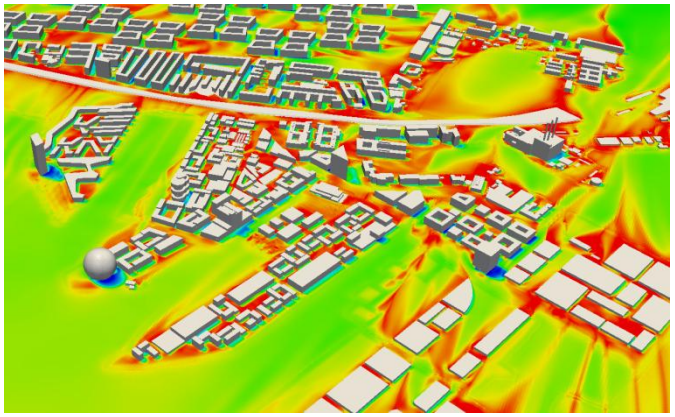
Prediction of pedestrian wind and thermal comfort and pollutant dispersal in an urban environment



Andrew Jackson, Eugene de Villiers,
Thomas Schumacher, Francisco Campos,
Meiring Beyers
Jonas Kastrup, Jens Chr. Bennetsen

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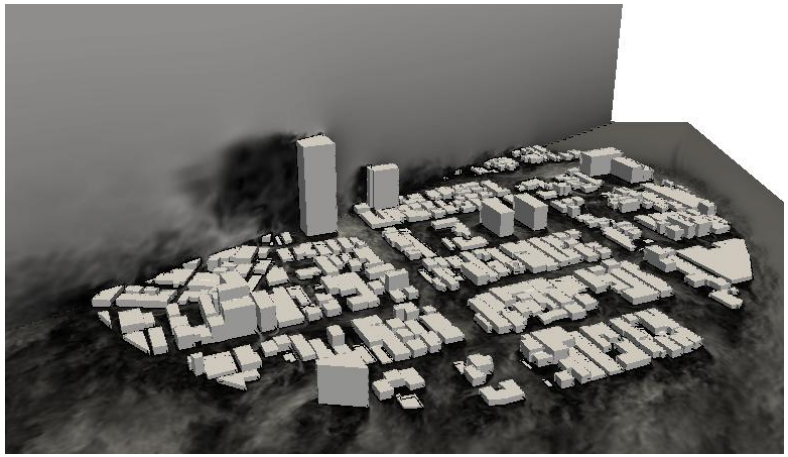
Klimaat Consulting & Innovation

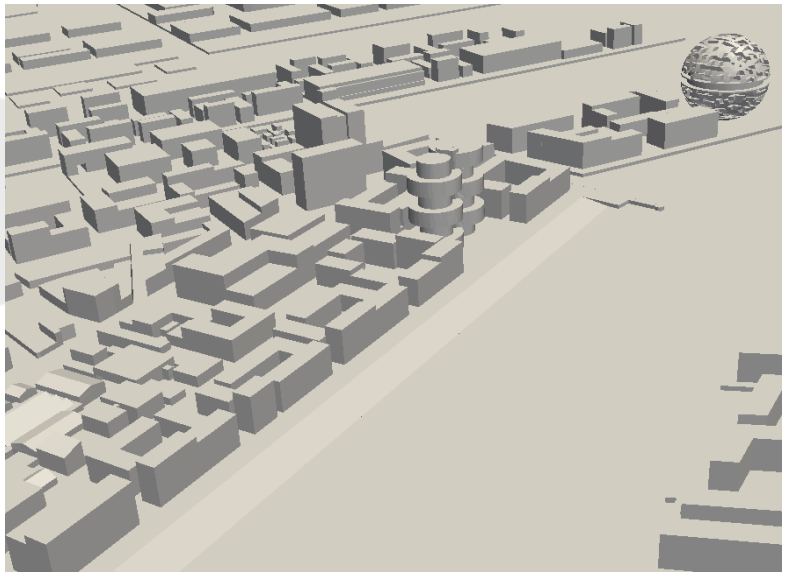
Ramboll Denmark

6th OPENFOAM Workshop
PennState University, USA
13-16 June, 2011

Content

- Sustainable Urbanism
- Wind Comfort
- Thermal Comfort
- Nordhavn
- Air quality
- Looking ahead





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- UK, Germany and Italy
- Open Source software for industrial application
  - CFD, FEM, Optimisation
  - OPENFOAM® , Code_Aster, Dakota
- Software services
  - Outsourcing/Consultancy
  - Training
  - Support
  - Development

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Sustainable Urbanism

- Efficient urban planning
  - Interaction of pedestrians with buildings and the spaces between them
- Requires: Understanding of urban microclimate
  - Wind/Thermal comfort
  - Pollution
  - Coupling to local meteorological and site data
    - Wind, Solar, Humidity
    - Pollution Sources, surface properties
- Open Source CFD
  - Fast, cost effective, accurate, extensible

- Aim: to produce a comprehensive urban comfort prediction tool incorporating state-of-the-art industry practices

Wind Comfort

- Dense complex constructions in cities can
  - Block wind reducing air circulation and air quality
  - Channel wind cause discomfort and safety issues
  - Lead to unexpected microclimates in outdoor areas
- Wind Comfort and Safety criteria from Bottema

  Bottema, 2000, M., A method for optimization of wind discomfort criteria, Buildings and Environment, 35.

  - Comfort criteria: $U + \sigma > 6 m/s$
  - Safety criteria: $U + 3\sigma > 20 m/s$; $\sigma_U = 0.151 U_{10} + 0.119$

  (U : mean local air velocity, σ_u : std dev of velocity, U_{10} : reference velocity *10m* above ground level)

- Exceedance probability: $P(U > U_{Critical}) = 100\% \cdot \exp\left(-\left(\frac{U_{Relative}}{A}\right)^k\right)$

  (k, A : Weibull parameters from measurement, $U_{relative}$: $f(U, U_{10}, U_{Critical})$)

Wind Comfort | Methodology

- Comfort matrix ($U_{Critical}$ = 6 m/s)

Wind comfort				
Exceedance probability (% of hours per year)	Grade	Activity area		
		Traversing	Strolling	Sitting
< 2.5	A	Good	Good	Good
2.5 – 5.0	B	Good	Good	Moderate
5.0 – 10.0	C	Good	Moderate	Poor
10. – 20.0	D	Moderate	Poor	Poor
> 20.0	E	Poor	Poor	Poor

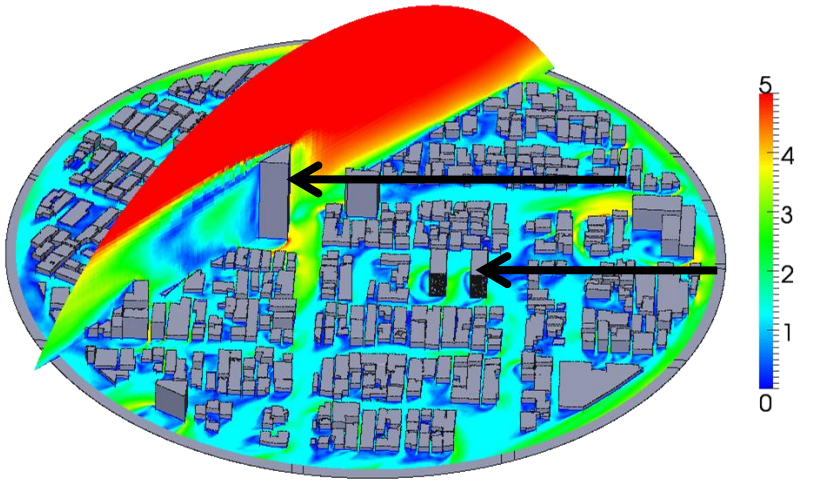
- Safety matrix ($U_{Critical}$ = 20 m/s)

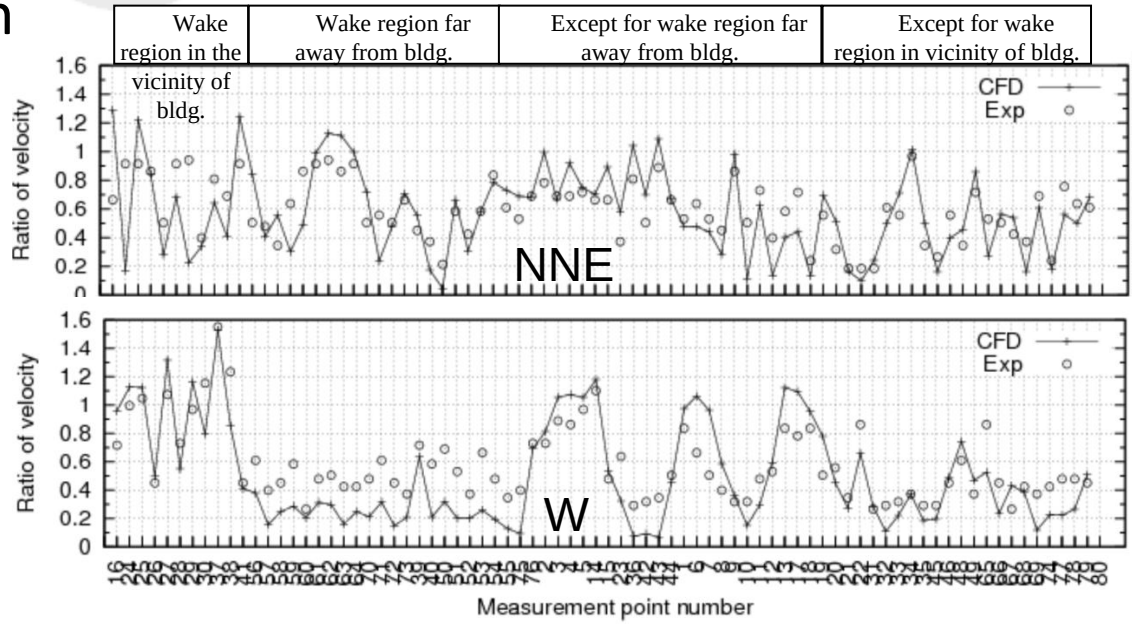
Wind safety	
Exceedance probability	**Level of wind safety**
<0.05	Safe
0.05-0.3	Limited Risk
>0.3	Unsafe

- Combine exceedance probability for all wind-rose directions and frequency for annualised comfort and safety indicator

Wind Prediction | AIJ Case E (Niigata)

- Steady-state RAS
  - sHM with feature lines
  - Automatic setup tool
  - Atmospheric BL inlet/outlet boundaries
  - *U, k, epsilon*
- Experimental Validation
  - Rel. Velocity Mag.
  - NNE & W shown
  - Similar accuracy to commercial tools
  - Considered sufficient for comfort/safety studies





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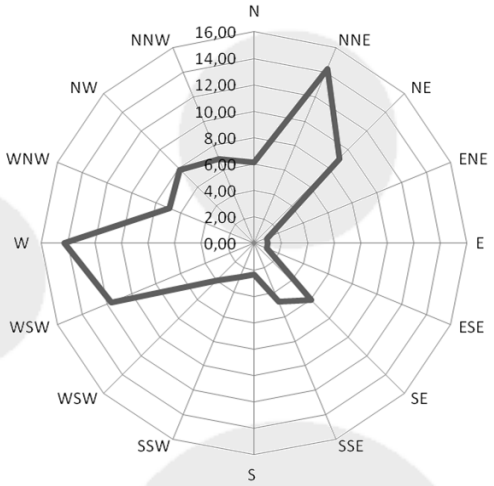
Wind Comfort | AIJ Case E (Niigata)

Wind rose frequency distribution



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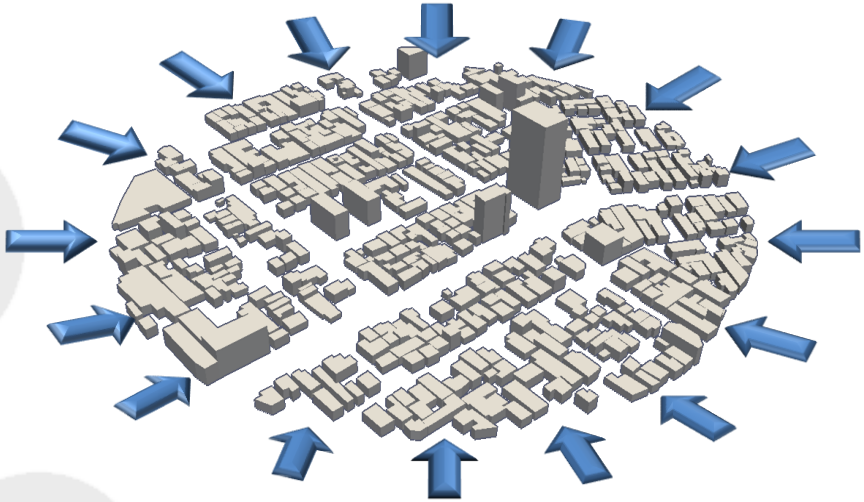
Specific Exceedance probability map from Weibul and CFD for 16 wind directions



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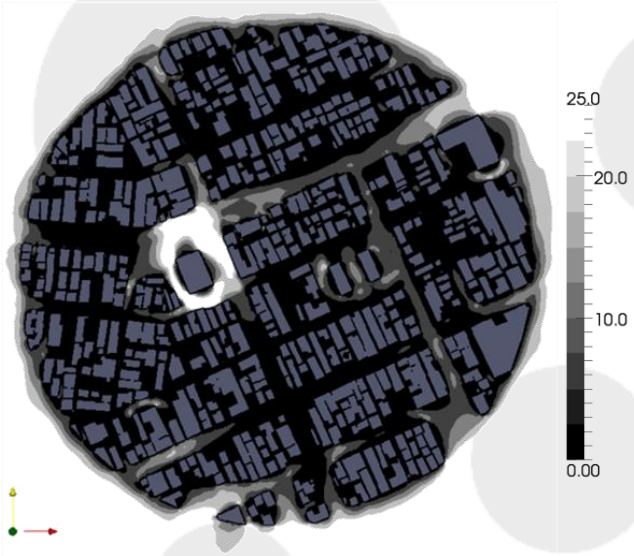

Annualised Exceedance Probability

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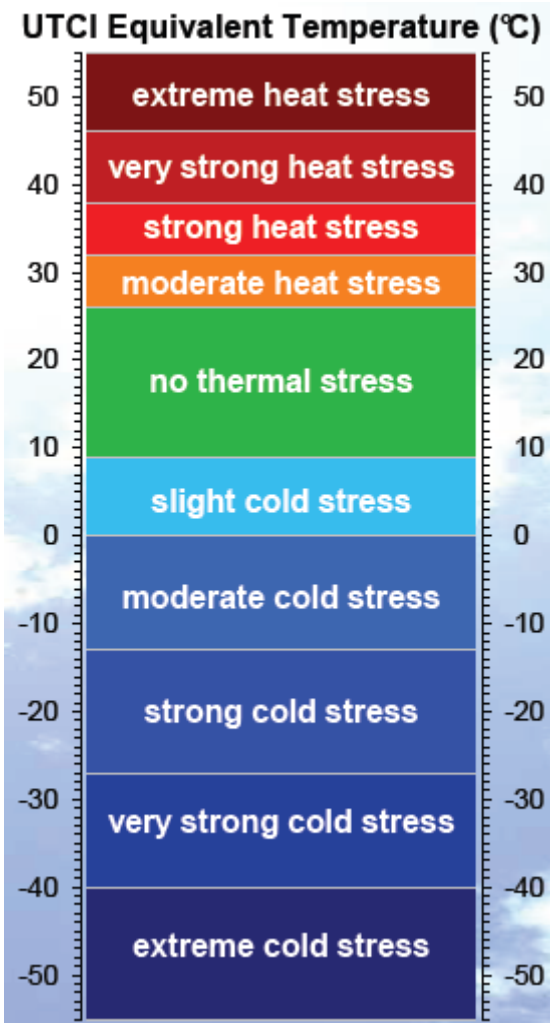
Thermal Comfort | Methodology

- UTCI equivalent temperature
  - Reduced Fiala physiological model
  - Includes following environmental effects:
    - Direct radiation (solar, sky)
    - Near-field radiation (buildings, ground)
    - Air temperature
    - Wind chill
    - Humidity
- Physiological response equivalent to air temperature under reference condition:
  - $T_r = T_a$
  - RH = 50% (T_a < 29 C), p_a = 2kPa (T_a > 29 C)
  - V_a,10m = 0.5 m/s
  - Activity walking 4 km/h, 135 W/m2
- Source: http://www.utci.org



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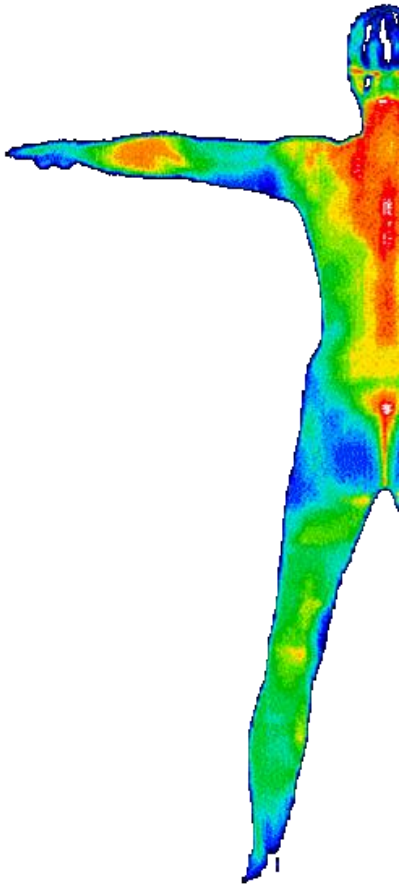
Thermal Comfort | Methodology

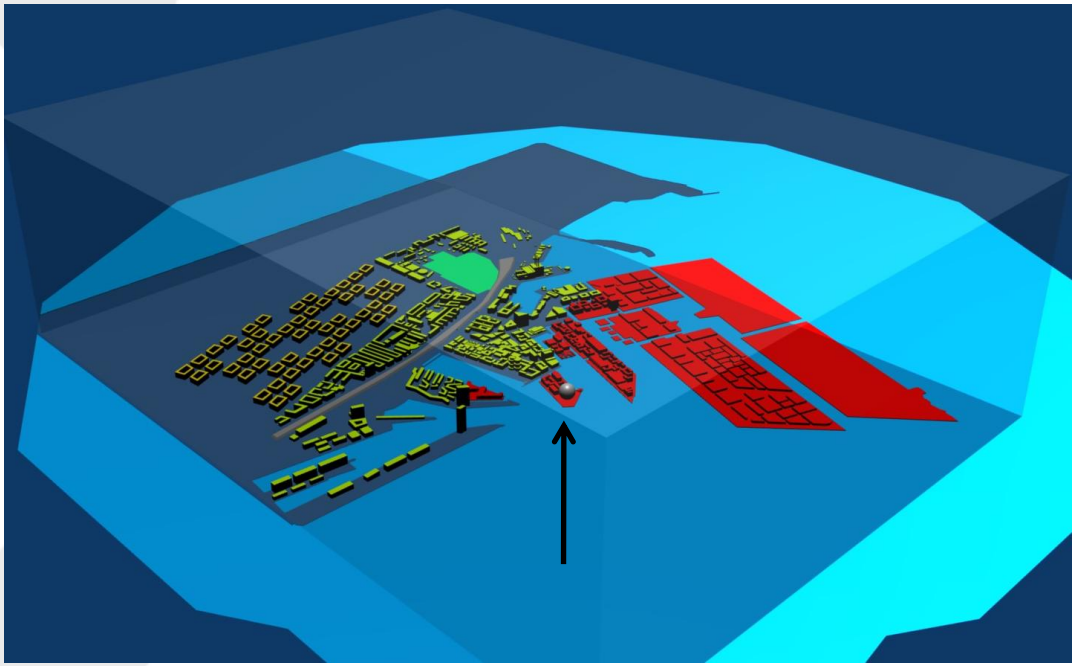
FOAM based developments

- Fast advancing front DOM radiation solver
  - Order of magnitude faster than standard
- Multi-source far-field directional environmental radiation (solar, sky)
- Humidity solver with evaporation/condensation (inc. heat of phase change)
- Incompressible buoyant thermal solver
  - Integrated humidity gradient diffusion
- Boundary based coupling of all components
  - Hybrid Thermal / Concentration / Turbulence / Velocity wall functions
  - 0D thermal capacitance



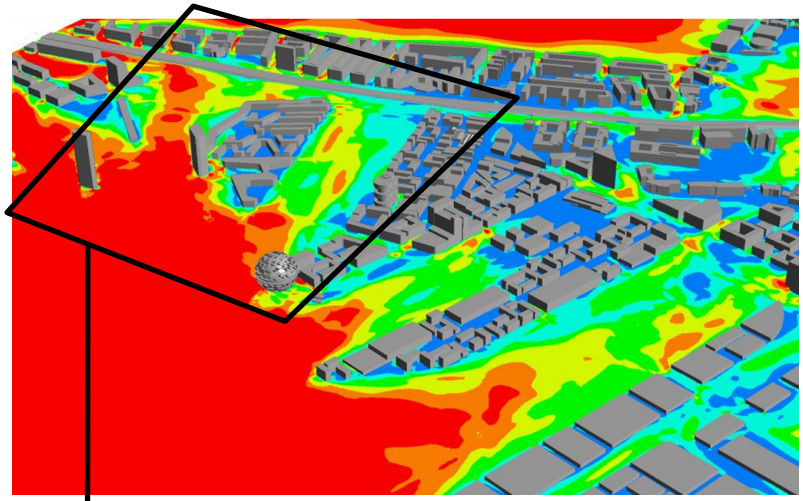
Nordhavn

- New 200 hectare development near Copenhagen
  - One of the most ambitious developments in Scandinavia
  - Strong emphasis on sustainability and environmental quality
  - Analysis focuses on accessible pier (arrow below)

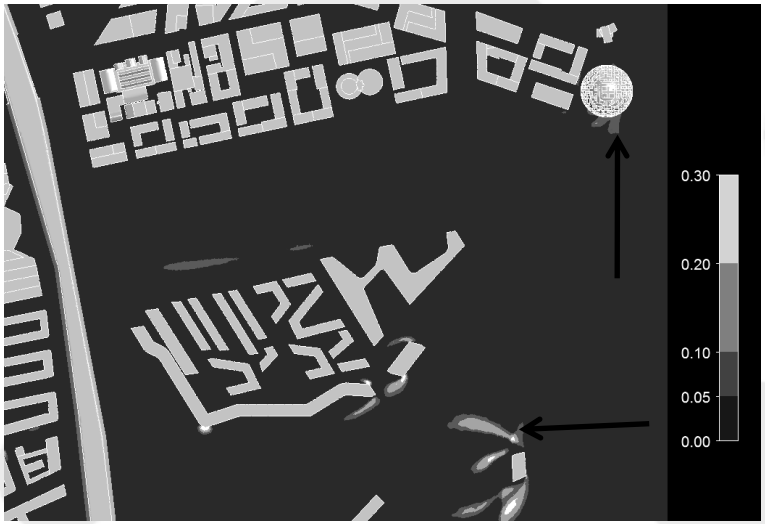


Nordhavn | Wind Comfort

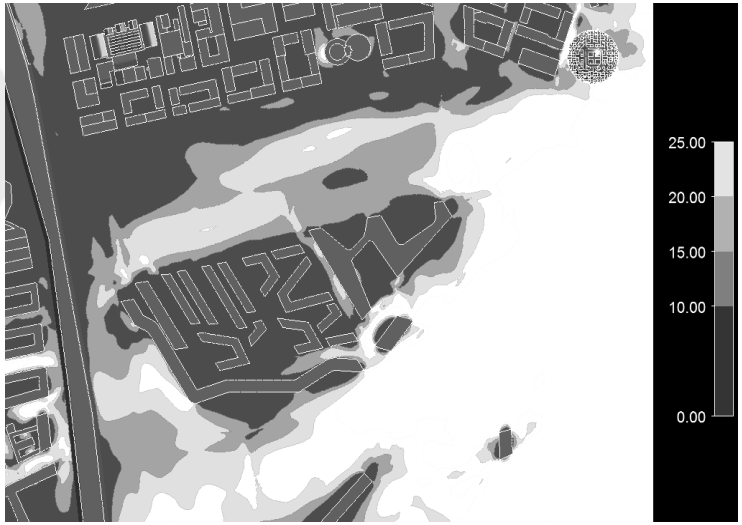
- Low comfort mostly over open water
- Area around globe building not comfortable
  - Some mitigation required on south side
  - Exclusion zone for tall building in south



Annualised Safety



Annualised Comfort



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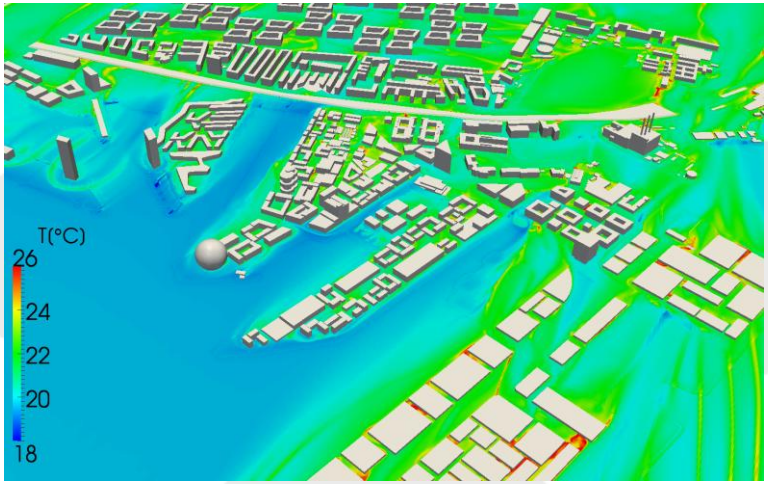
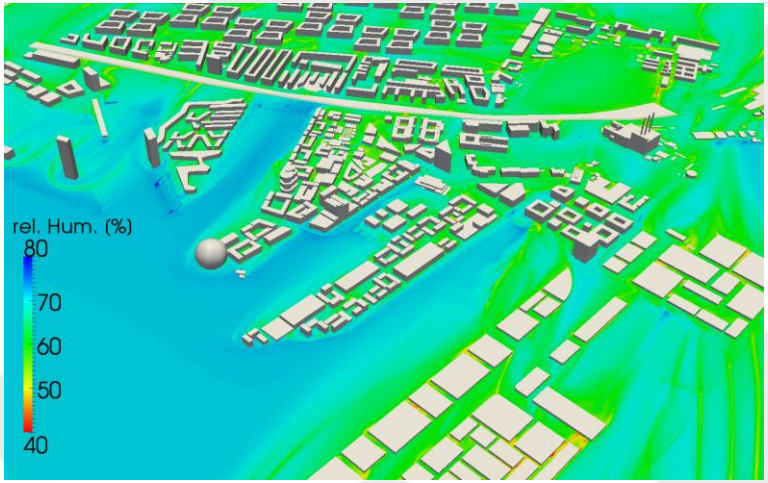
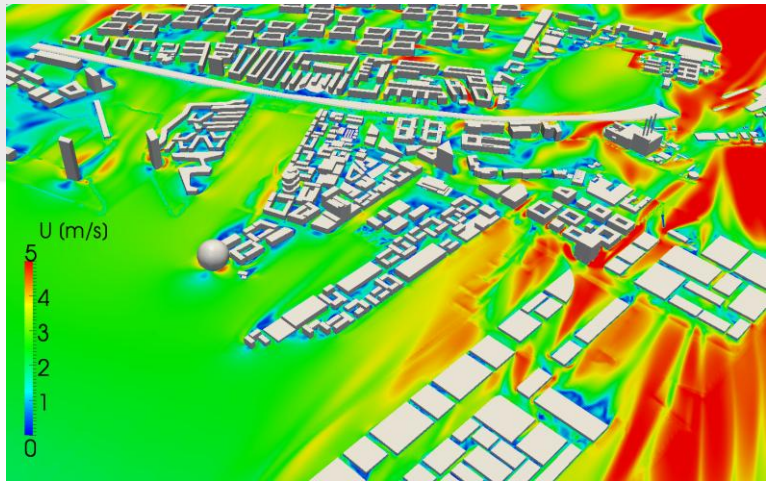
Nordhavn | Thermal Comfort

- Single wind direction : E – effect of ocean







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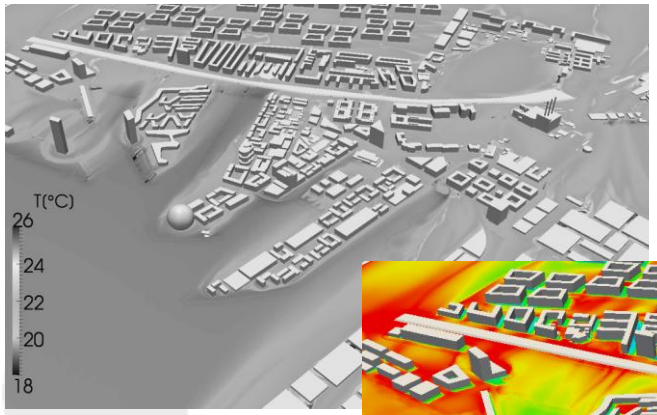
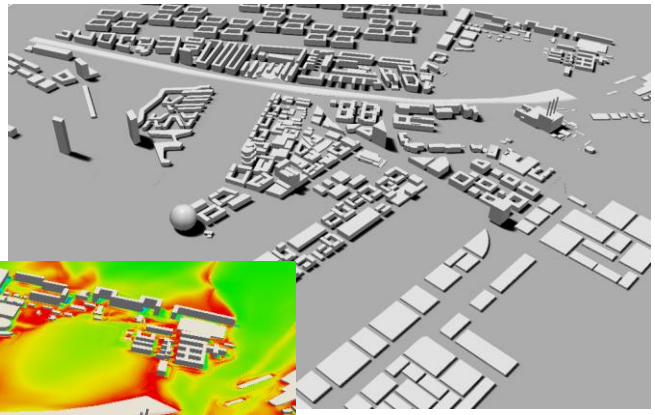
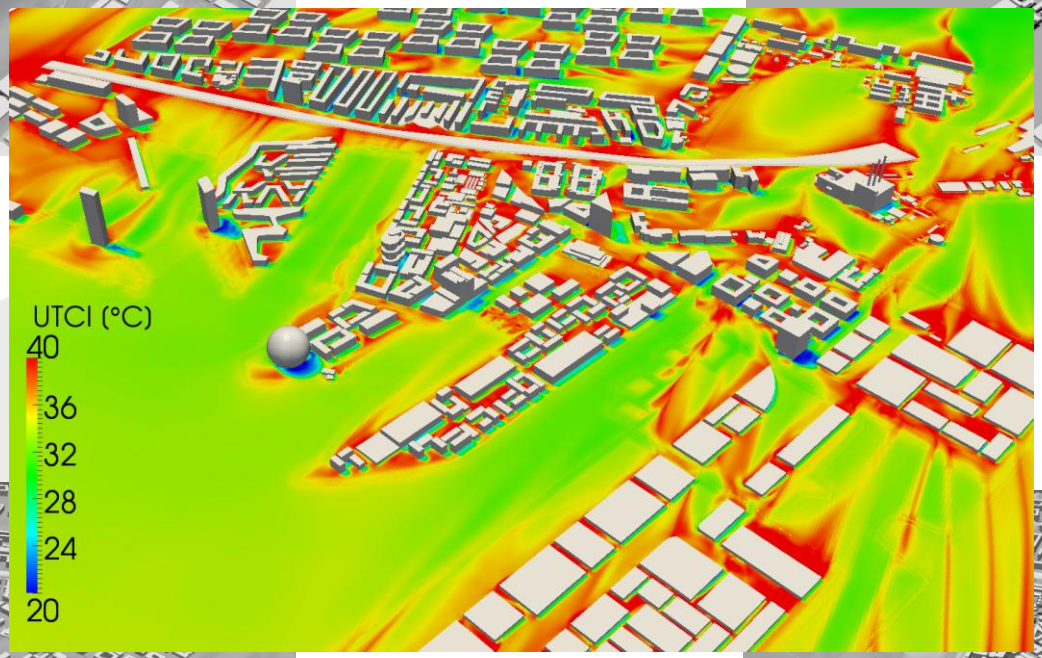
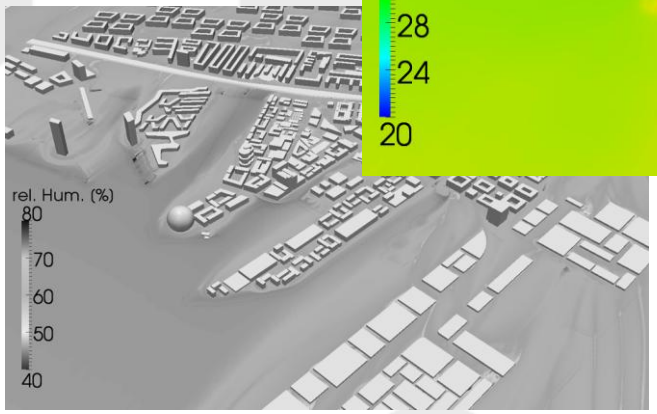
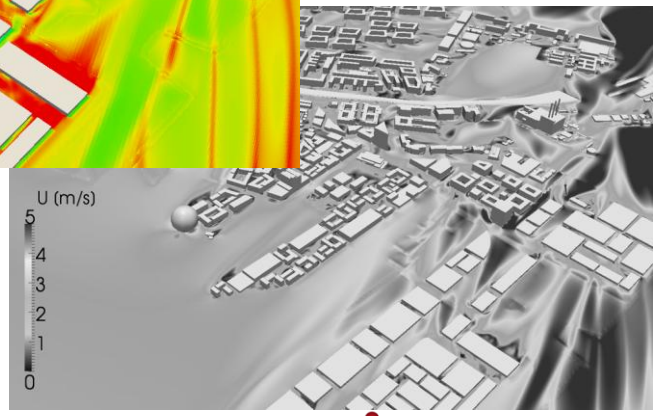
Nordhavn | Thermal Comfort











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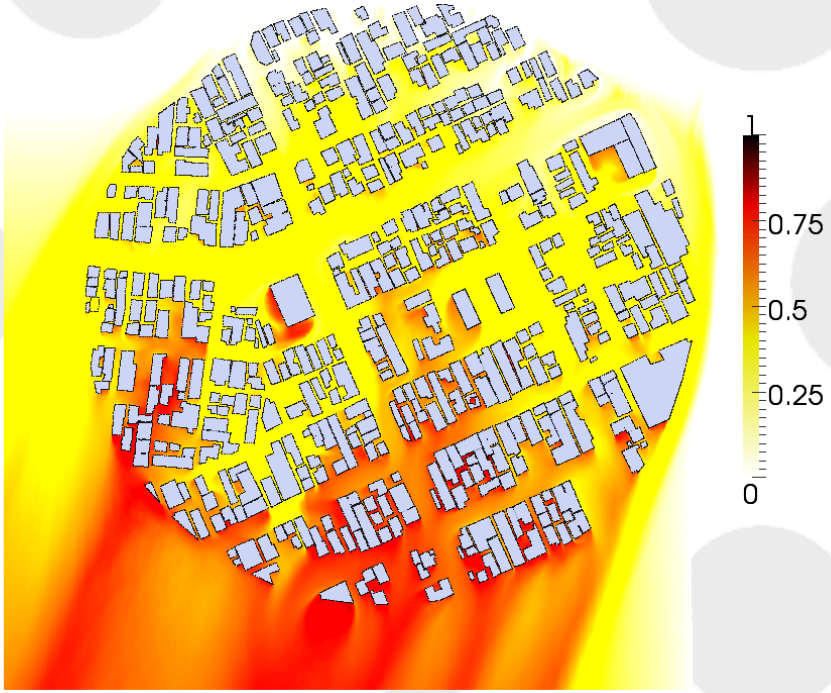
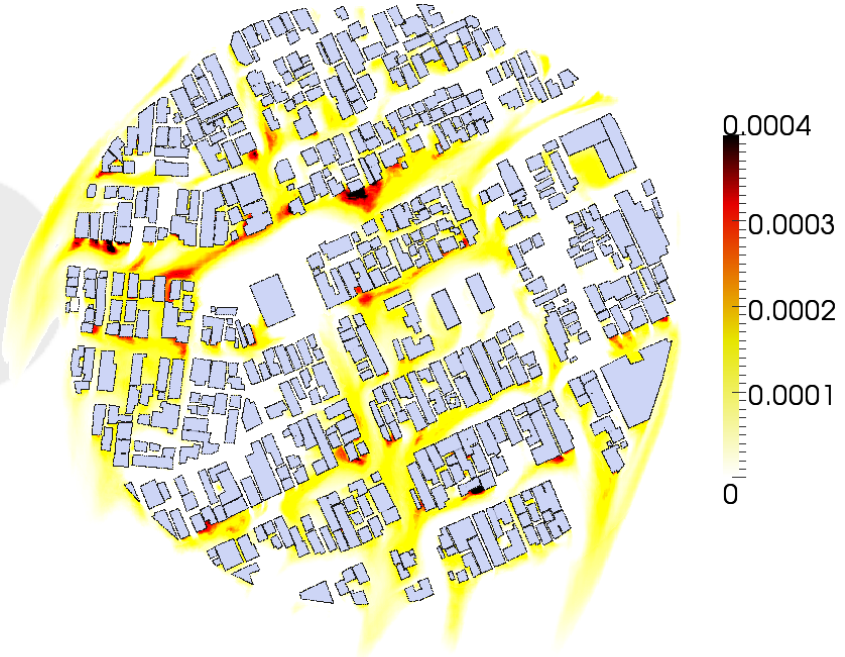
Air quality

- AoA
  - Aging only in volume surrounding buildings
  - Streamwise age gradient obscures local extrema
- Concentration transport
  - Sources from road surface
  - Requires knowledge of source strength
  - Basis for traditional indices: PFR, VF, AST, AER





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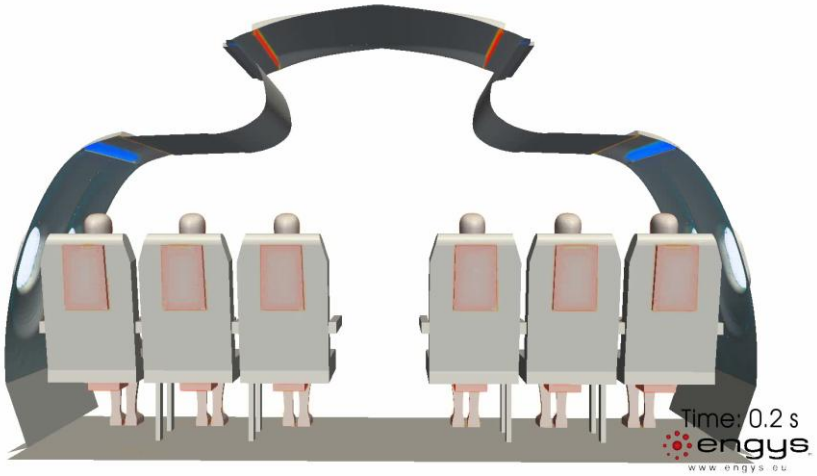
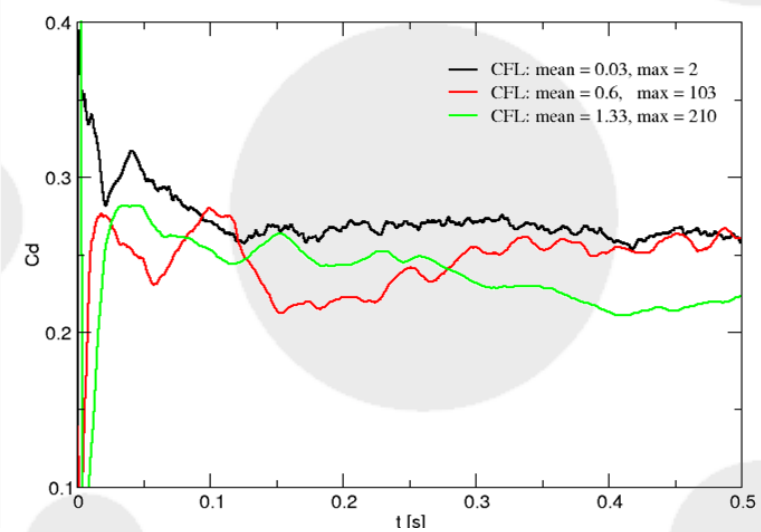
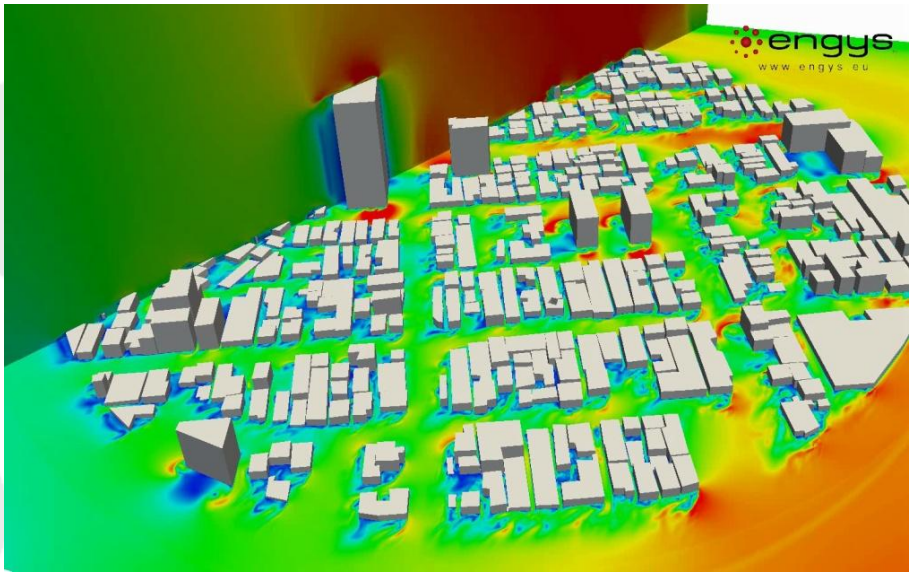
Looking ahead

- Steady RAS → DES
  - Higher accuracy, esp. for pollutant dispersal and wind comfort
  - Accelerated DES = 20x faster (higher CFL, better solvers, discretisation and algorithms)







  - Synthetic turb. inlet

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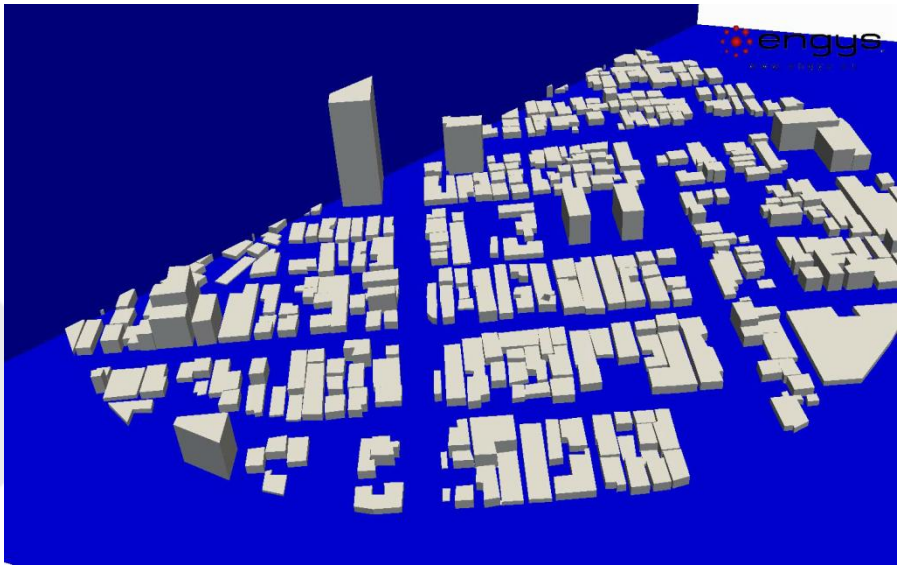
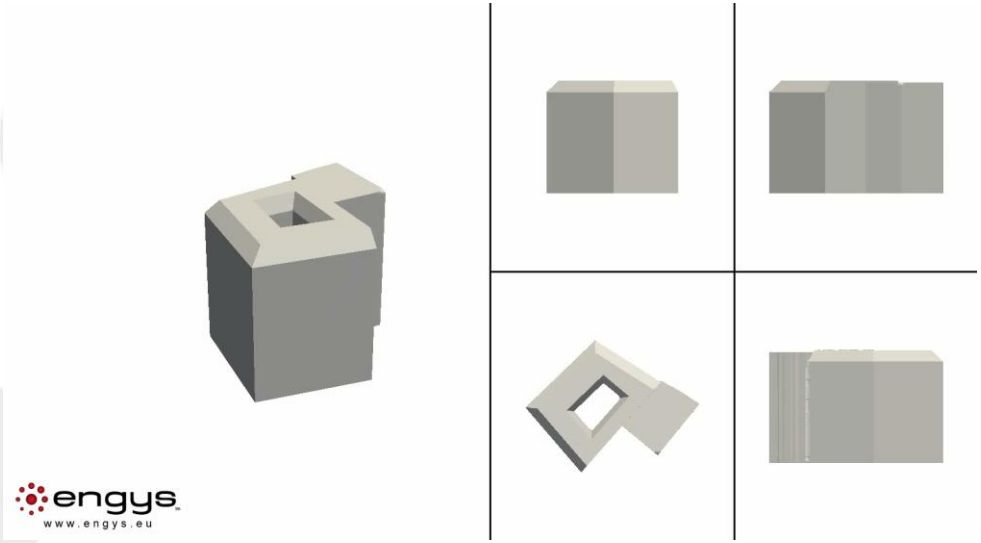
Looking ahead

- Improved components
  - Wall functions
  - Turbulence models
  - Environmental sub-models, e.g. trees, traffic, buildings
  - Better coupling to meteorological data, esp. solar
  - UTCI Exceedance Probability equivalent (?)
- Additional applications
  - Rain impact
  - Snow deposition
  - Wind loading for tall buildings





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Questions?

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