Urban scale modelling for climate applications

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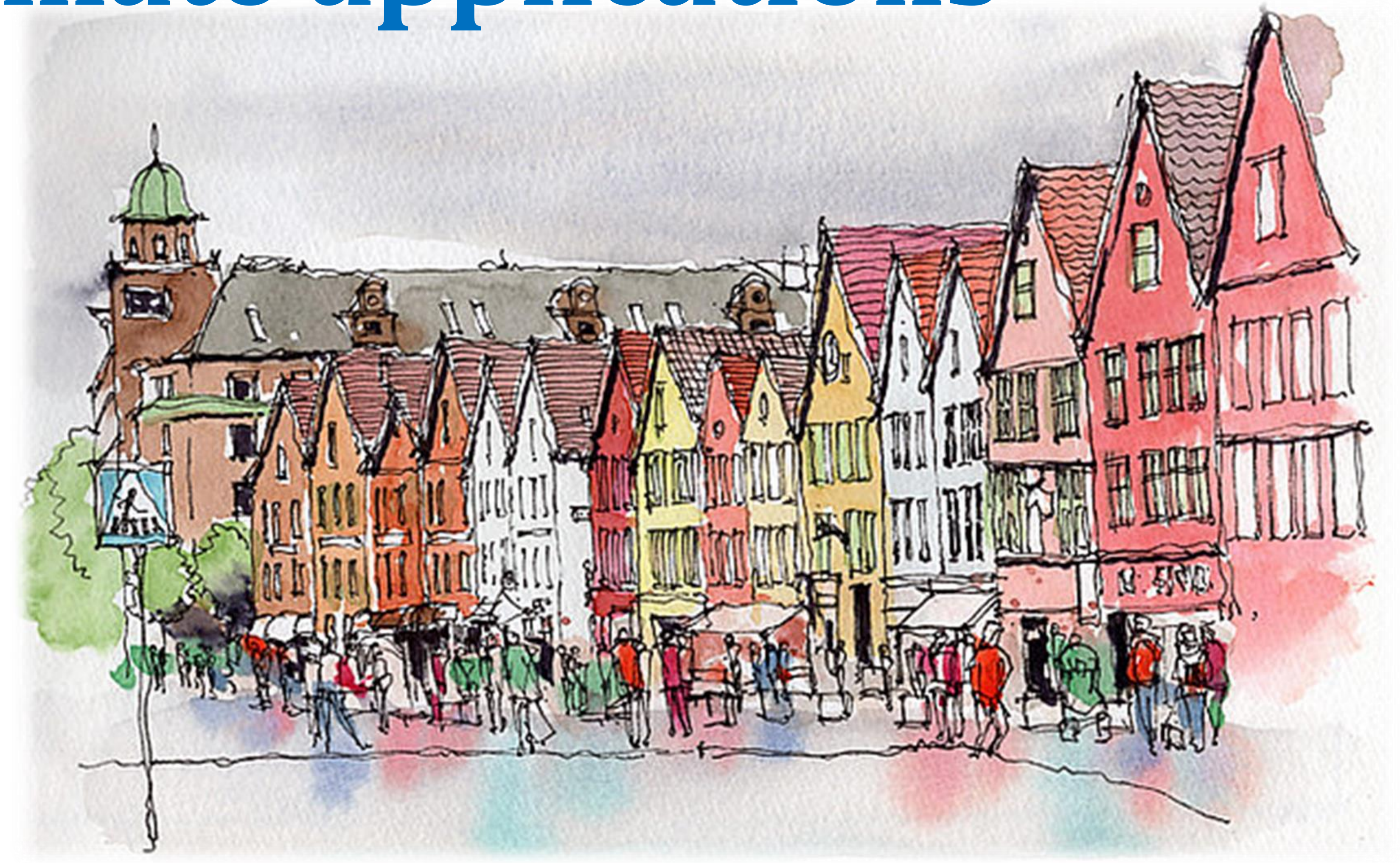


Problem setting

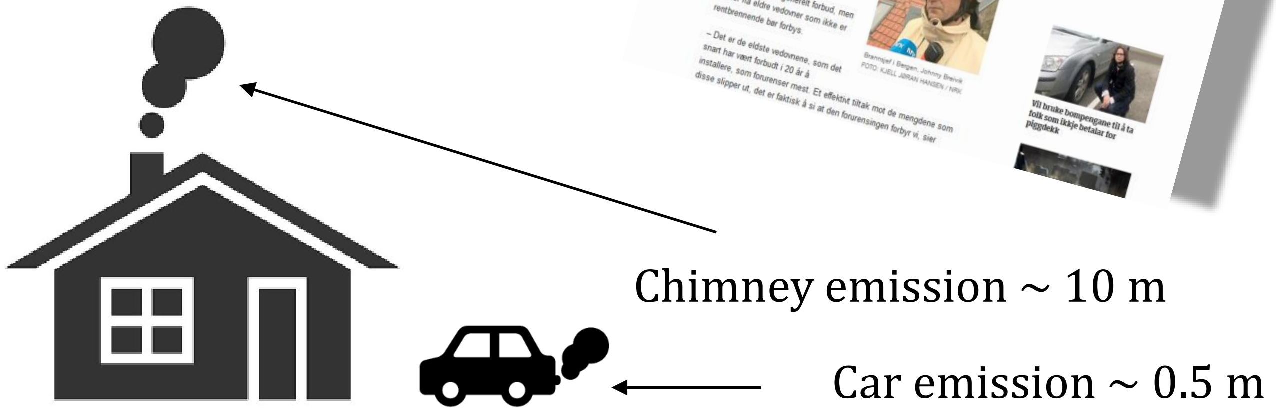
How to manage urban environment under multiple and diverse constrains in an optimal way?

Example

- *Public authorities wants to eliminate/reduce concentrations that exceed a given/prescribed threshold (40 mkg m^{-3})*
- *Public authorities have limited economic incentives (50 MNOK) and limited policy instruments (a directive to install new-type wood-burning ovens)*
- *The task is to evaluate air quality outcomes resulting from implementation of the designed policy scenarios*
- *The challenge (an optimization problem) is to find an optimum scenario that provides for the most within the available resources.*

Complications:

- Emissions come from different sources
- Policy measures change not only emissions but also behavior of people
- Scenario evaluation should be transparent and cost efficient



Quantitative information is not used in discussion and decision-making process

Symbolic context of the air quality problem

Inversjon – as a textual symbol

Giftloket – as a visual symbol

Single measurement point as an objective symbol


Fylket frykter kaos i kollektiv-trafikken på dager med dårlig luft

SKOLER KAN BLI STENGT

LØRDAG 24. MAI 2014

DATA-BARN for full musikk

BA

BERGENSAVISEN

Brann og Norge slåss om SUPERDUOEN

Slik er utsiktene for Bergen:

20 NYE ÅR UTEN FRISK LUFT

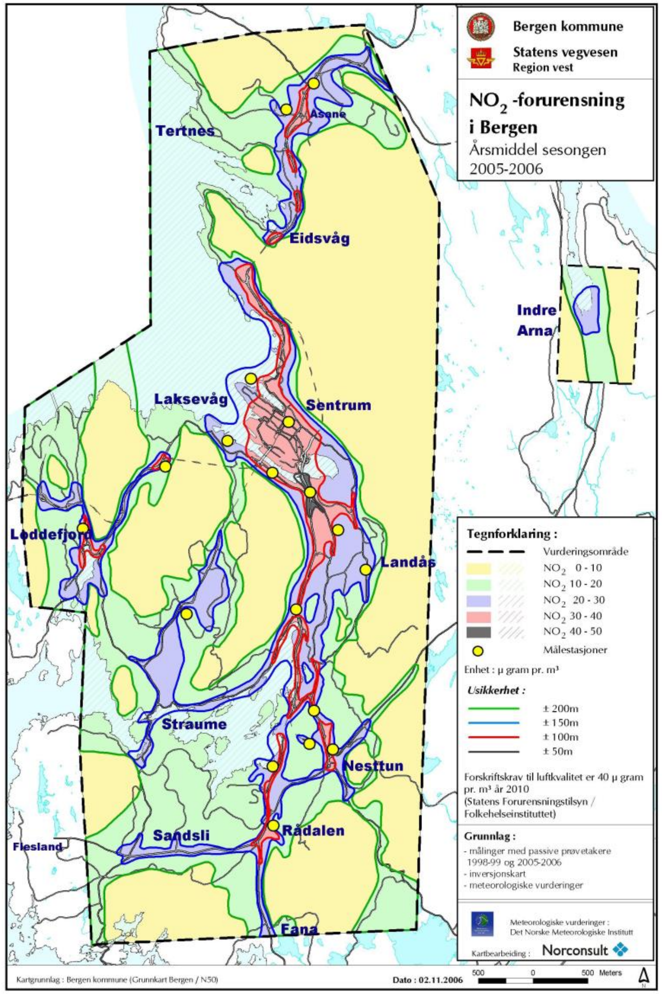
VINYL-REKYL

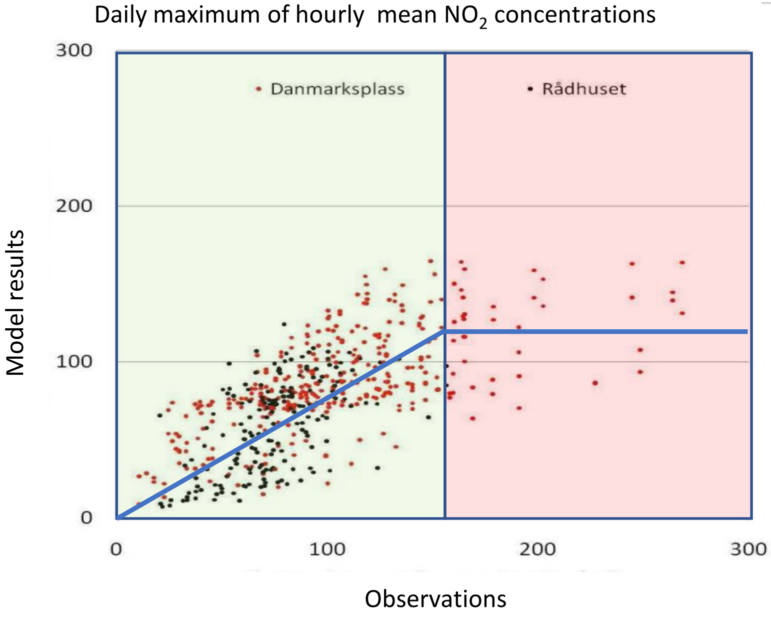
KONG-KLANG

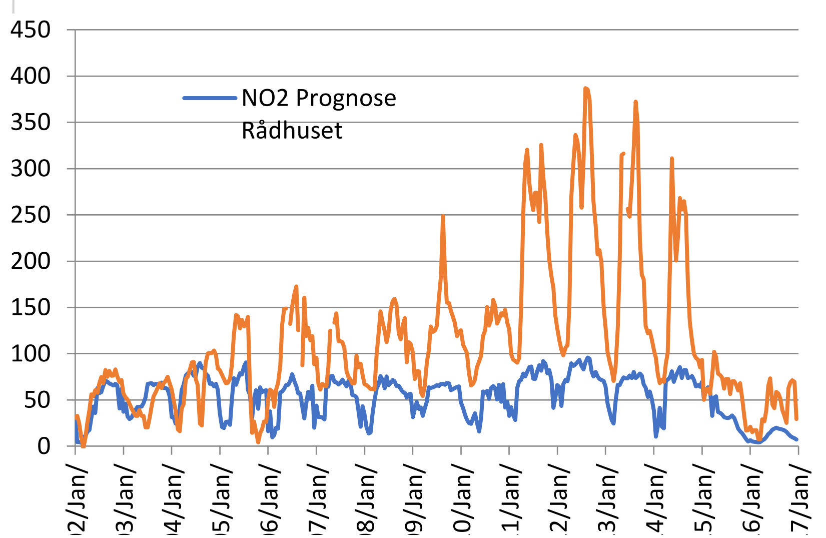
Vi tåler sammenligning

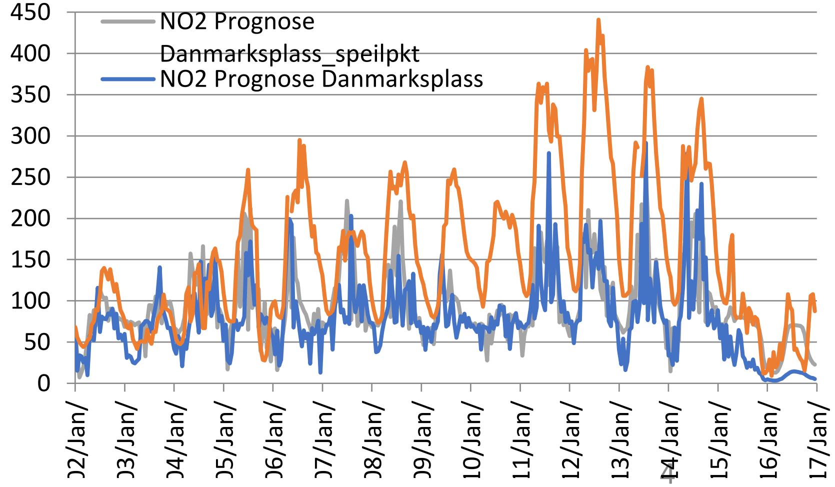
Traditional approaches are unsatisfactory

Gaussian approaches and RANS turbulence closures do not reproduce extremes









Bergen (2 – 16 Januar 2010)

Pål Rosland (Vegvesen)

Leiv Håvard Slørdal (NILU)

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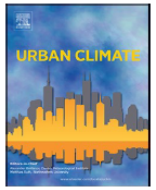
Urban Climate

journal homepage: www.elsevier.com/locate/uclim



Integrated urban hydrometeorological, climate and environmental services: Concept, methodology and key messages

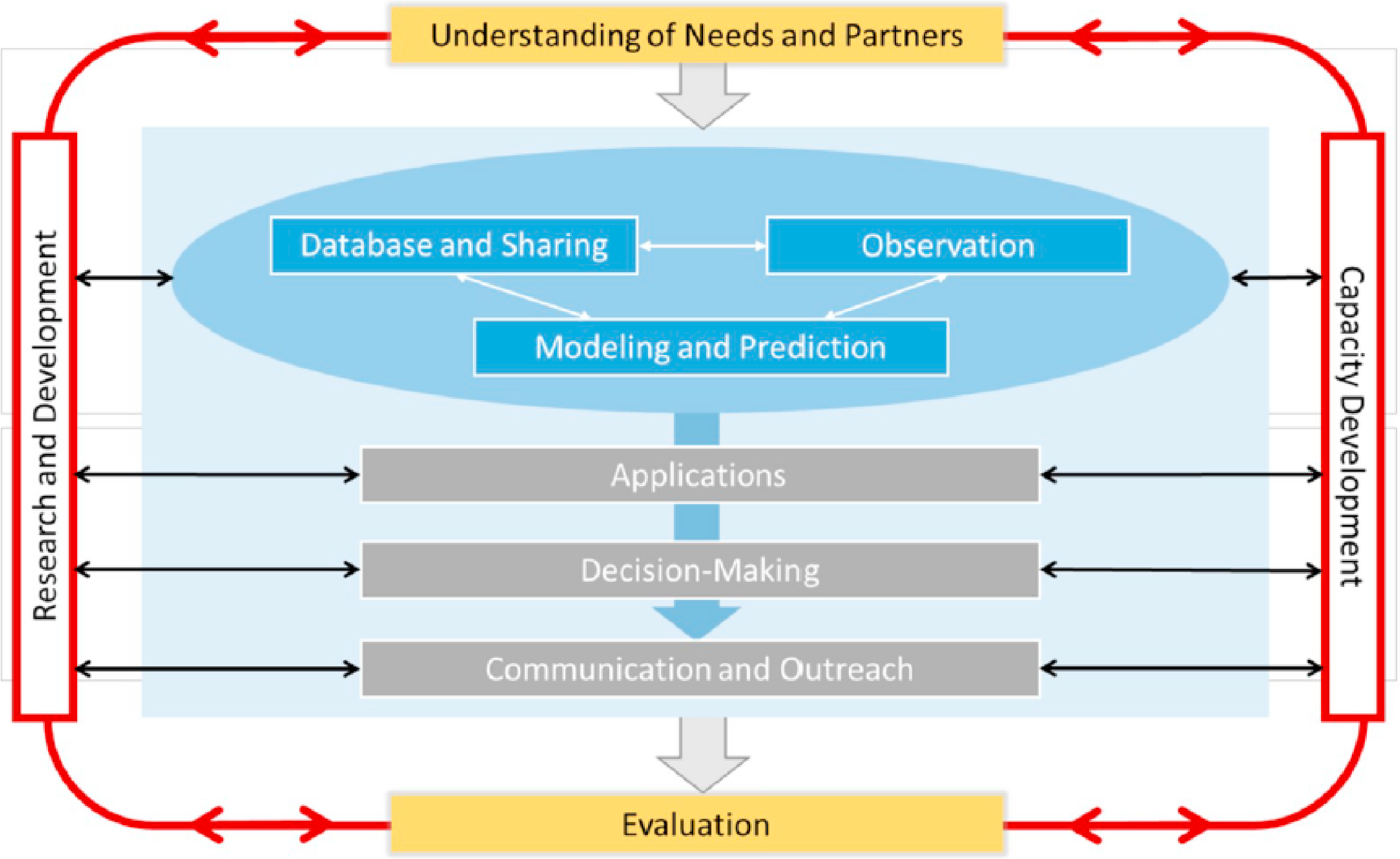
Sue Grimmond[a], Veronique Bouchet[b], Luisa T. Molina[c], Alexander Baklanov[d], Jianguo Tan[e], K. Heinke Schlünzen[f], Gerald Mills[g], Brian Golding[h], Valery Masson[i], Chao Ren[j], James Voogt[k], Shiguang Miao[l], Humphrey Lean[o], Bert Heusinkveld[m], Anahit Hovespyan[d], Giacomo Teruggi[d], Patrick Parrish[d], Paul Joe[n,*]

High-resolution atmospheric modeling

Integrated Urban hydrometeorological, climate and environmental Services **(IUS)** is a ***World Meteorological Organization (WMO) initiative*** to aid development of science-based services to support safe, healthy, resilient and climate friendly cities.

- Atmospheric boundary layer: static stability over horizontal heterogeneity
- Turbulent mixing and local flows
- Turbulence-resolving simulations: principles of large-eddy simulations
- Subgrid-scale filtering and turbulence closures
- Modeling system COSMO-PALM
- “Urbanization” of meso-scale meteorological models

Components of an Integrated Urban Hydrometeorological, Climate and Environmental Service (IUS) System

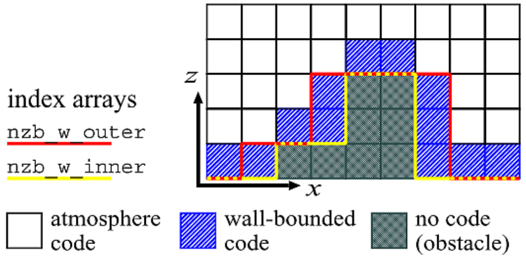


Model PALM

Scherer, D., Antretter, F., Bender, S., … Scherber, K. (2019). Urban climate under change [UC]2 - A national research programme for developing a building-resolving atmospheric model for entire city regions. *Meteorologische Zeitschrift*, 28(2), 95–104.

The Parallelized Atmospheric Large-eddy simulation Model (PALM) :

- Large-eddy simulation (LES) class model to resolve the most energetic part of turbulence explicitly
- Solves 3D primitive hydro-thermo-dynamical equations for incompressible Boussinesq fluids:
  - Momentum equations
  - Potential temperature equation
  - Scalar transfer equation
- C-type mesh
- Different advection and pressure schemes
  - **5th-order scheme** after Wicker and Skamarock (2002)
  - Multi-grid pressure solver
- Turbulence closure: **1.5-order TKE equation** closure in 3D
- Surface is described using cuboid approximation
- ***PALM has very rich set of features, which are not used in our simulations however***



The PALM model system has been mainly developed and is maintained by the ***PALM group*** at the Institute of Meteorology and Climatology (IMUK) of Leibniz Universität Hannover, Germany.

Large-eddy simulations

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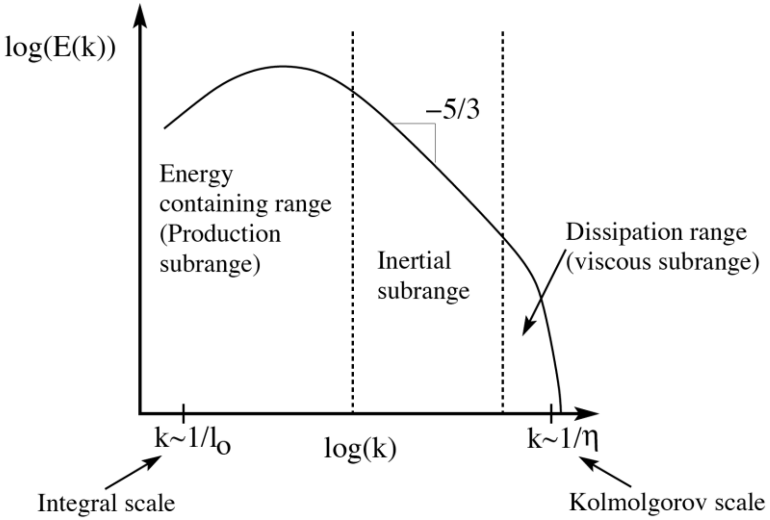
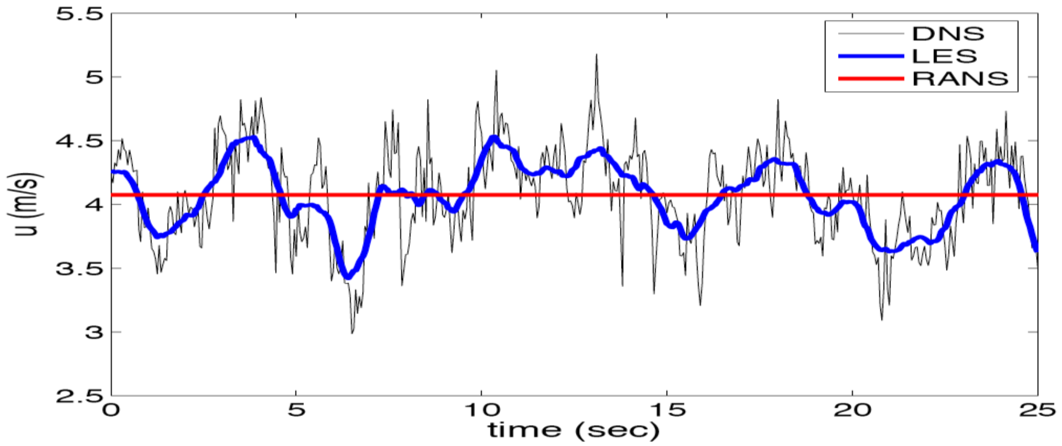


$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{Conservation of Mass}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2} + F_i \quad \text{Conservation of Momentum}$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial u_i \theta}{\partial x_j} = \nu_\theta \frac{\partial^2 \theta}{\partial x_j^2} + Q \quad \text{Conservation of scalar (temp, species, etc.)}$$

$$E(k) = c_k \epsilon^{2/3} k^{-5/3}$$



Turbulence subgrid-scale closure and filtering

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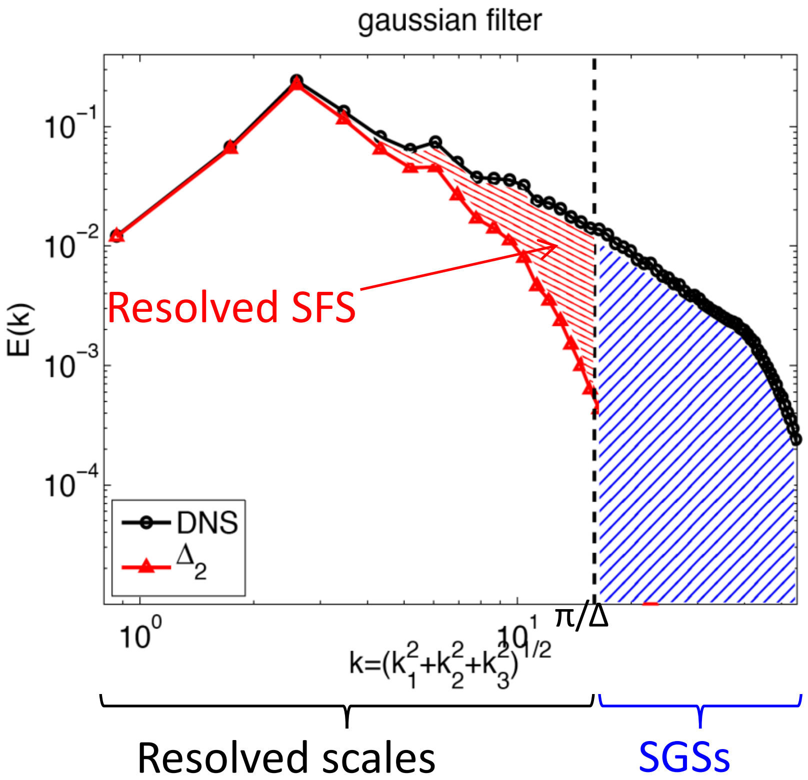


$$\phi = \tilde{\phi} + \phi'$$

$$\tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)$$

$$\widetilde{u_i u_j} = \widetilde{(\tilde{u}_i + u_i')(\tilde{u}_j + u_j')}$$

$$= \widetilde{\tilde{u}_i \tilde{u}_j} + \widetilde{\tilde{u}_i u_j'} + \widetilde{\tilde{u}_j u_i'} + \widetilde{u_i' u_j'}$$

$$\widetilde{\tilde{u}_i \tilde{u}_j} = \left(\widetilde{\tilde{u}_i \tilde{u}_j} - \tilde{u}_i \tilde{u}_j\right) + \tilde{u}_i \tilde{u}_j$$ **-> known**

L_{ij} - Leonard term (stress)

$C_{ij} = \widetilde{\tilde{u}_i u_j'} + \widetilde{\tilde{u}_j u_i'} \Rightarrow$ interaction between resolved and SFSs

$R_{ij} = \widetilde{u_i' u_j'} \Rightarrow$ SFS "Reynold's" stress **-> unknown**

Required closure for the turbulent stress term

$$\tau_{ij} = L_{ij} + C_{ij} + R_{ij} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j$$

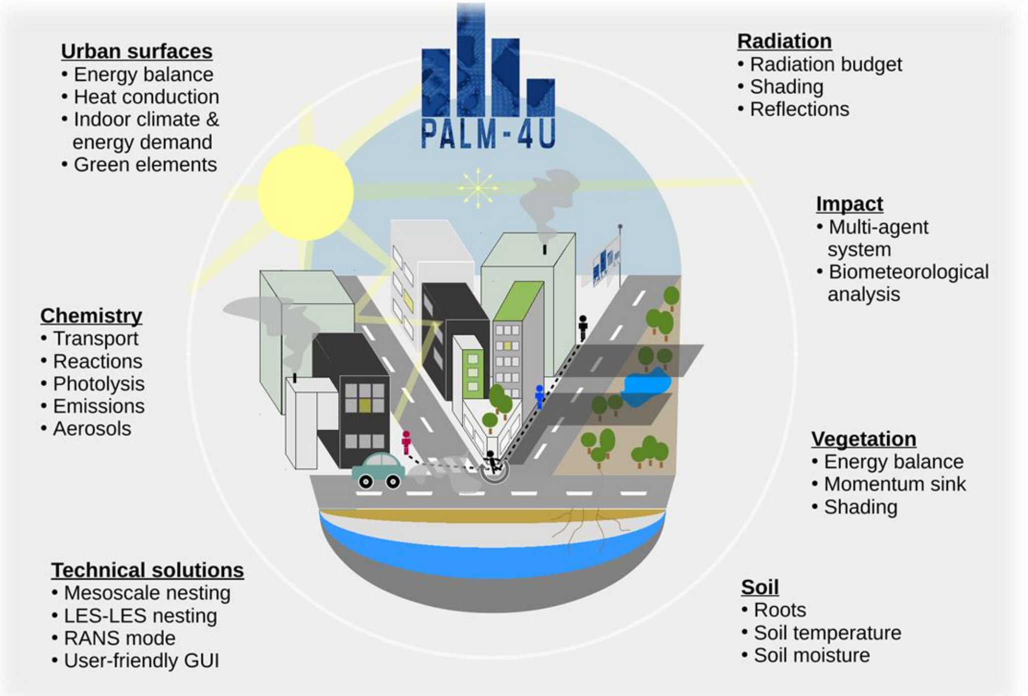
$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\nu_T \tilde{S}_{ij}$$ **-> parametrization (J. Smagorinsky)**

Model PALM (6.0)

The Parallelized Atmospheric Large-eddy simulation Model (PALM) with urban features PALM-4U ver. 6.0:

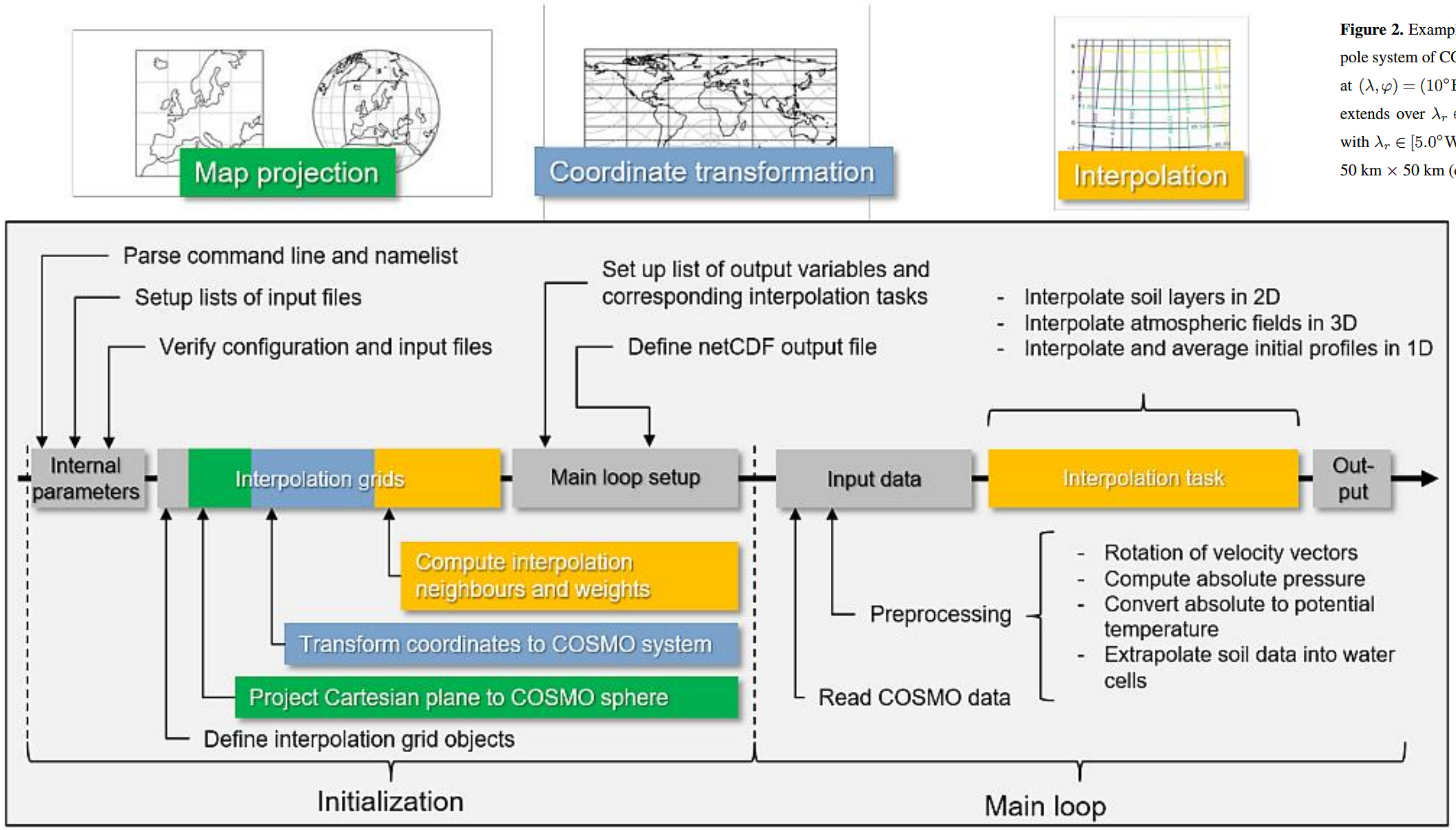
(Developed after our study)

- Excellent scaling, so far tested up to **32,000 cores**
- Online data analysis (during model runs) in order to avoid I/O bottlenecks
- Interactive land surface model, coupled to the RRTMG radiation model
- Wind turbine model (ADM-R) is implemented
- Ocean mode with salinity equation and equation of state for seawater
- **Coupled atmosphere-ocean mode on turbulence scales**
- Bulk cloud physics (Seifert-Beheng scheme)
- Embedded parallelized Lagrangian particle model for various applications
  - (footprint calculation, simulation of cloud droplet growth, visualization, etc.)
- Dynamic core and thermodynamics runs on multiple GPUs using CUDA-aware MPI
- Urban Features:
- Energy balance solvers for building and paved surfaces
- Radiative transfer within the urban canopy layer, including shadowing effects and multiple reflections between urban structures
- Wall material model for heat transfer between atmosphere and building
- Indoor climate module, predicting indoor temperature, energy demand, and waste heat
- Chemistry module for the transport and conversion of reactive species
- Model self-nesting that allows to increase either model domain size or to focus on near-surface processes
- A multi-agent system for urban residents, allowing for biometeorological studies and escape scenarios
- **Quasi-automatic external forcing by COSMO-DE model data**
- A Reynolds-averaged Navier Stokes (RANS) type turbulence parameterization can be used instead of LES to reduce computational costs
- Analysis tools and direct output of biometeorological quantities



https://palm.muk.uni-hannover.de/trac

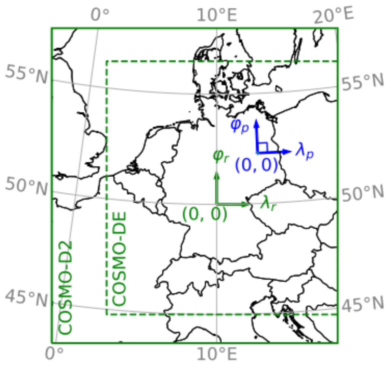
Modeling system COSMO-PALM



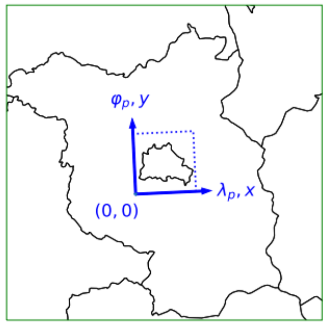
a)

Figure 2. Example PALM domain (blue) for Berlin nested within the DWD COSMO configurations (green). Panel **(a)** Shows the rotated-pole system of COSMO-DE and -D2, the rotated North Poles of which are both located at $(\lambda^N, \varphi^N) = (170°\mathrm{W}, 40°\mathrm{N})$, placing their origin at $(\lambda, \varphi) = (10°\mathrm{E}, 50°\mathrm{N})$ (see panel **(b)**). Panel **(b)** shows the horizontal domain extents of both COSMO configurations. COSMO-D2 extends over $\lambda_r \in [7.5°\mathrm{W}, 5.5°\mathrm{E}], \varphi_r \in [6.3°\mathrm{S}, 8.0°\mathrm{N}]$ (solid green), which is slightly increased compared to the COSMO-DE domain with $\lambda_r \in [5.0°\mathrm{W}, 5.5°\mathrm{E}], \varphi_r \in [5.0°\mathrm{S}, 6.5°\mathrm{N}]$ (dashed green). Panels **(b)** and **(c)** show an example configuration with a PALM domain of 50 km × 50 km (dashed blue).

Kadasch, E., Sühring, M., Gronemeier, T., Raasch, S., 2021. Mesoscale nesting interface of the PALM model system 6.0. Geosci. Model Dev. 14, 5435–5465. https://doi.org/10.5194/gmd-14-5435-2021



b)



c)

«Urbanization» of meso-scale models

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Urban canopy models in WRF /HIRLAM:

Both models have three different urban schemes included in the official releases: bulk approach, SLUCM, MLUCM (Chen et al. 2011, Baklanov et al., 2008)

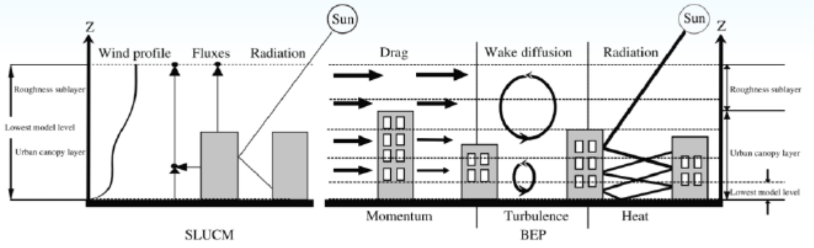
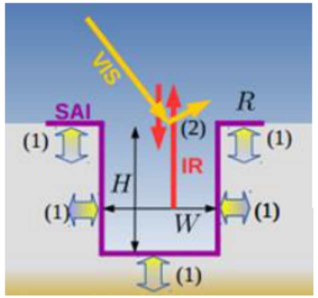


Figure 2. A schematic of the SLUCM (on the left-hand side) and the multi-layer BEP models (on the right-hand side).

Urban canopy models in COSMO:

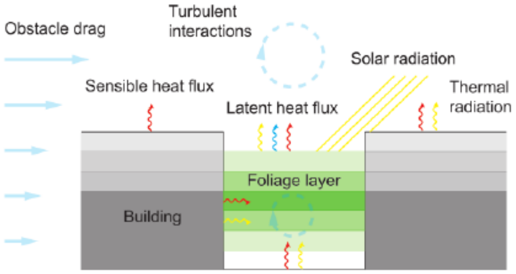
1) **TERRA_URB scheme** (Wouters et al., 2015; 2016) – fast and efficient scheme based on the bulk approach, planned be included to the official COSMO code in the last unified model version 6.0
   - Standard surface and soil properties from TERRA land model (albedo, emissivity, roughness, etc.) are modified by **SURY (Semi-empirical Urban canopy parameterization)**
   - Puddles parameterization for impervious surface
   - Pre-defined anthropogenic heat flux according to (Flanner, 2009)



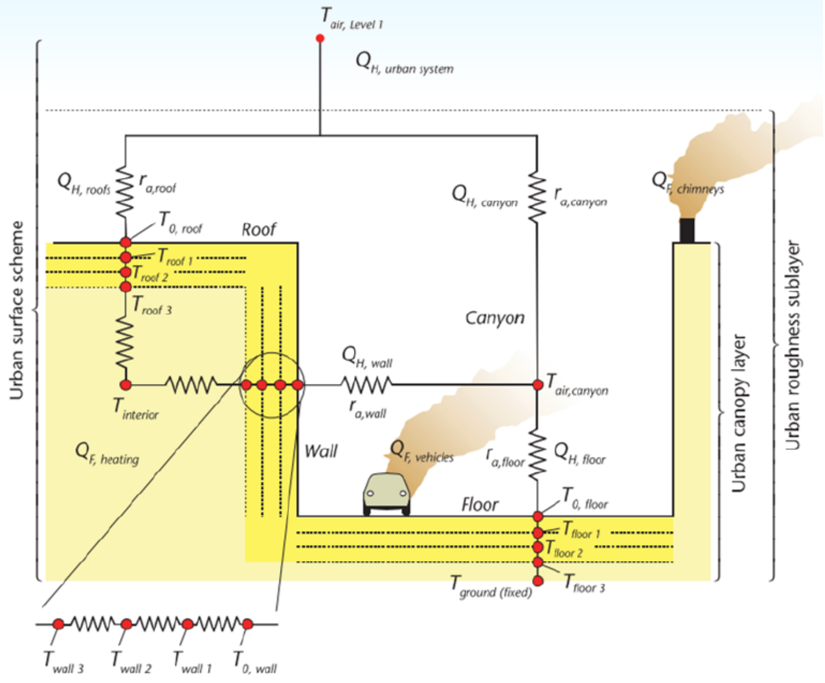
"Translation of urban canopy parameters into bulk parameters"

2) **TEB (Town Energy Balance)** – single layer urban canopy model (Masson, 2000; Trusilova et al., 2013), problems in coupling have been revealed

3) **DCEP** (Shubert et al., 2012) and **BEP-Tree** (Musetti et al., 2019) schemes - the most advanced multi-layer schemes for COSMO



BEP-Tree



TEB (Town Energy Balance) scheme (Masson, 2000)

Urban canopy parameters

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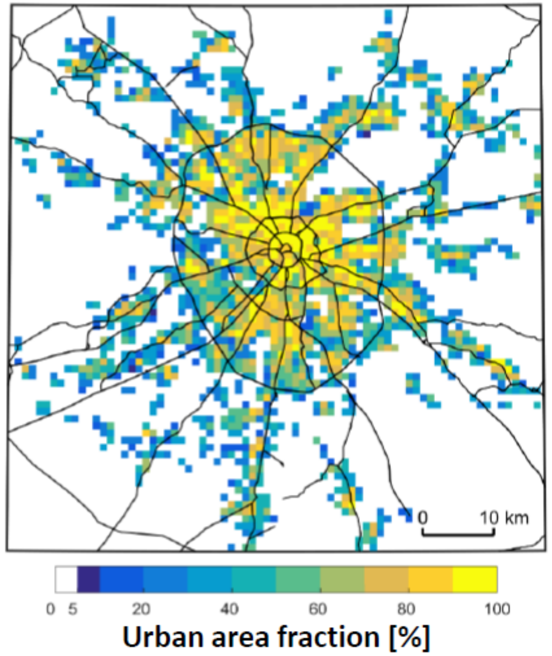
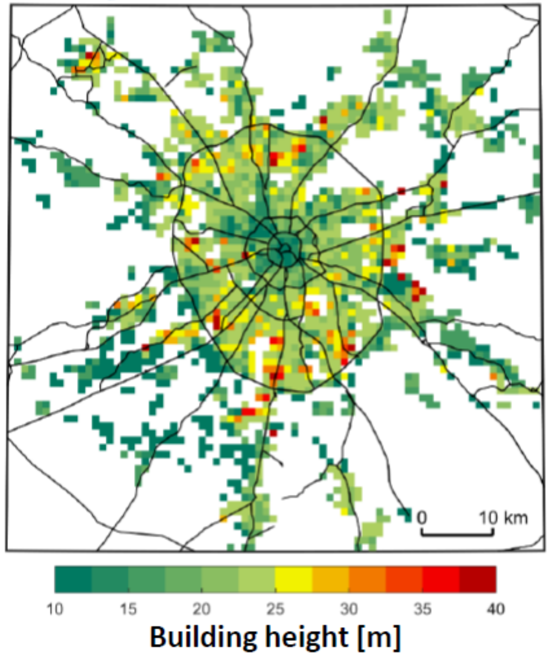
Required urban canopy parameters for TERRA_URB:

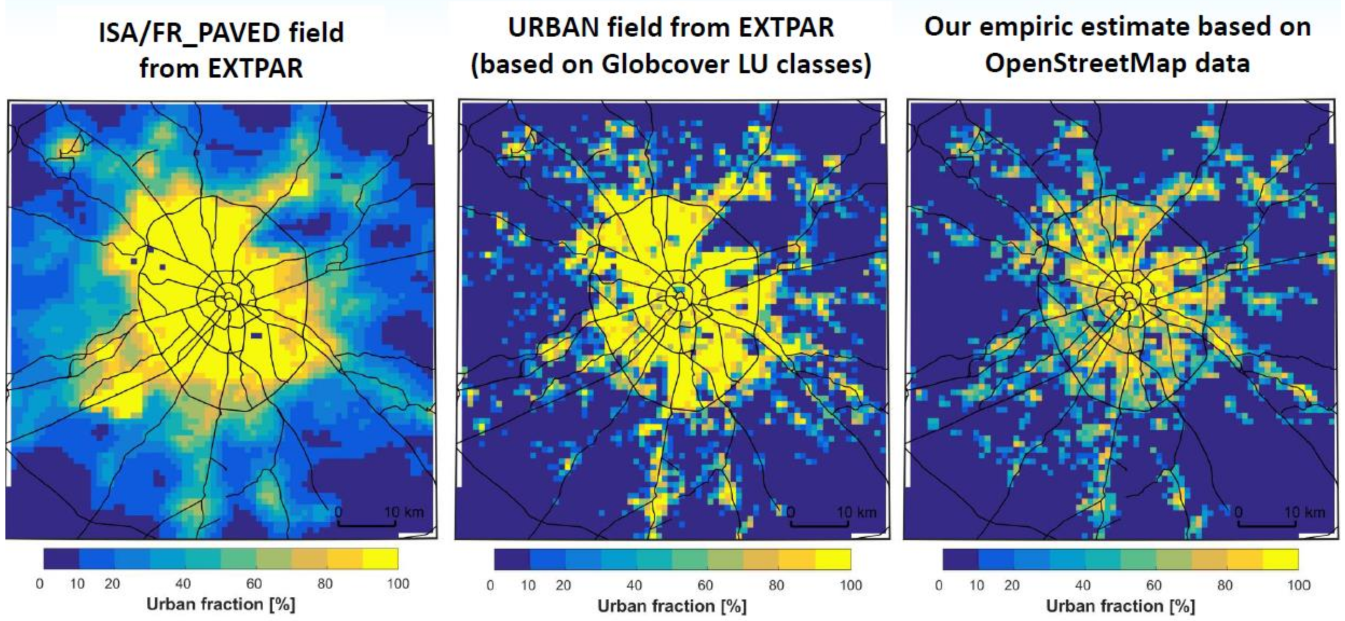
- **Urban area fraction (= impervious surface fraction, ISA)**
- **Annual-mean anthropogenic heat flux (AHF)**
- Building area fraction
- Building height H
- Street canyon aspect ration (H/W)

Additionally introduced as external parameters





Urban (impervious) fraction

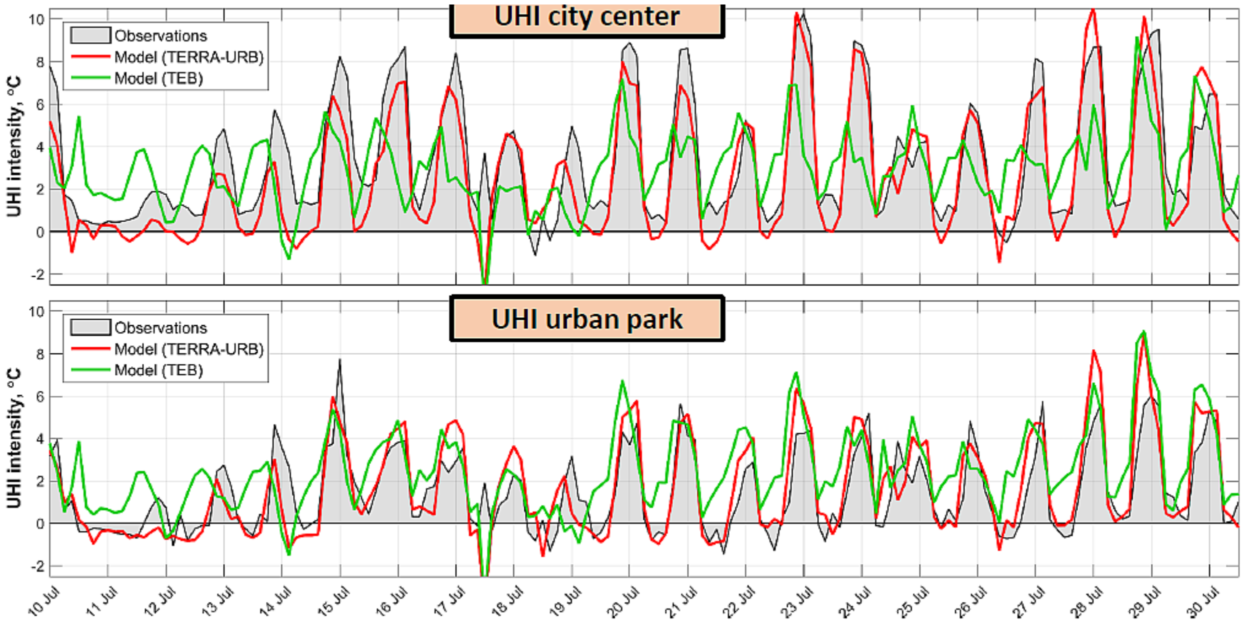


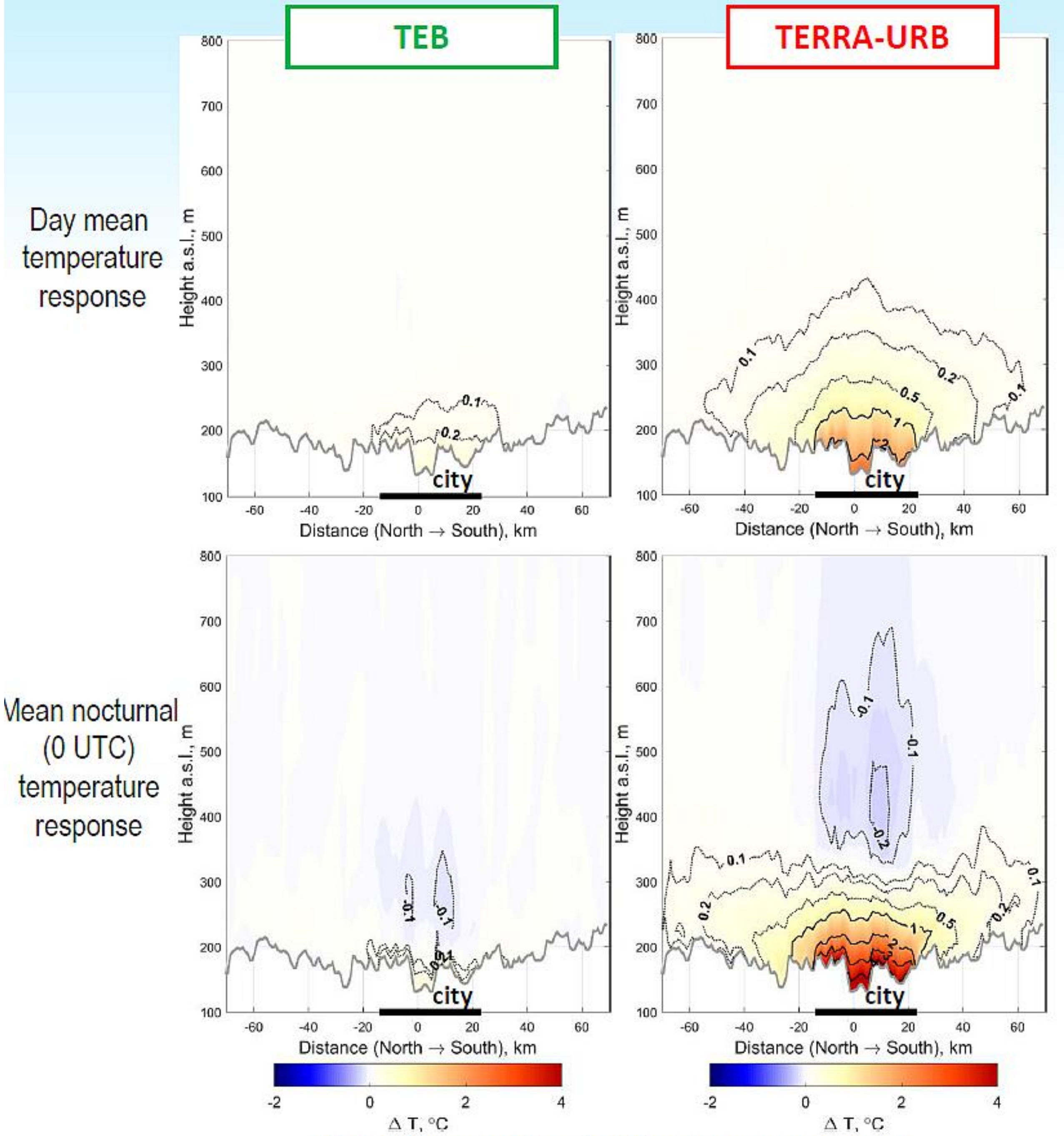
$$F_{urb} = \min[1 - F_{nat}, \max(F_{bld} + F_{road} + k_{ind} \cdot F_{ind} + k_{res} \cdot F_{res}; F_{bld} + F_{can})]$$

Natural ("green") fraction — Buildings — Roads — Industrial areas — Residential areas (courtyards) — Street canyons

Plurality of urbanization model results

© Mikhail Varentsov



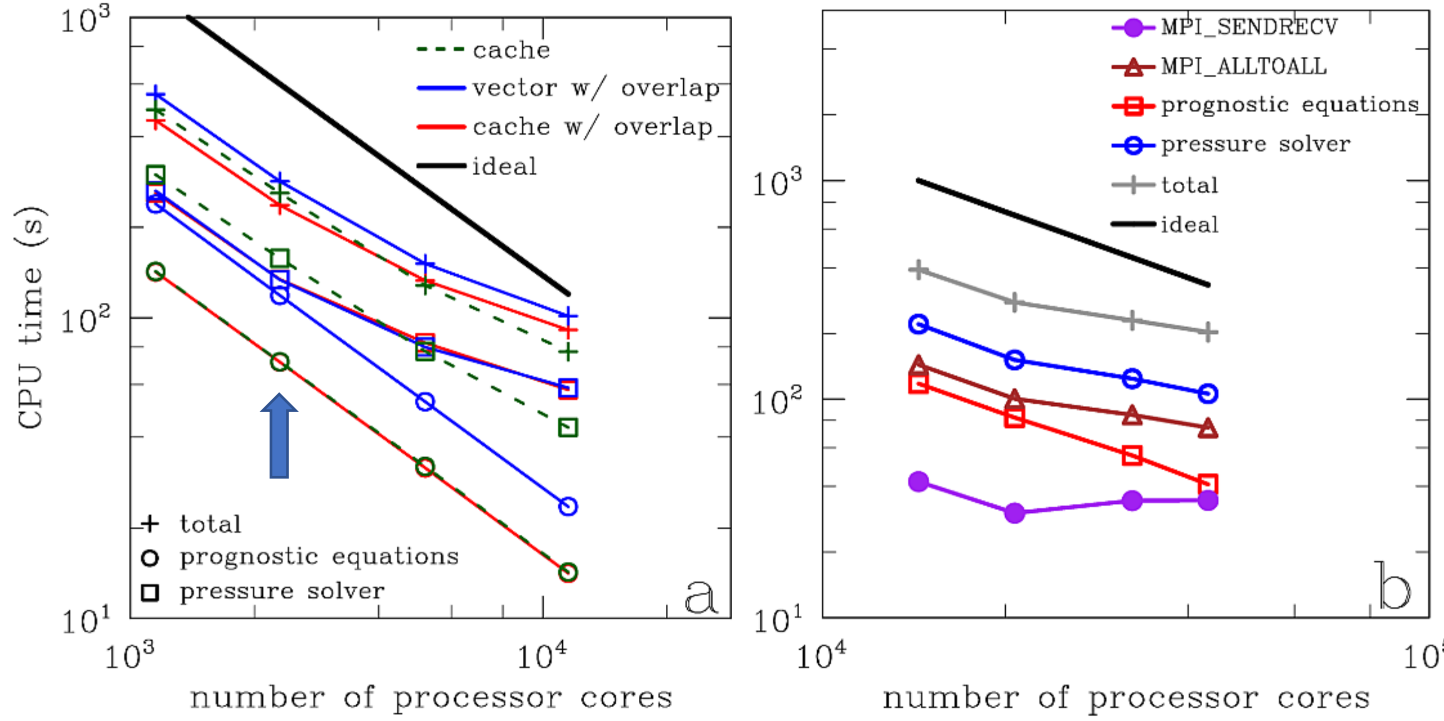


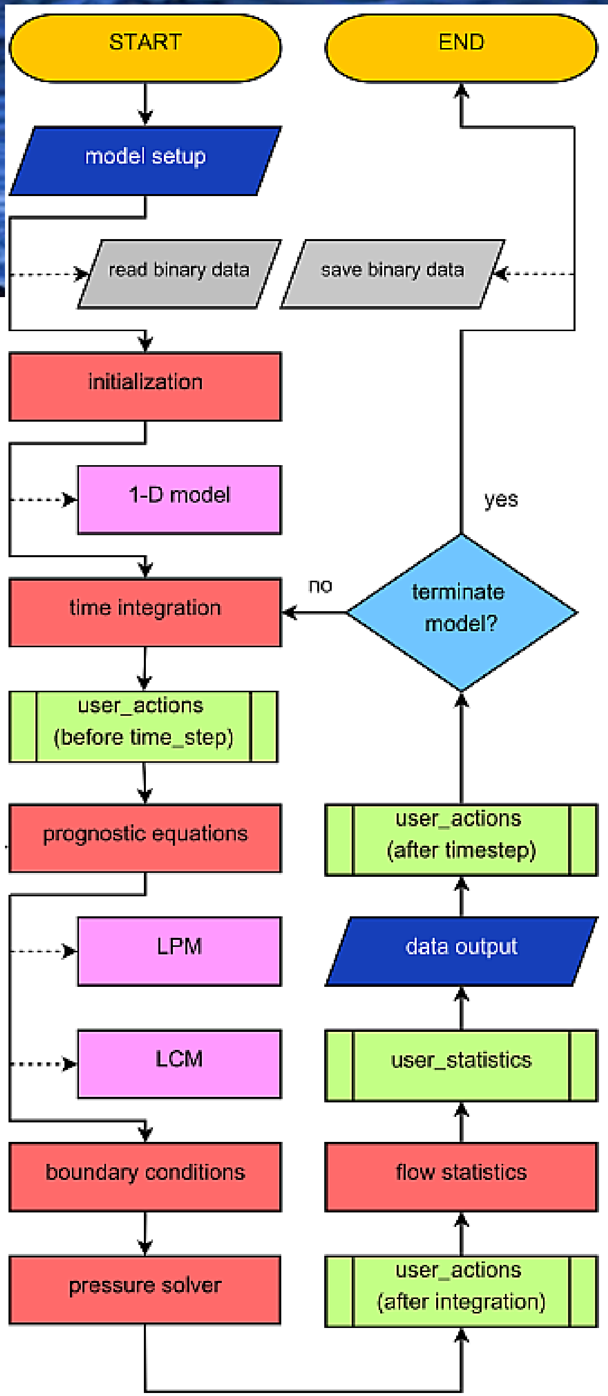
Vertical cross-sections, built for temperature response to switching on the urban scheme (for mean summer T)

Модель PALM

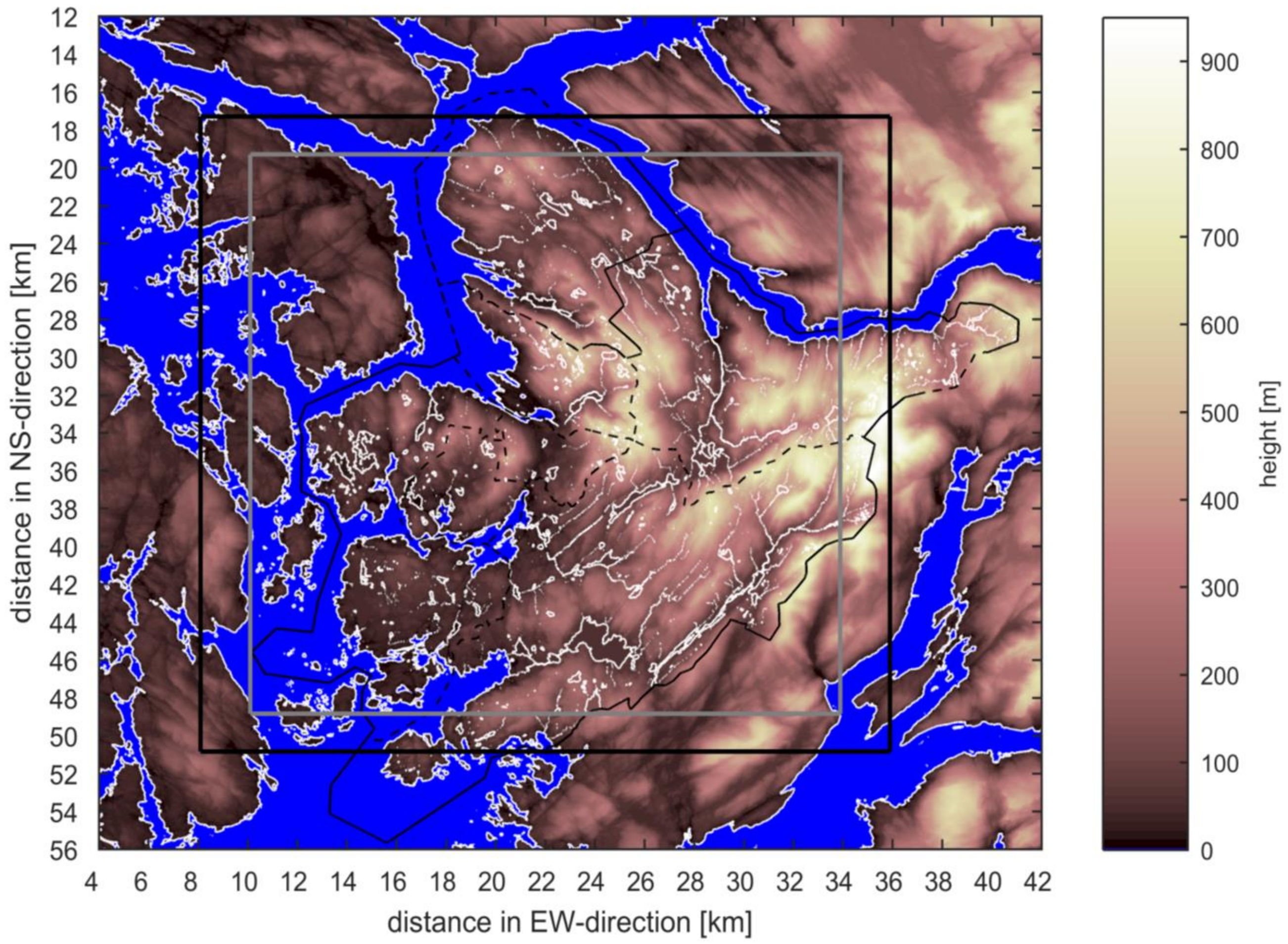
The Parallelized Atmospheric Large-eddy simulation Model (PALM):

- Optimized to run on massive-parallel
  - This study completed on HEXAGON (decommissioned in 2019) at SIGMA-2 Norwegian national HPC center
  - New studies run on FRAM at SIGMA-2 Norwegian national HPC center
- This study runs PALM on **2048** CPU cores; one run took about **6 hours**
- Allows to include user modules (user_actions) as independent subroutines





Model configuration



Topographic map of the Bergen area. The black square indicates the final model domain used for the PALM simulations; the gray square indicates the focus area for the analysis of the PALM simulations.

Periodic lateral boundary conditions.

The total domain size is 28800 x 34560 m^2 in the zonal and meridional directions, respectively, including buffer zones for linear interpolation between the periodic boundaries of 1000 m width.

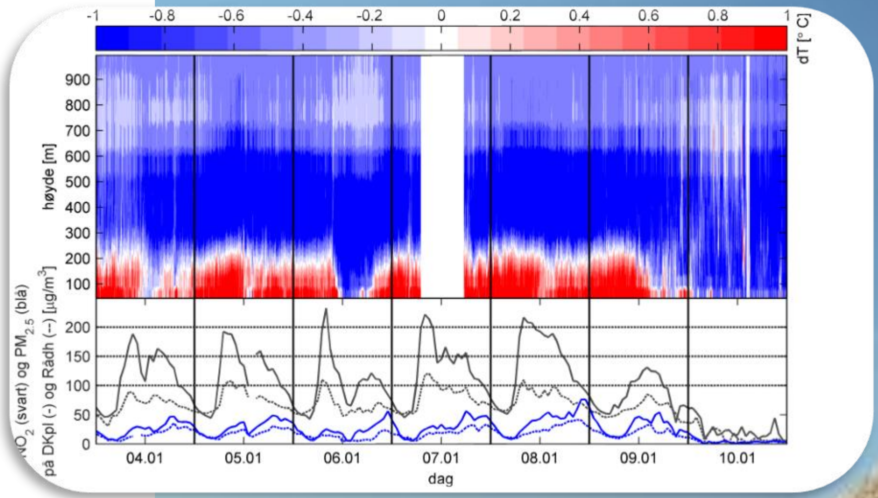
The horizontal grid cell resolution is 10 m.

The vertical resolution is 10 m up to a height of 660 m. Above that the vertical resolution increases by 1 % for each additional grid level. The total domain height is 160 levels or 2239 m.

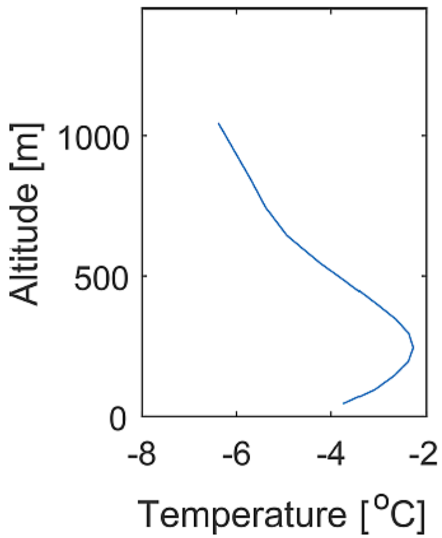
Digital elevation model (DEM) from the Norwegian mapping authority in the GeoTIFF format. We used ArcGIS in order to process the data and create a complete topography data set at 10 m horizontal resolution; linear interpolation to fix small gaps due to missing laser data.

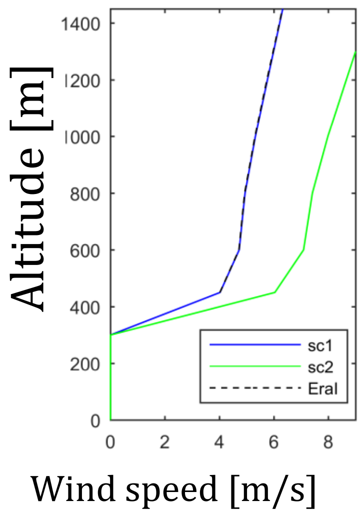
Initial conditions and scenarios

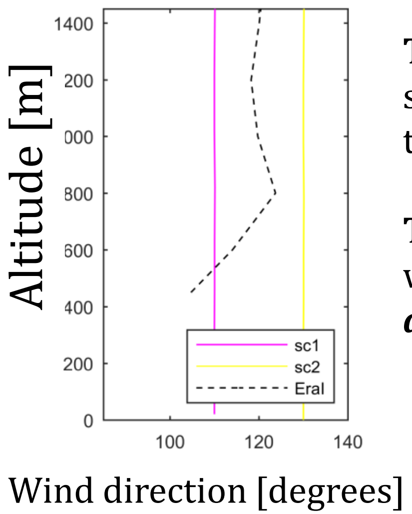
Temperature profiles, stability and inversions
https://veret.gfi.uib.no/?action=mtp



Initial conditions and scenarios

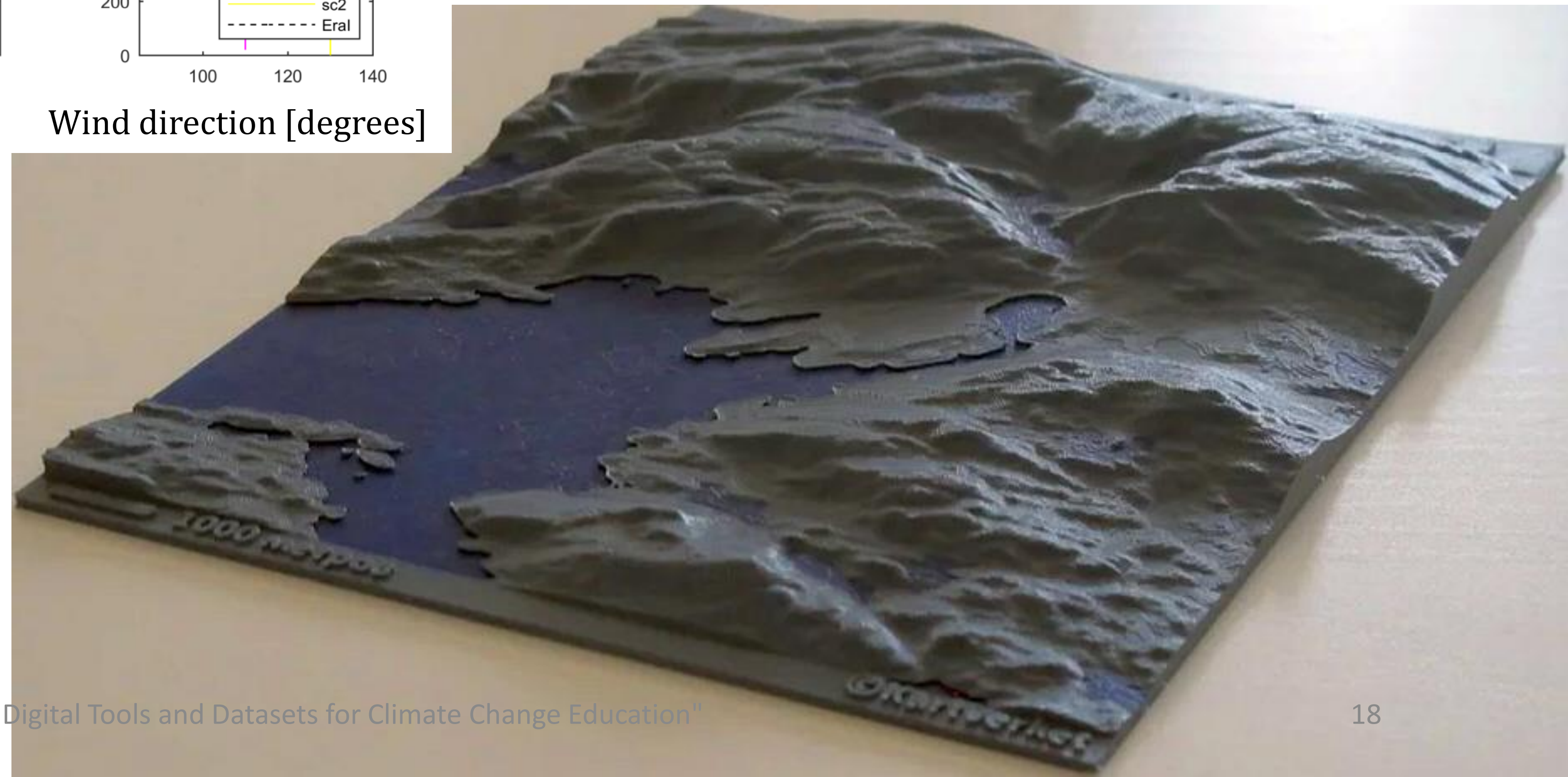






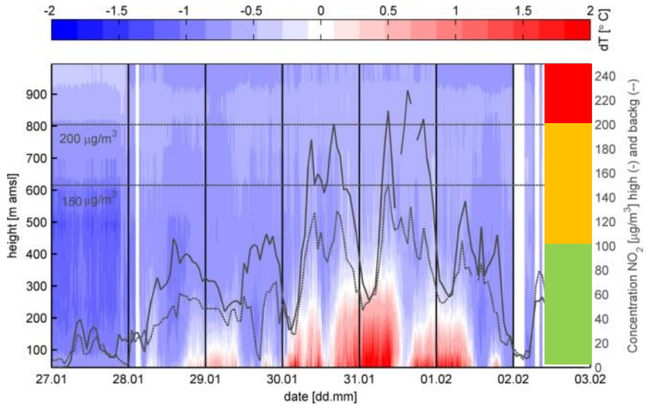
The First Scenario (sc1): Low speed south-eastern wind with sea surface temperature by 2.5°C warmer than the land surface temperature

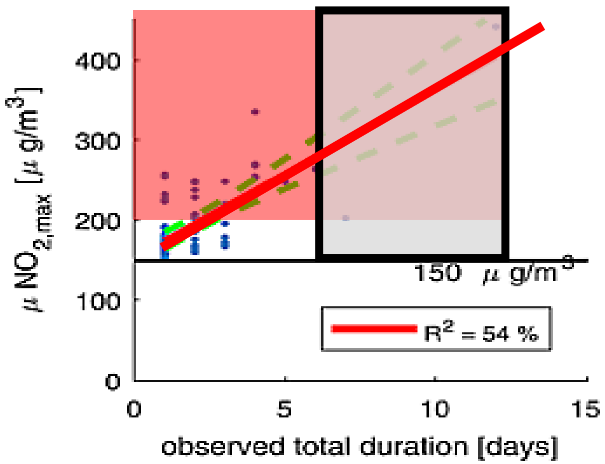
The Second Scenario (sc2): Low-to-middle speed more southern wind with equal sea surface and land surface temperatures – ***characterize air stagnation in the city centrum***

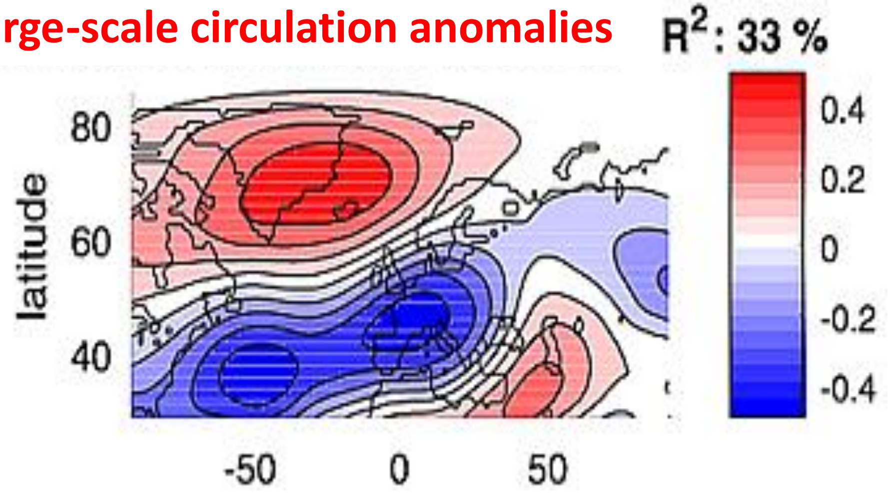


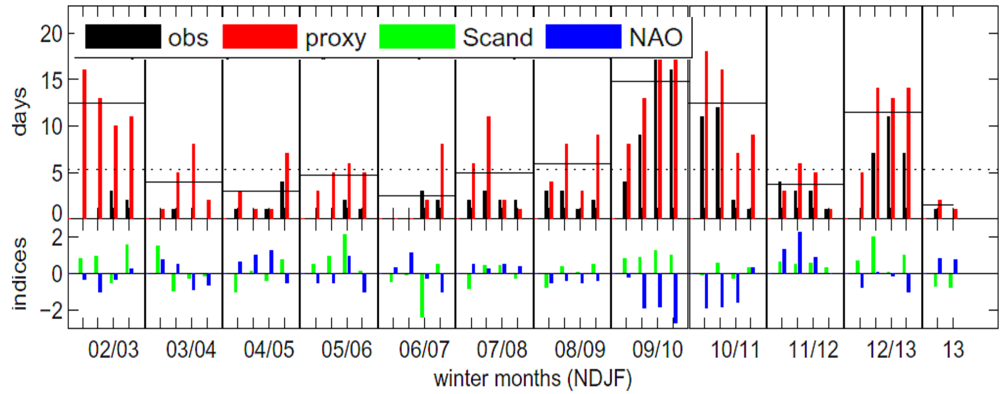
Influential scenarios

Extreme local hazards require persistent weather conditions and large-scale circulation anomalies





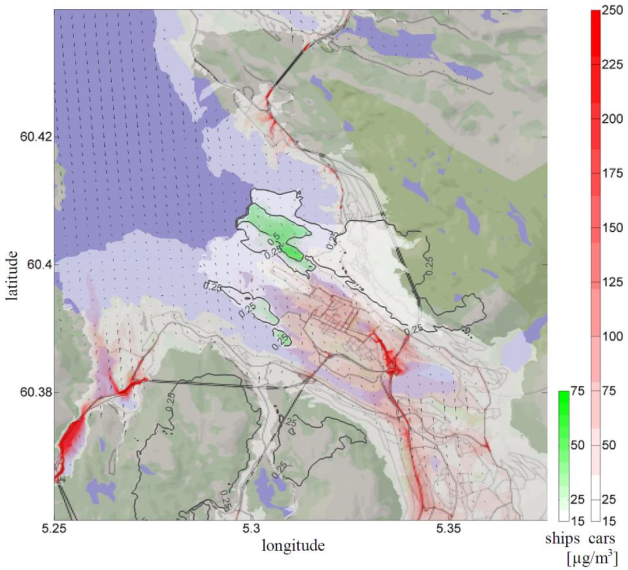




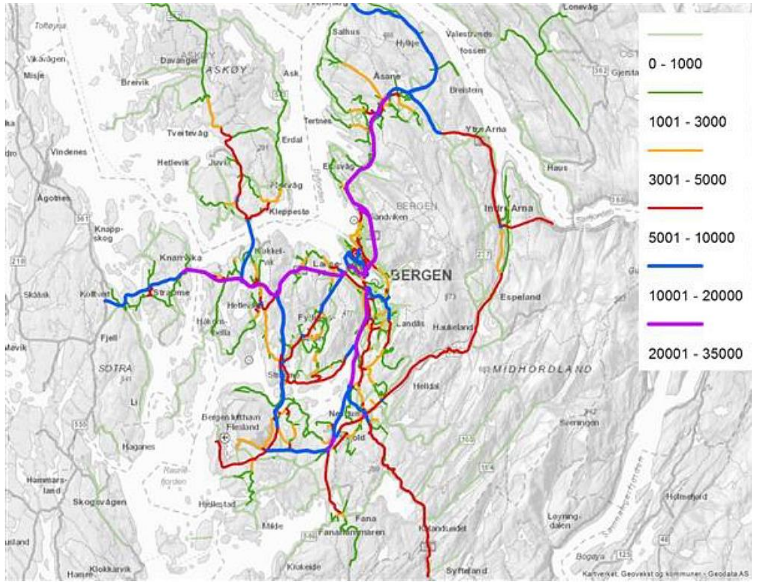
Extreme concentrations accumulate longer than **3 days**

The Greenland blocking

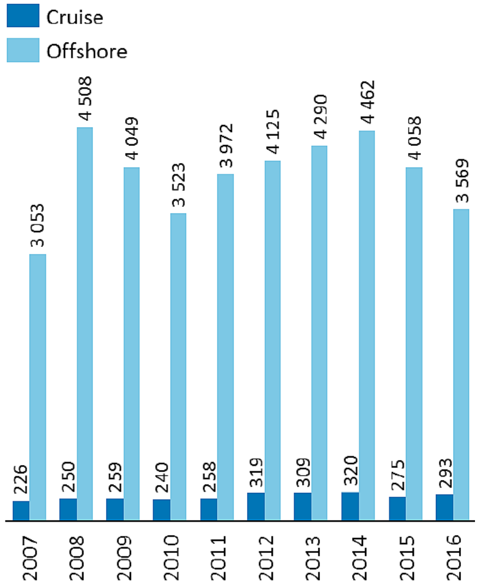
Corresponding local extremes could be captured by the high-resolution models



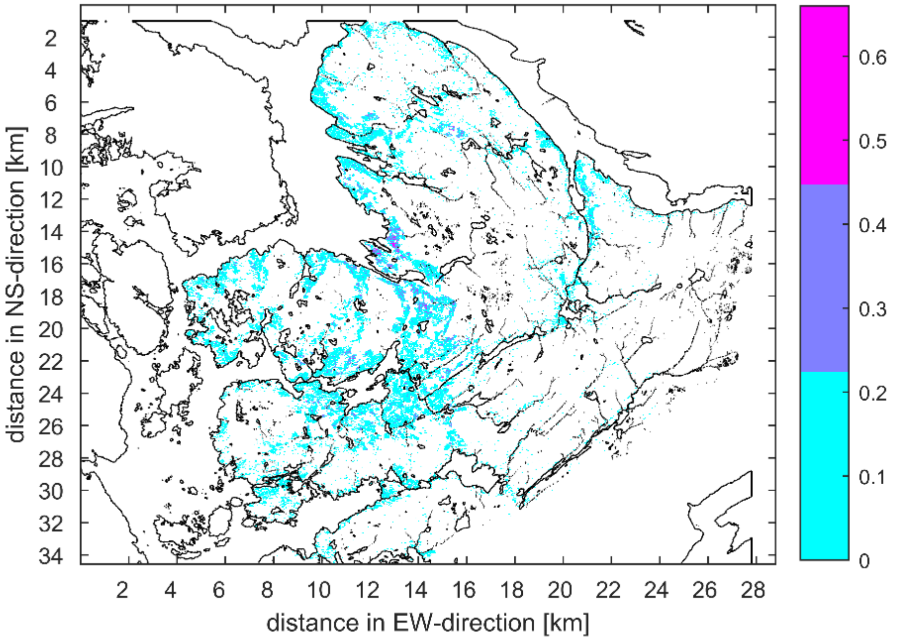
Pollution sources



Mean daily road traffic in Bergen
Source: NILU report no15, 2017



Total annual number of ships in the Bergen Harbour



Map with the locations of wood ovens in Bergen within the modelled domain (centred over Bergen).
The colour shading indicates the number of properties with a registered wood oven averaged over 3 x 3 boxes. Black lines indicate the waterfront. Based on data from Bergen Municipality and Fire department, respectively.

Road Traffic

Ships in the Harbor

Wood-burning ovens in private Households

Co-variability: Blocking – air quality

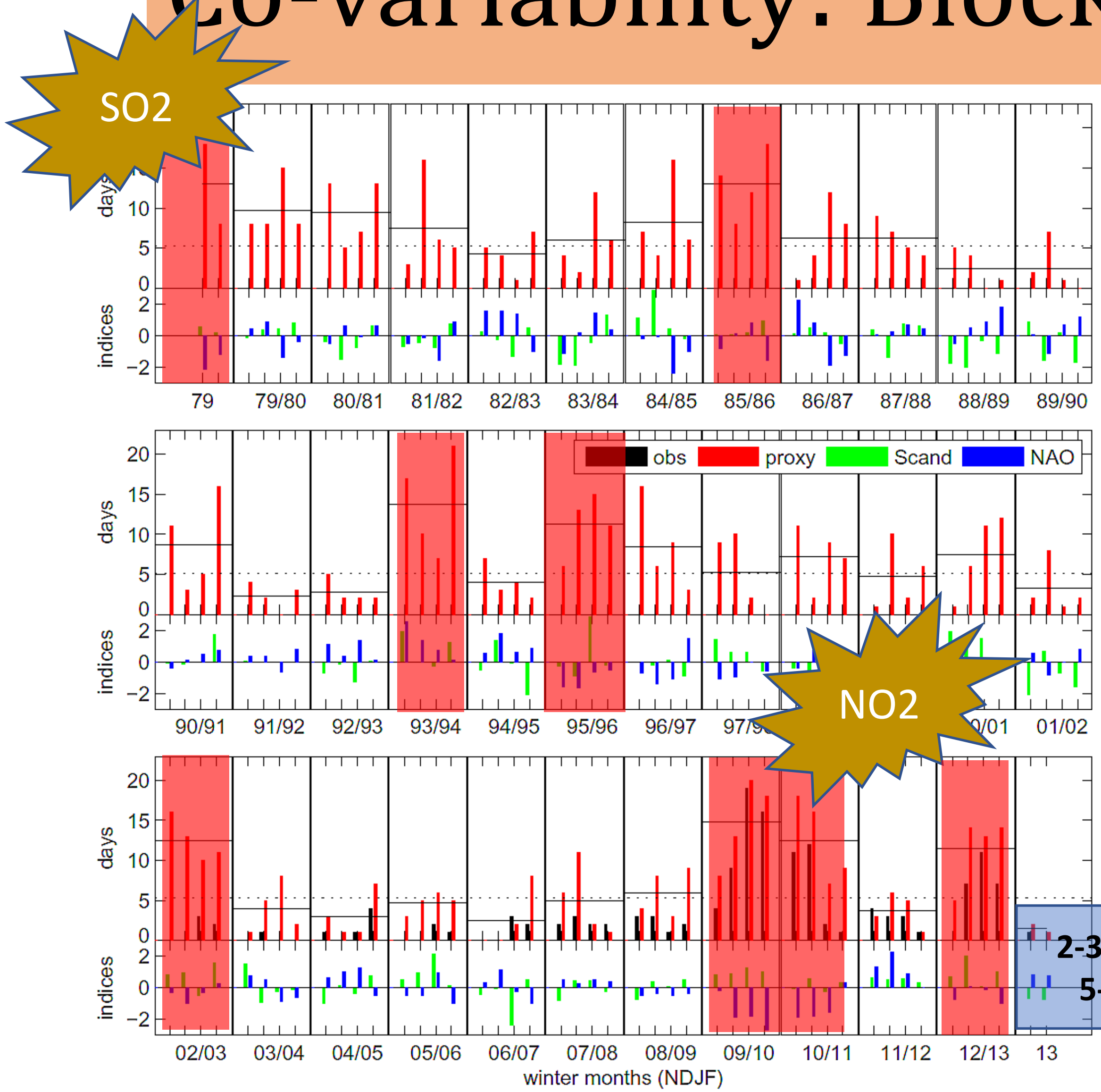


Table 1. The empirically identified thresholds for the atmospheric circulation proxy.*

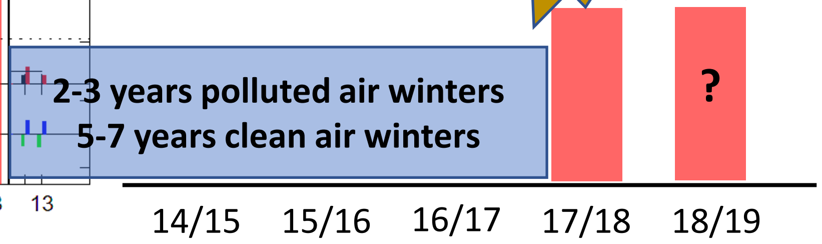
Variable	Thresholds	Thresholds (day-1)
Wind	05° < *wd* < 175°, *ws* < 3 m/s	00° < *wd* < 360°, *ws* < 4 m/s
	85° < *wd* < 155°, *ws* < 4 m/s	85° < *wd* < 165°, *ws* < 5 m/s
	85° < *wd* < 135°, *ws* < 5 m/s	105° < *wd* < 165°, *ws* < 6 m/s
	105° < *wd* < 135°, *ws* < 6 m/s	105° < *wd* < 115°, *ws* < 8 m/s
	105° < *wd* < 115°, *ws* < 7 m/s	
Temperature	$\Delta T < -0.7$ K	$\Delta T < -0.5$ K

*The atmospheric circulation proxy is set to 1 if all variables are within their respective ranges. Abbreviations: *wd* – wind direction; *ws* – wind speed and ΔT – temperature deviation from the climatological seasonal mean cycle.

Table 2. Detection and false alarm rate (Ryan et al., 2000) of the proxy and correlations between the monthly and seasonal sum of observed and predicted polluted days.*

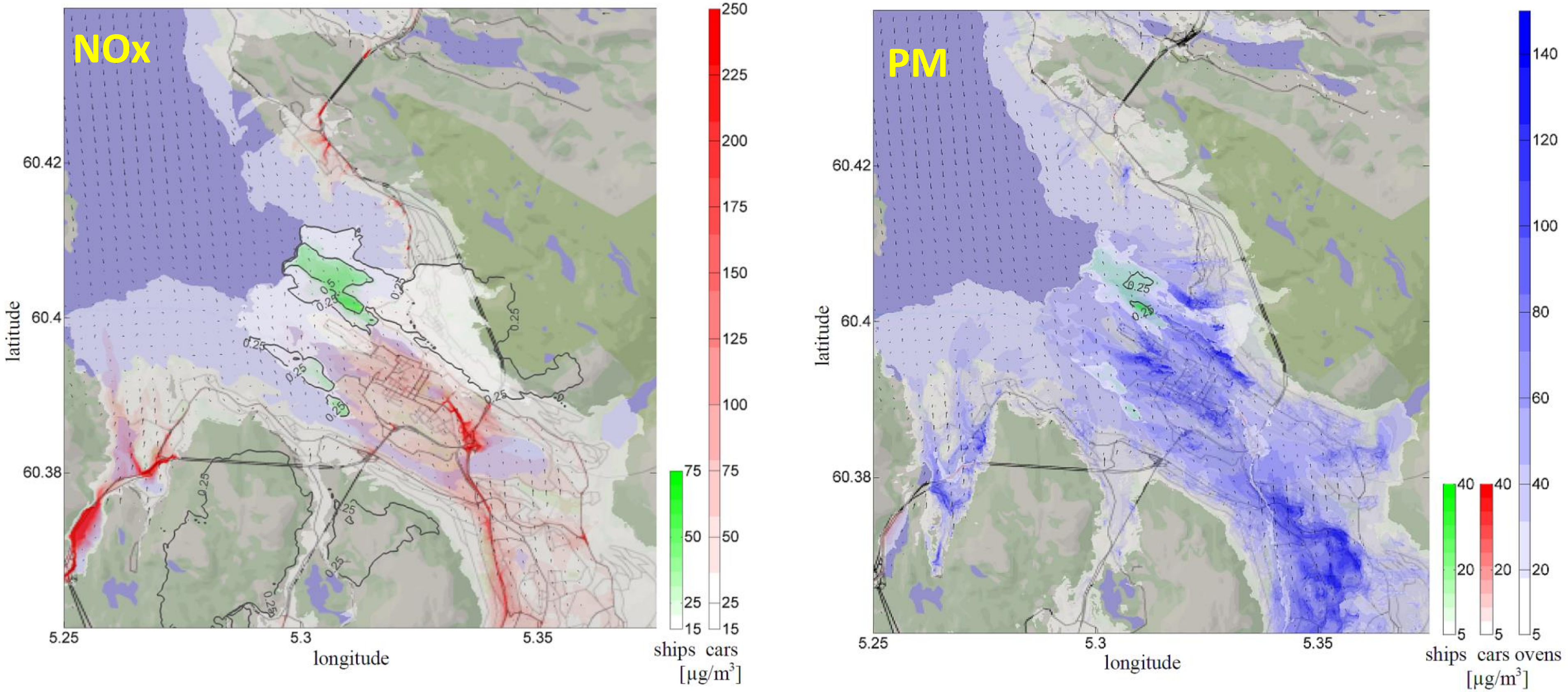
	Skill scores	Skill scores WE14
Detection rate	0.82	0.80
False alarm rate	0.55	0.62
Correct null prediction rate	0.87	0.84
Correlation days per month	0.89	0.85
Correlation days per season	0.93	0.93

*For the correlations on a seasonal basis, only complete winter-seasons (NDJF) are considered. All correlations are significant at the 99% level.



Model runs and interpretation of results

Wolf, T., Pettersson, L. H., and Esau, I., 2020: A very high-resolution assessment and modelling of urban air quality, Atmospheric Chemistry and Physics, 20, 625–647, https://doi.org/10.5194/acp-20-625-2020



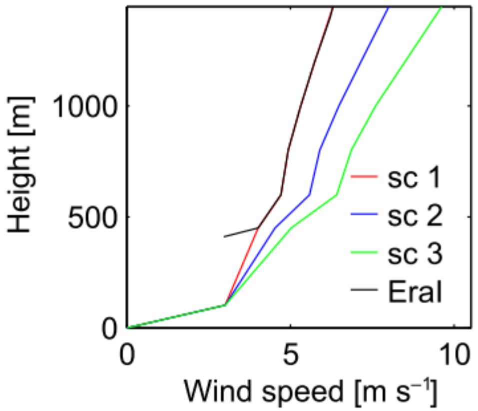
Model sensitivity

Wolf-Grosse, T., Esau, I., & Reuder, J. (2017). Sensitivity of local air quality to the interplay between small- and large-scale circulations: a large-eddy simulation study. *Atmospheric Chemistry and Physics*, *17*(11), 7261–7276. https://doi.org/10.5194/acp-17-7261-2017

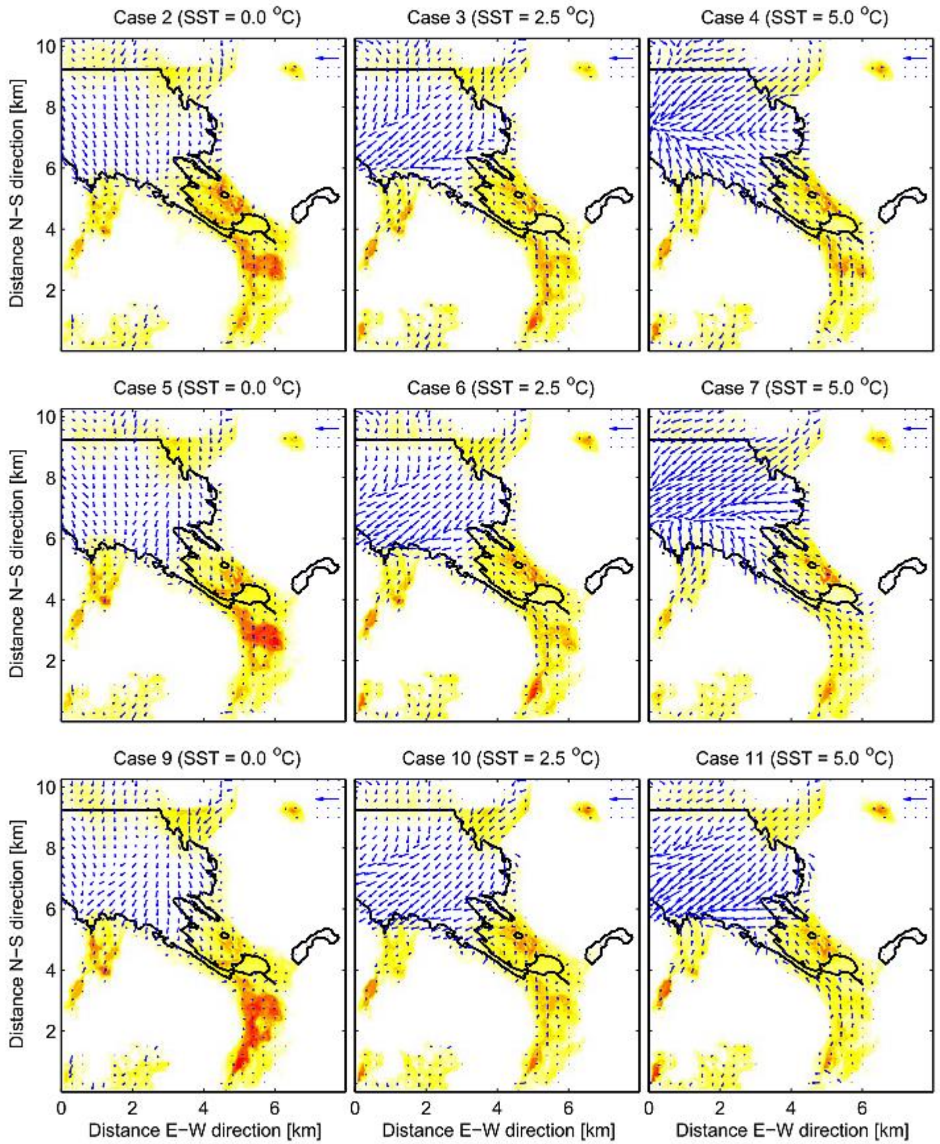
Table 1. Model simulations.

Case	Wind scenario	θ_{fjord} (K)	$T_{2\,\text{m}}$ (fjord) (K)[b]	$T_{2\,\text{m}}$ (area 1) (K)[b]	$T_{2\,\text{m}}$ (area 2) (K)[b]
Case 0[a]	sc 1	–	–	–	–
Case 1	sc 1	270.7	271.5	269.8	268.0
Case 2	sc 1	273.2	273.6	271.3	269.1
Case 3	sc 1	275.7	275.4	272.0	270.1
Case 4	sc 1	278.2	277.4	273.0	271.6
Case 5	sc 2	273.2	273.7	271.5	269.0
Case 6	sc 2	275.7	275.4	272.2	270.8
Case 7	sc 2	278.2	277.4	273.3	272.8
Case 8	sc 2	280.7	279.1	274.4	273.3
Case 9	sc 3	273.2	273.7	271.7	269.8
Case 10	sc 3	275.7	275.5	272.5	271.0
Case 11	sc 3	278.2	277.3	273.5	272.4
Case 12	sc 3	280.7	279.1	275.1	275.2
Case 13[c]	sc 3	273.2	273.7	271.7	269.8
Case 14[c]	sc 3	275.7	275.5	272.5	271.1
Case 15[c]	sc 3	278.2	277.3	273.5	272.4

[a] Simulation with Neumann BC and $H_s = 0\,\text{K m s}^{-1}$ over entire domain. [b] Calculated from a linear extrapolation of the potential temperature gradient between the two lowest grid points above topography. Absolute temperature calculated with reference pressure 1000 hPa. The mean temperatures over land contain areas up to 70 m surface elevation. In inversion conditions this results in a higher mean temperature than only for the lowest areas. [c] Emissions only from the largest street in the Bergen Valley.



Wind fields at 55m height and passive tracer concentration 2m above the surface. The top, middle, and bottom panels show the results for wind speed scenario 1, 2, and 3. All data are means over the last four output steps of the 12 h simulation. Each output step is an average of 15 min.



Modeling scenarios for optimization of environmental management

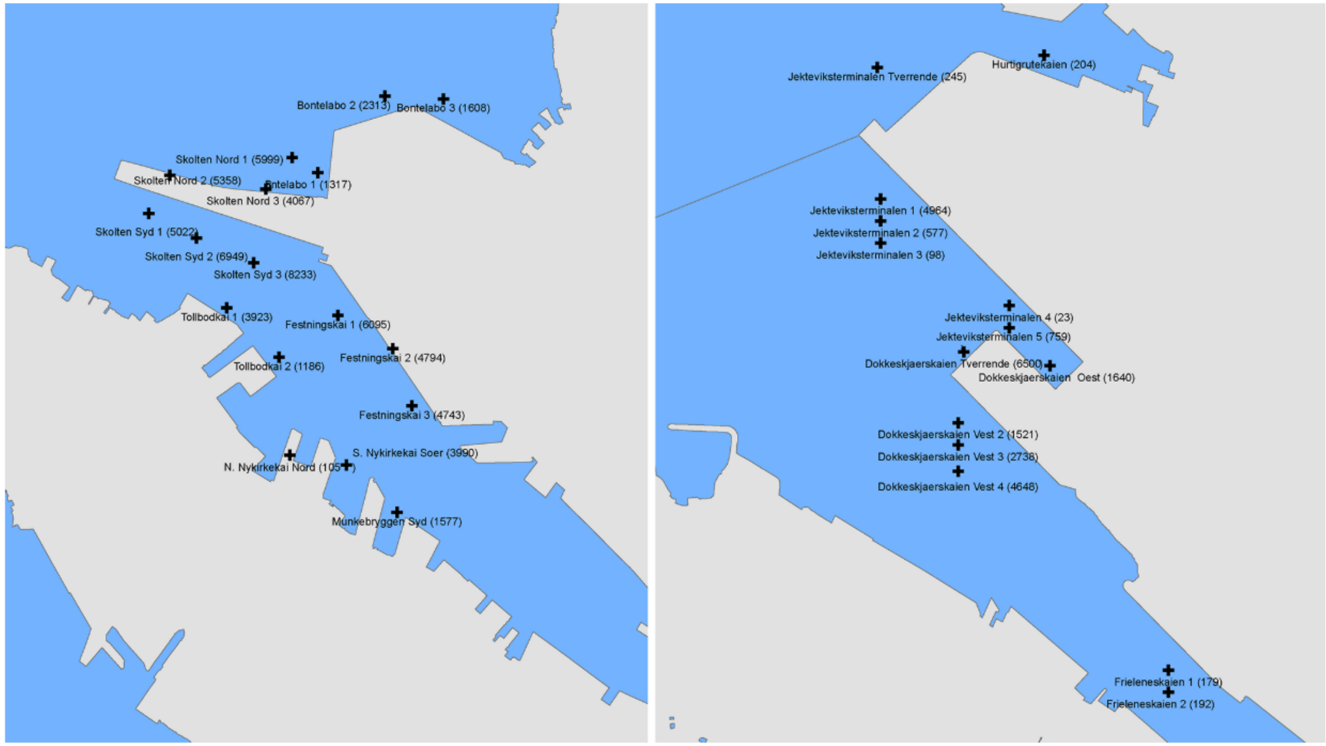
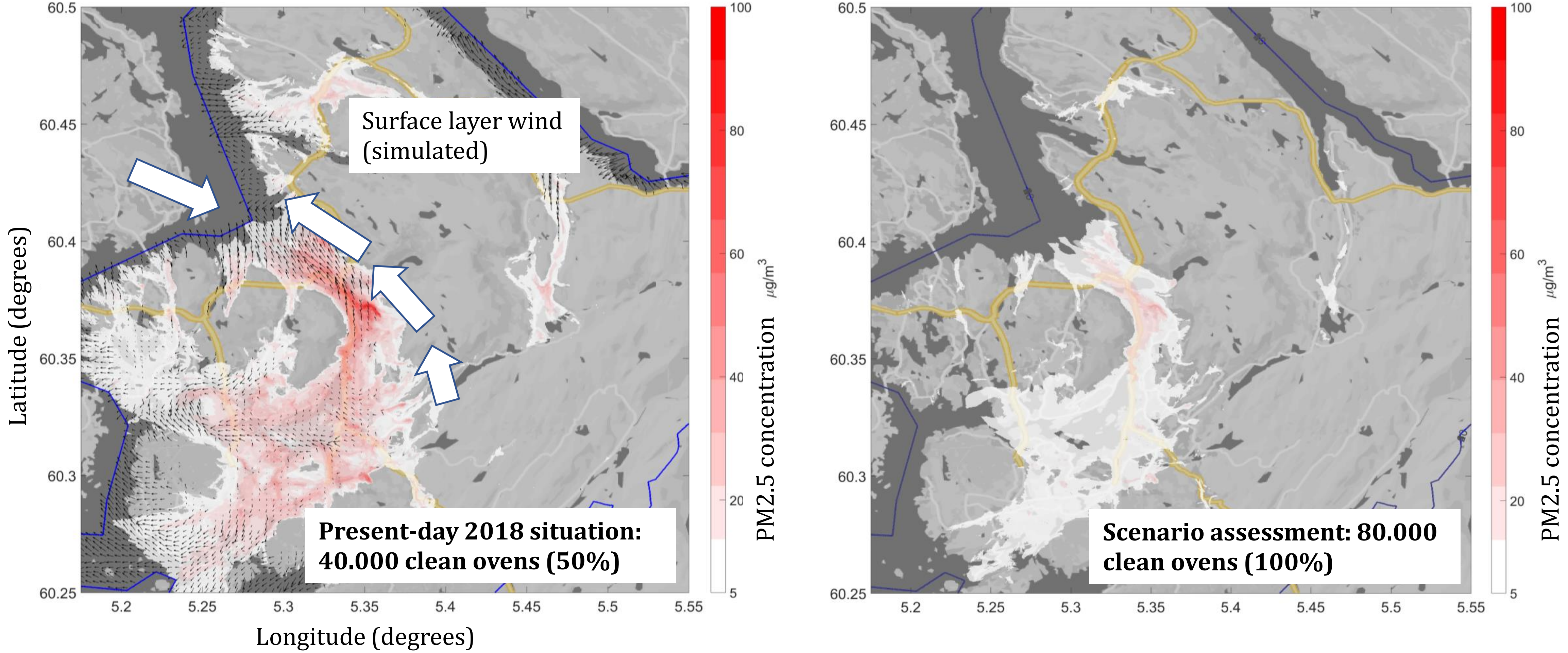


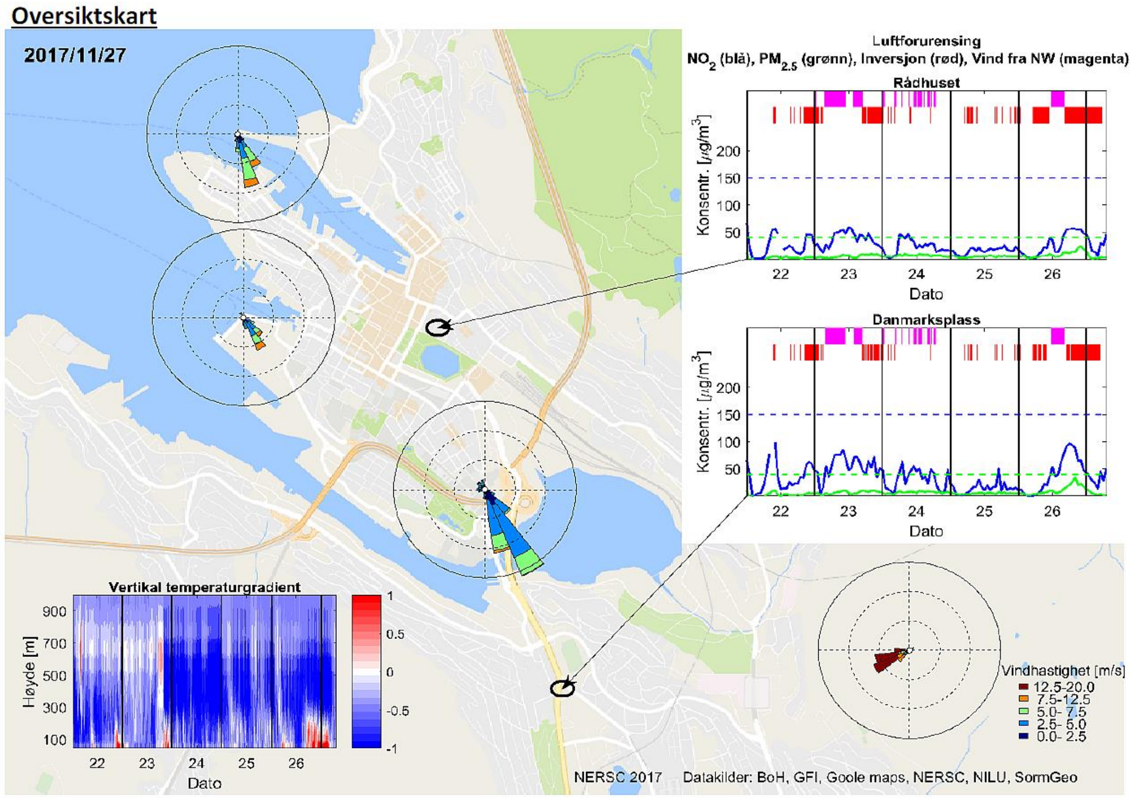
Figure A3. Ship positions in Bergen harbour. The numbers behind the names of the harbour docks indicate the number of hours with supply ships docked at each of the harbour docks from January 2015 to March 2016.

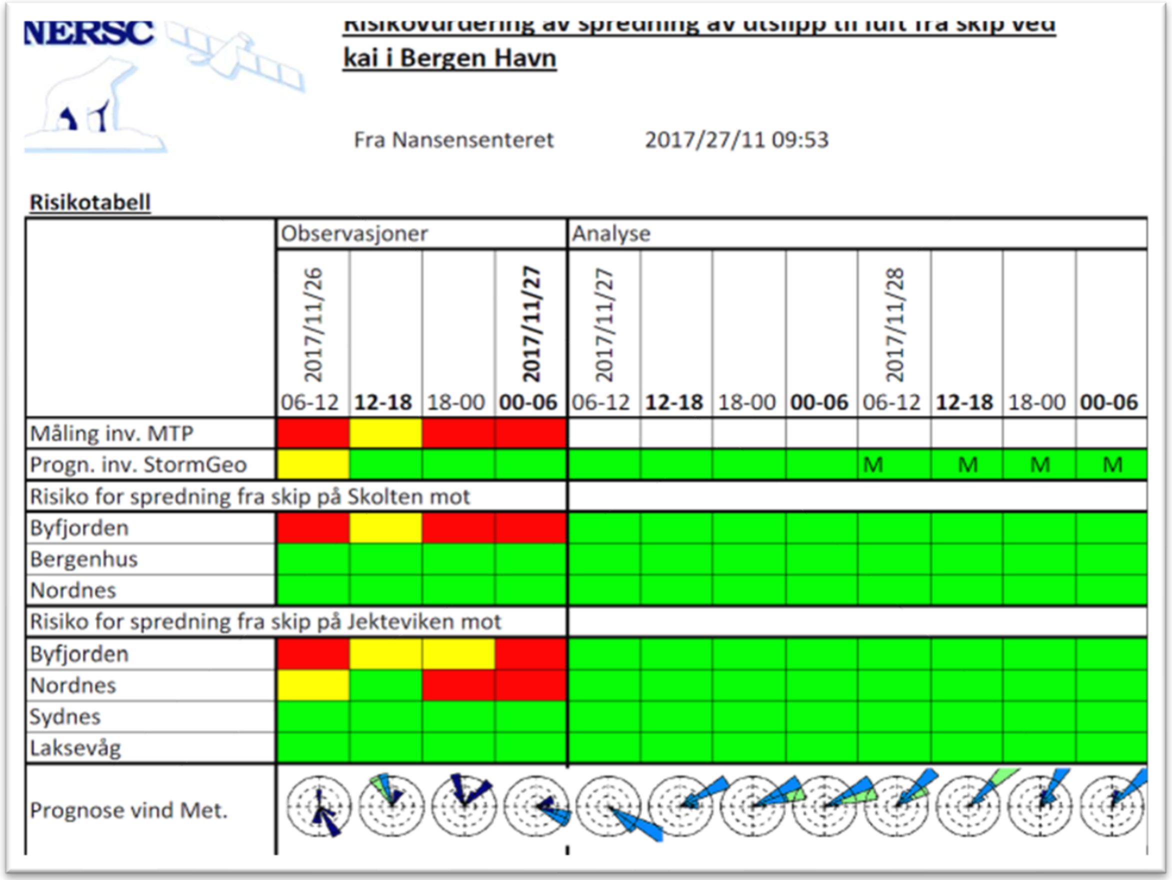
Modeling scenarios for optimization of environmental management



The PM2.5 concentrations from wood-burning household fireplaces (ovens): Present day oven composition impact (left panel) versus future composition impact (right panel) in the first typical **winter scenario**

Urban modeling for climate services





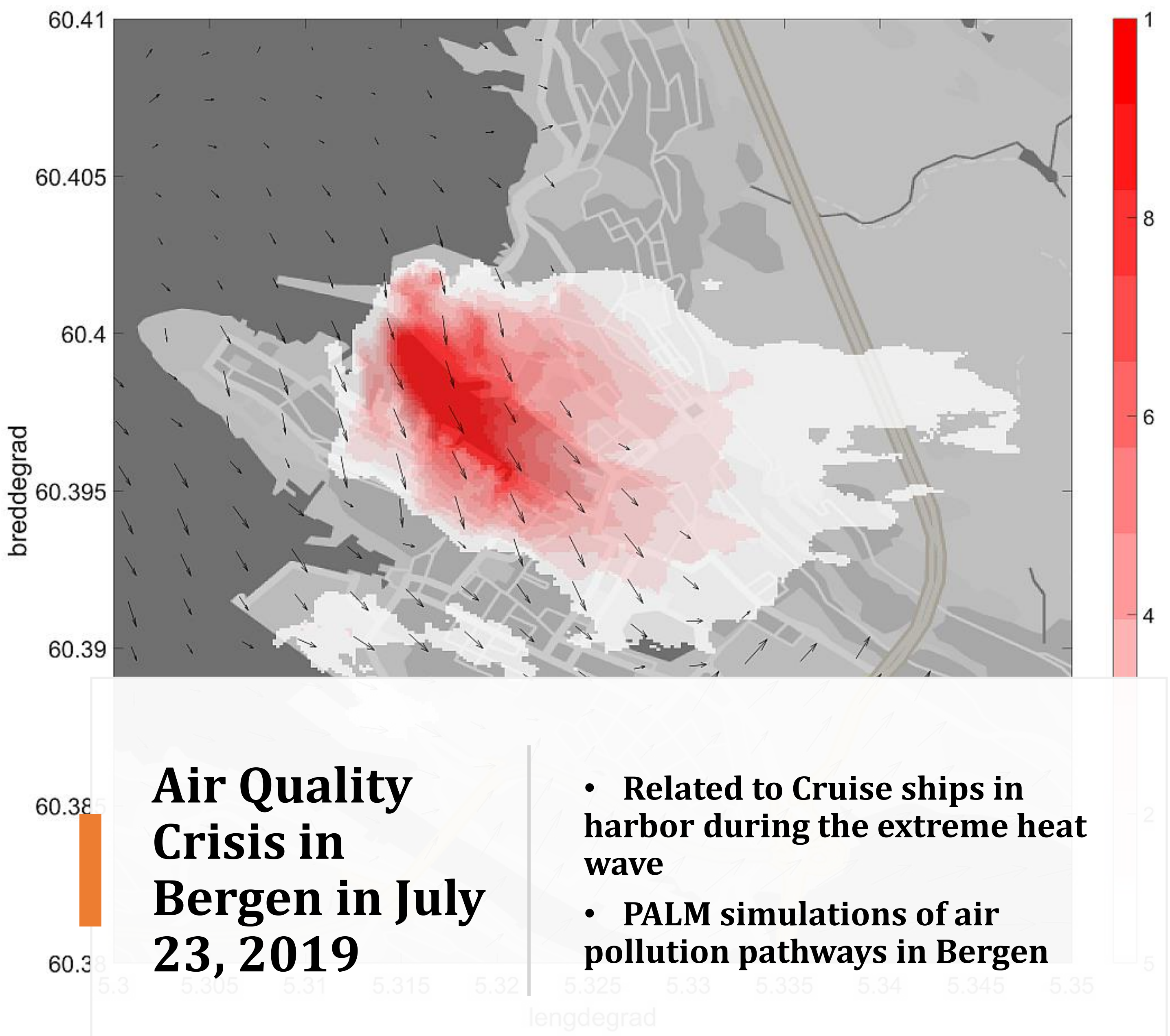
NERSC

Risikovurdering av spredning av utslipp til luft fra skip ved kai i Bergen Havn

Fra Nansensenteret 2017/27/11 09:53

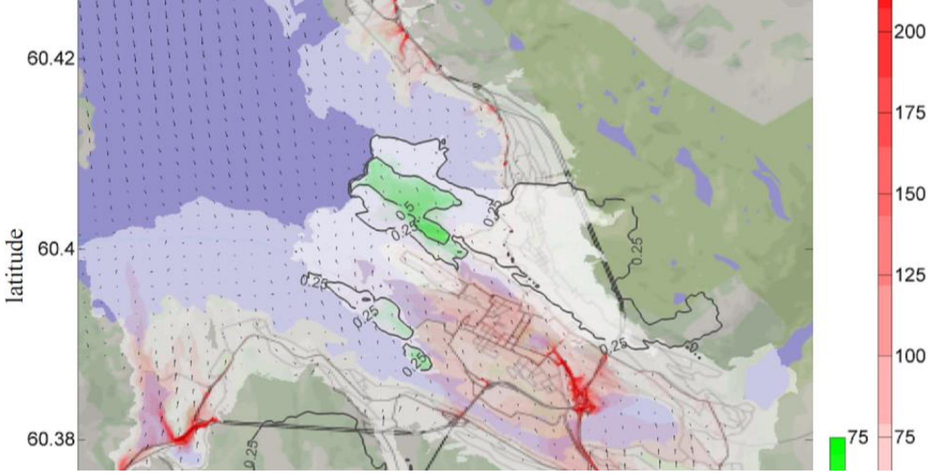
Risikotabell

	Observasjoner				Analyse							
	2017/11/26 06-12	**12-18**	18-00	**2017/11/27 00-06**	2017/11/27 06-12	**12-18**	18-00	**00-06**	2017/11/28 06-12	**12-18**	18-00	**00-06**
Måling inv. MTP												
Progn. inv. StormGeo									M	M	M	M
Risiko for spredning fra skip på Skolten mot												
Byfjorden												
Bergenhus												
Nordnes												
Risiko for spredning fra skip på Jekteviken mot												
Byfjorden												
Nordnes												
Sydnes												
Laksevåg												
Prognose vind Met.												



Air Quality Crisis in Bergen in July 23, 2019

- **Related to Cruise ships in harbor during the extreme heat wave**
- **PALM simulations of air pollution pathways in Bergen**



FORURENSNING OVER BYEN: Slik så det ut fra Laksevåg tirsdag ved 8-tiden. FOTO: HELGE MISJE JOHANNESEN

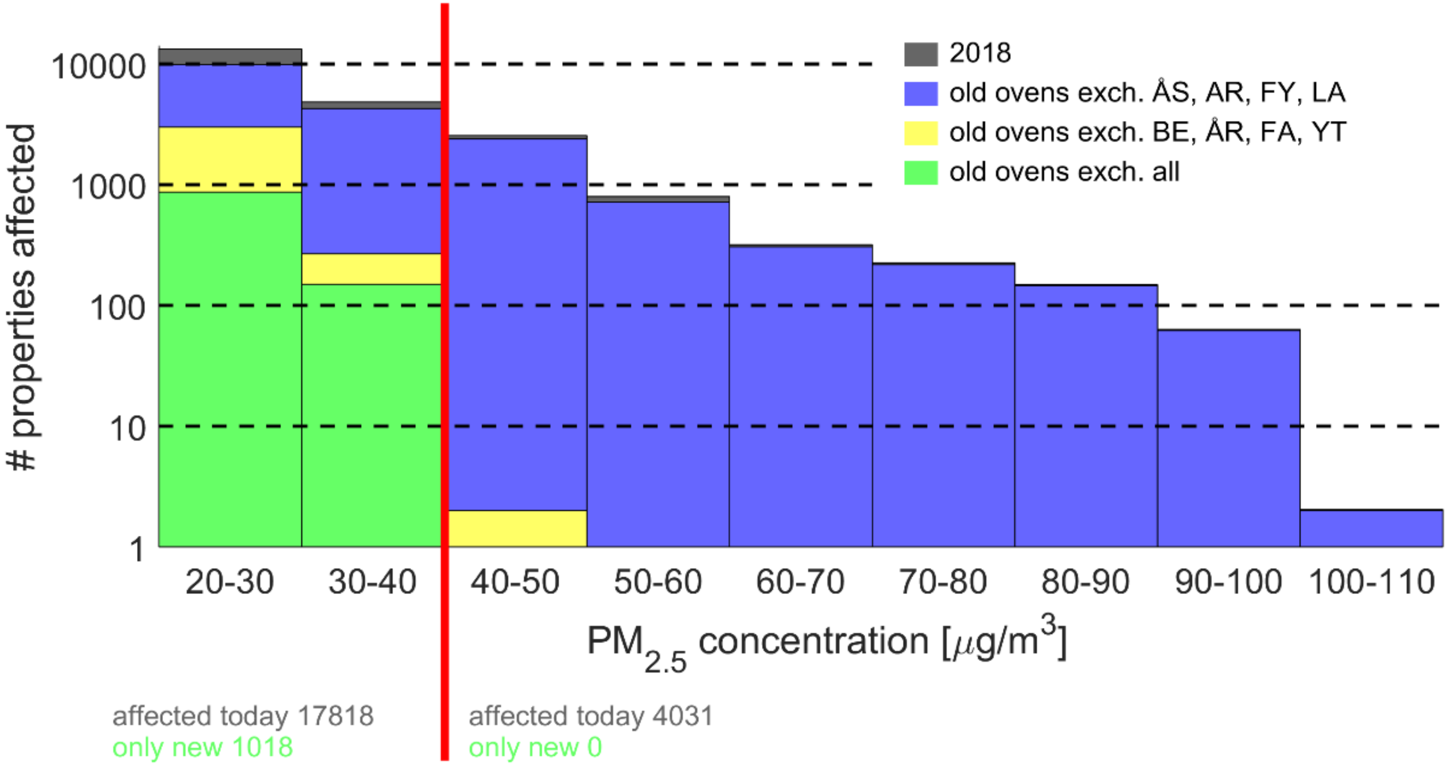
– Skipene som spyr ut forurensing burde vært senket for lenge siden

– Har ikke sett det verre i sommer. Dette kan vi ikke leve med. Rydd opp!

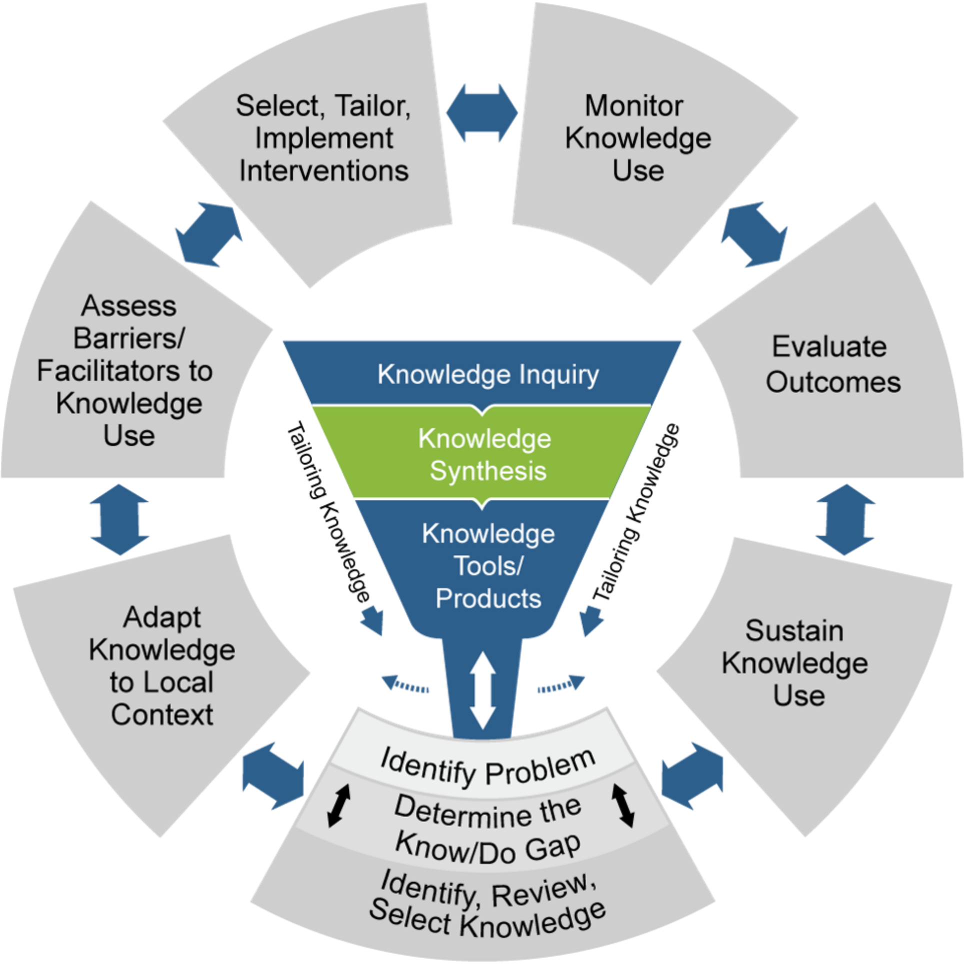
The Bergen study: Effective Scenarios

The effects of different policy measures (identified by colors) on the PM2.5 concentration exposures given in the number of affected households

Yellow policy measures: Policy and economic incentive focus on just a few central urban districts will lead to practical elimination of dangerous (40 mkg/m3 or more) level exposure of households

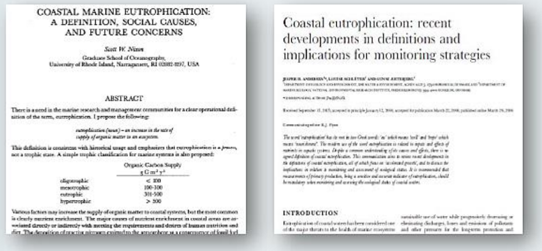


Communication of urban climate modeling



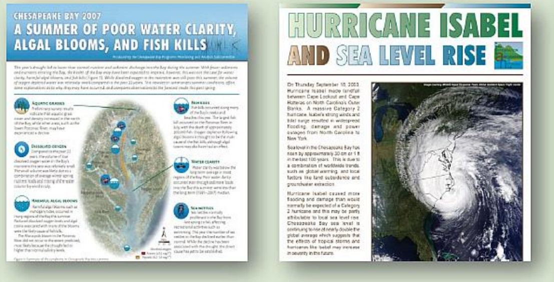
Recognize differences in communication techniques

Scientific writing



- Providing scientific context (references)
- Text > graphics
- Authorship exclusive
- Focus on results & interpretation

Science communication



- Providing societal context (examples)
- Text ≈ graphics
- Authorship inclusive
- Focus on conclusions & recommendations