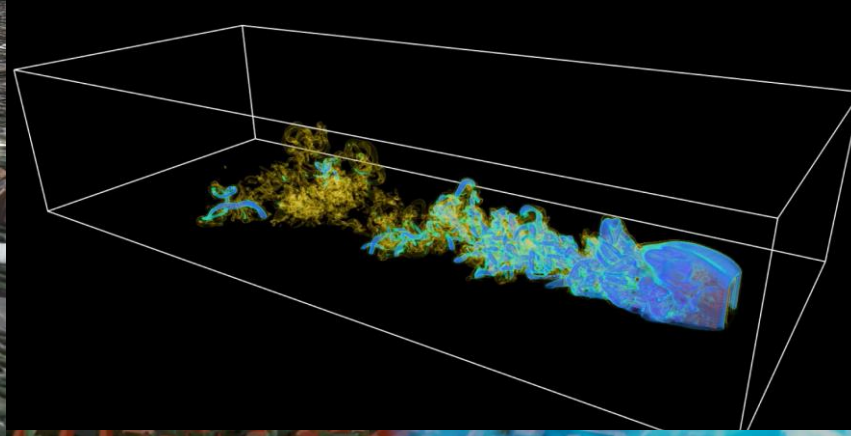


The PALM Model System Release 25.10: Applications in Micrometeorology, Urban Planning, Civil Construction and Renewable Energy

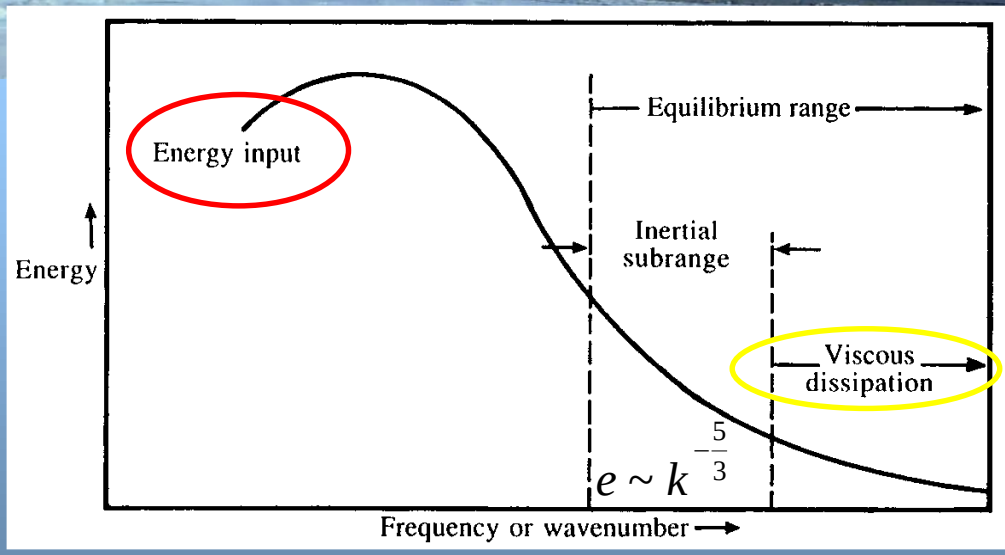
Siegfried Raasch and Coauthors
Leibniz University Hannover, pecanode GmbH, Germany

Basic Features of Atmospheric Turbulence

Turbulence characteristics

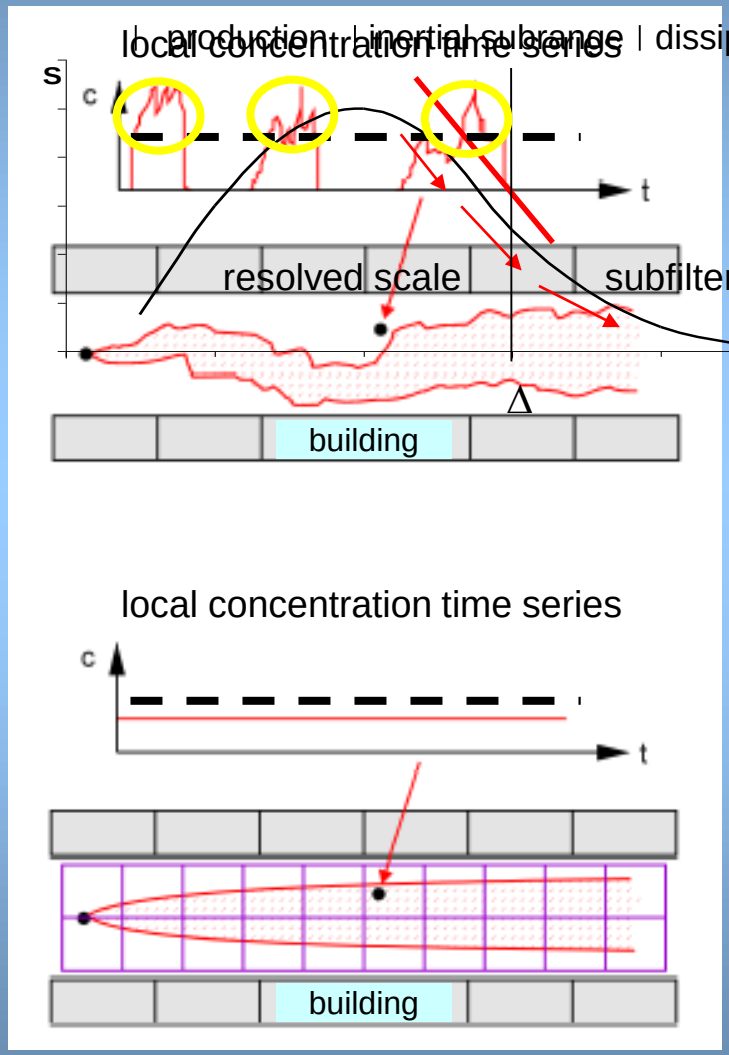
- **Energy production and dissipation on different scales**
  - Large scales (**L**): shear and buoyant production
  - Small scales (η): viscous dissipation

- **Large eddies:** 10^3 m, 1 h **L**
  Small eddies: 10^{-3} m, 0.1 s **η**



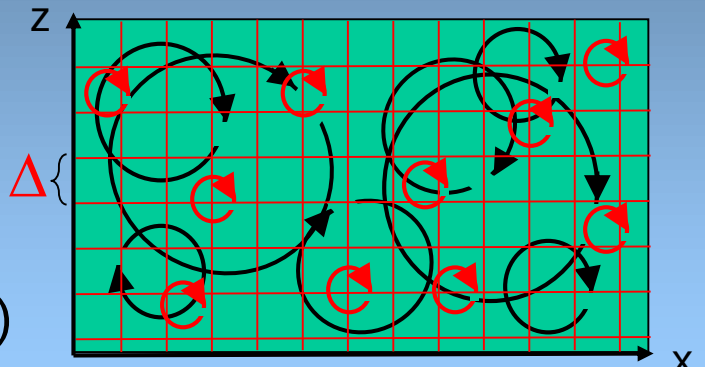
Garratt (1992)

LES in a Nutshell



after Schatzmann and Leitl (2001)

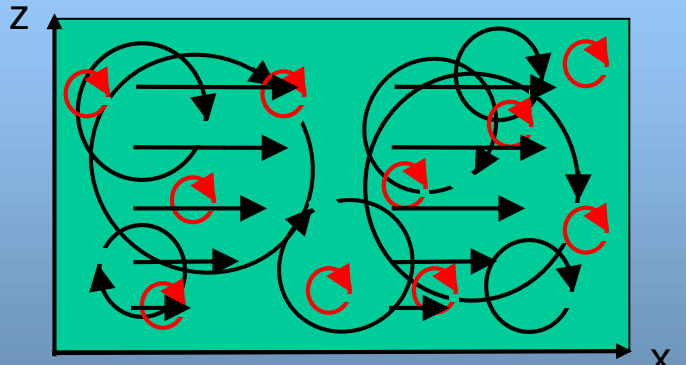
fluctuations (**u**, c)



LES: volume average

critical concentration level

smooth result

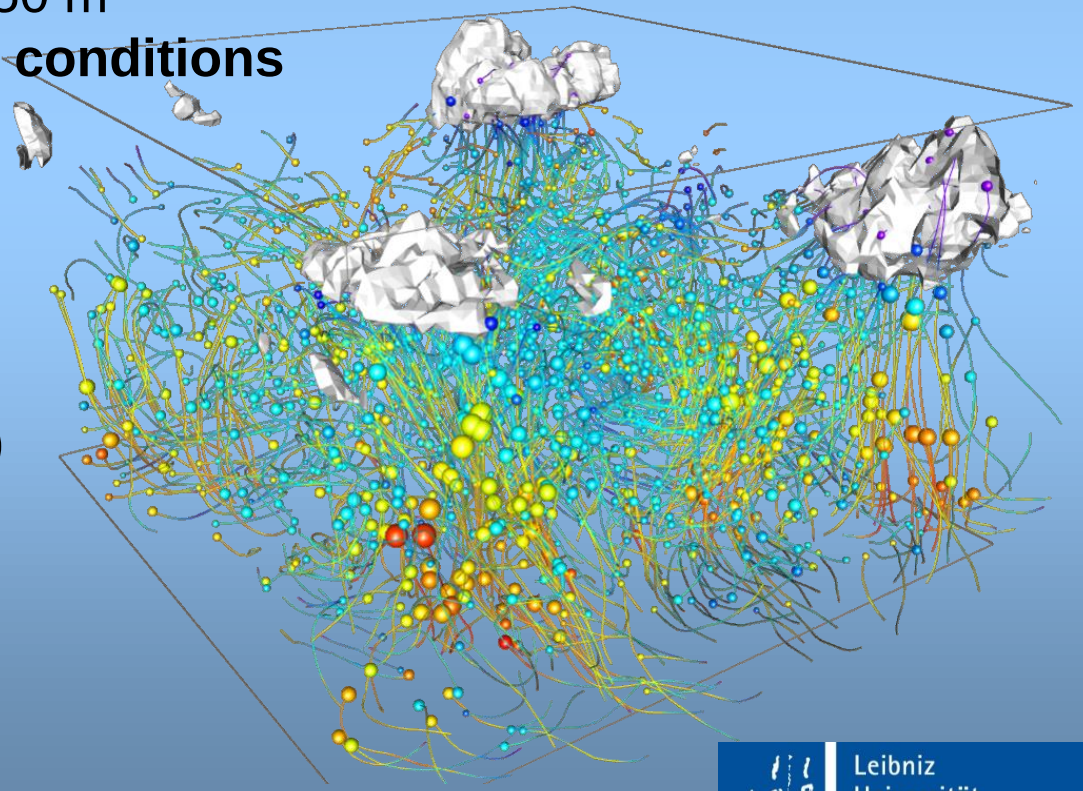


RANS: ensemble average

A Simple LES of the Atmospheric Convective Boundary Layer (CBL)

Setup:

homogeneously heated surface, **temperature inversion at z = 800 m,**
domain size: 2 * 2 km^2, Δ = 50 m
cyclic horizontal boundary conditions

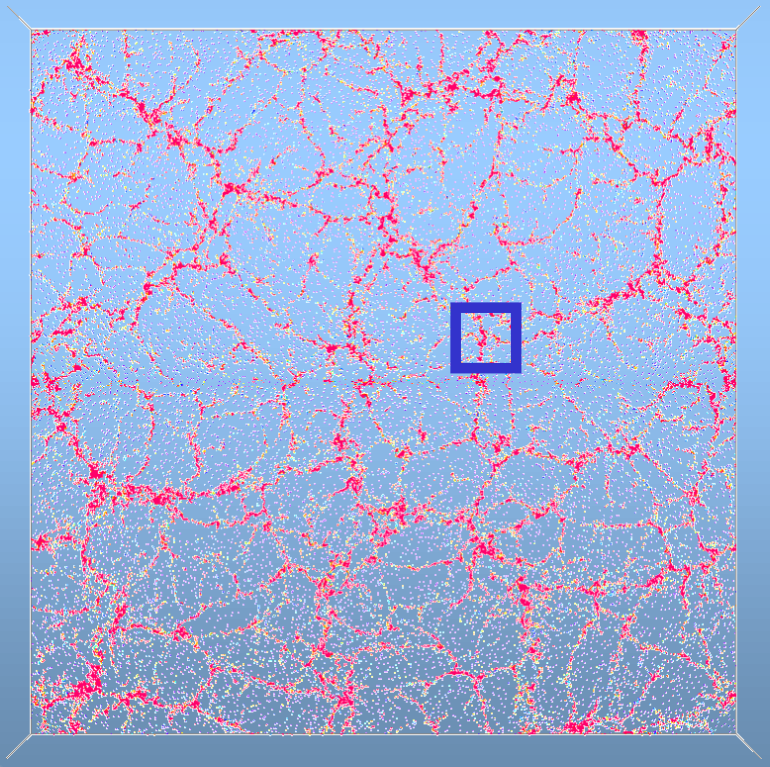


- particles = passive tracers
- colour ~ buoyancy: ↑ ↓
- diameter ~ |vertical velocity|
- (isosurface = cumulus cloud)

An Advanced Example:

Coherent Structures in a Highly Resolved Convective Boundary layer

domain size: $4 * 4\ km^2$
grid spacing: $\Delta = 2m$
grid points: 10^9
color: buoyancy: **red**: pos., **blue**: neg.



horizontal cross section at z = 20m

dust devils

PALM* Model System Features

* **PALM** = **PA**rallelized **L**ES **M**odel

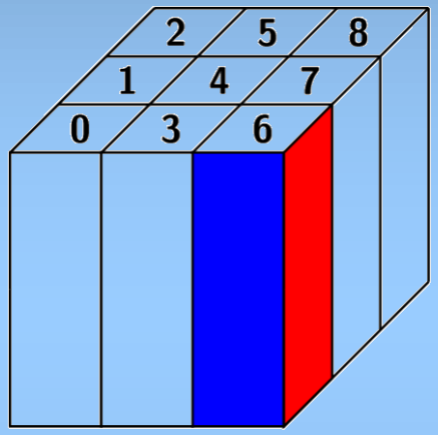
for further details see:

http://docs.palm-model.org

- **turbulence resolving community model for micro-scale atmospheric and oceanic flows**
- **Fortran 2008 code, developed since 1997 originally at LUH**
- **more than 1000 users worldwide, international developer team**
- **solves anelastic NS-equations (direct (FFT) or multigrid Poisson solver)**
- **2d domain decomposition, cartesian grid allowing for complex 3d topography features**
- **modular structure (full atmospheric chemistry using KPP, SALSA aerosol model, Lagrangian particle model, ICON cloud physics, wind turbine model, ...)**
- **self-nesting using MPI one-sided communication, mesoscale-nesting (COSMO, ICON, WRF)**
- **detailed modelling of surface processes (soil model based on TESSEL, urban surface model including radiation modelling via ray-tracing, indoor model, model for resolved-scale vegetation)**
- **online data analysis, all output in netCDF format**
- **highly optimized for cache-based and vector processors, very good scaling for up to 50.000 cores**
- **maintained via gitlab (strict rules for developers, CI test pipelines) https://gitlab.palm-model.org**

PALM – General Parallelization Technique

- **2D-domain decomposition as general parallelization method**



  - **guarantees very good load balancing**
  - **provides the chance for sufficient scaling up to ~ 100.000 cores (and more)**

- **parallelization/communication with MPI or/and OpenMP (hybrid), one-sided communication (MPI-3) partly used**
- **OpenACC parallelization using CUDA-aware MPI is implemented for the PALM core**

  Knoop et al., 2018: Int. J. Computational Science and Engineering.

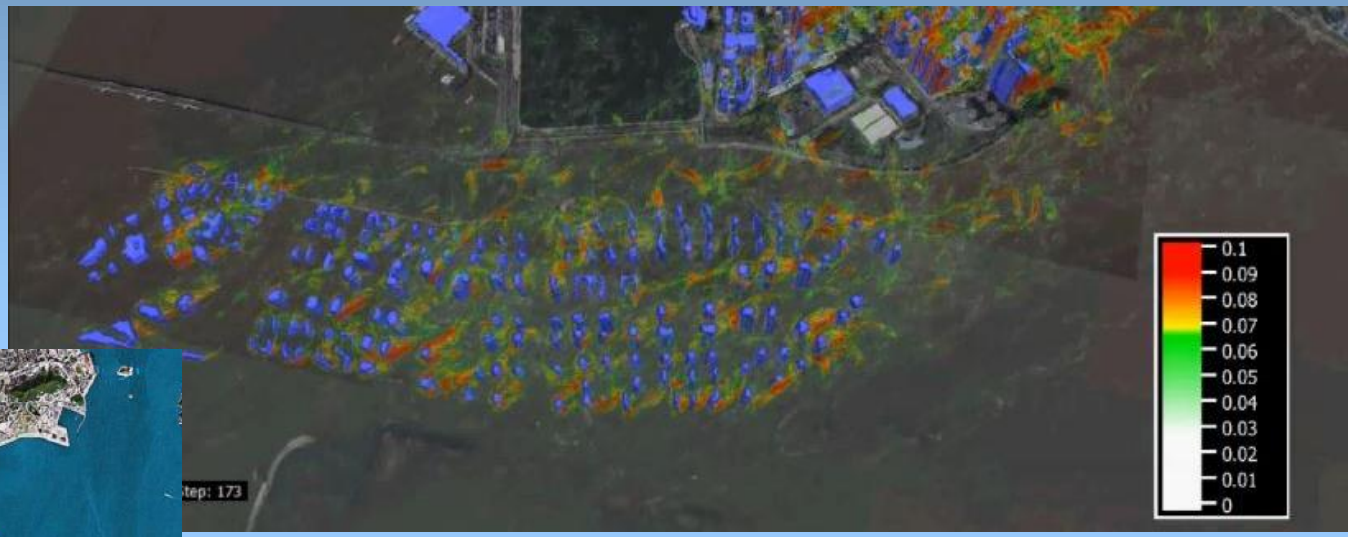
- **PALM is part of SPEC-Accel benchmark**

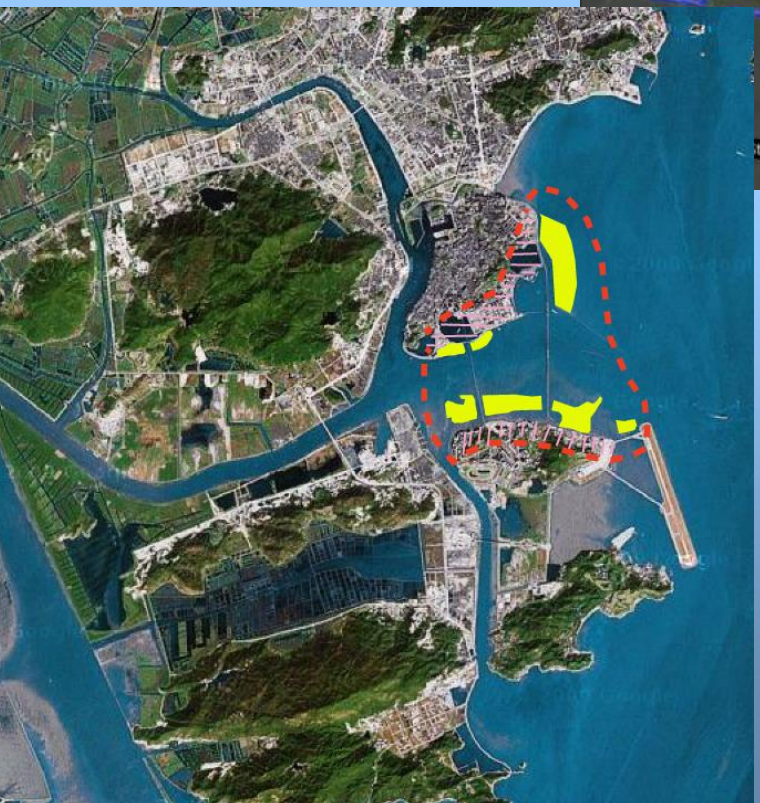
Urban Canopy Flow (I)

Urban canopy flow of complete cities: Macau

PALM simulations

Δ = 2m
5000*3000*500 gridpoints





Macau
Effects of new reclamation areas on air quality at pedestrian level in existing parts of the city

Urban Canopy Flow (II)

Urban canopy flow of complete cities: Macau

PALM simulations

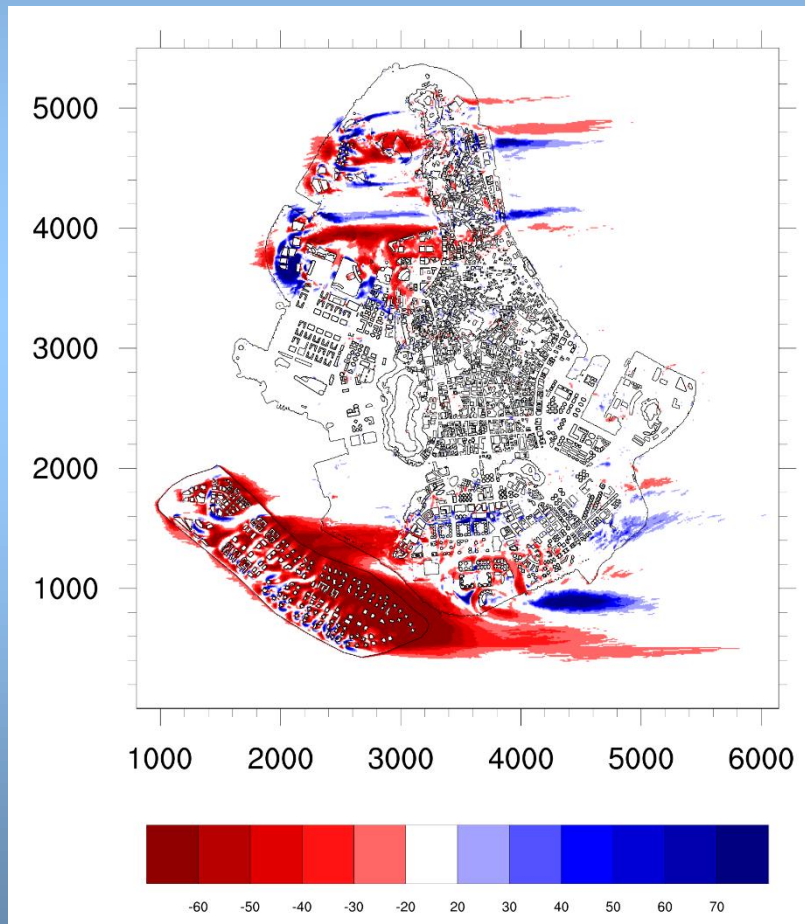
Δ = 2m
5000*3000*500 gridpoints

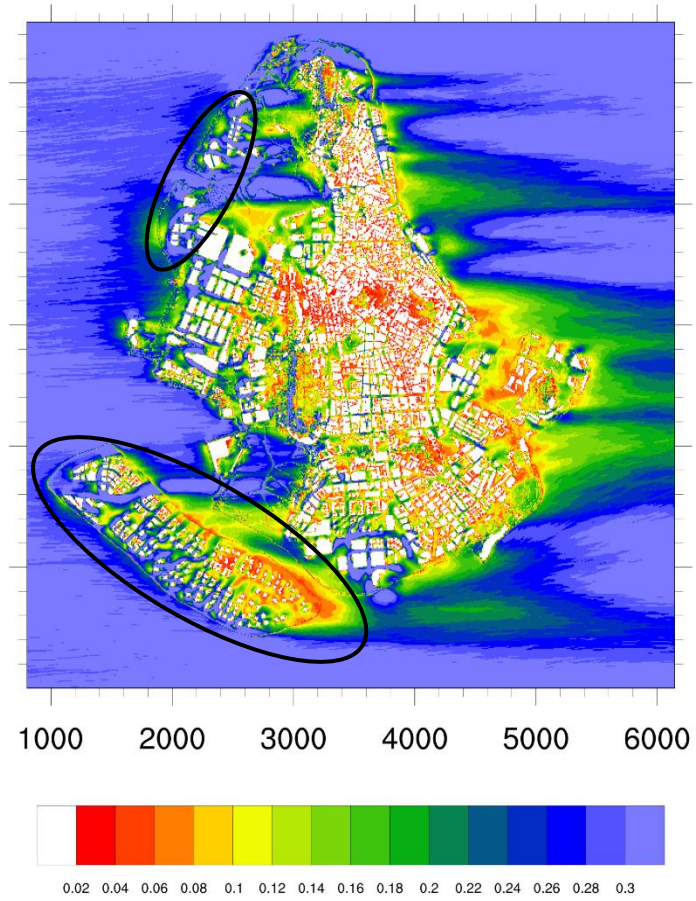
- **neutral stratification is assumed, as usual in assessment studies**

current condition

change of u in %

with new reclamation areas





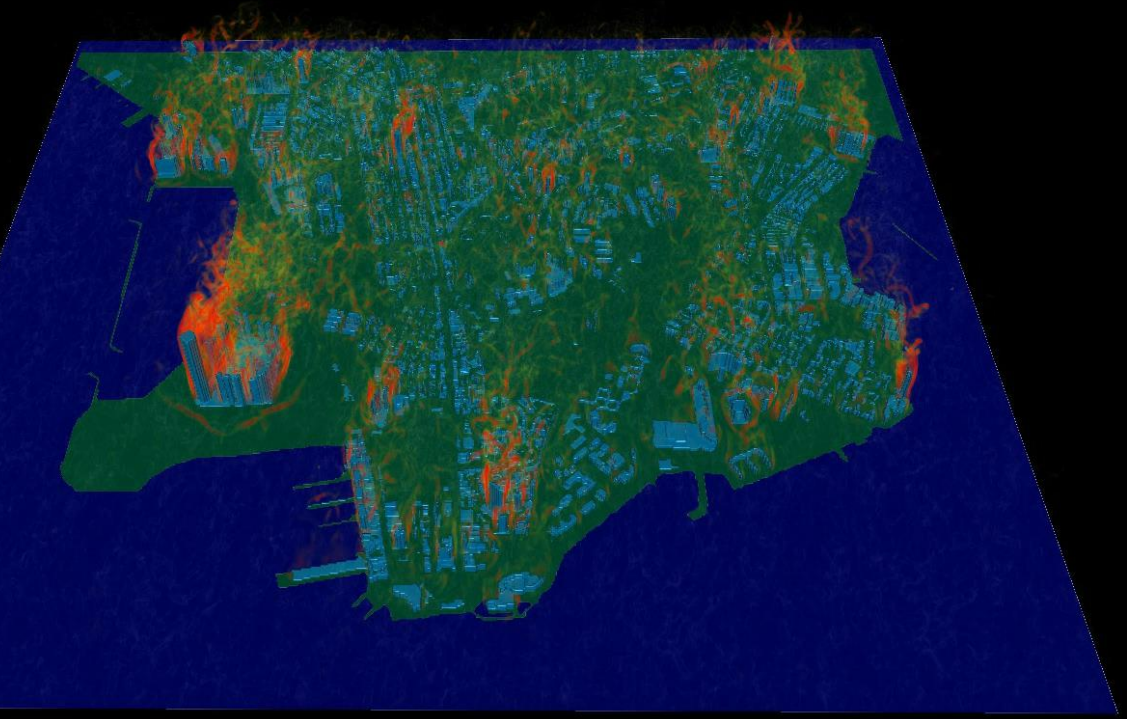
Urban Canopy Flow (III)

Urban canopy flow of complete cities: Kowloon (Hong Kong)

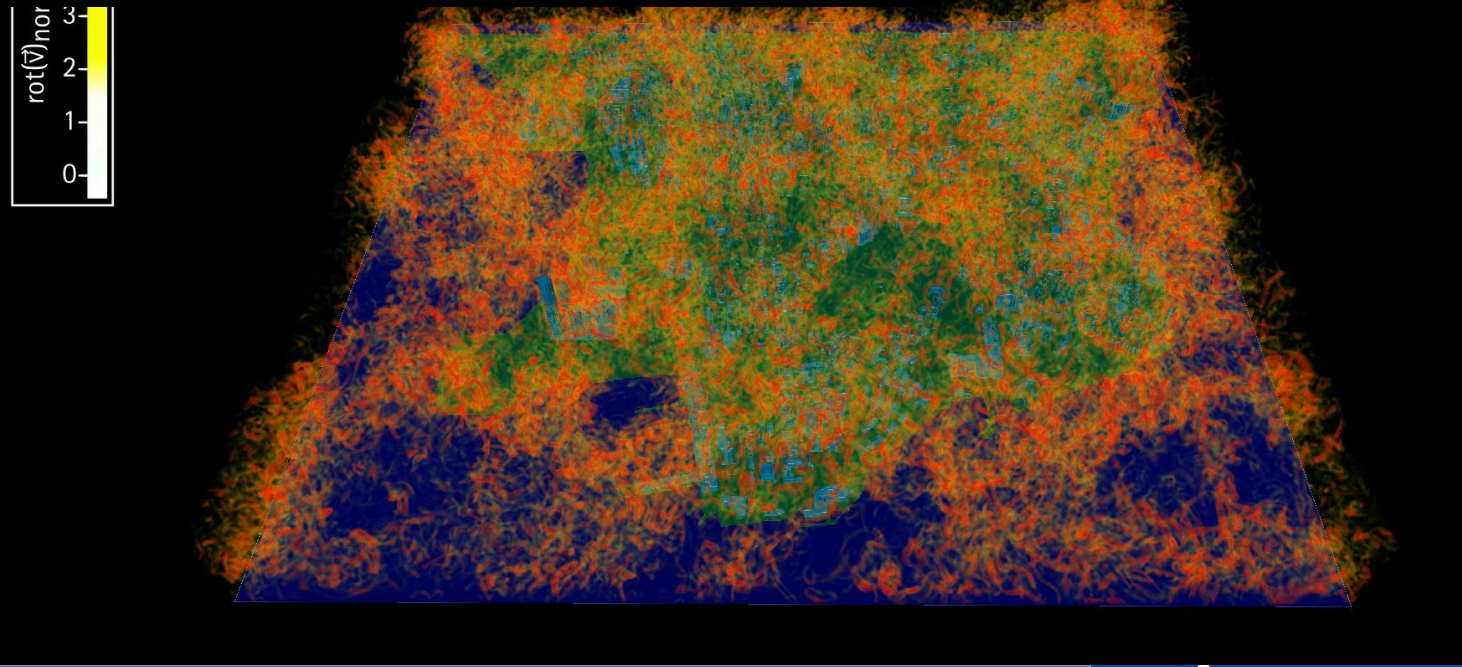
Kowloon:

Effect of stratification (atmospheric stability) on the ventilation

- ventilation studies are generally carried out for neutral stratification
- under weak wind conditions, buoyancy may play a major role
- weak wind conditions frequently appear during hot and humid summer months in south-east asia



/isualization created with VAPOR (www.vapor



Urban Canopy Flow (III)

Urban canopy flow of complete cities: Kowloon (Hong Kong)

Kowloon:
Effect of stratification (atmospheric stability) on the ventilation

- ventilation studies are generally carried out for neutral stratification
- under weak wind conditions, buoyancy may play a major role
- weak wind conditions frequently appear during hot and humid summer months in south-east asia

- **during daytime conditions (unstable stratification) buildings have only weak effects on ventilation**

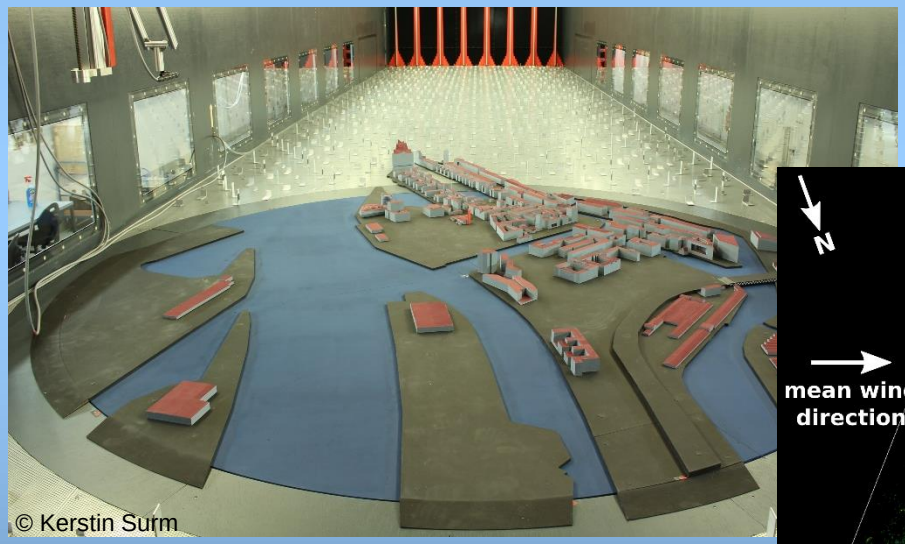
  Gronemeier et al., 2017: Effects of unstable stratification on ventilation in Hong Kong, *Atmosphere*, **8**, 168.

- **important new field of application for LES, since most of wind tunnels cannot handle stratified flows**
- **<u>but(!): wind tunnel very important for LES validation</u>**

Comparison PALM / wind tunnel

Simulation of *Harbour City* (Hamburg)

- wind tunnel boundary conditions have been exactly replicated in the LES
- neutral stratification

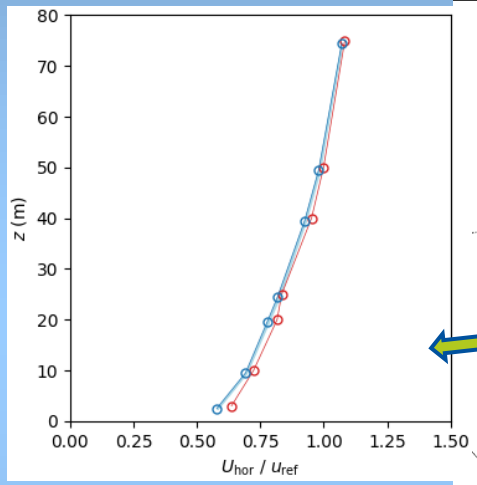


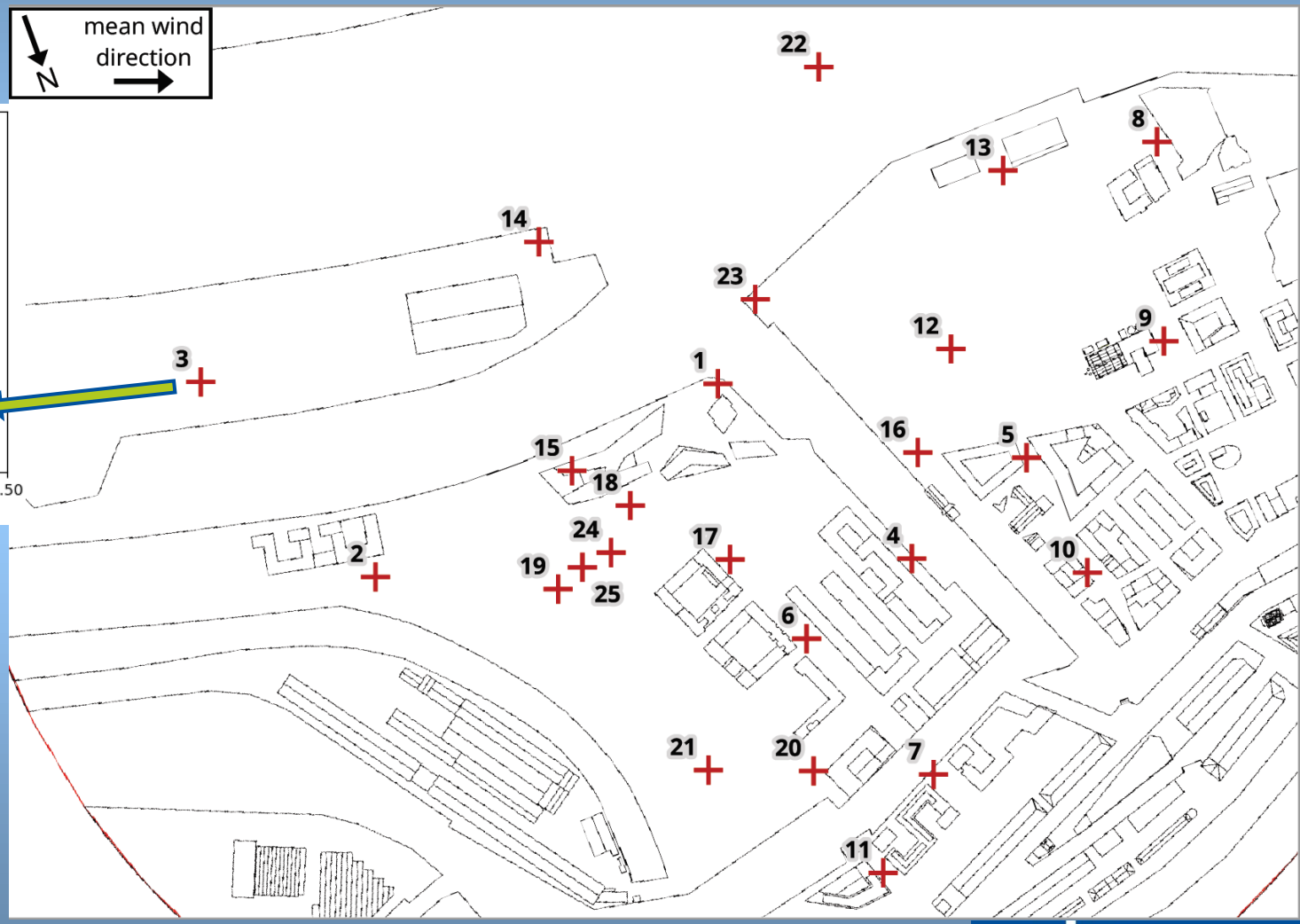
“Wotan“, EWTL Hamburg

PALM Simulation

Comparison PALM / wind tunnel

Simulation of *Harbour City* (Hamburg), results

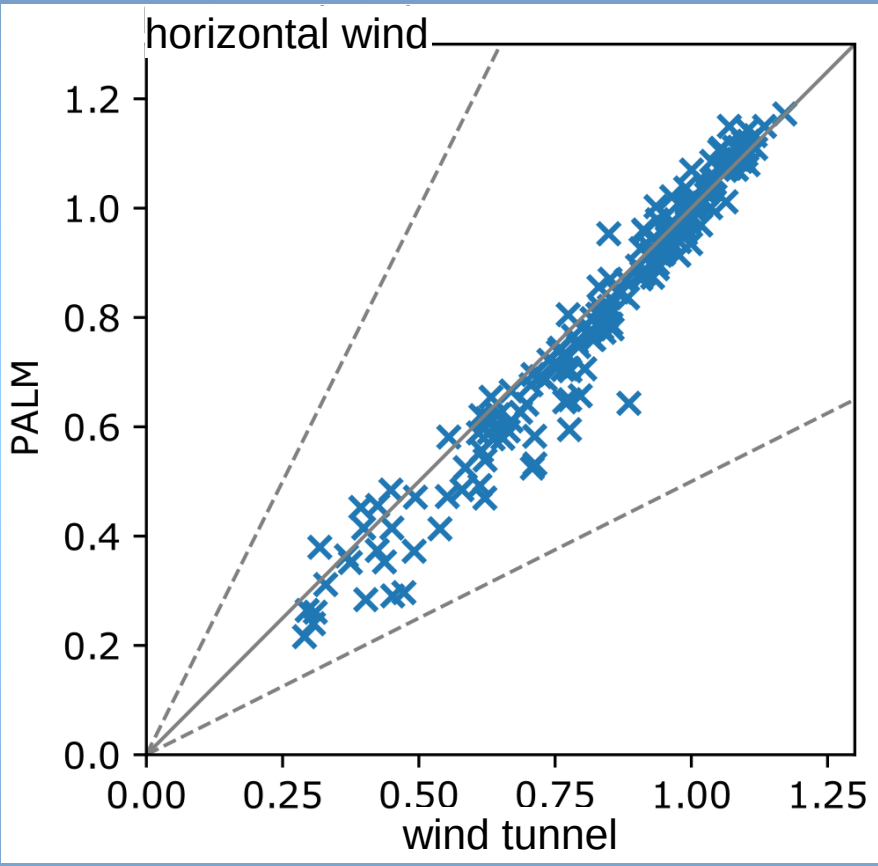


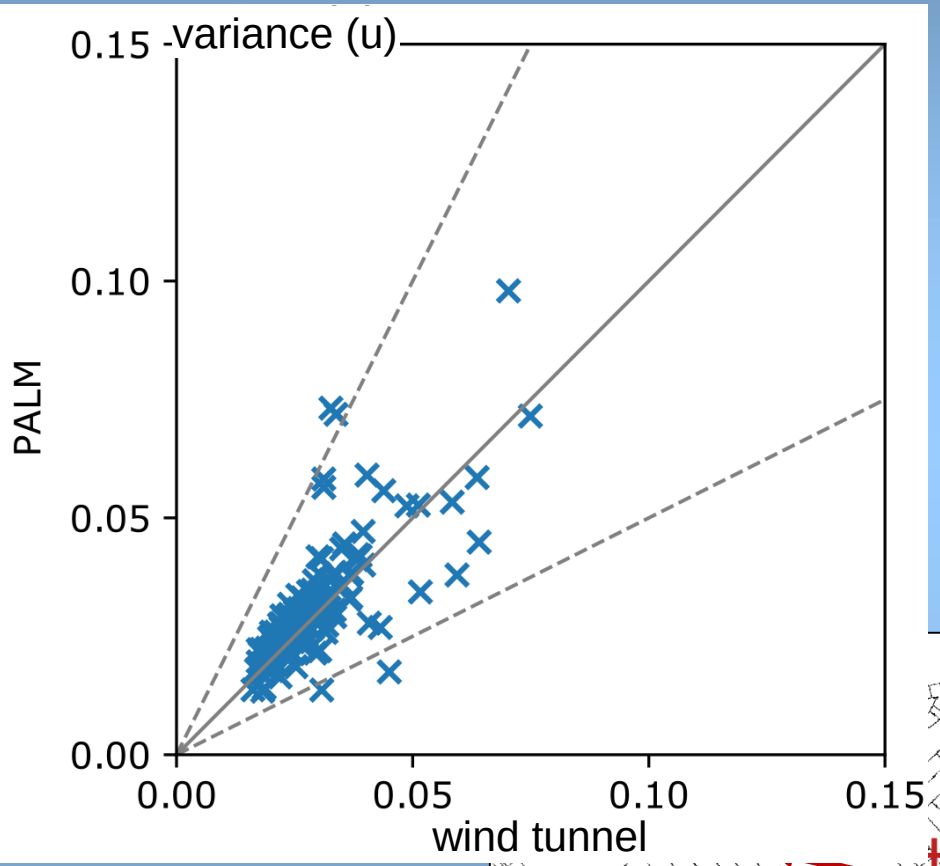


- 25 stations within the city district
- profile measurements of wind speed and variances

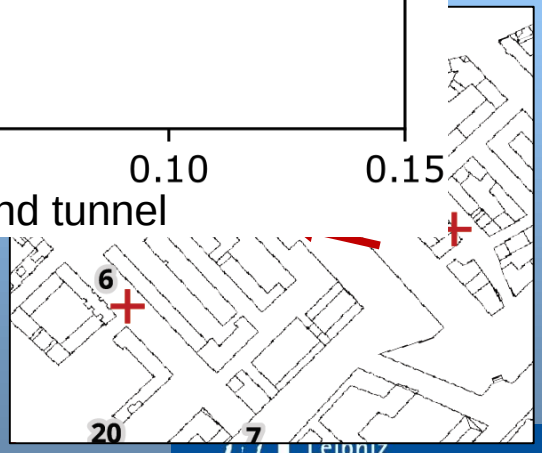
Comparison PALM / wind tunnel

Simulation of *Harbour City* (Hamburg), results



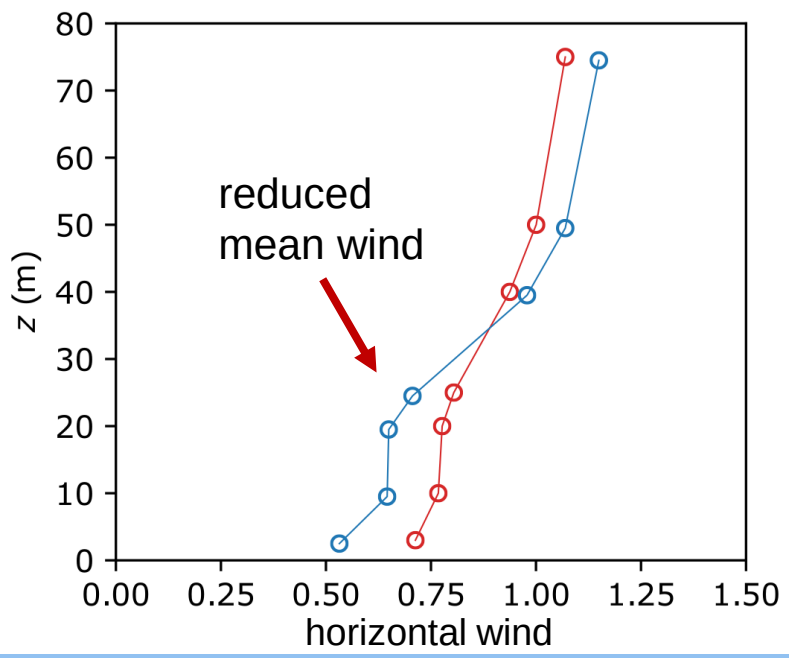


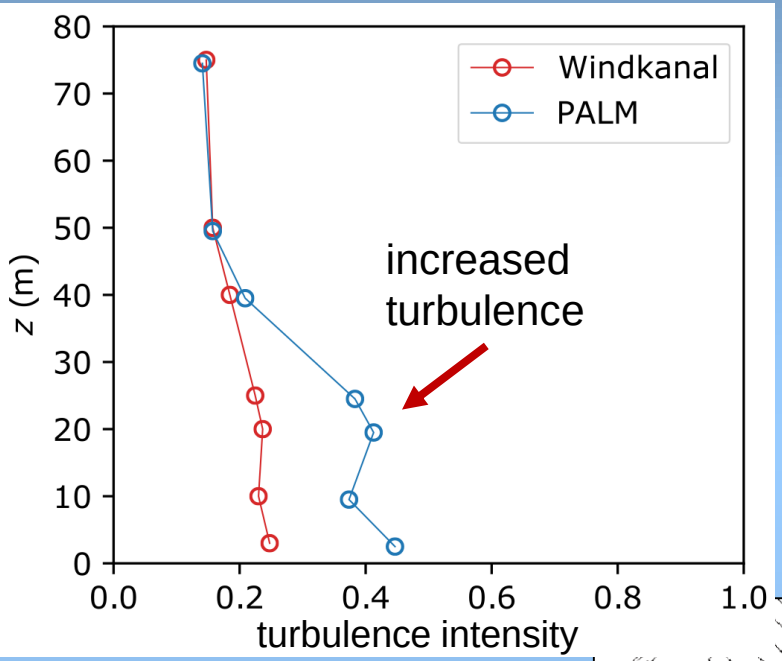
- in general, good comparison between measurement and simulation



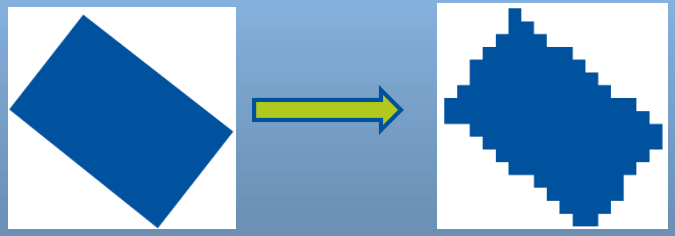
Comparison PALM / wind tunnel

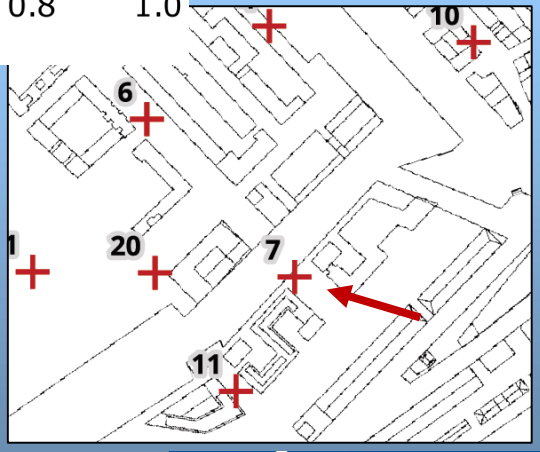
Simulation of *Harbour City* (Hamburg), results





- bigger corner eddies due to discretized buildings walls
- will be improved by introducing immersive boundaries (cut-cell method)





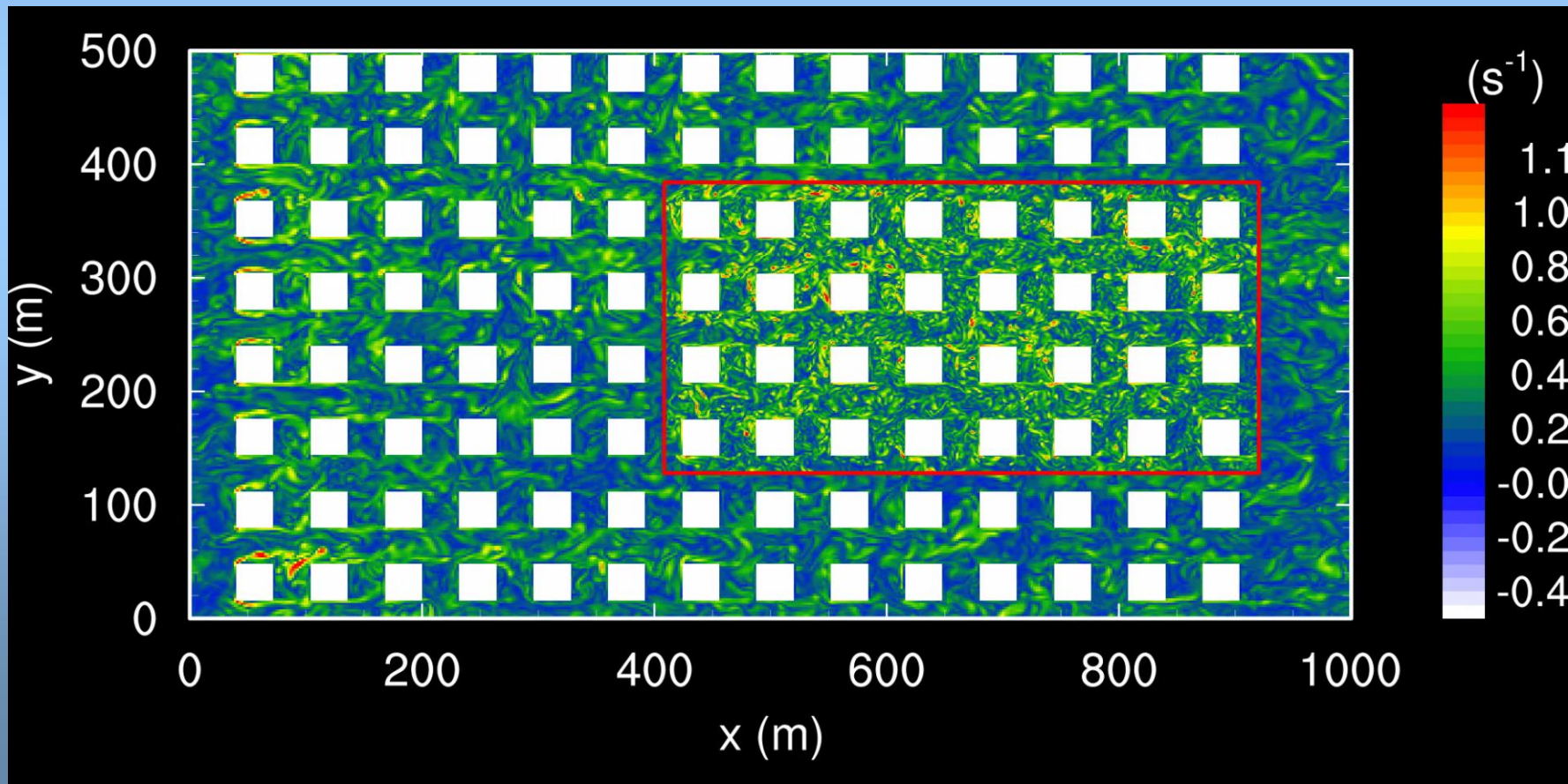
Gronemeier et al., 2021: Evaluation of the dynamic core of the PALM model system 6.0 in a neutrally stratified urban environment: comparison between LES and wind-tunnel experiments, *Geosci. Model Dev.*, **14**, 3317–3333.

PALM 25.10 Selected Components (I)

LES-LES nesting

- since our areas of interest are always fixed in space, we don‘t have a need for adaptive meshes
- a one-way or two-way nesting method is used instead
- animation shows the flow for a regular array of cubes (buildings)

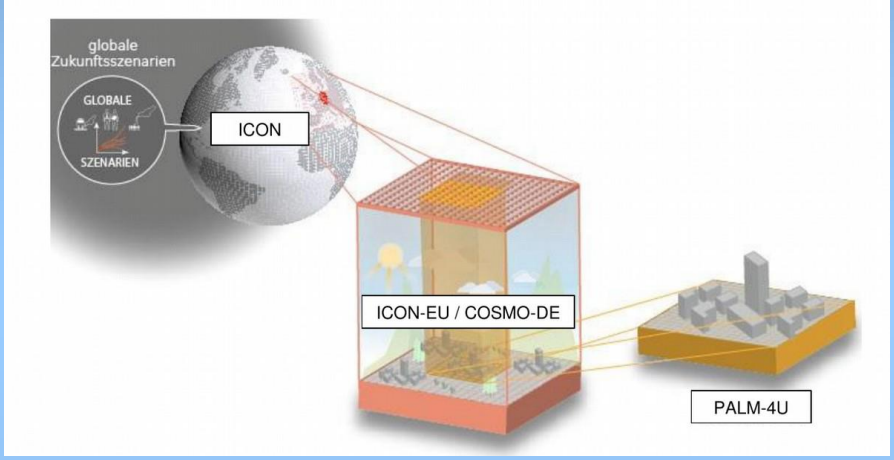
vorticity

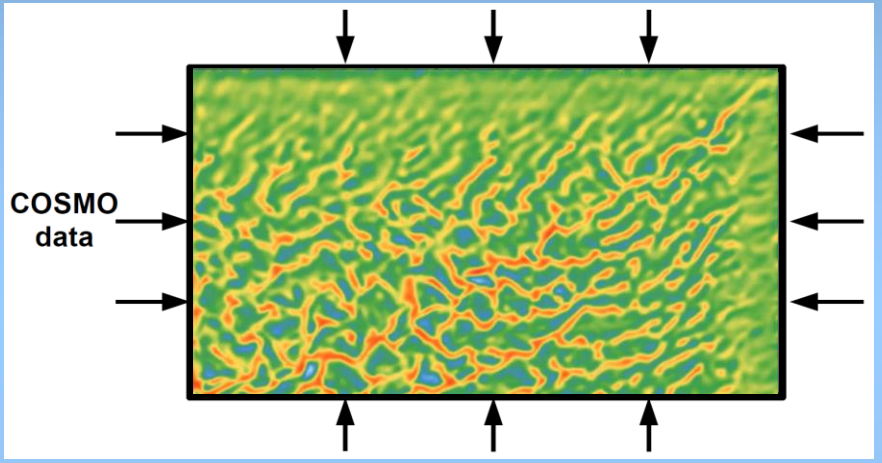


PALM 25.10 Selected Components (II)

Nesting into larger-scale models

offline one-way-nesting, e.g. into DWD-COSMO/ICON model





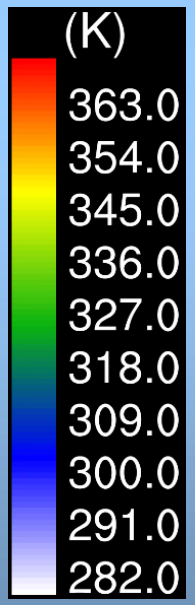
provides

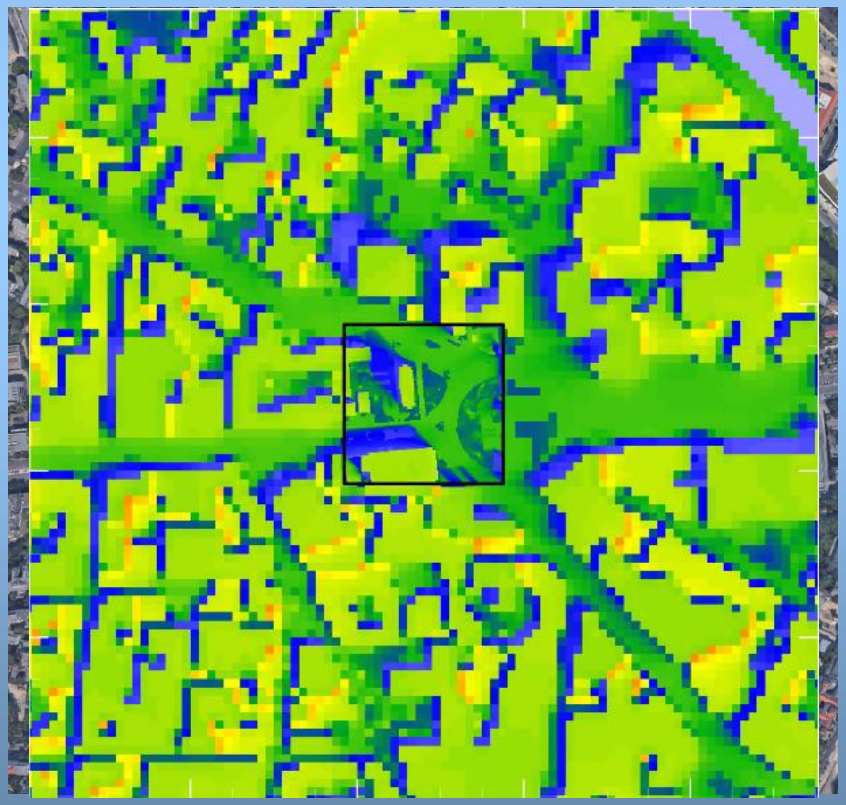
- ICON-derived initialization and forcing data to consider changing synoptic conditions during PALM run
- WRF-PALM interface available, too
- inflow turbulence via statistical turbulence generator

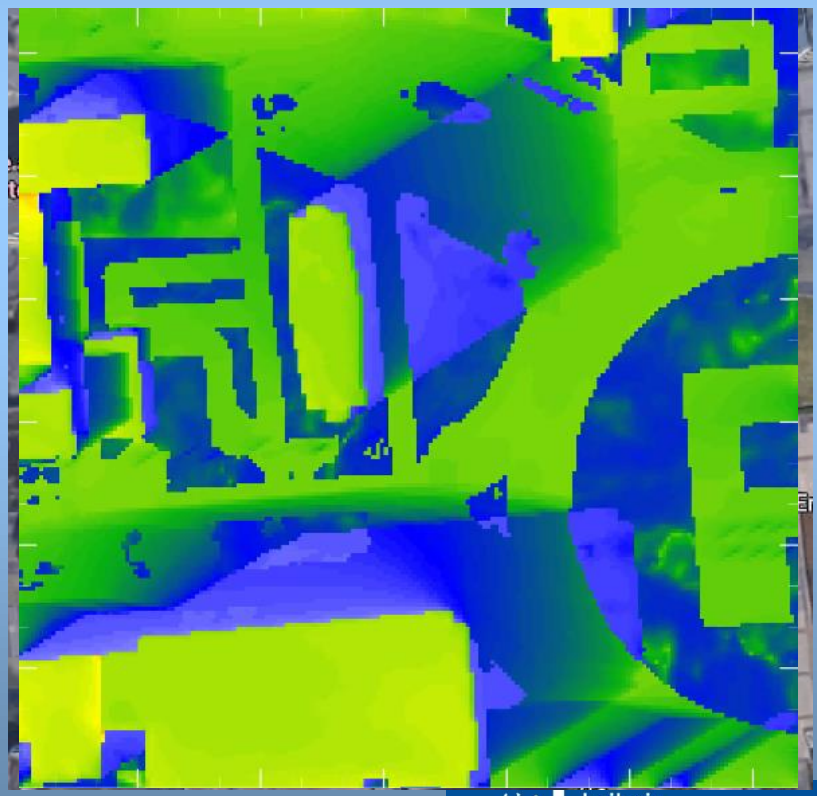
PALM 25.10 Selected Components (III)

Building surface energy balance / radiation

Test setup for a typical summer day, Ernst-Reuter-Platz (Berlin):
1 x 1 km^2 @ 10m + 200 x 200 m^2 @ 1m





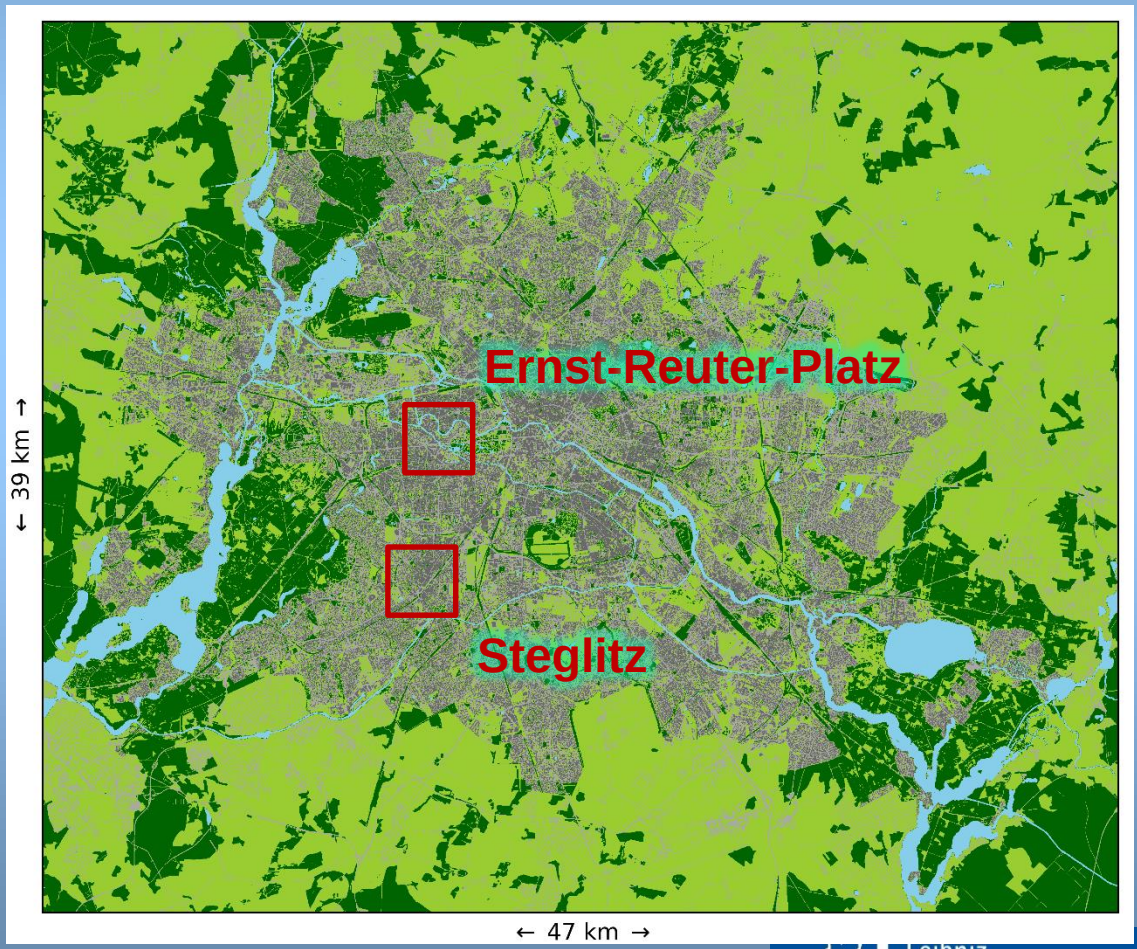


surface temperature

PALM Validation by Observations

Full City Simulation of Berlin for winter/summer episodes

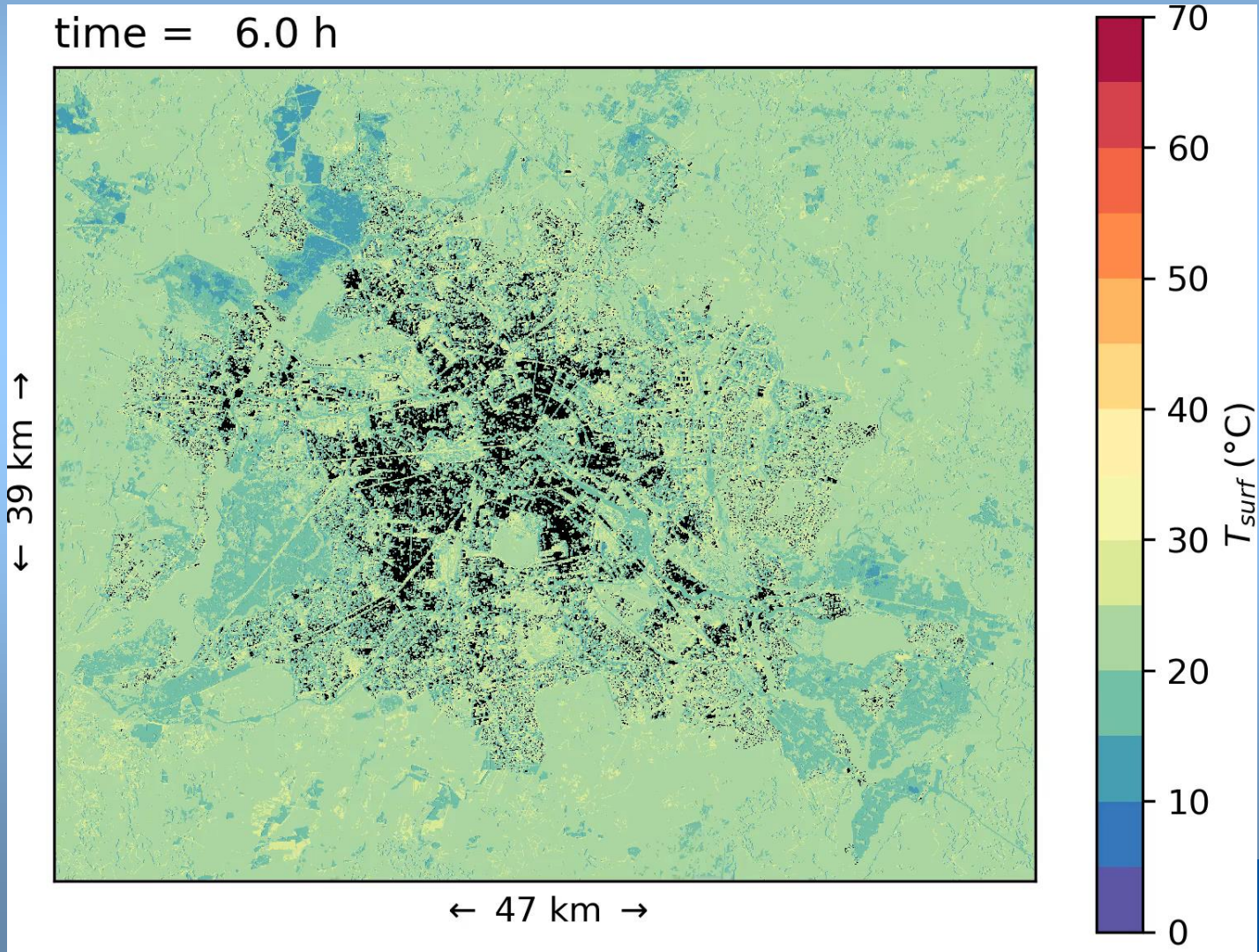
- grid spacing of Δ = 16 m
- two nested domains with Δ = 2 m
- lateral boundary conditions provided by weather forecast model (COSMO-forecast, DWD)
- > 10 surface types
- 6 building types



PALM Validation by Observations

Full City Simulation of Berlin for winter/summer episodes

- summer episode
- surface temperature (except building roofs, black color)

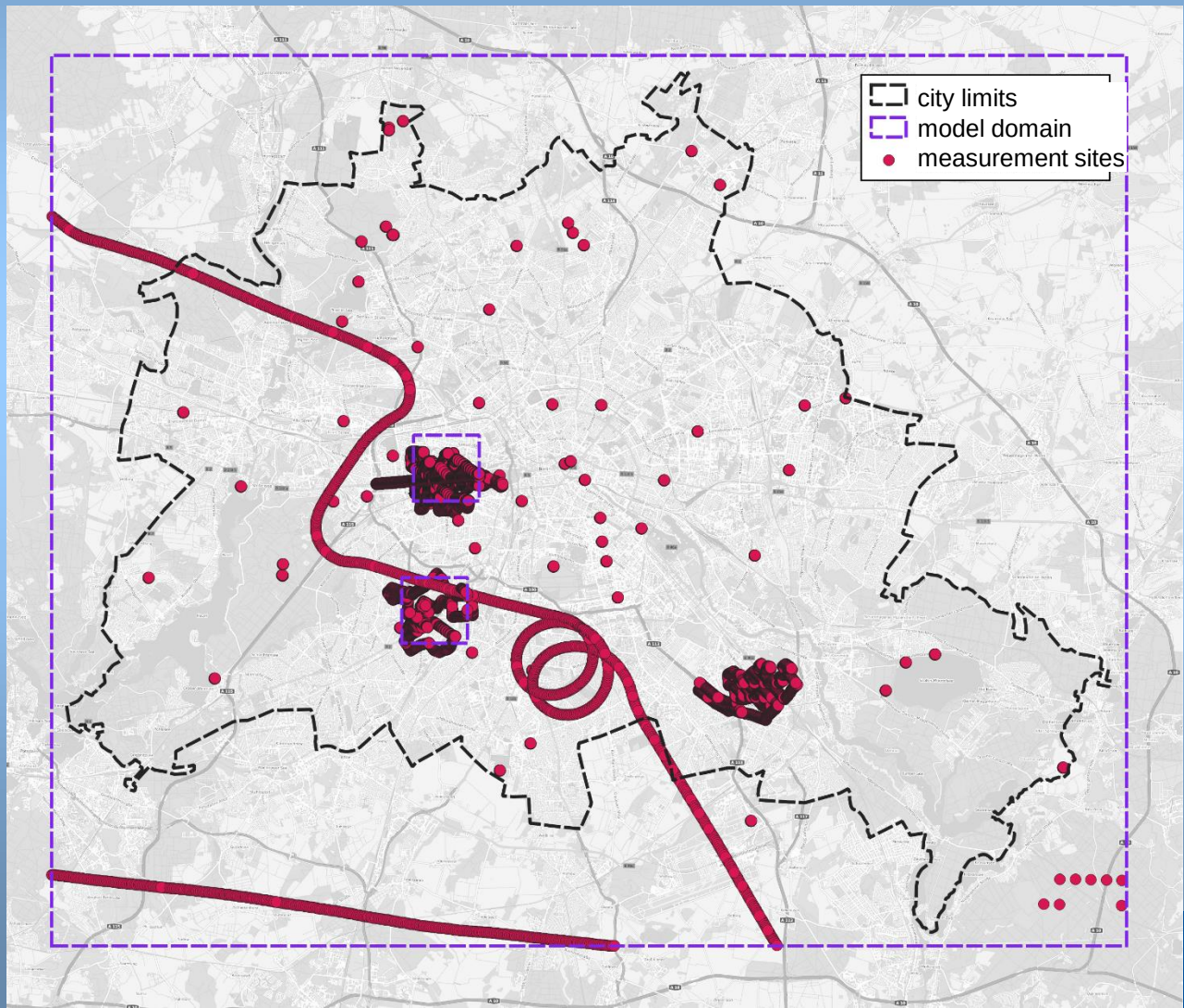


PALM Validation by Observations

Full City Simulation of Berlin for winter/summer episodes

Measurement overview

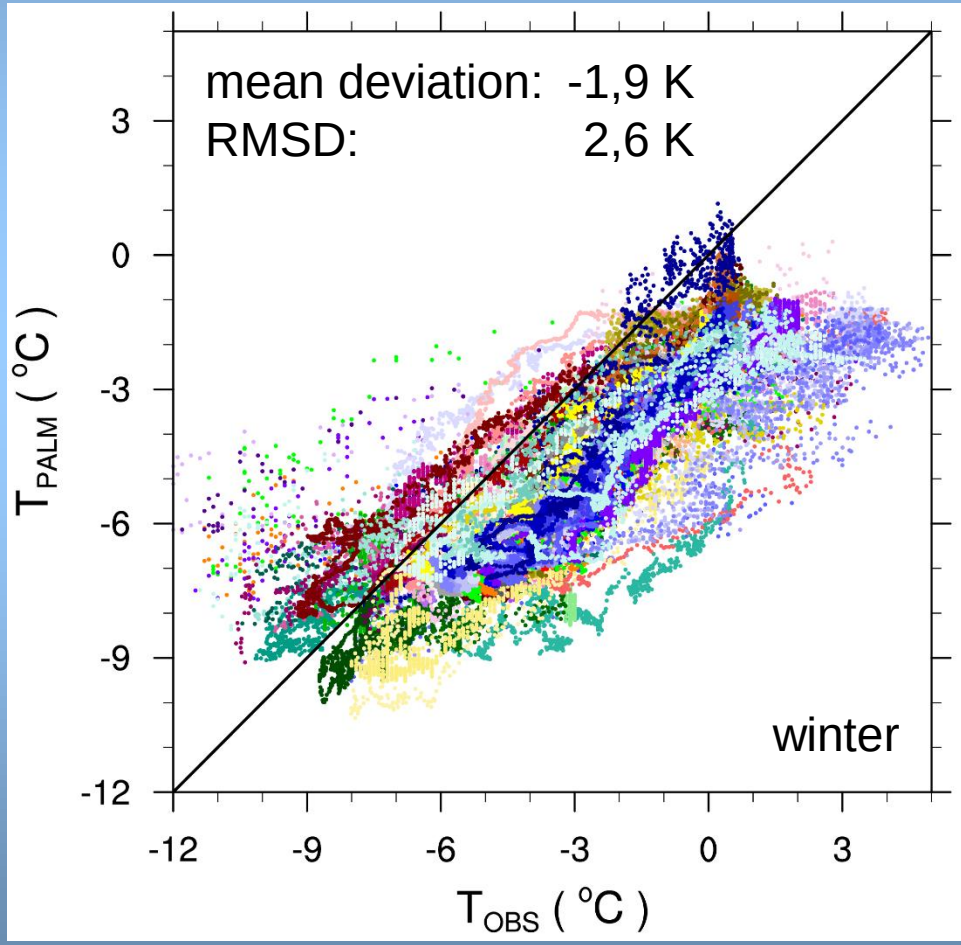
- 110 measurement facilities
- point measurements
- profile measurements
- trajectories

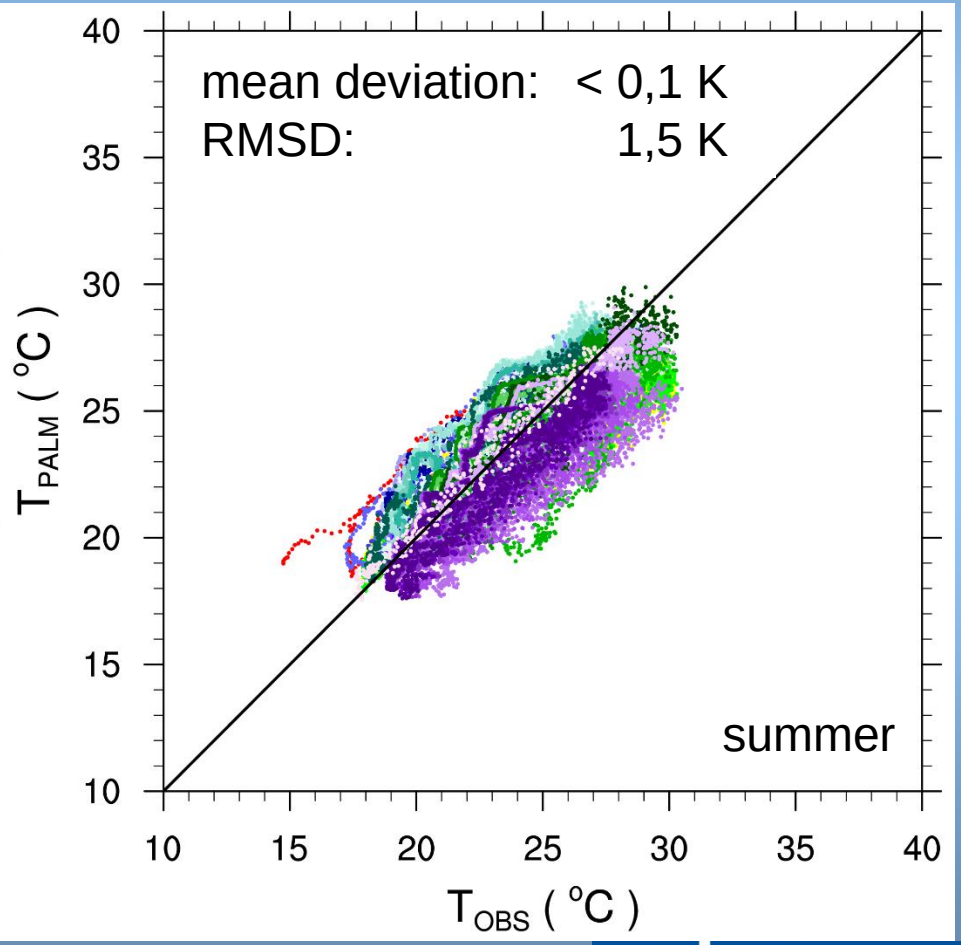


PALM Validation by Observations

Full City Simulation of Berlin for winter/summer episodes

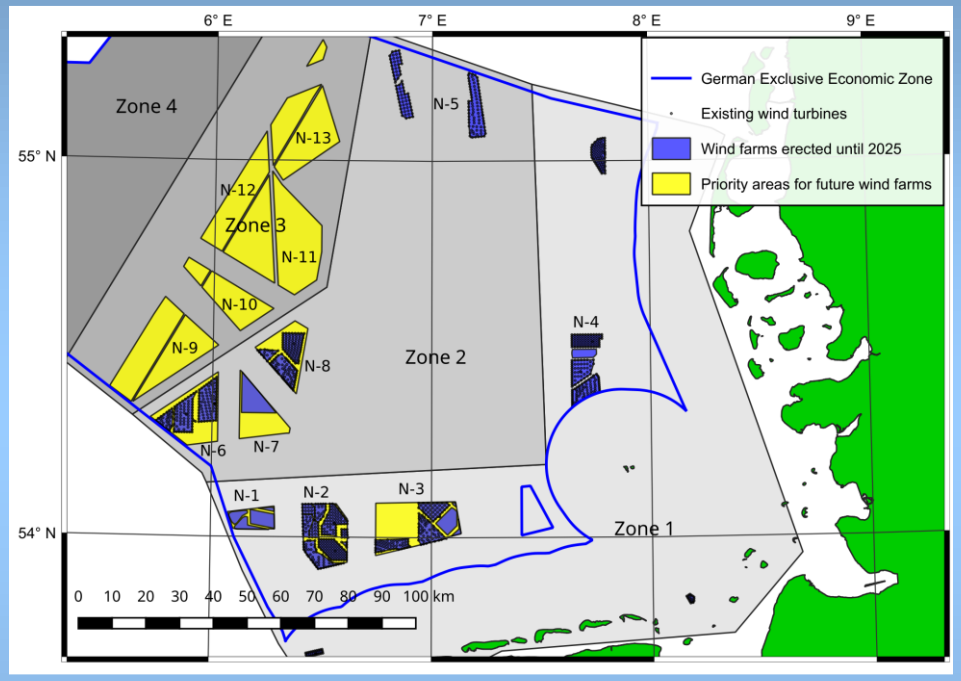
Temperature comparison: Overview

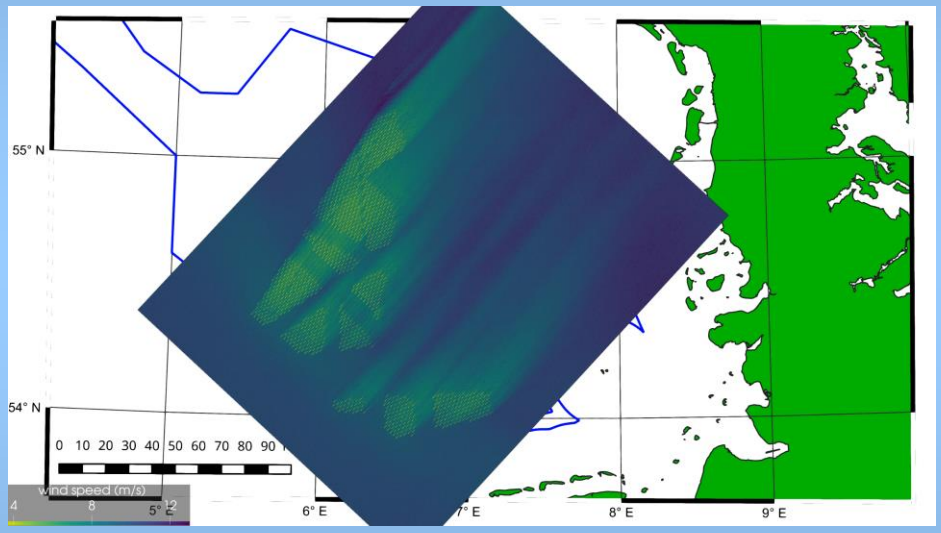




Recent Applications

Multi-gigawatt offshore windfarms





New wind farms in German Bight

- **planned capacity: 40 GW by 2040**

PALM run:

- **domain size 205 x 164 km^2**
- **Grid spacing Δ = 20 m**
- **2088 turbines, 15 MW**

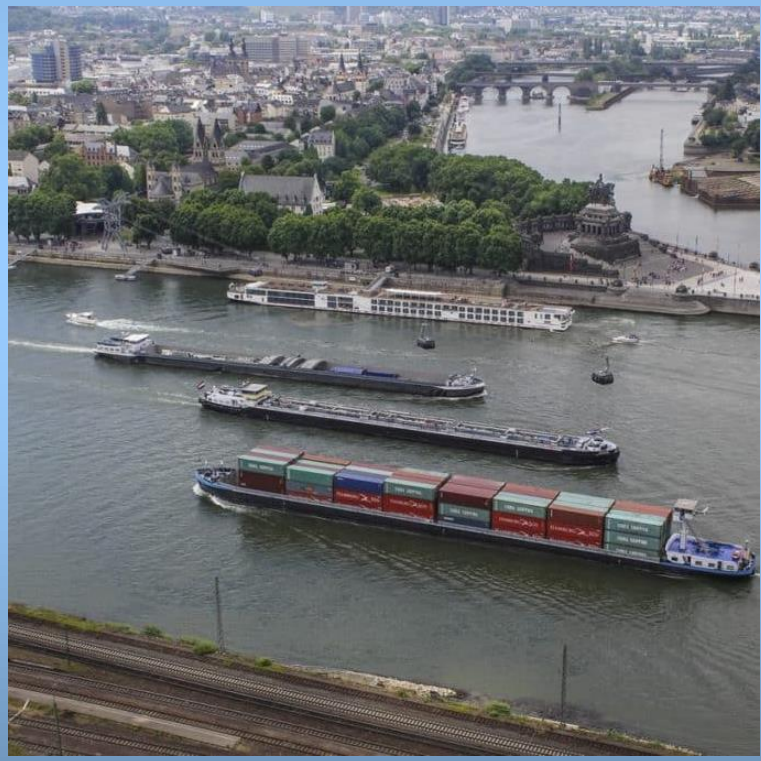
Maas and Raasch, 2022: Wake properties and power output of very large wind farms for different meteorological conditions and turbine spacings: a large-eddy simulation case study for the German Bight, *Wind Energ. Sci.*, **7**, 715–739.

Recent Applications

Dispersion of Ship Exhaust Plumes

pecanode

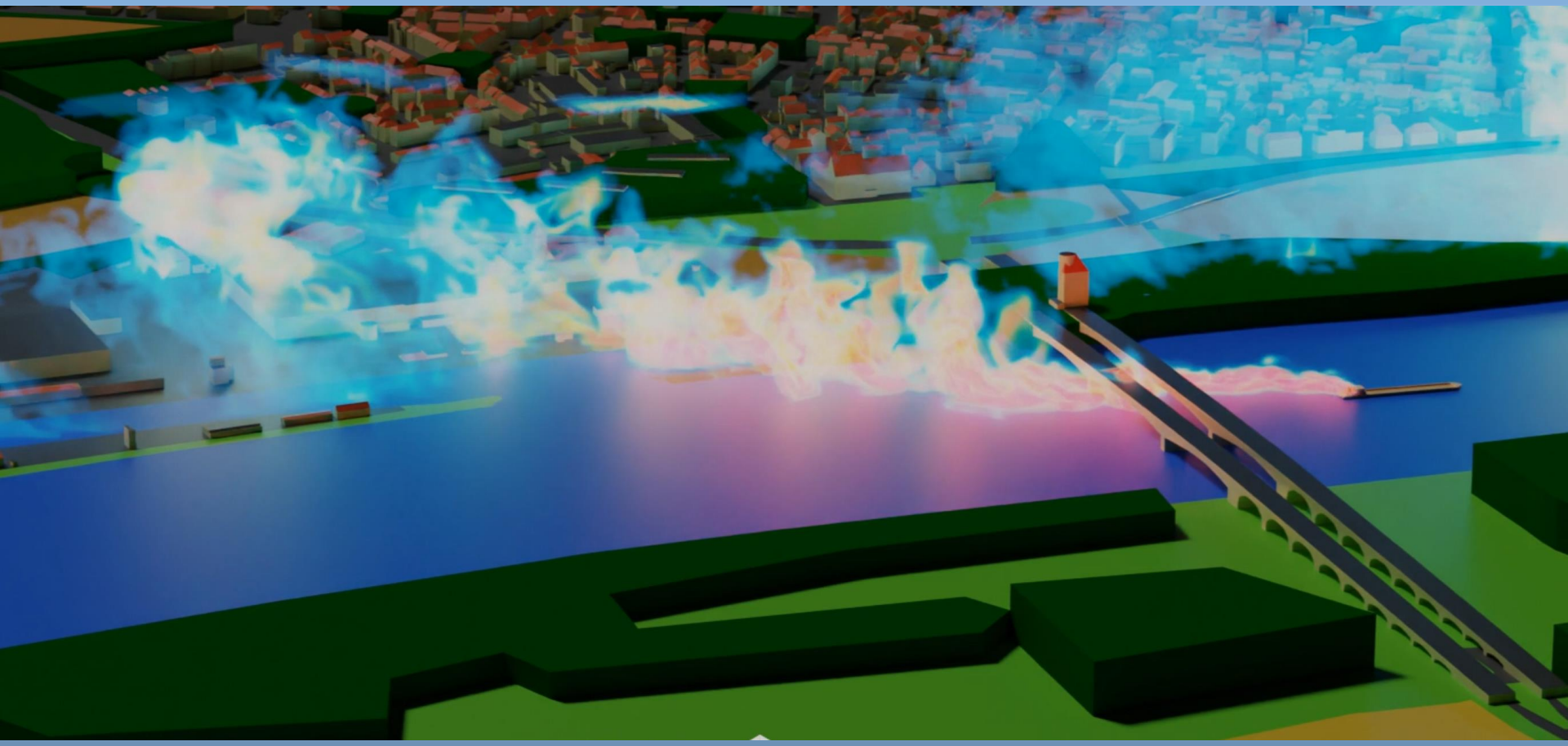
- **project funded by the Federal Institute for Water Research**
- **main interest**
  - better understanding the 3D dispersion of ship emissions
  - how to interpret single point observations / measurements
  - how to estimate ship emissions from observed immissions
- **method**
  - high resolution simulations for typical weather conditions, different types of ships with different speed
  - time/space dependent emissions have been implemented



Recent Applications

Dispersion of Ship Exhaust Plumes

pecanode

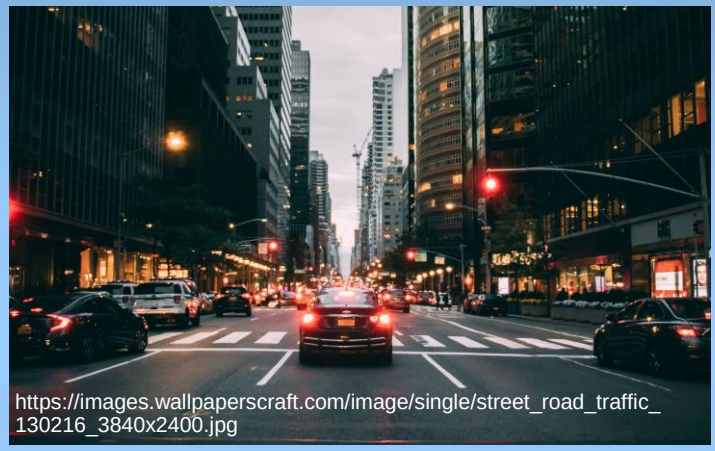


Recent Applications

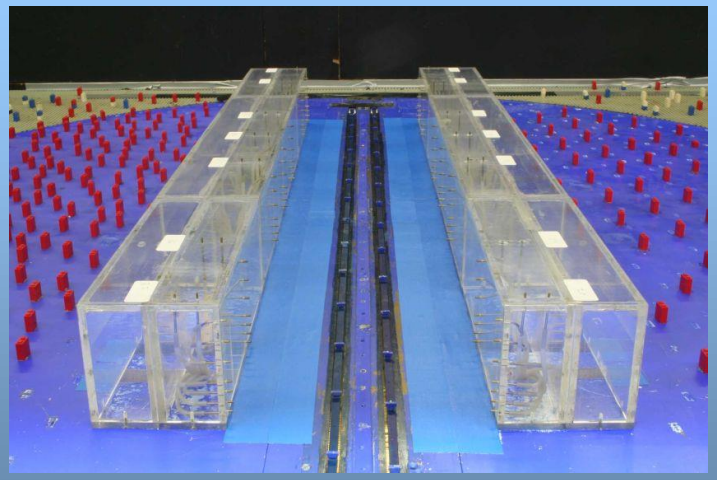
Dispersion of Emissions from Moving Cars

- **PhD project funded by the German Research Foundation**

- **main question**
  - how does turbulence generated by moving cars effects the dispersion of pollutants in street canyons
- **method**
  - high resolution simulations for an idealized street canyon
  - wind tunnel setup for validation
  - effect of cars implemented via “moving air blocks”

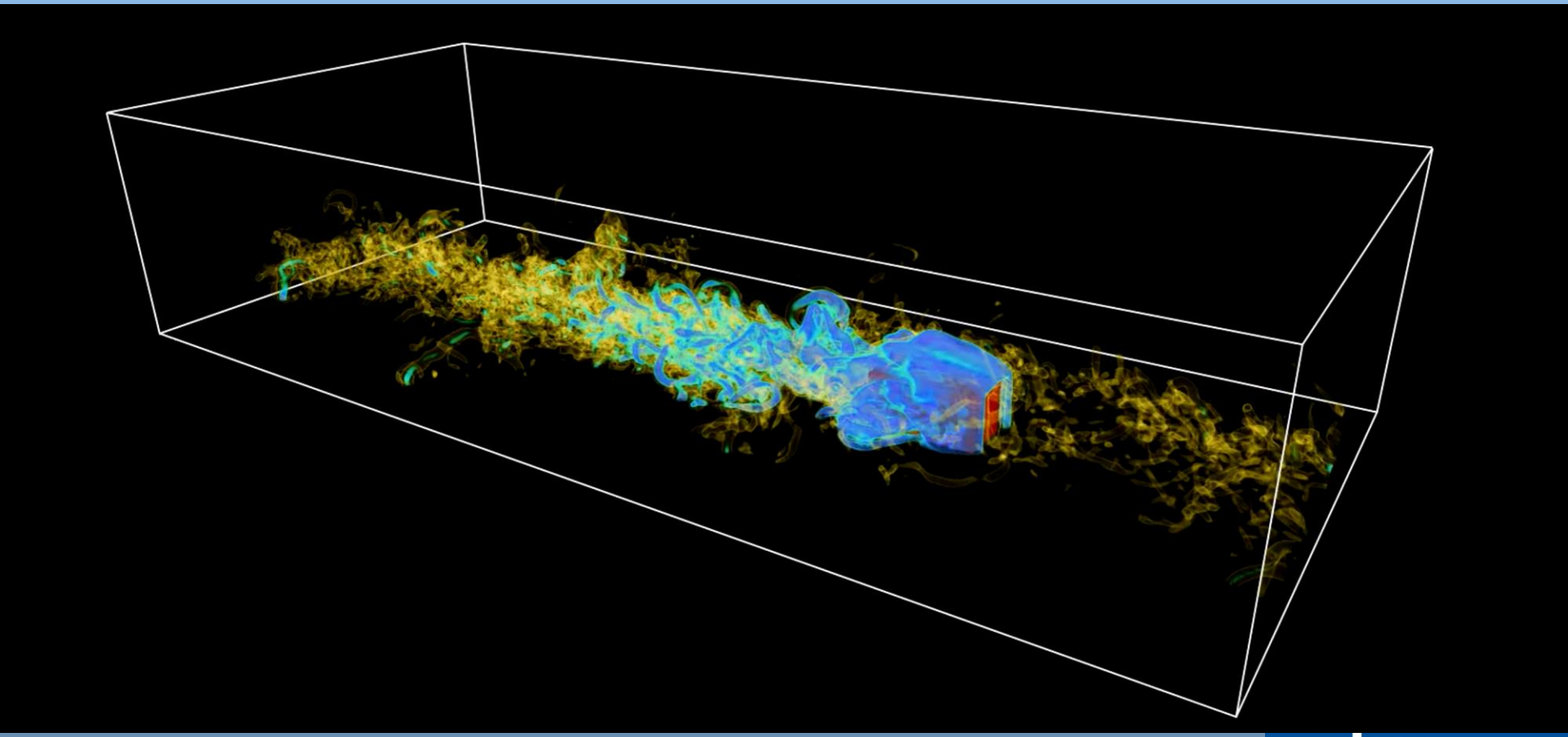


https://images.wallpaperscraft.com/image/single/street_road_traffic_130216_3840x2400.jpg



Recent Applications

Dispersion of Emissions from Moving Cars



Recent Applications

Dust emission by dust devils

- **dust devils may significantly contribute to continental aerosol production**
- **literature reveals a large uncertainty**
- **global estimates:**

Koch and Renno (2005)	35%	26±18%
Jemmeth-Smith et al. (2015)	3.4%	0.9-31%

Problem:
- measurements

- **regional LES study:**

Klose et al. (2016)	Australia	0.03 - 0.19%

- resolution (10m)
- dust emission scheme (CTDE)

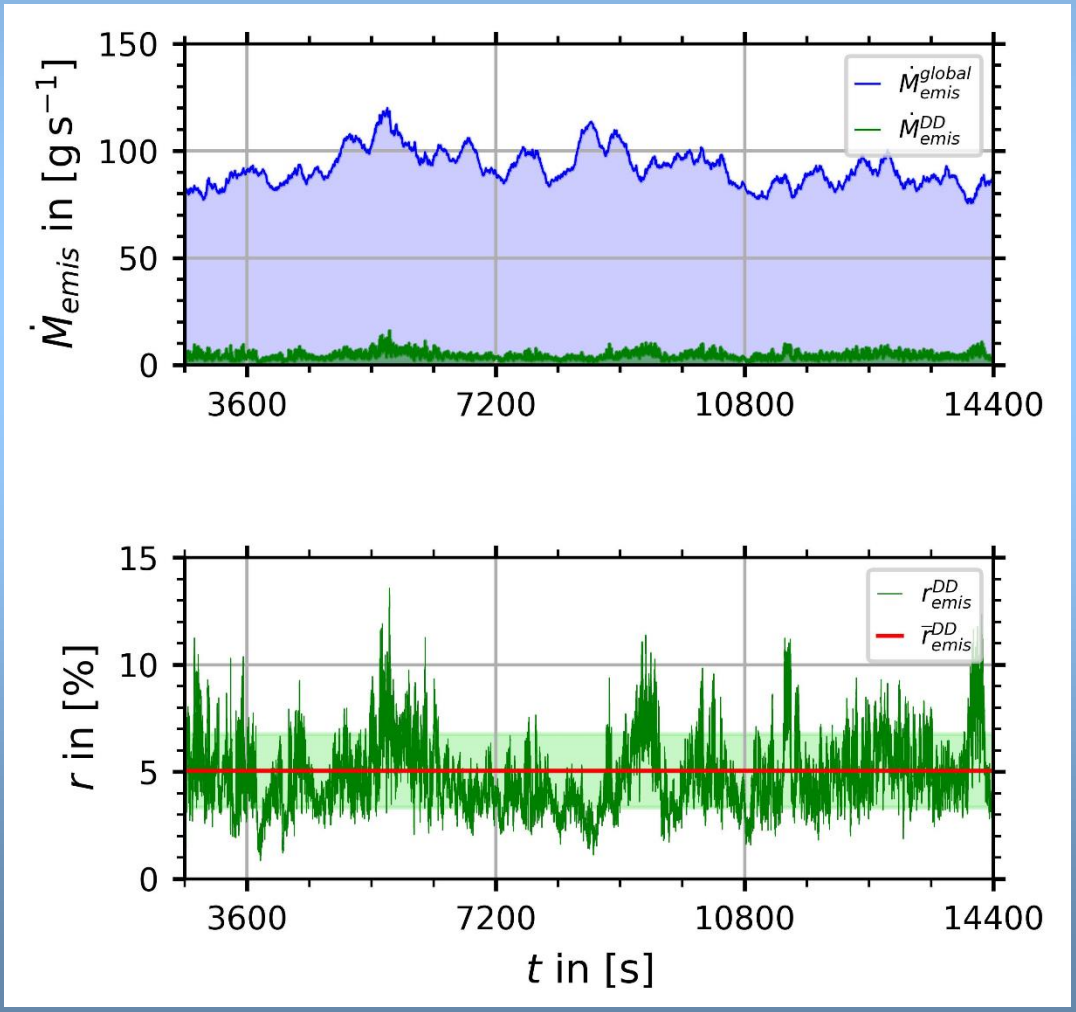
Our study	4 x 4 km^2 Δ = 1m (nest)	?

AFWA dust scheme (emissions caused by saltation bombardement)

Recent Applications

Dust emission by dust devils

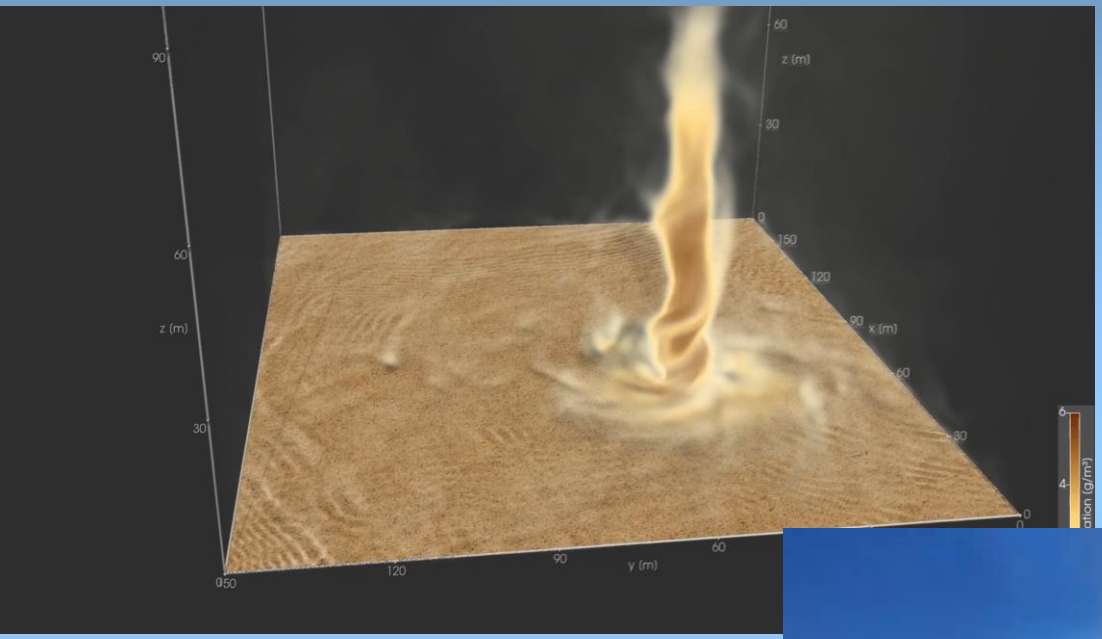
Dust mass flow rate $\dot{M}_{emis}(t)$



- $\dot{M}^{DDs}_{\mathrm{emis}}(t) \approx 4.6\ g\ s^{-1}$
- $\dot{M}^{global}_{\mathrm{emis}}(t) \approx 90.2\ g\ s^{-1}$
- $r(t) = 5.1 \pm 1.7\ \%$

Recent Applications

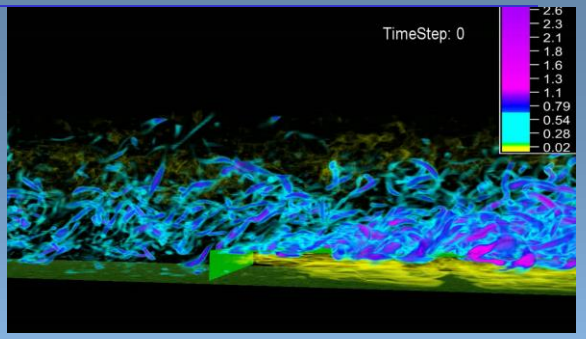
Dust emission by dust devils



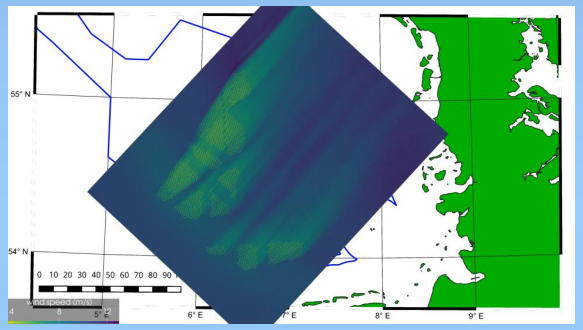
Animation shows one of the stronger dust devils that developed during the simulation.

Comparison with observed dust devil.

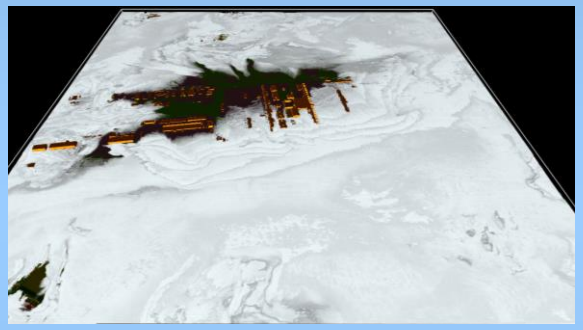
Other Recent Applications



Interpretation of measurements in canopies

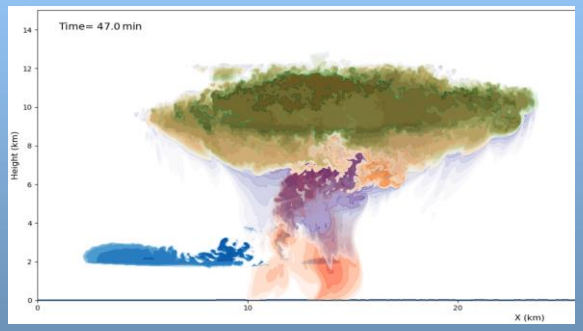


Large offshore windparks

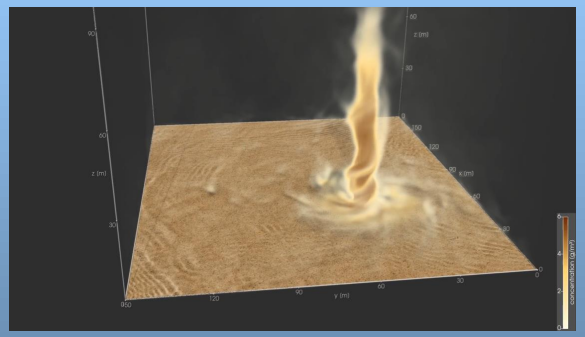


Fog forecast for airports

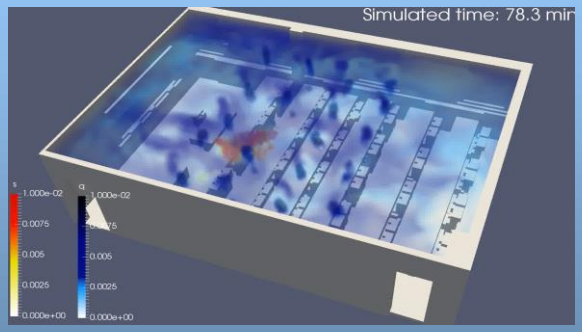
Turbulence effects on drones



Evolution of a Cumulonimbus



Dust emission by dust devils



Aerosol dispersion in lecture room

Leibniz Universität Hannover

PALM – Future Developments

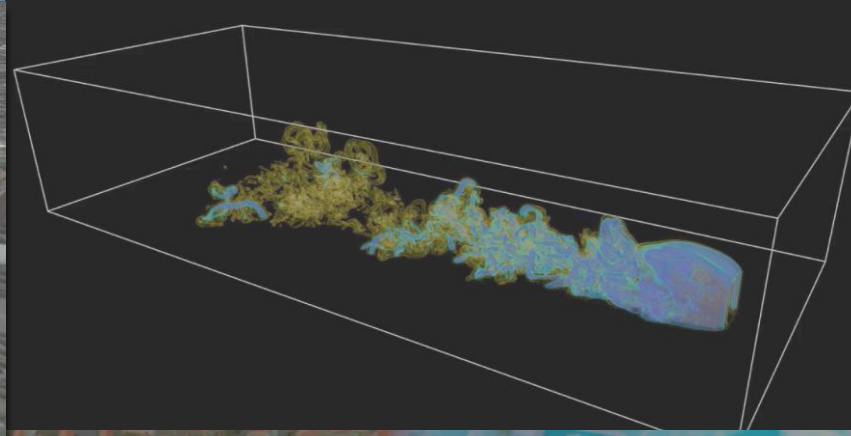
- **Release 26.10:** PV module, wind throw model, traffic induced turbulence module
- **2027:** lake model, compressible NS equations

PALM is open source (GPL v3) → https://palm-model.org

Download: https://gitlab.palm-model.org

New documention server: https://docs.palm-model.org

Animations: https://www.youtube.com/users/palmhannover



Thank You!

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