be directly used to address local environmental challenges.

Effective communication with local stakeholders was crucial in disseminating the project's findings. To achieve this, the project used webGIS and storytelling to convey complex information in an accessible manner. The project developed a web GIS platform called "Air Quality in Cities and Thermal Comfort: Stories of Urban Air," available in English, Czech, and Norwegian. The platform includes stories about Prague and Bergen, highlighting urban environmental information.

The Bergen webGIS story presents model results and remote sensing studies focused on understanding the impact of environmental challenges. The story highlights measures being taken to address these challenges, such as reducing emissions from wood-burning stoves and promoting sustainable transportation. Structured around a three-step process—understanding the impact, assessing vulnerability and risk, and exploring options—the Bergen story aims to identify effective ways to build a more sustainable and resilient urban environment.

Data and Methods

Communication with stakeholders in Bergen operationalized the area of public interest, where the main efforts were concentrated. Although datasets were retrieved over the whole Bergen municipality, the central districts were prioritised in data analysis (figure 1).

Fig. 1 The 3D map of the project domain in central Bergen. The domains include areas of required project application cases: Bergen Port; Tunnel entrances (Fjelltunnelen, Damsgårdtunnelen, Bytunnelen, Arnatunnelen); Major road conjunctions (Bystasjon, Danmarksplass, Puddefjordsbroen); Major parking houses; Major cultural objects (UNESCO Bryggen, Grieghallen) and shopping malls.

Observations in Bergen

An observational dataset for studies of urban air quality hazard scenarios combines a selection of meteorological, air quality, and geospatial (urban features) data. The preliminary methodology of the data collection and processing for Bergen is described in Wolf et al. (2020) and Varentsov et al. (2020). The Bergen observational data set includes: 11 years of 5 min temperature profiles by MTP-5HE in Bergen centre; 55 DAVIS PRO stations; 4 air quality stations; 7 regular meteorological stations; rain lidar and cloud data from meteorological testbed; 190 citizen stations; a set of remote sensing data products. The data are sampled for two distinct periods:

- Summer – covers 2019-07-20 to 2019-07-27 when one of the strongest historical heatwaves with maximum air temperatures exceeding +30◦C affected Bergen.
- Winter – covers 2021-02-04 to 2021-02-15 when one of the strongest historical coldwaves with temperatures below -10oC and ice covering some the fjords (not observed since 1986) affected Bergen

The dataset combines the observations and surface features within the central urban area – the Bergen valley and Byfjorden where air quality observations are available and the most of available data records are found.

The diverse data sets were converted in CSV, EXCEL, and NetCDF data formats. Python scripts for reformatting the data, reading, control, and eventual visualisation were prepared and are available now. The most intense work was done with NETATMO and MTP-5HE data. The data set was prepared for further analysis in WP4 (deliverables in 2023). Analysis of MTP-5HE data will be published in a peer-reviewed journal in 2023.

The meteorological testbed in Bergen is served with a diverse automated observations. There was no plans for special observational campaigns and additional data collections in the city. Table 1 presents data sets involved in the project. All required data have been downloaded and processed for the project's purposes.

Variable	**Dataset**	**Comment**
Air temperature profile	MTP-5HE dataset	Current data are available from https://veret.gfi.uib.no/
Surface layer meteorology (temperature, pressure, precipitation, humidity, wind)	Regular WMO meteorological dataset	Norwegian Meteorological Service from Norsk Klimaservicesenter (met.no)
Surface layer meteorology (temperature, wind, precipitation)	Davis Pro station network in the framework of a school project	Data are avaialble from Siste målinger - Bergensværet (bergensveret.no)
Surface air temperature	Amateur NETATMO stations	Current data are avaialvle from www.netatmo.com
Air quality data (NOx, PMx, O3)	Dataset from Norwegian Air Research Institute (NILU) and Bergen Municipality	Data are available from https://luftkvalitet.nilu.no/historikk

The most severe air pollution event occurred in January 2010. Persistent temperature inversions led to hourly mean NO_2 concentrations above 400 µg m^{-3} and exceedances of the national target for air quality of hourly mean concentrations of 150 µg m^{-3} at least once per day during 19 days in January 2010. Since 2010, several severe air quality hazards have occurred in Bergen. It is important to take into account that air pollution sources causing the hazards in 2010 (NO_2 exhaust of diesel personal cars), 2019 (NO_2 exhaust of large cruise ships), and 2021 ($PM_{2.5}$ exhaust of wood-burning stoves in households) were different. All episodes triggered public and media attention from the local up to the national levels. This attention justifies our choice of the two latest episodes for the project case study.

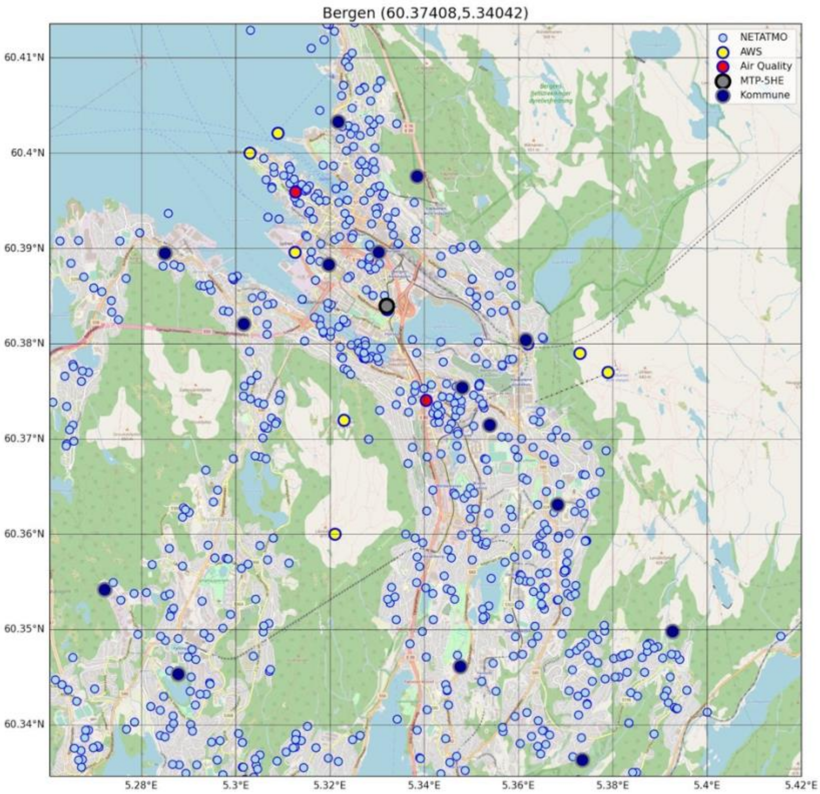


Fig. 2. Locations of all time series (meteorological and air quality) in the project domain (the central part of Bergen municipality). NETATMO is the citizen (amateur) temperature sensor network; AWS is the professional certified automatic weather station network; Kommune is the educational (amateur) weather station network based on DAVIS VANTAGE PRO stations. MTP-5HE is the meteorological temperature profiler. Air Quality is the network of air quality observing stations. Observe that actual accessibility and quality of data vary.

The winter episode 2021-02-04 through 2021-02-15 (Julian days 35-46) is characterised by persistent cold anticyclonic weather, high air pollution, particularly from domestic wood-burning. The summer episode 2019-07-20 through 2019-07-27 (Julian days 201-208) is characterised by persistent hot anticyclonic weather, high air pollution, particularly from cruise ships in the city central districts.

Time series

The dataset includes sampling of time series of meteorological observations from regular and irregular (amateur) stations, from the meteorological temperature profiler MTP-5HE, and from the air quality stations. The basic time series – the most complete and quality-controlled ones – are obtained from Florida AWS, Danmarkplass NILU air quality station, and MTP-5HE at GFI. Fig. 3 shows the combined presentation of the meteorological and air quality data during the winter episode.

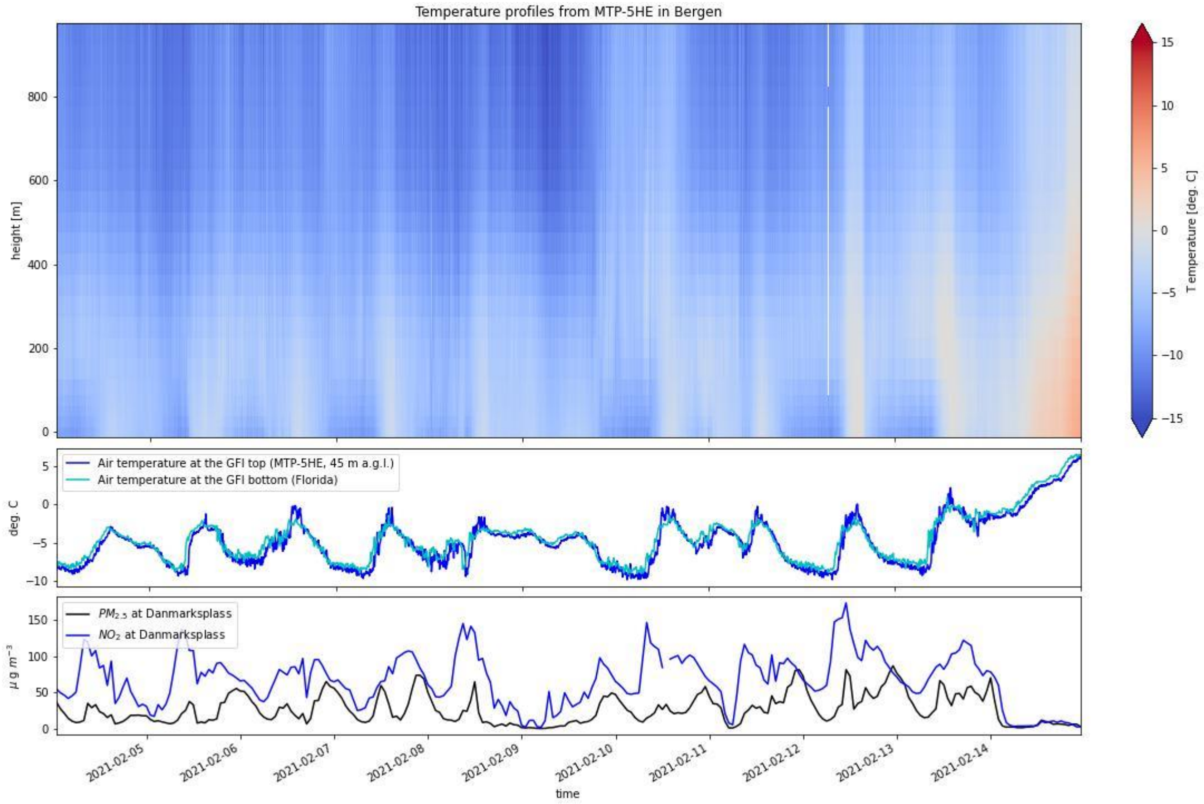


Fig. 3. Combined presentation of the meteorological and air quality conditions during the winter episode.

Geo-spatial and special data sets

Furthermore, the -simulations and data fusion require additional datasets on the state of the surface, physiography, morphology, etc. The datasets are collected from different national sources: Digital Elevation Model (DEM, 1 m resolution from laser scanning) from the Norwegian Kartverket (mapping service) Høydedata og dybdedata | Kartverket.no; Emission inventory data were obtained directly from Bergen Fire Department (wood-burning emissions) and the National Road Authority (traffic emissions). Figure 1 shows locations of the observational points and minimum temperatures (if relevant).

The digital elevation model could be obtained from different sources. The quality-controlled DEM was obtained from the Norwegian mapping authority's (den Norske Kartverket) service. DEM is available in 1 m, 10 m and 50 m resolution in UTM33 projection (converted to EPSG:4326 and EPSG:3857). DEMs of 10 m and 50 m are downloaded for this project. This data is used to setup the PALM model.

There is also auxiliary DEM available from COPERNICUS EOBrowser and ASTER.

DEM from the Norwegian mapping authority has been included by the TURBAN Czech partners in the collection of surface features used for generation of the static driver setup file for the PALM model: **bergen_lod01_static.nc**.

A number of urban feature geospatial datasets have been obtained from Bergen authorities. They are:

- Urban real-estate property codes
- Household warming installations
- Street density

Description	Reference
Digital Elevation Model of the Norwegian mapping authority's (den Norske Kartverket)	https://www.kartverket.no/api-og-data/terrengdata DEM access: https://hoydedata.no/LaserInnsyn2/
High resolution interactive 3D map of Norwegian municipalities	http://3d.kommunekart.com
Detailed online municipality planning maps	https://kommunekart.com/?funksjon=vispunkt&y=-34413.22697587573&x=6715278.148425088&zoom=13&srid=32633
EU digital Elevation Model COPERNICUS EU DEM v1.1	https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1?tab=download

Table 2. Sources of geospatial data

The meteorological, air quality, and satellite observations for the two selected episodes (winter 2021 and summer 2019) have been retrieved from the data sources.

The observations are processed and made open access through the Dataverse.no service; dataset reference:

Ezau, Igor, 2023, "TURBAN – Observational datasets for studies of urban air quality hazard scenarios in Bergen, Norway", https://doi.org/10.18710/QHUAZ2, DataverseNO.

Scenarios in Bergen

The model setup for scenario simulations and ran a number of numerical experiments. The help from the Czech team was essential in this work. We evaluated the feasibility of different runs on the FRAM supercomputer at the SIGMA2 facility in Norway. The high load FRAM enforced us to concentrate on simulations for the central Bergen districts (see Fig. 4 - blue domain). Then, static and dynamic drivers for the PALM simulations were created. The dynamic driver is based on the mesoscale WRF model output prepared by the Czech colleagues. Both scenario episodes were obtained. The static drivers were prepared using the database of the Czech colleagues with added information from the Norwegian mapping authorities. A selection of nested domains has been identified and drawn from the database.

The further work was focus on the domains around Danmarksplass, Bergen. This location integrates both urban effects, challenges and opportunities, namely:

- Air pollution challenge: high average concentrations of pollutants; reliable air quality and meteorological observations; significant public interest and impact on population health.
- Urban climate effects: high population density; the most significant micro-climatic effects - urban ventilation corridors; reliable, diverse, and frequent meteorological observations, incl. temperature profiling.
- Urban development opportunity: important urban development project nearby (see Fig. 4 - the blue domain); changes in traffic intensity, car composition, and patterns.

We have started the PALM investigation of the urban development effects on selected microclimate episodes and studies of the ventilation corridor effects centred at Danmarksplass. The new model version PALM v22.10 has significantly extended the urban modelling capability. Therefore, the previously obtained PALM results could be used only for model comparison and sensitivity specification studies.

Intercomparison of the previous and new PALM runs in this project will highlight the achieved improvements in the model and its increased relevance to stakeholders. The comparison assures that the simulations in the chosen domain provide satisfactory results and that there is no need to inflate the model domain. This analysis is thought of as contributions to V8 and V15 deliverables.

Our analysis of accepted and proposed development plans has resulted in three development scenarios for simulations:

1. The Dense Bergen Scenario (Fig. 5) assumes transition to high building blocks in the domain that covers industrial areas and a part of the sea inlets. Emission from transit traffic will double, but both local emission and ship emission will be eliminated - the port will be electrified and non-electric vehicles will be forbidden from the centre.

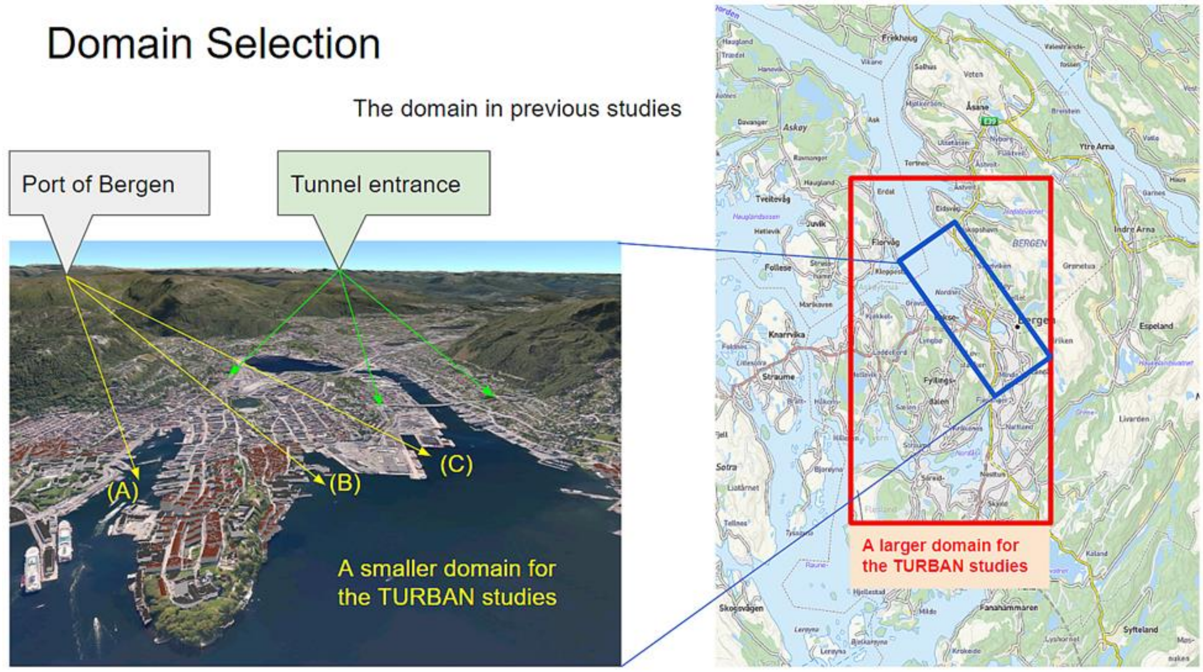


Fig. 4. The PALM domain selection for the project scenario simulations.

2. The Green Bergen Scenario (Fig. 6) assumes a ban on further densification in the domain. The industrial areas and the waterfront will be converted into recreational and tourist areas with larger public access. The transit traffic will be limited to the present numbers. The local and ship emissions will be eliminated.
3. The Business Bergen Scenario (Fig. 7) assumes redevelopment and densification of business and industrial areas but only minor changes in the residential and green areas. The transit traffic emission will double. The local and ship emissions will not change.

The actual development areas will be taken from the municipality development plans and adopted to the simulation domain resolution.

Episode selection

Winter episode	04 – 15 February 2021	Persistent anticyclonic weather conditions
Summer episode	20 – 27 July 2019	Persistent anticyclonic weather conditions

Figure 5. An example of proposed urban development (Venezia in Bergen) in the selected Bergen domain, which is taken into account in the Dense Bergen Scenario. Image source: BOB vil lage tre-Venezia i Bergen – E24.

Figure 6. An example of proposed urban development (Sustainable Laksevåg in Bergen, at present the container port area) in the selected Bergen domain, which is taken into account in the Green Bergen Scenario. Image source: Kunstige øyer og småbåtliv: Se hvordan Bergen kan bli når fergene forlater Dokken - Tu.no.

Figure 7. An example of proposed urban development (Business-as-usual) in the selected Bergen domain, which is taken into account in the Business Bergen Scenario. Image source: VPB Media.

Data fusion

The work is in progress. A working prototype of the kriging-based data fusion is now being ported from MATLAB to the PYTHON modelling environment. The NETATMO acquisition package in python is completed and tested. The work on data fusion has started. We implement the data fusion on the basis of PYKRIGE and GEOSTAT packages (https://geostat-framework.readthedocs.io/projects/pykrige/en/stable/). This development constitutes the base for V11 "Data fusion technology/software package" The results (Fig. 8) shows robustness of the kriging method for NETATMO stations.

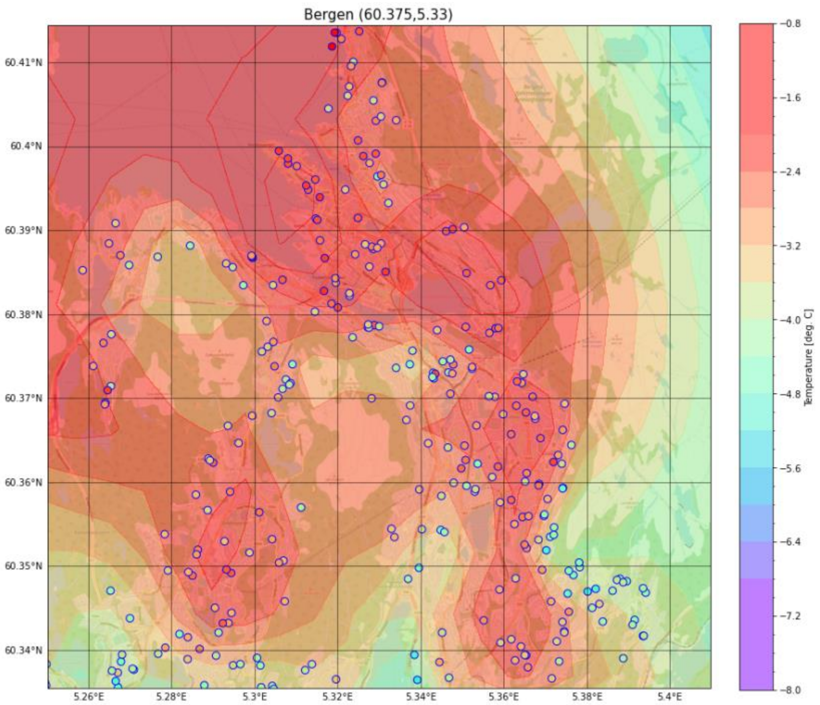


Fig. 8 Preliminary results of the NETATMO temperature kriging (winter episode) with PYKRIGE package and the Hole-Gaussian variogram.

Satellite data

In the project, we focused on free and open data sources, ready-to-use products, or data with easy processing steps. It guarantees easy access and use of the same data source inside and for the project users.

Bergen's analysis is carried out in two spatial scales and three scenarios for modeling development. Therefore, we primarily focused on satellite data in medium and high resolution and satellites that provide data in the thermal channel and the visible spectral range.

MODIS satellites provide required Land Surface Temperature and vegetation data in medium resolution. The MOD11A1 Version 6 product provides daily per-pixel Land Surface Temperature and Emissivity (LST&E) with 1 kilometer (km) spatial resolution in a 1,200 by 1,200 km grid. The pixel temperature value is derived from the MOD11_L2 swath product. Above 30 degrees latitude, some pixels may have multiple observations where the criteria for a clear sky are met. When this occurs, the pixel value results from the average of all qualifying observations. The daytime and nighttime surface temperature bands are associated with quality control assessments, observation times, view zenith angles, clear-sky coverages, and bands 31 and 32 emissivities from land cover types.

The spatial information about the distribution and type of urban vegetation can be assessed using the Normalized Difference Vegetation Index (NDVI). NDVI reflects vegetation productivity and health. NDVI is based on the contrast between red and

NIR reflectance of vegetation, as chlorophyll is a strong absorber of red light, whereas the internal structure of leaves reflects highly in the NIR.

NDVI was obtained from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1) Version 6 data are generated every 16 days at 250 meters (m) spatial resolution as a Level 3 product. The algorithm chooses the best available pixel value from all the acquisitions from the 16 days. The criteria used are low clouds, low view angle, and the highest NDVI/EVI value. Along with the vegetation layers and the two quality layers, the HDF file will have MODIS reflectance bands 1 (red), 2 (near-infrared), 3 (blue), and 7 (mid-infrared), as well as four observation layers.

LANDSAT 8 with 30 m resolution in the visible spectrum and 100 m in thermal channels. A six-step algorithm is required to derive LST from Landsat data. Processing and analysis we carried out in ArcGIS. In addition to the LST data, we calculate other parameters for LANDSAT, such as TOA - Top of atmospheric spectral radiance; BT - of radiance to at-sensor temperature; NDVI; Pv - the proportion of vegetation; LSE - Land surface emissivity and Albedo. We present a fusion of the ground surface temperature map from LANDSAT and the proportion of vegetation in an urban area obtained from NDVI. on Figure 9.

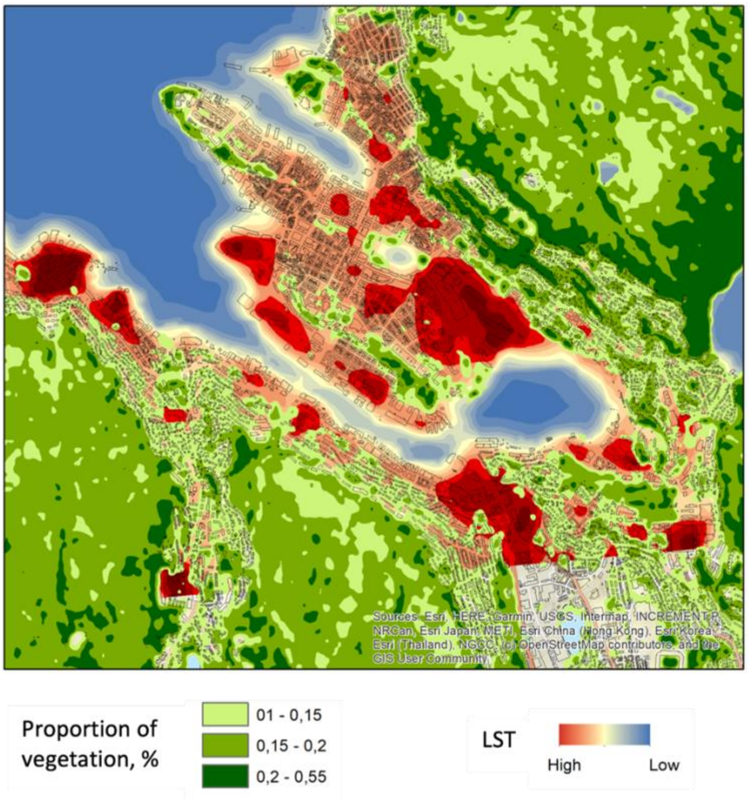


Figure 9. LST map and proportion of vegetation in Bergen for the summer scenario.

WebGIS data

The GIS software used here is ESRI®ArcMap version 10.4.1 for Desktop. The workflow has three stages: data collection, preparation, and comparison. The steps proposed contribute to novel ways to identify and compare spatial configurations by efficiently aggregating and comparing spatial and non-spatial data from different base units (i.e., levels of scales) and different sources. For example, a buffer operation combines spatial and non-spatial data to better compare building-level data with street network values.

Geospatial input data

The spatial data consists of the object (a point, line, or polygon with x-y coordinates) and an attached attribute table of relevant information to the spatial object (i.e., shape, size, ownership information, etc.).

The main input parameters describe:

Urban structures are represented as line segments (from axial dra, wing) and include attribute data such as network values of closeness and betweenness.

Urban form is represented as polygons with building attribute data such as dimensions, age, and functions.

Building density is calculated via the dimensions and spatial location of the land use plots. The center contains the dimensions and spatial location of the network of roads, streets, paths, and alleyways.

Transport use, the amounts of traffic, and maximum speeds on the roads and streets are used to calculate transport energy usage.

Part of the spatial data files are georeferenced axial maps hand-drawn by researchers and validated with local experts. The rest were secondary data downloaded from open-source online resources via ArcGIS Editor for OpenStreetMap (OSM). Information on transport capacity and building use were proprietary data provided on request by local authorities (Bergen Kommune) and national authorities (the Norwegian Public Road Administration)

The other input for WebGIS consists of:

1) Land cover layer (typically ESRI Shapefile)

Land cover is available only for cities covered by Copernicus Urban Altas geodatabase (UA2018; see https://land.copernicus.eu/local/urban-atlas). This approach classifies all the UA2018 classes to the Palm Input Data Standard (PIDS) classes with a default setting. These data are intersected with an Open Street Map (OSM) layer with building footprints (freely downloadable on https://download.geofabrik.de/europe.html). Each polygon in the shapefile defines the terrain type (pavement, vegetation, water, building). The special case is sea, which was not considered in UA2018 and was added manually.

2) Digital elevation model (raster in GeoTiff format)
A Copernicus EU-DEM (see https://land.copernicus.eu/imagery-in-situ/eu-dem) is a recommended Digital elevation model (DEM) input. Note that the EU-DEM resolution is 25 m. If a more detailed resolution is needed, resampling is used. Up to 10m provides good results. 5 m is the lowest limit.

3) Building heights (raster in GeoTiff format, also vector format is possible) In the Capital cities in Europe are mostly covered by the Copernicus Building Height (BH) layer (see https://land.copernicus.eu/local/urban-atlas/building-height-2012). Freely available 10m high-resolution raster layer containing height information generated for core urban areas of capitals. When the BH layer is not available, it is possible to use a parameterization based on UA2018 classes, PIDS types, or any other source.

Remote sensing data

The ground surface temperature map was developed using Landsat data. Landsat B10 and B11 thermal channels with 100 m resolution were processed to obtain LST values. The distribution of vegetation and vegetation density was performed by distributing the Normalized Vegetation Difference Index (NDVI) in urban areas.

ArcGIS Server

ArcGIS server makes our data—such as features, tables, maps, tools, imagery, and locators—available to TURBAN project clients and, potentially, the entire Internet through web services.

Web services, essentially, are our data. They access the data in storage locations, allowing them to share that data without giving people direct access to the storage locations. Regarding feature and imagery data, we can publish web services that access the data without duplicating it. If the data is relatively static, we can cache the data in a location separate from our data source to improve drawing performance.

The type of data we want to make available to others and what we want people to do with that data determine the type of web service we publish.

We publish web services to visualize and query our urban spatial data in a map format. The two main types of spatial data we share in this way are feature and imagery. The map contained the feature information and allowed the user to obtain information about objects of interest.

Map services allow other users to view and interact with GIS content on the web. Map services support rendering and querying and can be configured to draw dynamically from data or new or existing cached tiles.

This ArcGIS option was used to make thematic layers interactive for users. This makes it possible to switch between layers, zoom, and access attribute information visually in pop-up windows.

Project results to communicate to the public

Bergen, a picturesque coastal city in Norway, confronts a spectrum of environmental issues that impact its inhabitants' well-being. These challenges, including air pollution, cruise ship emissions, and extreme heat events, have garnered increased attention due to their potential health and environmental consequences.

View of Bergen Harbor

The central areas of Bergen account for 12% of the municipality's total built-up area. The area has a population of 83,669, according to the latest statistics. Approximately 30% of the city's population lives in the core areas. Bergen's population density varies by location. The city's population density is 630 people per km^2. For comparison, in the central part, the population density is much higher - 2111 people per km^2. This is because the core areas are more densely developed and contain a higher concentration of residential, commercial, and cultural institutions.

The municipality of Bergen has set a goal of densifying 50% of new housing within the city's central parts and increasing the number of new dwellings by 10,000 by 2030. https://www.archdaily.com/947137/third-nature-designs-regenerative-city-plan-for-bergen-norway

This policy shift aligns with global trends toward creating low-carbon, low-emission cities to combat climate change and the depletion of natural resources.

As a city experiencing densification over the years, Bergen has seen the development of more tall buildings and narrow streets, which can create an urban canyon effect in certain areas. An urban canyon is a term used to describe a narrow, street-like space flanked on either side by tall buildings. This can create a canyon-like effect, where sunlight is blocked out, and shadows are cast over the area, giving it a unique character. While the urban canyon effect can contribute to a city's visual interest and character, it can also negatively impact air quality, thermal comfort, and the urban environment more broadly. Urban planners can incorporate green spaces and vegetation into building design to mitigate these impacts, improve air quality, and reduce the heat island effect. They can also prioritize pedestrian-friendly infrastructure to make urban canyons more accessible and livable for residents and visitors.

Inversions and air quality

Inversions are a weather phenomenon that exacerbates air pollution in urban areas. Typically, air temperature decreases with altitude, which allows pollutants to disperse and mix with cleaner air. However, during an inversion, a layer of warm air forms above a layer of cool air, which traps pollutants close to the ground. Inversions often occur during calm and clear weather conditions, which are also associated with high-pressure systems. These conditions are ideal for forming temperature inversions as the cool air near the surface cannot mix with the warm air above. This can lead to the accumulation of pollutants, such as nitrogen oxides and delicate particulate matter, in urban areas.

Inversions can last for several days. During this time, people with respiratory conditions, children, and the elderly are at greater risk of health problems due to exposure to high levels of pollutants. That is why cities need to monitor air quality and issue alerts when concentrations of contaminants exceed safe levels, especially during periods of inversion. Air pollution in Norway link to the Norwegian Institute of Public Health (NIPH).

Bergen has a history of poor air quality, particularly during wintertime when persistent ground-based temperature inversions occur. The valley in which the city is located shelters it from extreme wind events and traps pollutants, leading to high concentrations of nitrogen dioxide (NO2) from road traffic. This often exceeds legally regulated air quality thresholds and poses a significant threat to the health and well-being of the population. In January 2010, Bergen experienced it's most severe documented and reported air pollution event, attracting national and international media attention. The incident highlighted the urgent need for measures to improve air quality in the city.

A film shows temperature inversion over Bergen. https://youtu.be/tEh5YTDJiAU

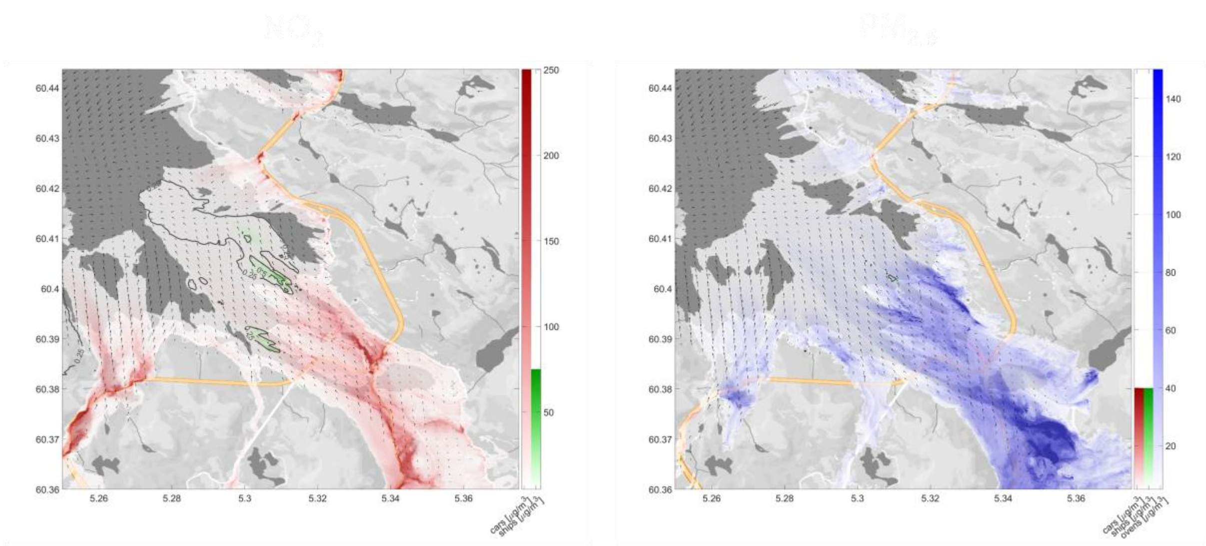
The TURBAN project aims to improve our understanding of how urban areas affect air quality and thermal comfort. It uses advanced computer models to simulate airflow, heat transfer, and pollutant dispersion in urban areas. The model simulates complicated urban air motion and pollution transport pathways in a city with a high geographical resolution and characterizes street-level winds, temperature, moisture, and air quality. It assessed the impact of pollution sources such as road traffic, ships in the harbor, and house wood-burning fireplaces on the air quality. And also urban pollution pathways with a model for flows in the atmosphere.

Modeling approach: The Parallelized Large-Eddy Simulation Model (PALM) was utilized for its turbulence-resolving capabilities (Maronga, 2015; Wolf, 2020 & 2021). This model simulated urban air motion and pollution transport with high geographical resolution. The impact of sources like road traffic, harbor ships, and wood-burning fireplaces on air quality and pollution pathways was assessed by focusing on influential meteorological scenarios, especially calm weather conditions conducive to pollutant accumulation. Street-level winds, temperature, moisture, and air quality were characterized. Simulation outcomes illustrated pollutant distribution and concentration around urban areas. The study produced vulnerability maps (Figure), highlighting the districts most impacted by each weather and emission scenario. Overall, the largest contribution to air pollution over inhabited areas in Bergen was caused by road traffic emissions for NO_2 and wood-burning fireplaces for $PM_{2.5}$ pollution. (Wolf, 2020 & 2021).

In addition, it investigated an opportunity to reduce particulate matter (smoke) air pollution due to wood burning in households. The modeling revealed that almost no households would be exposed to dangerous air pollution if just two central Bergen districts, Bergenhus and Årstad, had installed cleaner wood-burning ovens.

Dispersion and concentration of NO_2 and $PM_{2.5}$ in central Bergen

The main contributors to pollution are road transport and wood burning. NO_2 and $PM_{2.5}$ values exceed the limit values. Sources: Car traffic, Wood-burning Cruise ships



Dispersion and concentration of NO_2 (left panel) and $PM_{2.5}$ (right panel) in central Bergen.

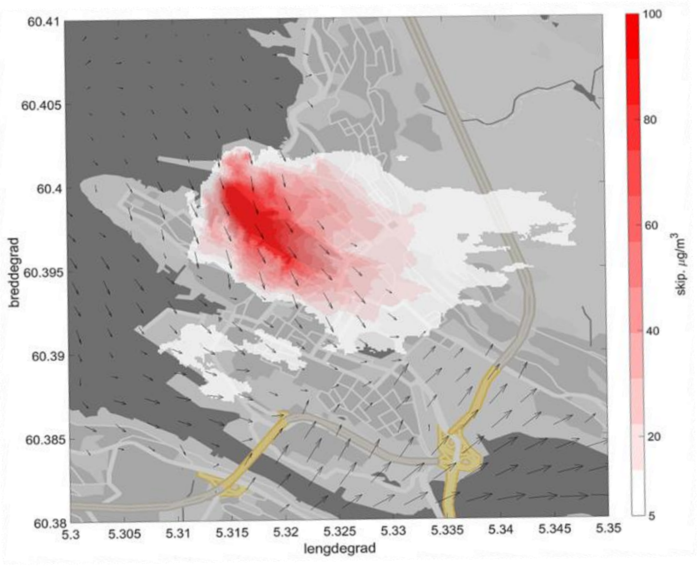
Wood-burning emission mitigation: Addressing localized sources of air pollution, particularly residential wood-burning, requires tailored strategies. Concentrated efforts in specific areas have been identified as an effective way to combat particulate matter and air pollution. This targeted approach demonstrates the potential to significantly reduce pollutants by addressing pollution at its origin. By pinpointing areas with higher emission levels, Bergen can enact policies that directly address pollution sources, thereby contributing to improved air quality across the city (Wolf, 2021).

Cruise ship emissions

Bergen is known as the "gateway to the fjords" and is set to receive about 300 cruise ships and 600,000 passengers a year, more than any other port in Norway.

As a gateway to the fjords, Bergen is a sought-after destination for cruise ships, welcoming hundreds of vessels and passengers annually. However, the environmental impact of cruise ship emissions cannot be ignored. These emissions, including sulfur dioxide, nitrogen oxides, particulate matter, and carbon dioxide, raise concerns about air quality and public health. When cruise ships dock, they often continue running engines for onboard systems, contributing to localized pollution. The areas near the port and along the shipping route bear the brunt of these emissions, necessitating measures to mitigate their effects

Cruise ships in Bergen harbor, as featured in Bergen Tidene, Published on July 23, 2018.



[PALM simulation](#) of pollution from cruise ships in July 2018.

Maritime emission reduction: Bergen's role as a prominent maritime hub necessitates focusing on reducing ship emissions. Implementing a shore power system at the port exemplifies a pioneering move to cut emissions by allowing ships to connect to the grid while docked. Collaborative efforts with cruise ship operators and stakeholders further emphasize the commitment to curbing emissions within the port area. By introducing economic incentives and collaborative measures, the city aims to create a cleaner and healthier environment around the port and adjacent regions (Wolf et al., 2021).

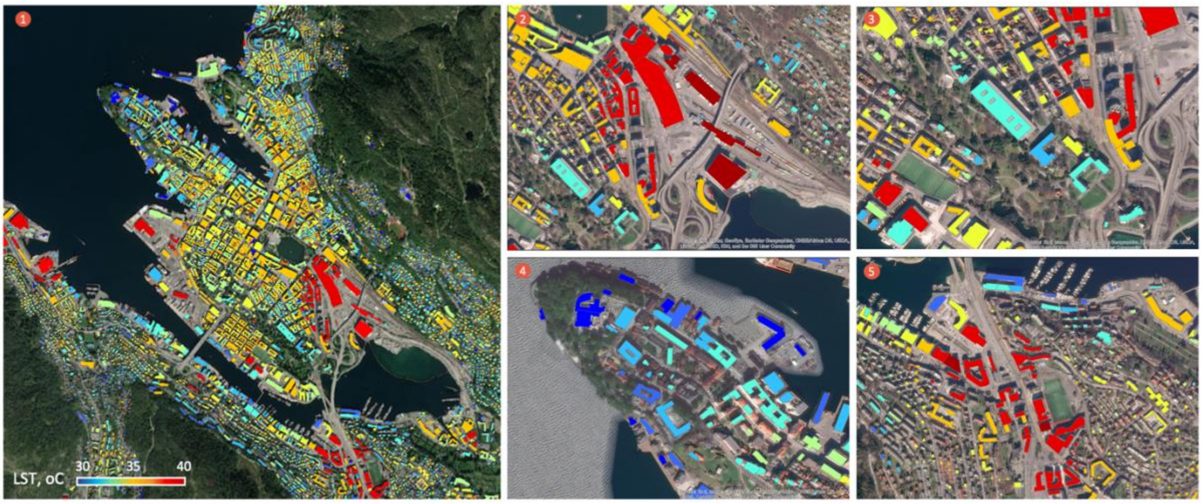
Urban Heat Island

During the Western European heatwave in the summer of 2019, Bergen reached its highest temperature record at 33,4 °C.

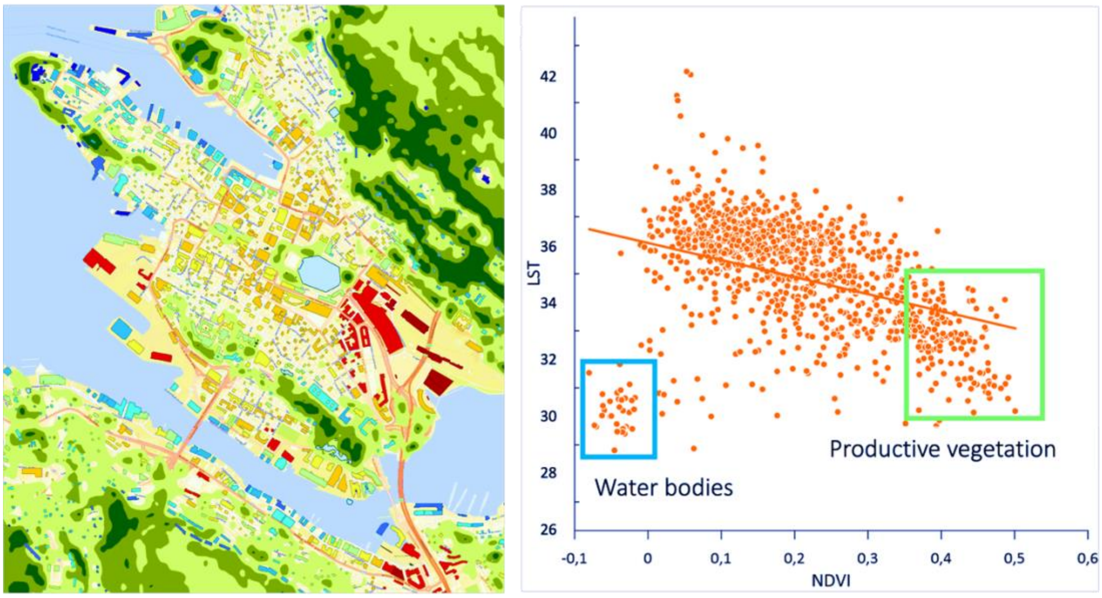
Contrary to its reputation for mild and rainy weather, Bergen has experienced increased extreme heat events. The number of days with temperatures exceeding 25°C has tripled since 1960. The summer of 2018 and the following summer of 2019 marked a milestone, with temperatures soaring to 33.4°C, surpassing previous records. While unusual for Bergen, these heat waves pose health risks, especially for vulnerable populations. As climate change intensifies, the city's residents and infrastructure face challenges adapting to these increasingly frequent and severe heat events.

A distinctive feature of urban climates is their high spatial heterogeneity, determined by various urban forms, land cover types, anthropogenic activity on different spatial scales, and the complexity of the surface–atmosphere interaction in cities. As a result, [various urban environments in the city create specific microclimatic conditions.]

Landsat zooms in on cities' hottest neighborhoods to help combat the urban heat island effect. The heat distribution in the city is uneven, and we observed local heat stress areas with significantly higher temperatures than the surrounding ones. The Land Surface Temperature map derived from Landsat data enables detailed identification of the hottest urban neighborhoods, aiding efforts to mitigate the urban heat island effect. The artificial surfaces and the lack of vegetation create a micro-island of heat at the Bergen bus station. Buildings with flat black roofs, asphalt around them, and a lack of vegetation are typical environments for developing a local hotspot (2). Satellite remote sensing enables building scale mapping of the urban thermal environment.



(1) Localized areas of increased thermal stress. Landsat LST map, July 2019, overlaid on ArcGIS base map. (2) In areas characterized by a lack of vegetation and extensive pavement, such as urban downtowns or industrial zones, microclimatic conditions often include elevated temperatures due to the heat-absorbing properties of pavement. These areas may experience urban heat islands with increased heat retention. (3) Urban locations surrounded by bodies of water and lush vegetation typically exhibit more temperate microclimates. The presence of water bodies and vegetation can mitigate temperature extremes, providing a cooling effect and contributing to improved air quality. (4) Urban parks are characterized by abundant vegetation and green spaces. They create microclimatic conditions conducive to lower temperatures and improved air quality. The vegetation in parks provides shade and helps reduce heat, making them cooler and more comfortable areas within the city. (5) Areas along waterfronts that lack substantial vegetation can have distinct microclimates. The proximity to water bodies can moderate temperatures, leading to milder conditions than inland areas without vegetation.



Left, NDVI map of Bergen and right correlation between land surface temperature and vegetation

Urban greenery for temperature regulation: To counteract the urban heat island effect, the importance of urban green spaces emerges as a vital mitigation strategy (Pereira, 2023). In Figure 8, the left panel, featuring the vegetation-temperature map, prominently illustrates that areas surrounded by vegetation and located in close proximity to water bodies experience more comfortable temperatures. On the right panel of Figure 8, a detailed analysis reveals a clear correlation between elevated temperatures and areas lacking vegetation. Incorporating trees and water bodies in urban planning significantly mitigates temperature stress, creating cooler microclimates. This approach exemplifies how strategic urban design can not only lower temperatures but also enhance residents' quality of life and well-being.

The presence of green spaces composed of trees and water bodies reduces air pollution and temperature stress and creates a comfortable urban environment.

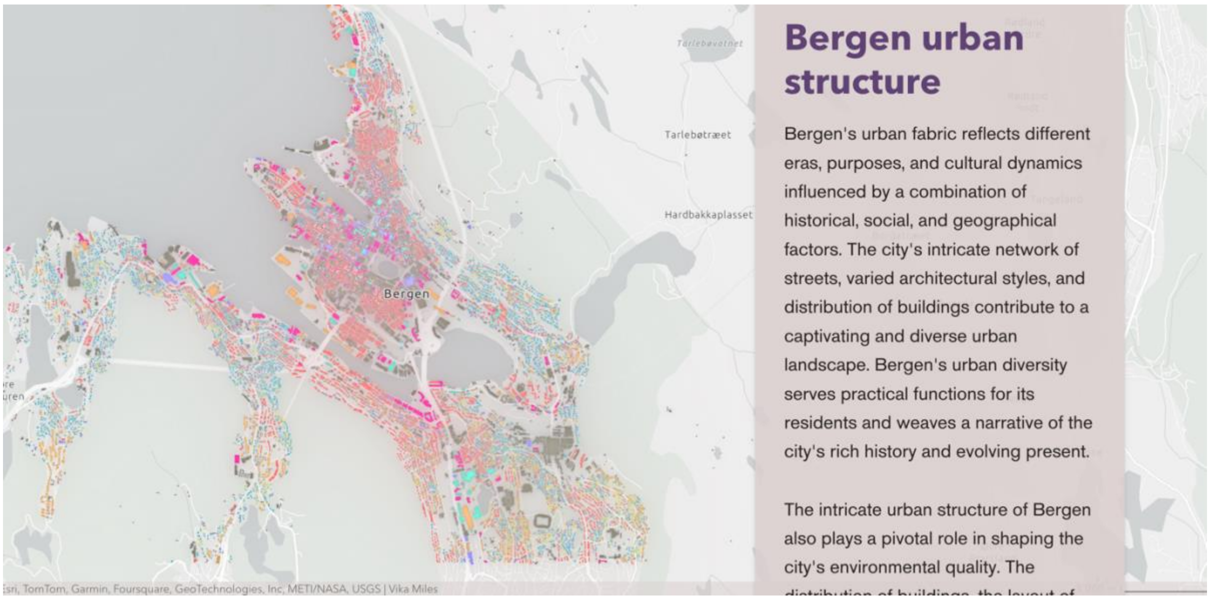
By simulating the complex interactions between buildings, streets, and the atmosphere, researchers hope to understand better how different urban designs and strategies can impact air quality and thermal comfort. Also, they investigate the measures to reduce the effect by studying the impact of green roofs, street trees, and other urban green spaces on air quality and thermal comfort. Or by giving concrete science-proof recommendations to the city authorities.

TURBAN Web-GIS

We integrate TURBAN knowledge through thematic maps that link urban landscapes and various urban features with quantitative information from model scenarios.

Bergen urban structure

Bergen's urban fabric reflects different eras, purposes, and cultural dynamics influenced by a combination of historical, social, and geographical factors. The city's intricate network of streets, varied architectural styles, and distribution of buildings contribute to a captivating and diverse urban landscape. Bergen's urban diversity serves practical functions for its residents and weaves a narrative of the city's rich history and evolving present.



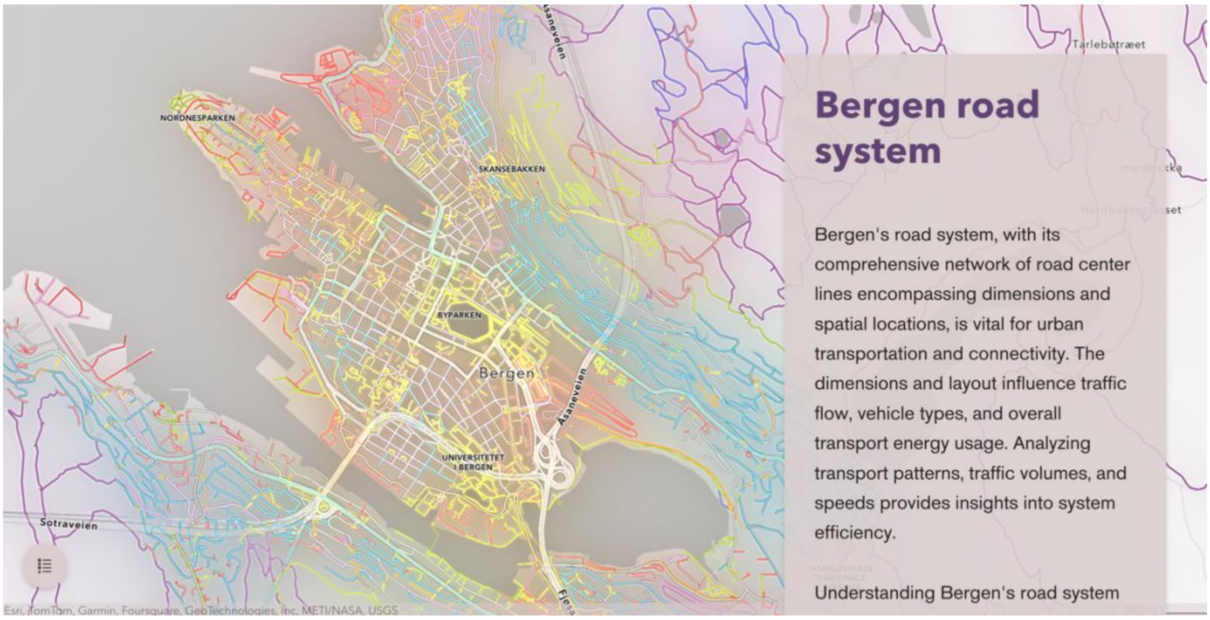
The intricate urban structure of Bergen also plays a pivotal role in shaping the city's environmental quality. The distribution of buildings, the layout of streets, and the overall design significantly impact factors such as air quality and thermal comfort. The varied architectural styles and spatial arrangements influence how air circulates within the city and the presence of green spaces, which in turn can affect the overall air quality

Understanding the interplay between Bergen's urban structure and environmental factors is essential for informed decision-making. By analyzing metrics related to building dimensions, street connectivity, and other relevant factors, policymakers gain insights for implementing strategies to improve air quality and thermal comfort. Identifying critical hot spots allows for targeted interventions, ensuring a more comfortable and healthier urban environment for Bergen's residents.

In essence, Bergen's urban diversity not only contributes to its aesthetic appeal and historical significance but also holds implications for the well-being of its inhabitants by influencing the city's air quality and thermal comfort. This holistic perspective fosters a balanced approach to urban planning, where the preservation of cultural heritage goes hand in hand with creating a sustainable and comfortable living environment.

Bergen road system

Bergen's road system, with its comprehensive network of road center lines encompassing dimensions and spatial locations, is vital for urban transportation and connectivity. The dimensions and layout influence traffic flow, vehicle types, and overall transport energy usage. Analyzing transport patterns, traffic volumes, and speeds provides insights into system efficiency.



Understanding Bergen's road system intricacies is crucial for calculating transport energy consumption. Factors like traffic density and road design impact energy efficiency. This data informs policymakers on optimizing transport energy, reducing environmental impact, and improving overall mobility efficiency.

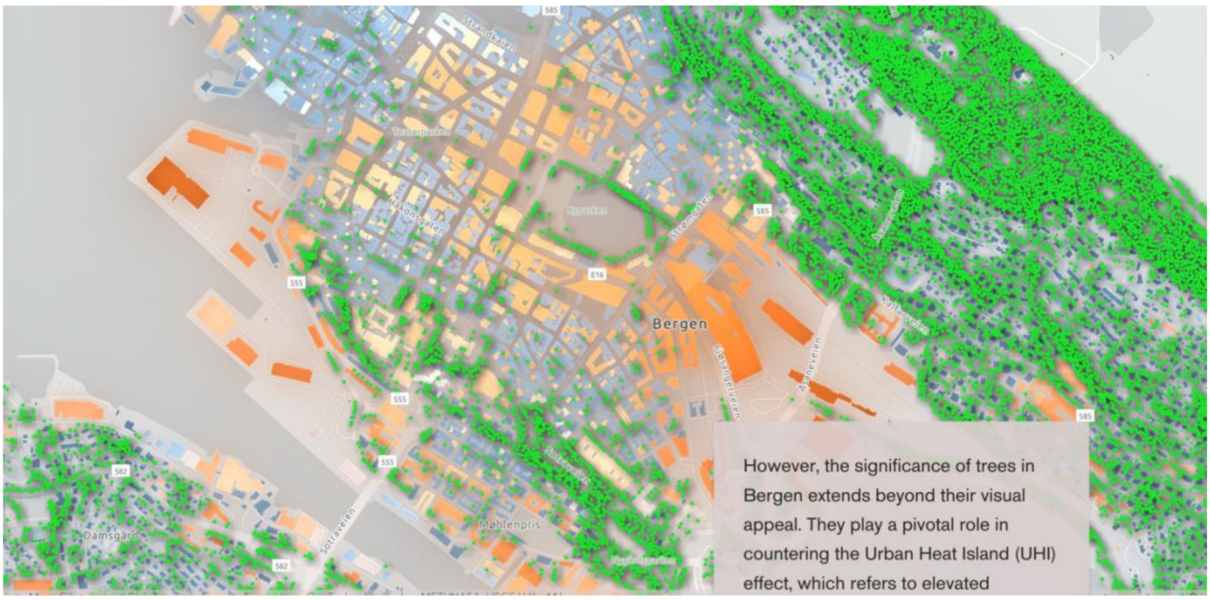
Integrating road system data with energy usage insights enables informed decisions on infrastructure, traffic management, and sustainable transportation solutions. This holistic approach aligns Bergen's road system with energy efficiency and environmental sustainability goals. However, the dominance of roads in urban areas may pose challenges to air quality and thermal comfort, requiring solutions like green infrastructure and smart urban design for a healthier and more livable urban environment.

Bergen trees

Bergen's urban landscape is graced with diverse trees, offering aesthetic beauty and promoting environmental well-being. From native evergreens to deciduous varieties, these trees bring unique colors and shapes to the city.

Functioning as more than just ornamental elements, Bergen's trees serve crucial roles. They enhance the city's charm in parks and public spaces, contribute to improved air quality by absorbing pollutants, and create habitats for wildlife, fostering biodiversity. Additionally, they play a vital role in climate regulation, mitigating the Urban Heat Island effect by providing shade and reducing temperatures. Bergen's commitment to green spaces ensures that the benefits of trees are seamlessly woven into the city's fabric, providing recreational spaces for residents and visitors alike.

However, the significance of trees in Bergen extends beyond their visual appeal. They play a pivotal role in countering the Urban Heat Island (UHI) effect, which refers to elevated temperatures in urban areas compared to their rural surroundings. Trees contribute to this mitigation in several ways: by providing natural shade to reduce sunlight absorption, releasing cooling water vapor through evapotranspiration, creating a green canopy that absorbs and reflects solar radiation, and improving air quality by absorbing pollutants.



Strategic urban planning is essential to optimize trees' effectiveness in mitigating the UHI effect. This involves identifying high-heat areas for targeted tree planting, utilizing diverse species to enhance cooling effects and promote biodiversity, and ensuring regular maintenance to uphold the health and longevity of urban trees.

Bergen's emphasis on tree distribution and strategic placement reflects a commitment to creating a resilient and sustainable urban environment. This approach balances urban development and addressing heat-related challenges, fostering a cityscape that prioritizes the well-being of its residents and the environment.

The Web GIS is built on the cloud-based ArcGIS (online) software to create and share interactive web maps. As part of the dissemination and project result communication, the project developed a web GIS platform called "Air Quality in Cities and Thermal Comfort: Stories of Urban Air, developed in project TURBAN" (https://project-turban.eu/). The TURBAN general part content provides navigation between different methods of measuring and modeling urban air. It was developed in a question-answer format with illustrations for Prague. The general part is available in English, Czech, and Norwegian. The TURBAN stories collect stories about Prague (https://arcg.is/1rvfeO0) and Bergen (https://arcg.is/P0u9D) and can be read in English, Czech, or Norwegian.

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