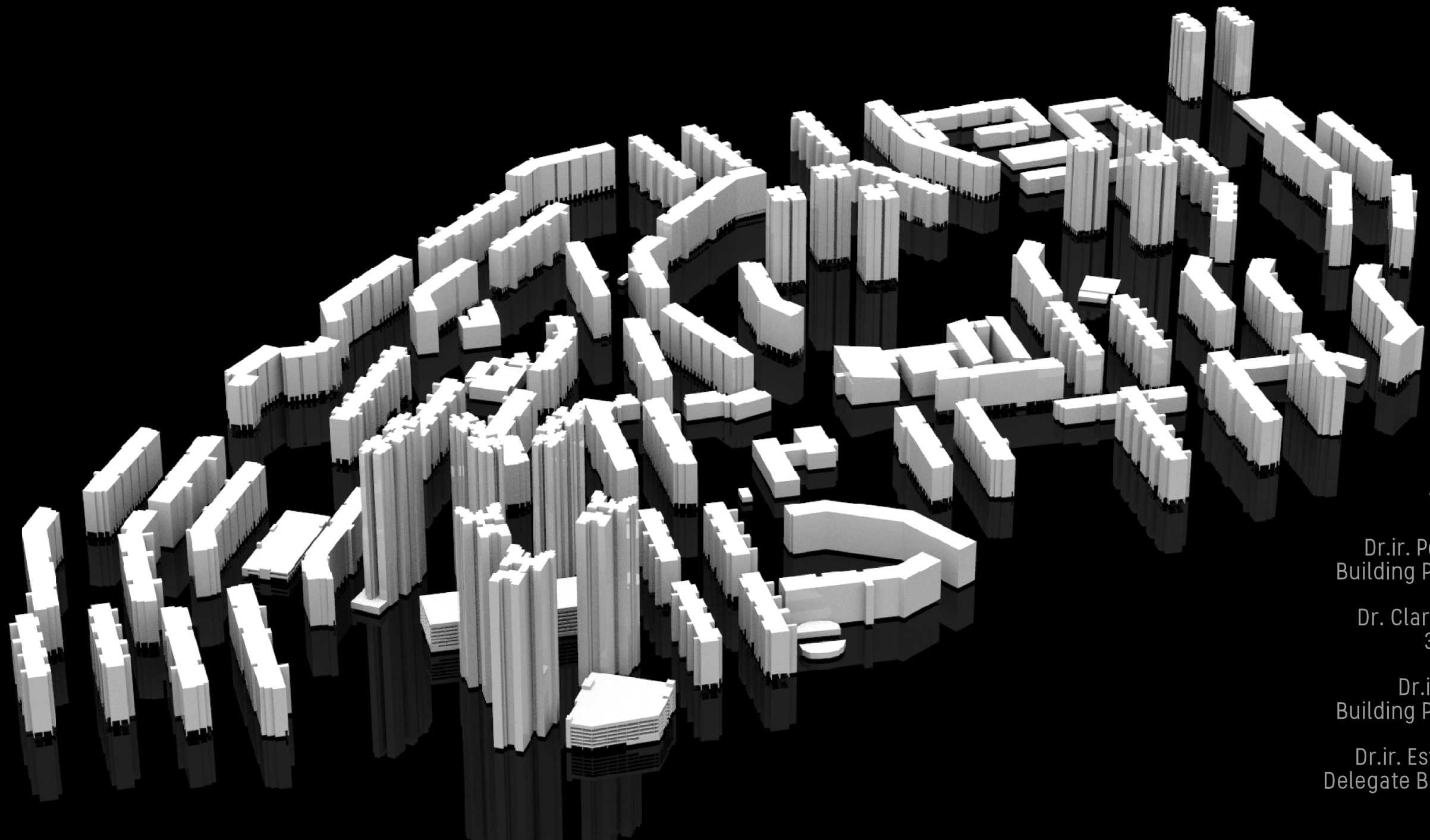


EXPLORING THE EFFECTS OF VOID DECKS ON URBAN VENTILATION IN SINGAPORE

A Computational Design & Simulation Approach for
Wind Microclimate-Informed Urban Planning

by
AVIVA OPSOMER



Thesis Committee

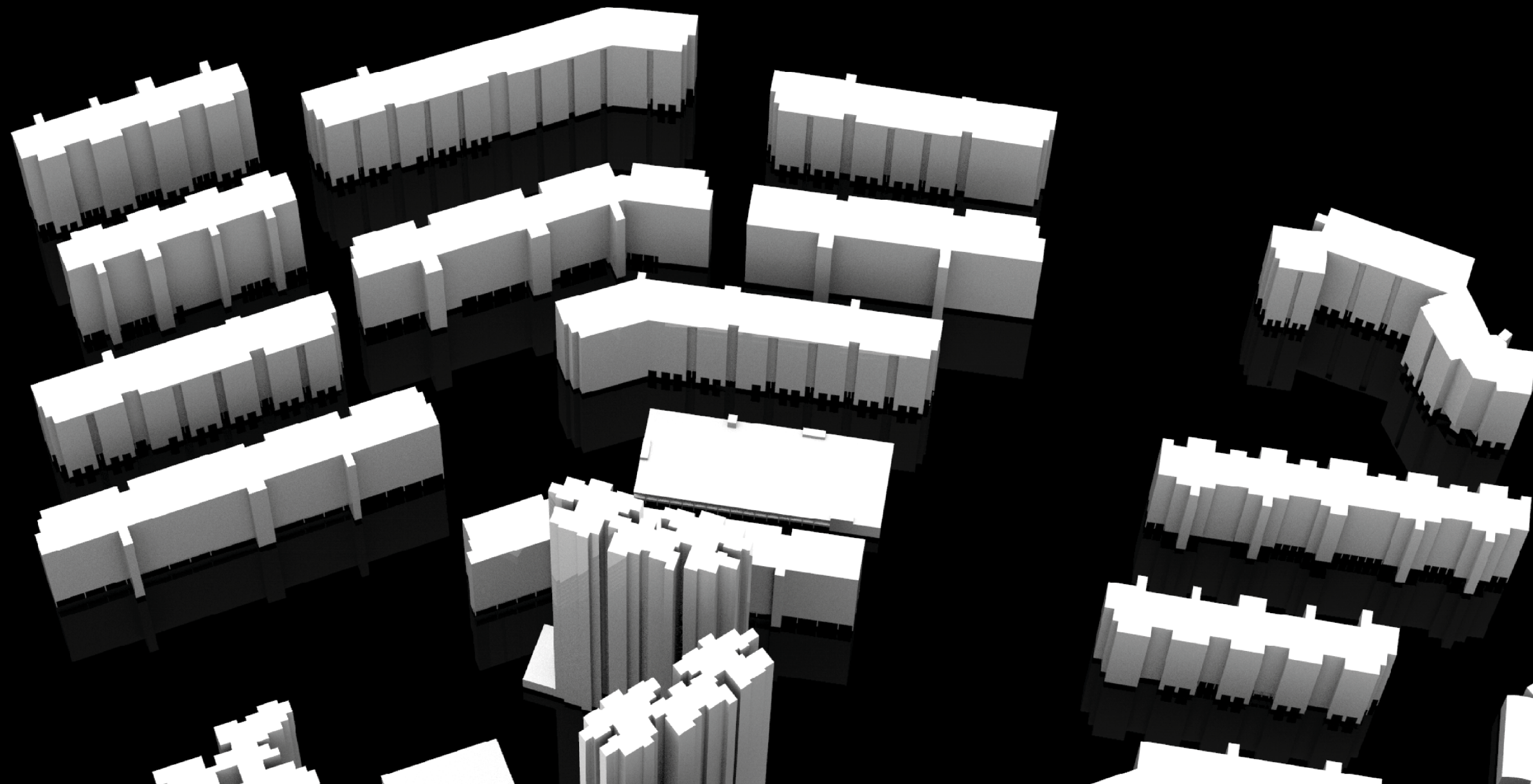
Dr.ir. Peter van den Engel
Building Physics & Services

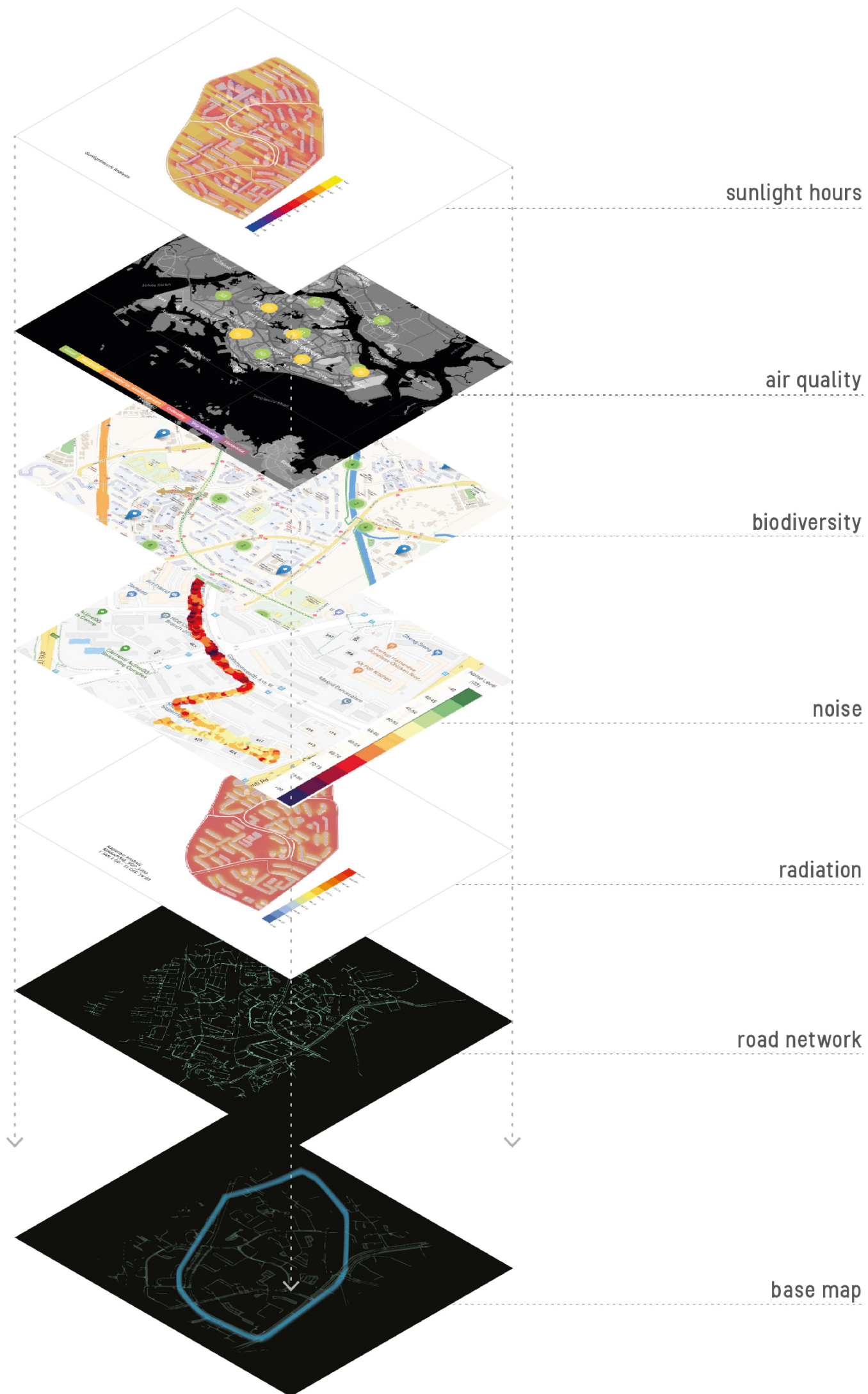
Dr. Clara García-Sánchez
3D GeoInformation

Dr.ir. Martin Tenpierik
Building Physics & Services

Dr.ir. Esther Gramsbergen
Delegate Board of Examiners

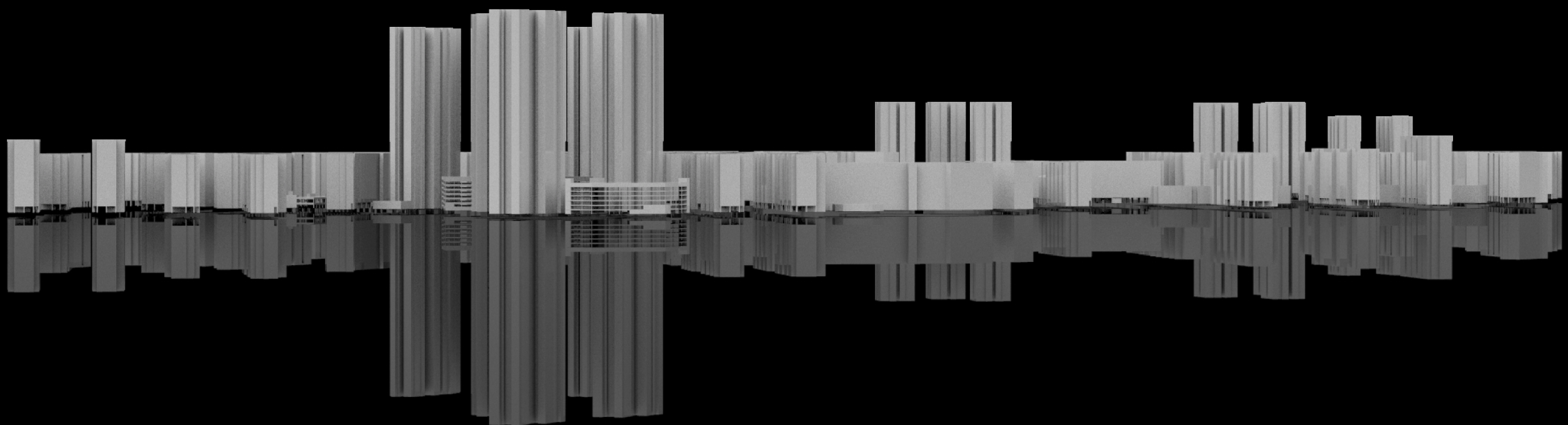
WIND MICROCLIMATE-INFORMED URBAN PLANNING

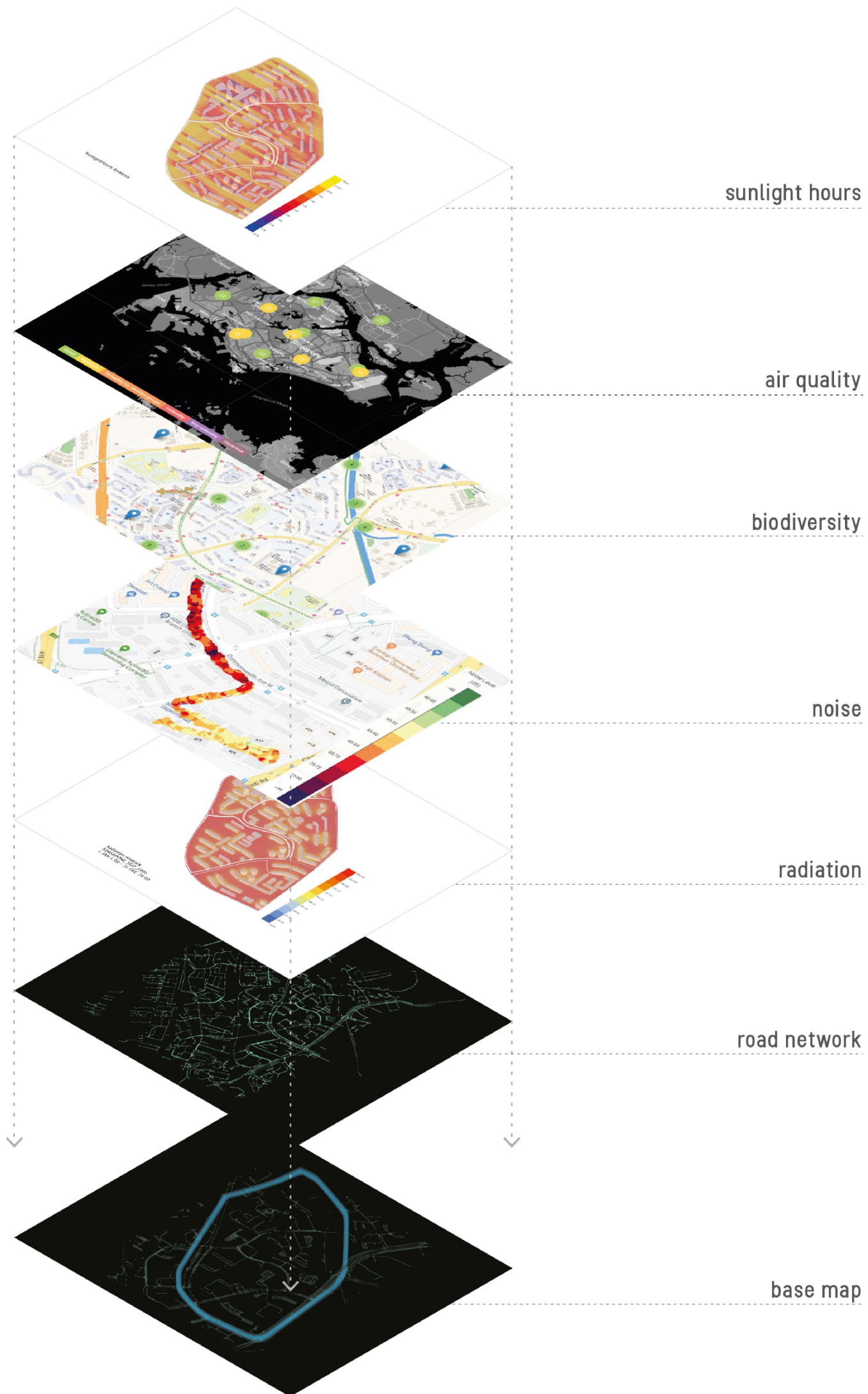




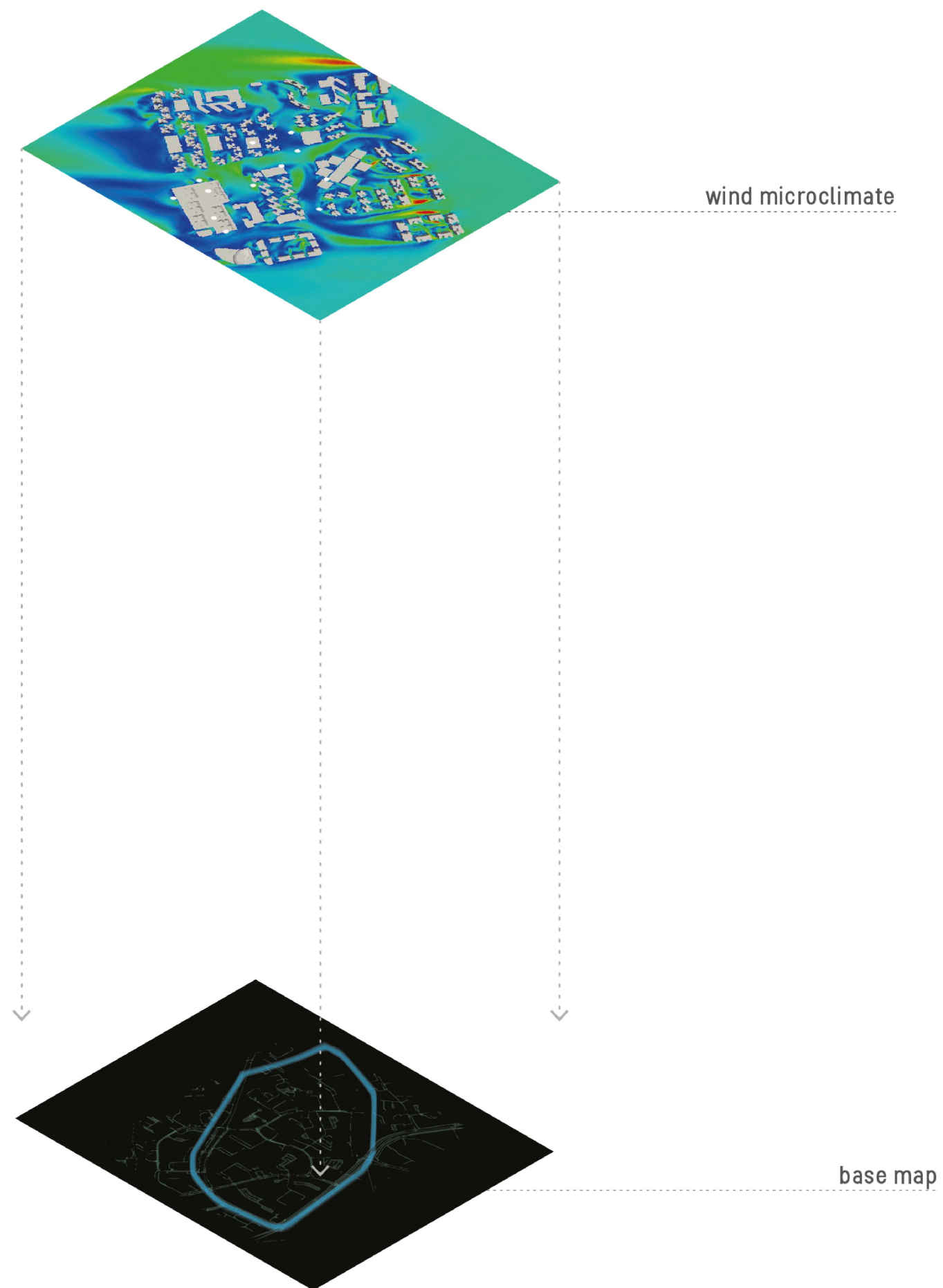
“Urban planners can use different design tools, adapted to different phases of projects design, to assess qualitatively and quantitatively solar radiation in urban areas. But, *wind is a microclimatic parameter generally neglected by urban planners*. However, wind speed at pedestrian level is one of the most important environmental parameters determining user satisfaction in urban open spaces.”

(Reiter, 2010)

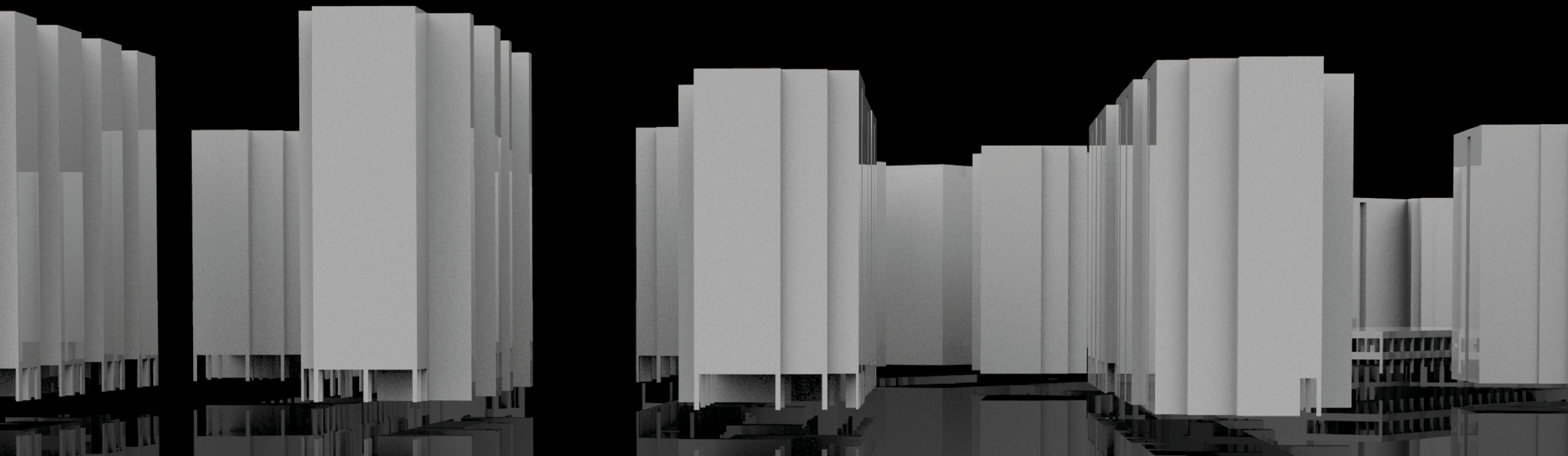




MISSING LAYER?



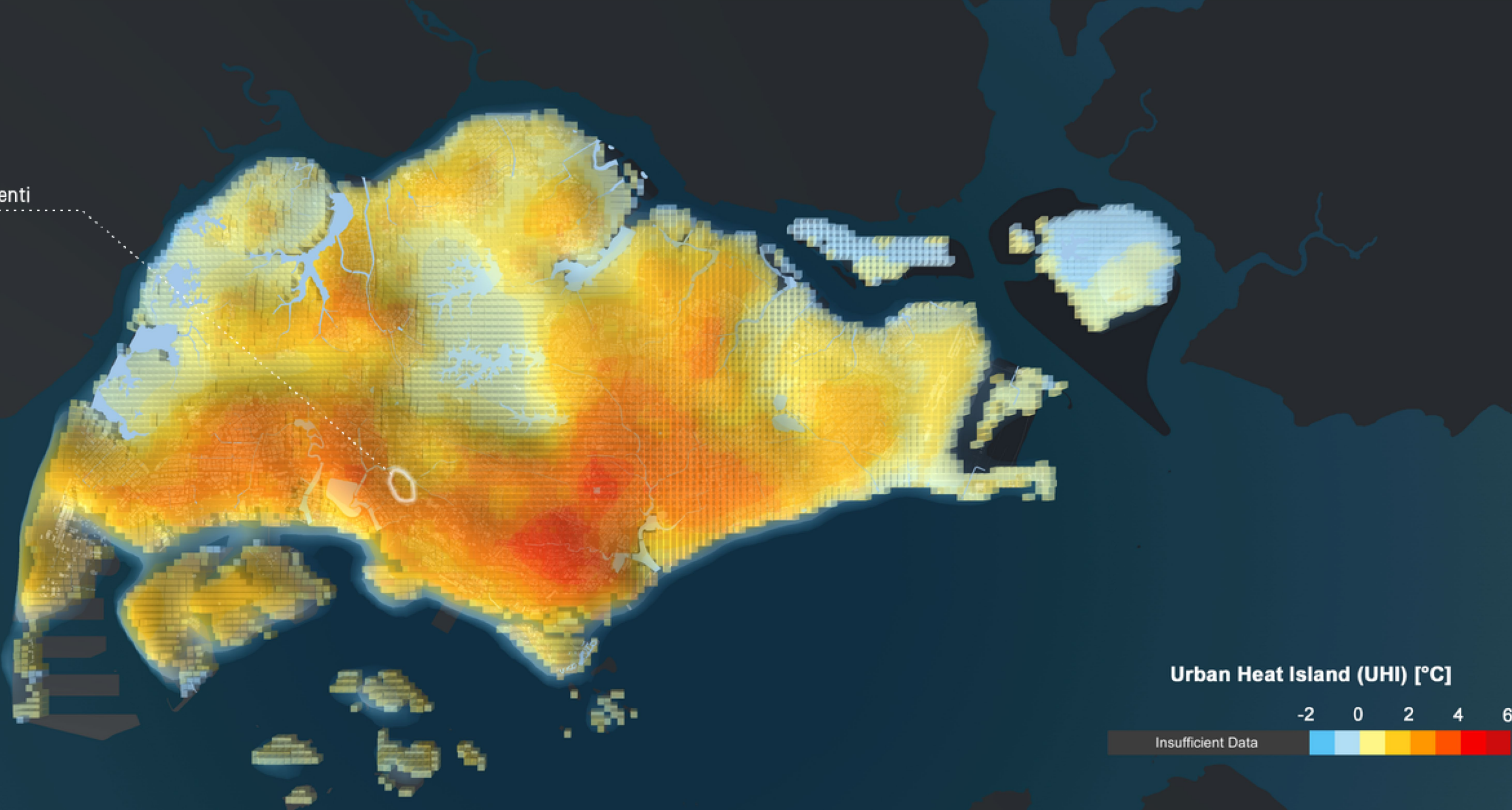
RELEVANCE FOR SINGAPORE



HIGH TEMPERATURES & UHI

Singapore Views
Developed by CIVAL
Cooling Singapore

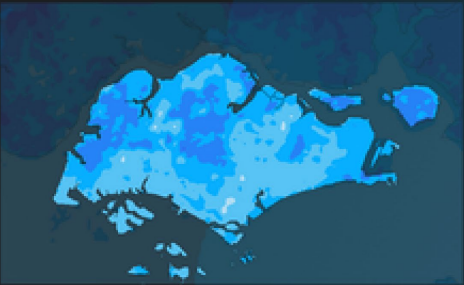
study area, Clementi



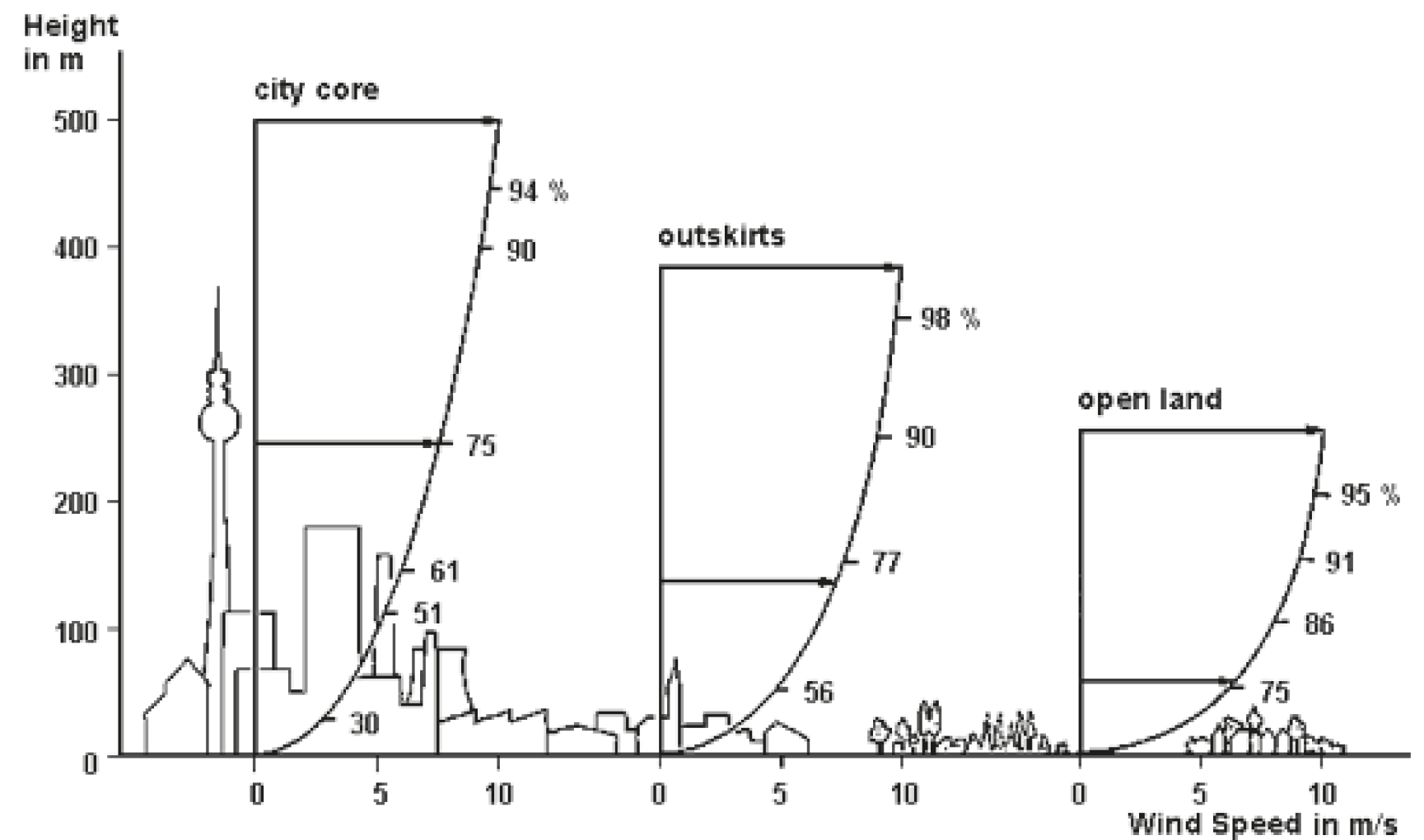
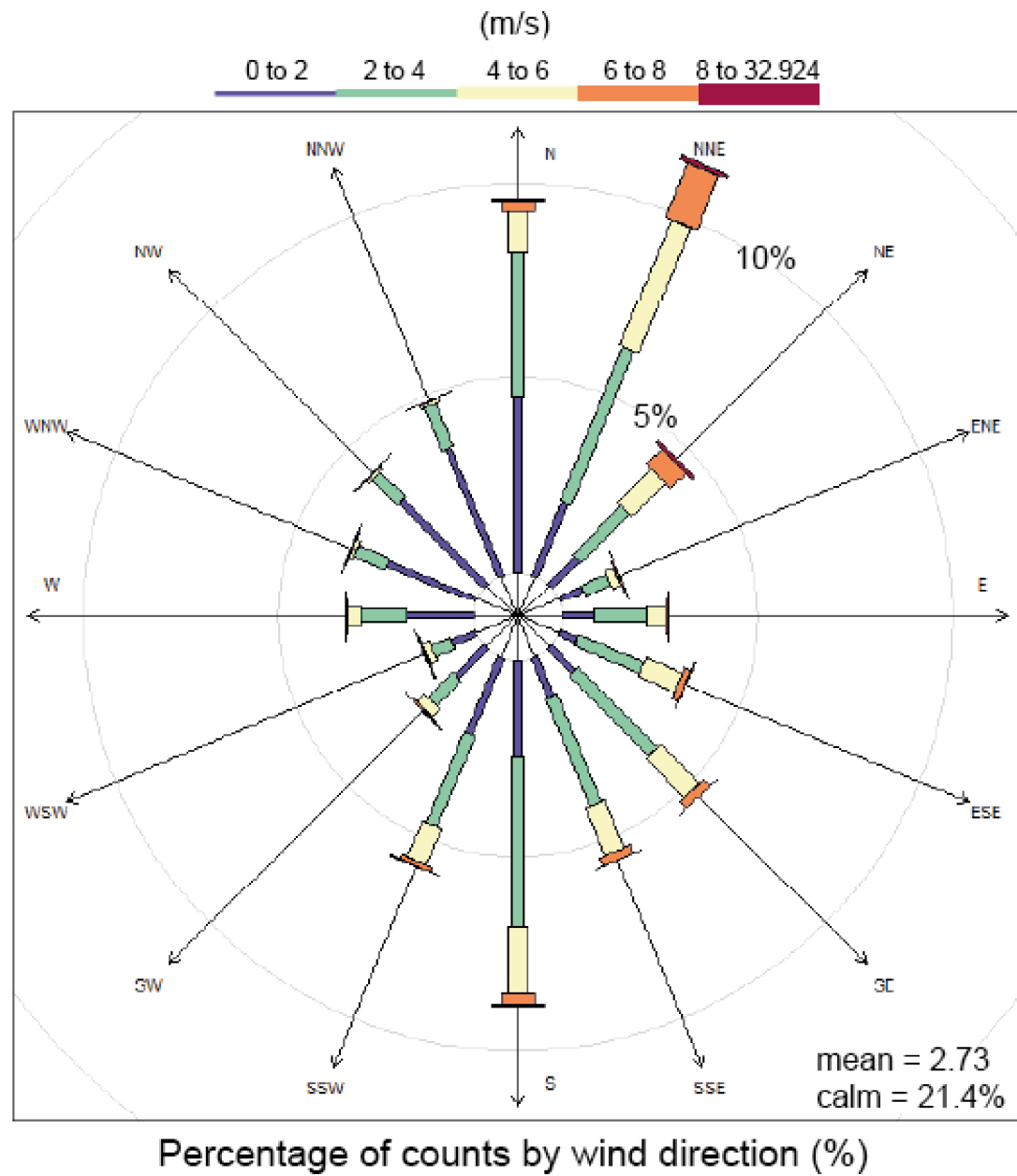
Baseline



Current Situation (2016)



LOW WIND SPEEDS DUE TO GEOGRAPHICAL LOCATION & URBAN CONTEXT



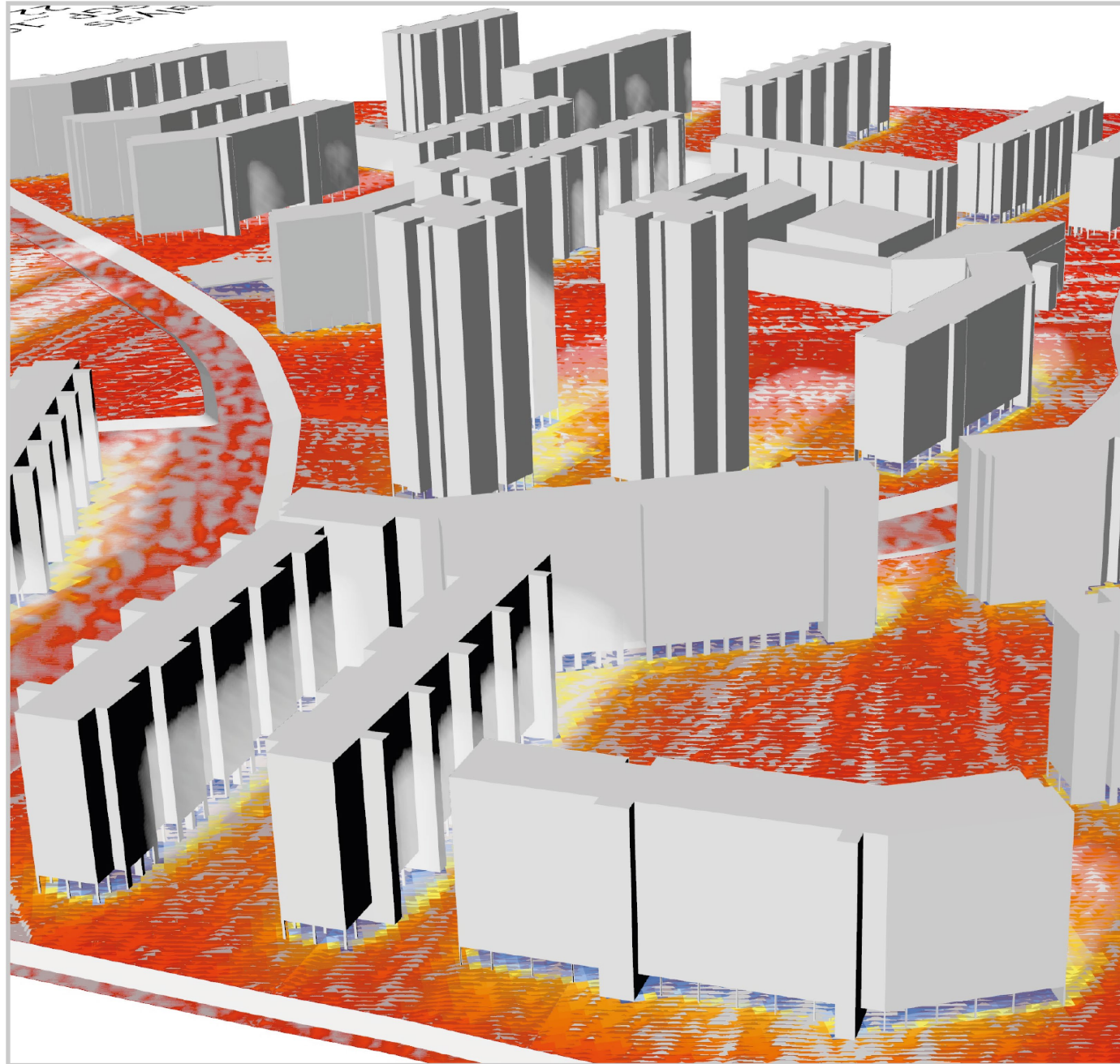
VOID DECKS AS EXPANSION OF PEDESTRIAN ROUTE NETWORK



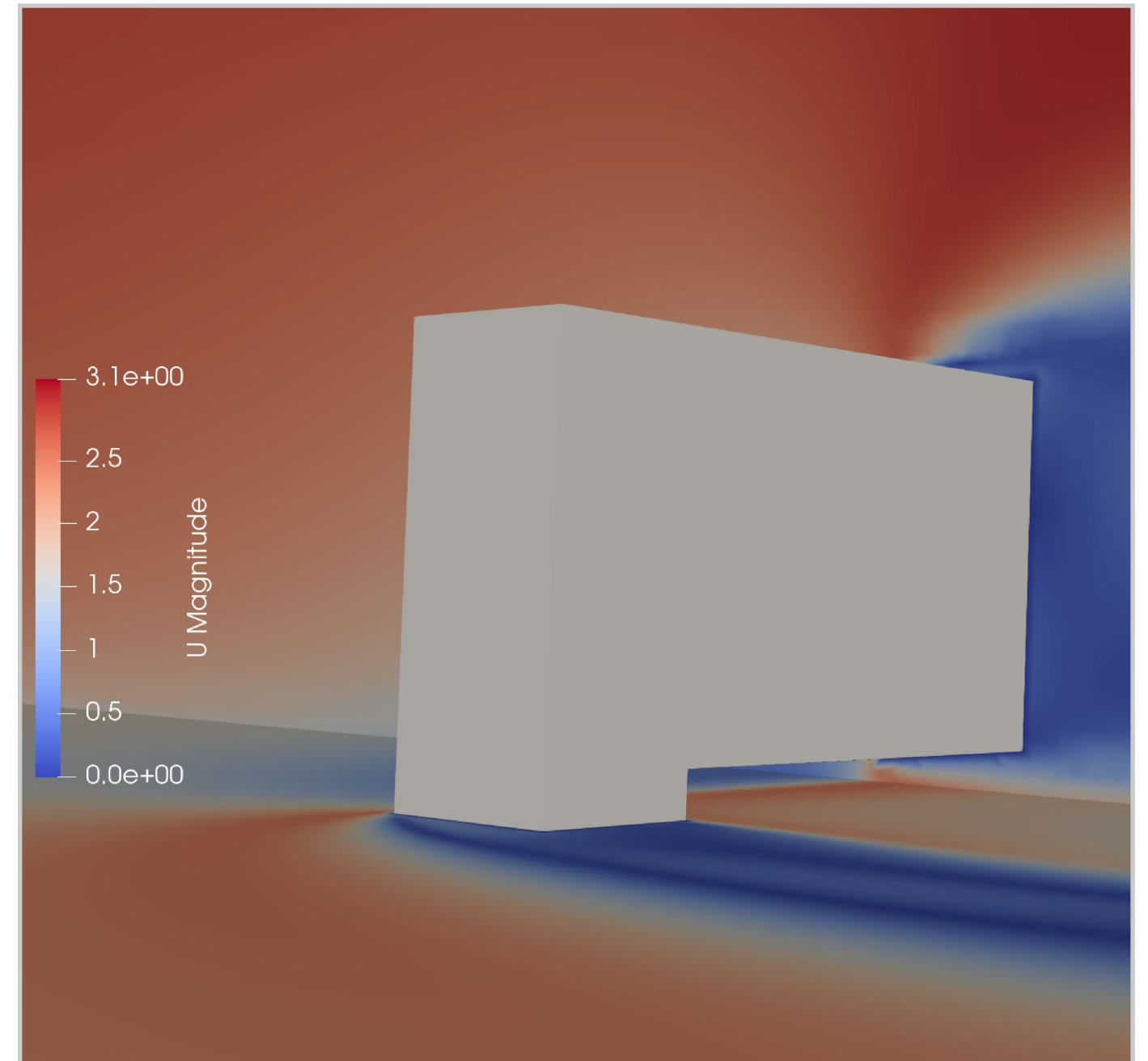
VOID DECKS AS OUTDOOR INTERACTIONAL SPACE



VOID DECKS & THE URBAN MICROCLIMATE



PROVIDING SHADE & SHELTER FROM RAIN



INCREASING WIND SPEEDS

MAIN RESEARCH QUESTION:

How can the geometry design of void decks be optimized to enhance urban ventilation for outdoor thermal comfort in Singapore while ensuring good pedestrian comfort?

STUDY AREA



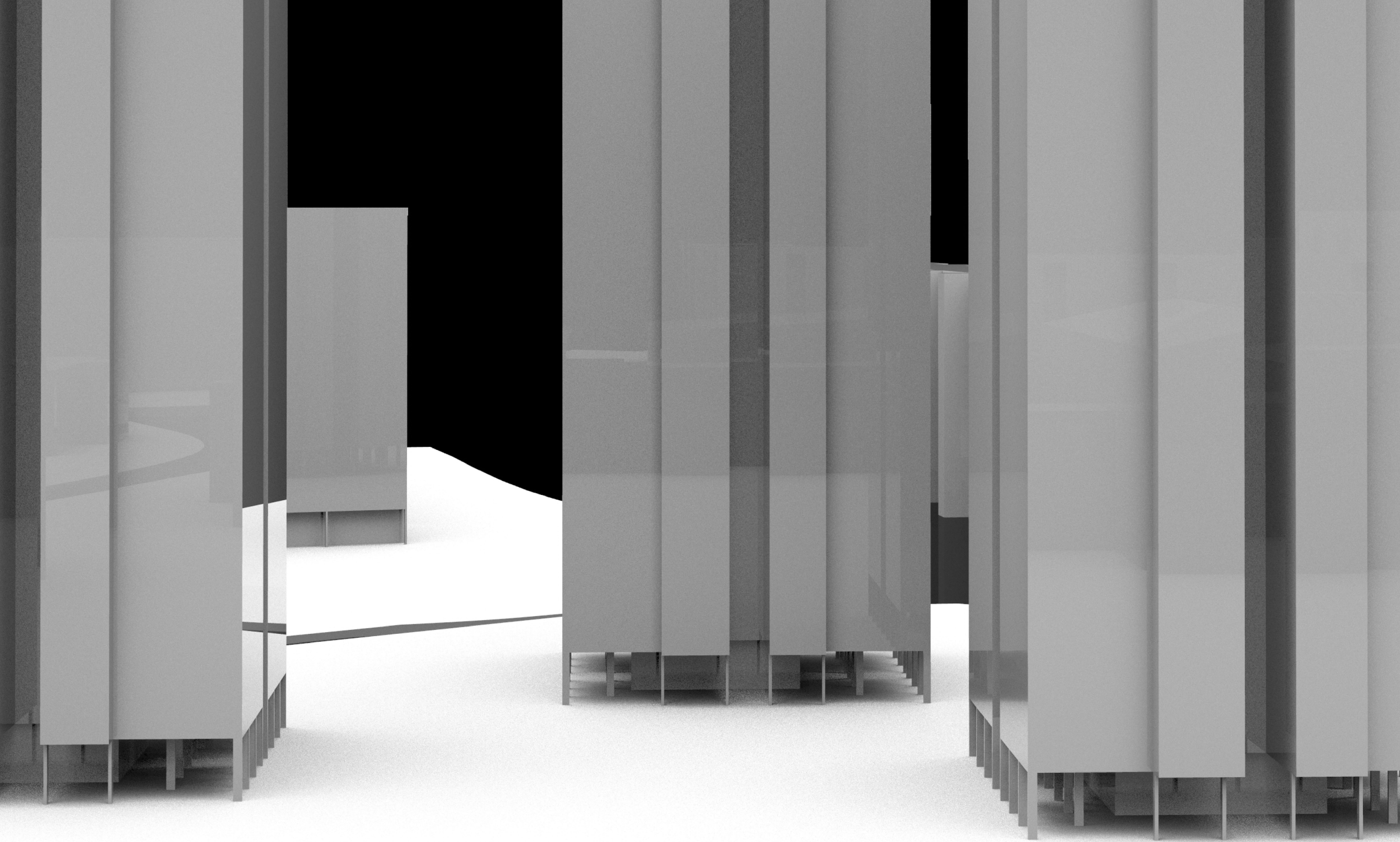
STUDY AREA
Clementi

← Clementi Avenue 6 →

← Commonwealth Avenue West →

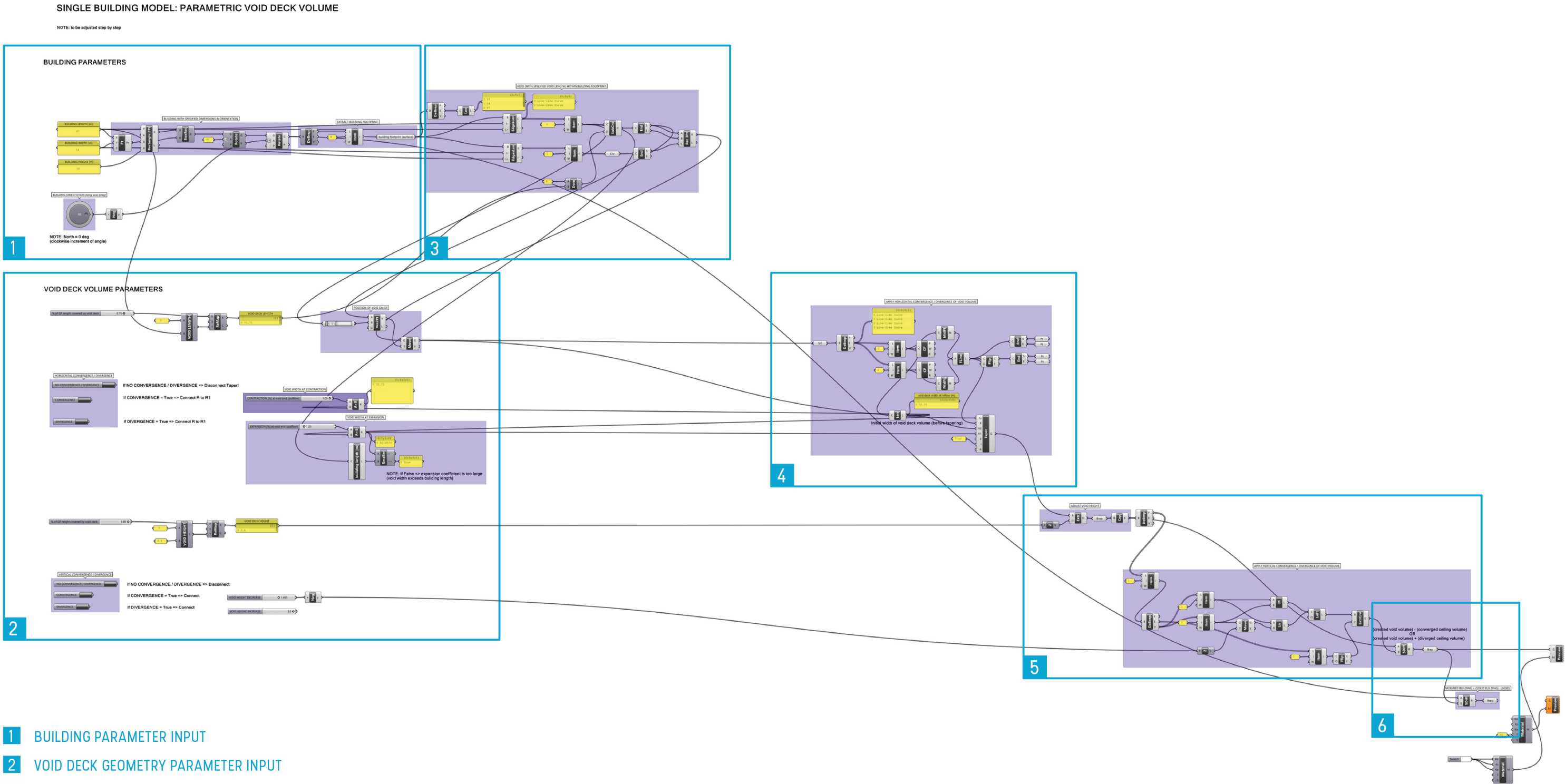
← Ulu Pandan Park Connector →

← Clementi Road →



VOID DECK GEOMETRY STUDY

PARAMETRIC VOID DECK MODEL – BUILDING SCALE



- 1 BUILDING PARAMETER INPUT
- 2 VOID DECK GEOMETRY PARAMETER INPUT
- 3 VOID DECK BASE GEOMETRY CREATION (SPECIFIED VOID LENGTH)
- 4 VOID GEOMETRY MODIFICATIONS: HORIZONTAL CONVERGENCE / DIVERGENCE
- 5 VOID GEOMETRY MODIFICATIONS: VOID HEIGHT & VERTICAL CONVERGENCE / DIVERGENCE
- 6 SUBTRACTION OF BUILDING VOLUME WITH CREATED VOID DECK VOLUME



REPRESENTATIVE BUILDING FOR VOID GEOMETRY VARIANT STUDY

building length = 97 m
building width = 14 m
building height = 34 m



1 BASE CASE: no horizontal / vertical convergence or divergence



2A horizontally converging void (straight taper)



2B horizontally converging void (curved taper)



3A horizontally diverging void (straight taper)



3B horizontally diverging void (curved taper)



4 vertically converging void



5 vertically diverging void



6 horizontally & vertically converging void



7 horizontally converging & vertically diverging void



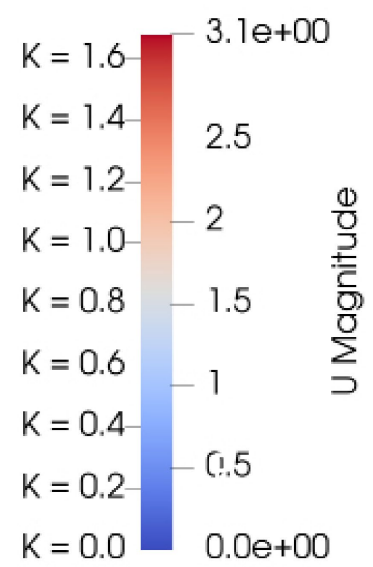
8 horizontally diverging & vertically converging void



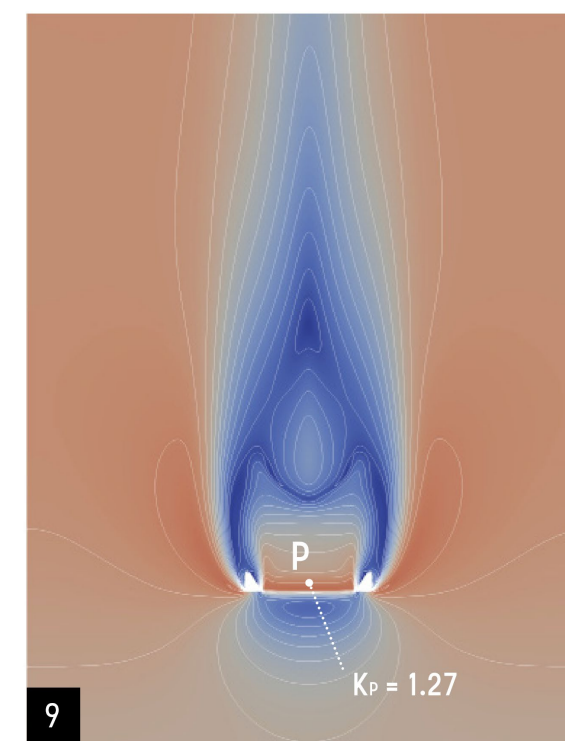
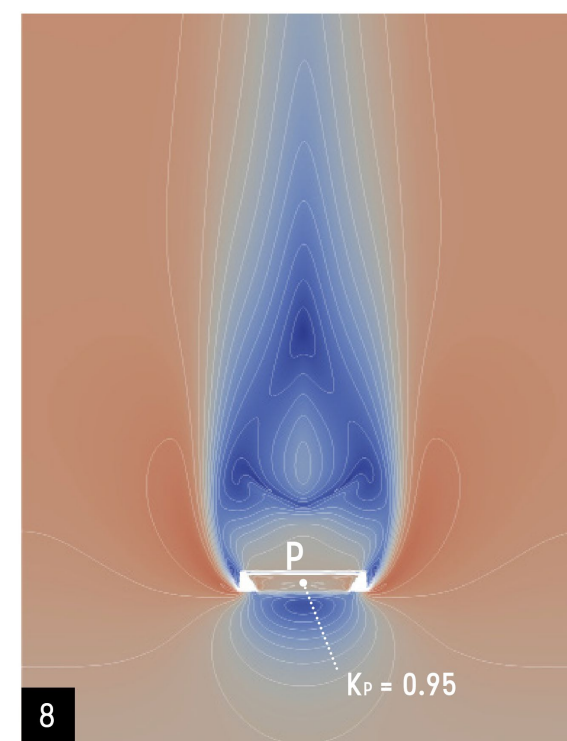
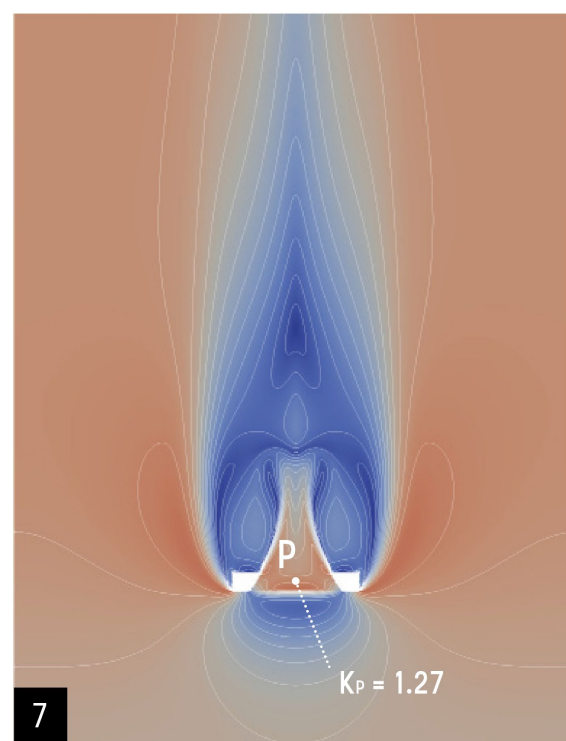
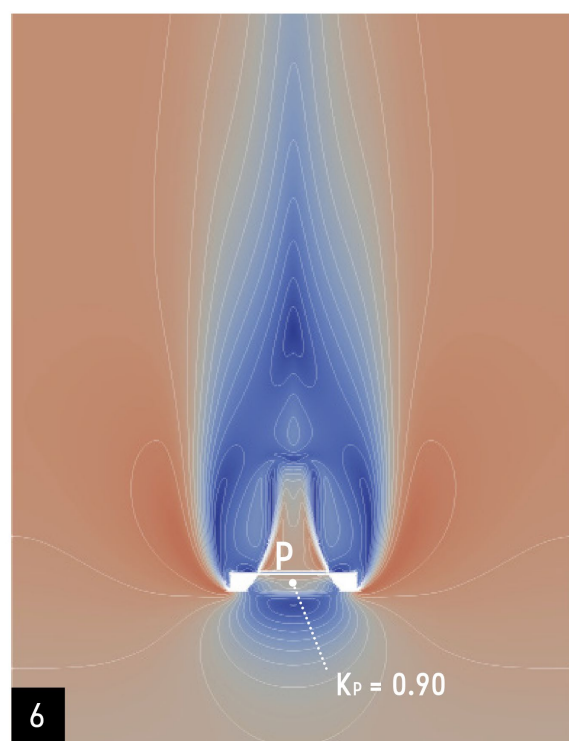
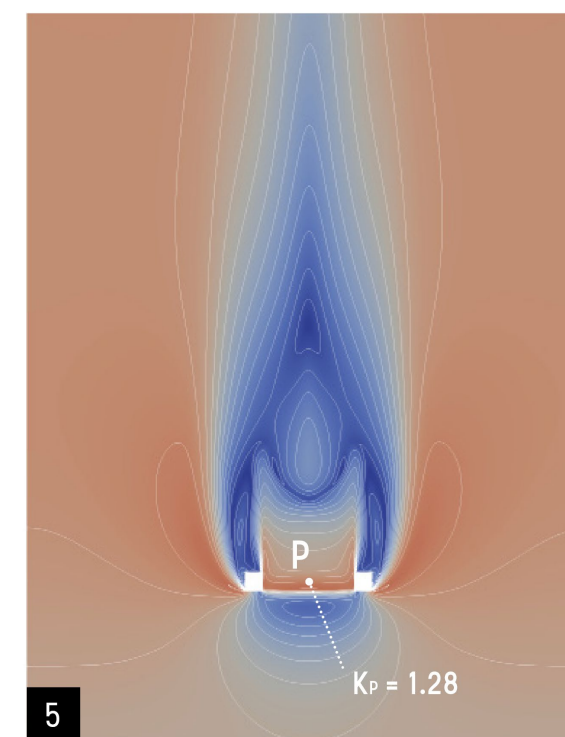
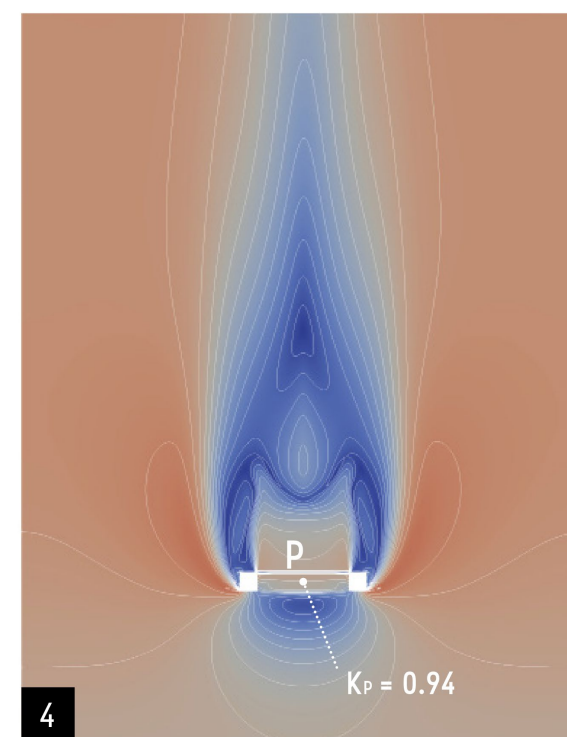
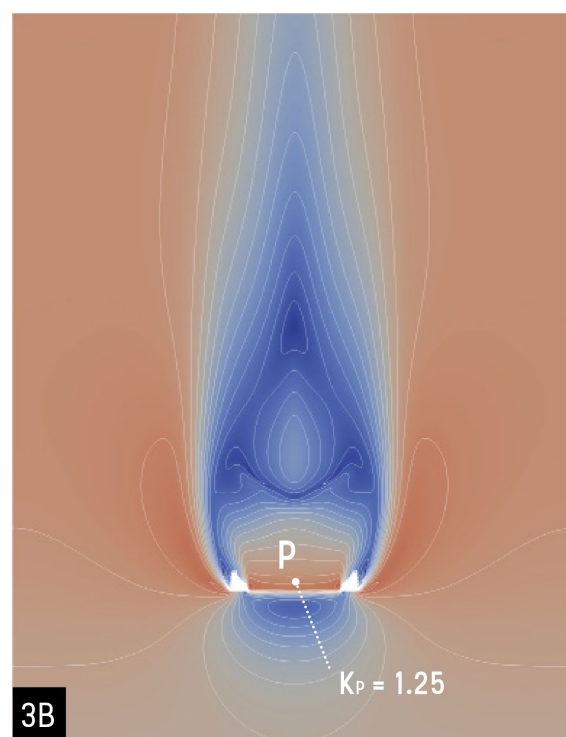
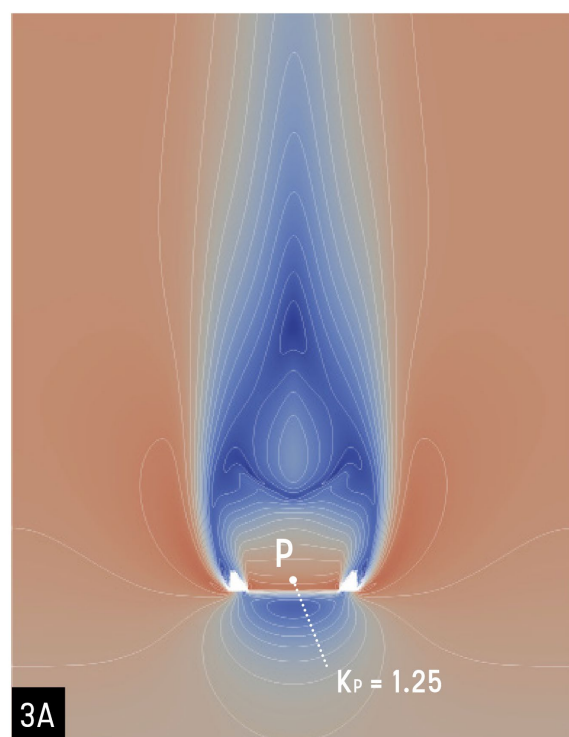
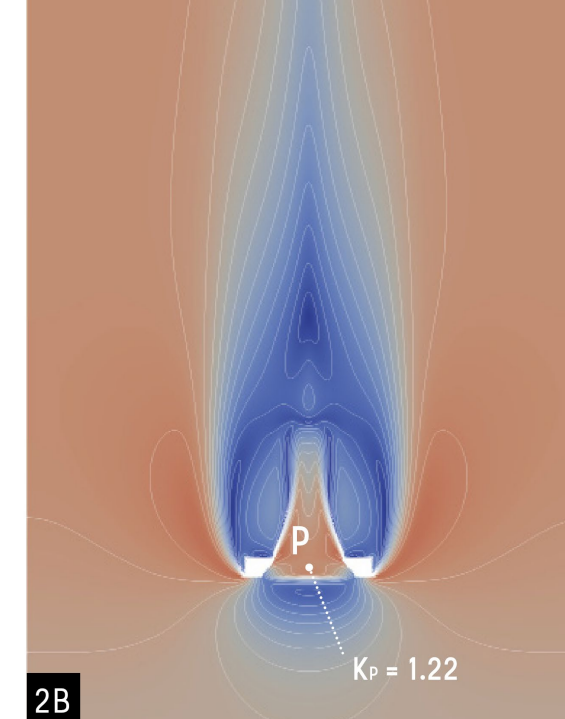
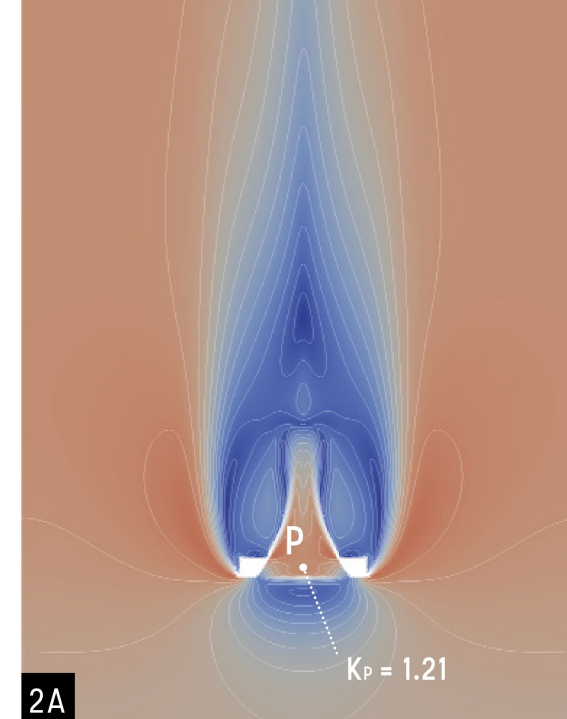
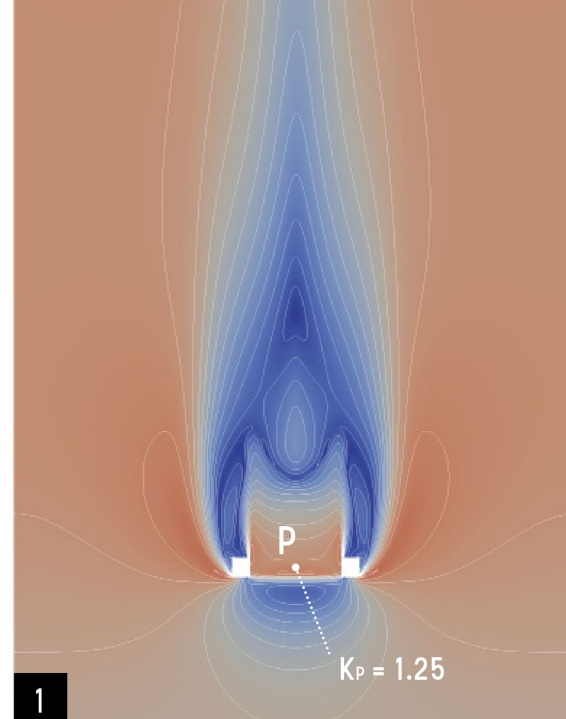
9 horizontally & vertically diverging void

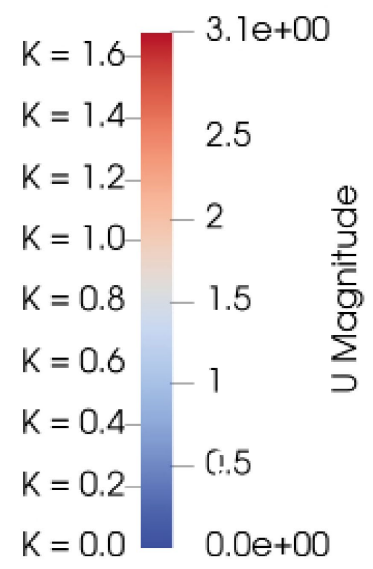
VOID GEOMETRY VARIANTS OVERVIEW

VARIANT	void geometry	description
1	BASE CASE	<ul style="list-style-type: none"> no convergence/divergence in horizontal nor vertical direction % of ground floor length covered by void deck: 75% % of ground floor height covered by void height: 100% (void deck height = 3.6m)
2A	horizontally converging void - straight taper	contraction at void outflow: 75% of void inflow
2B	horizontally converging void - curved taper	contraction at void outflow: 75% of void inflow
3A	horizontally diverging void - straight taper	expansion at void outflow: 125% of void inflow
3B	horizontally diverging void - curved taper	expansion at void outflow: 125% of void inflow
4	vertically converging void	void height decrease at outflow: 1.485m
5	vertically diverging void	void height increase at outflow: 1.485m
6	horizontally & vertically converging void	<ul style="list-style-type: none"> horizontal contraction at void outflow: 75% of void inflow void height decrease at outflow: 1.485m
7	horizontally converging & vertically diverging void	<ul style="list-style-type: none"> horizontal contraction at void outflow: 75% of void inflow void height increase at outflow: 1.485m
8	horizontally diverging & vertically converging void	<ul style="list-style-type: none"> horizontal expansion at void outflow: 125% of void inflow void height decrease at outflow: 1.485m
9	horizontally & vertically diverging void	<ul style="list-style-type: none"> horizontal expansion at void outflow: 125% of void inflow void height increase at outflow: 1.485m

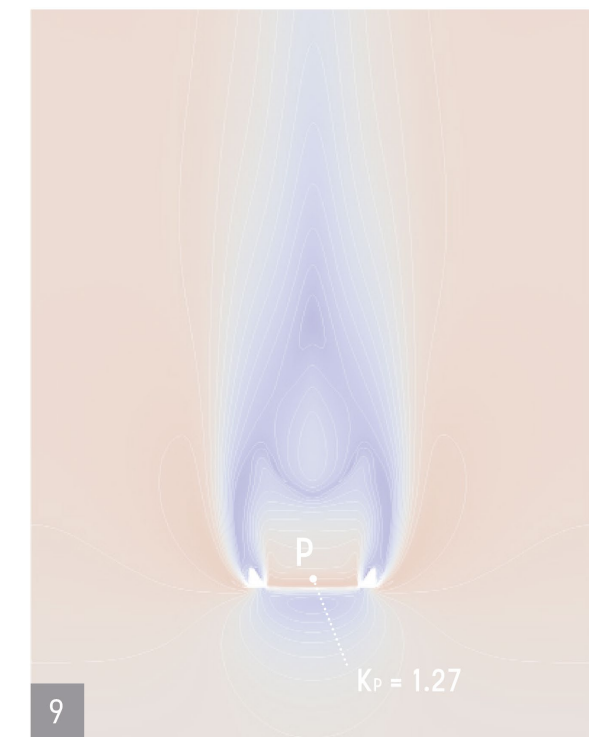
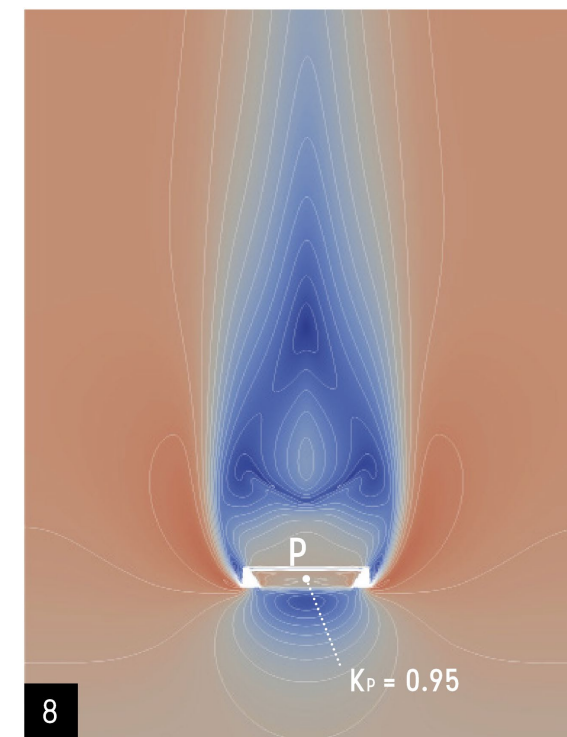
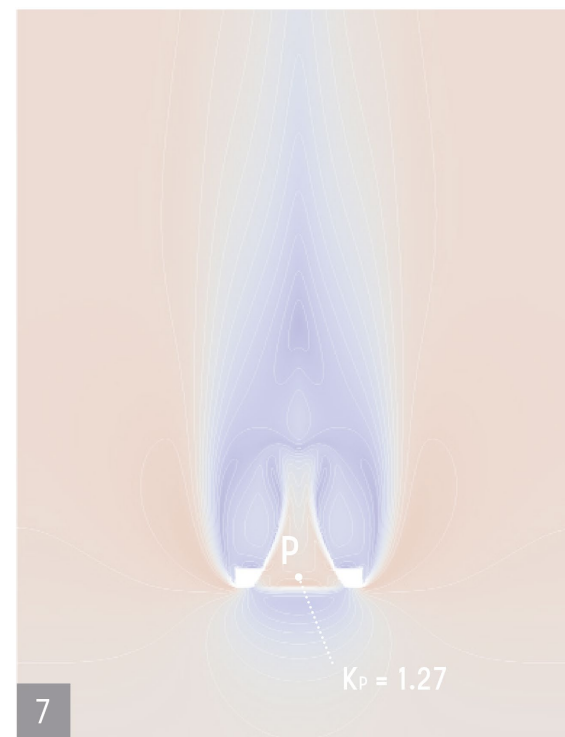
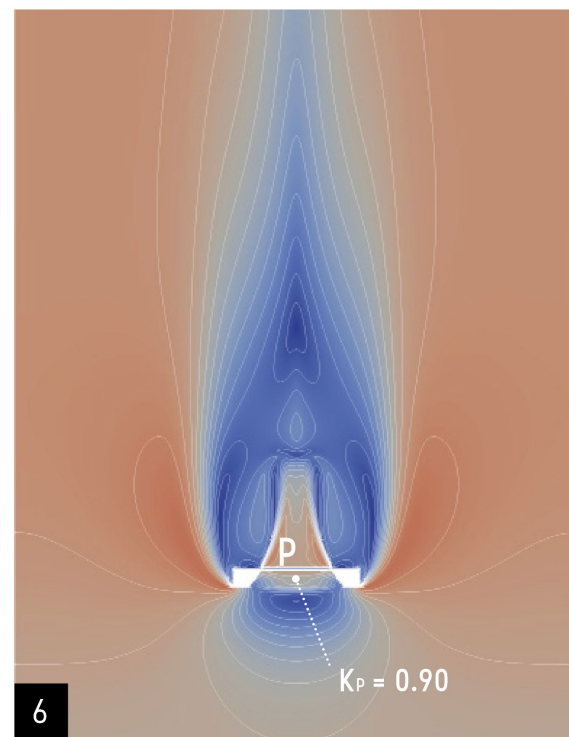
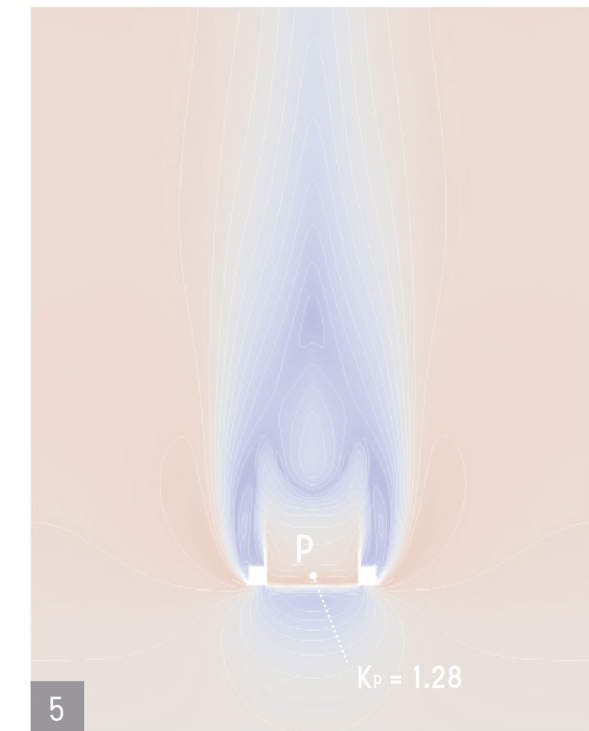
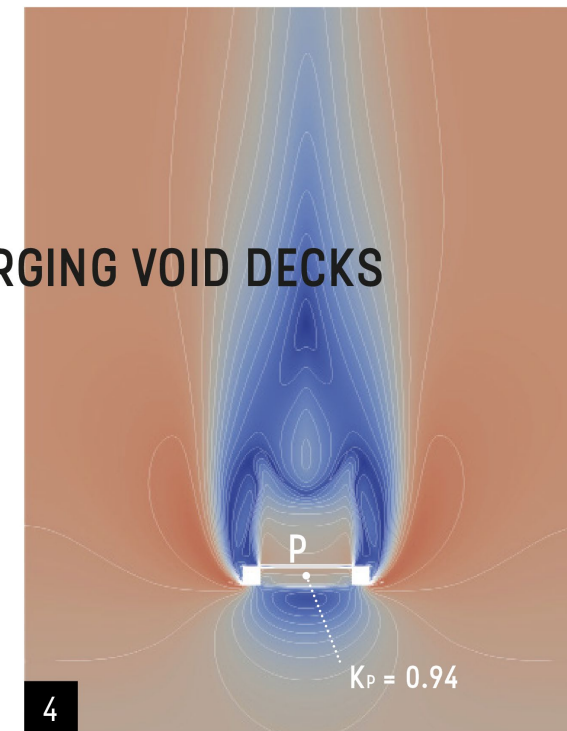
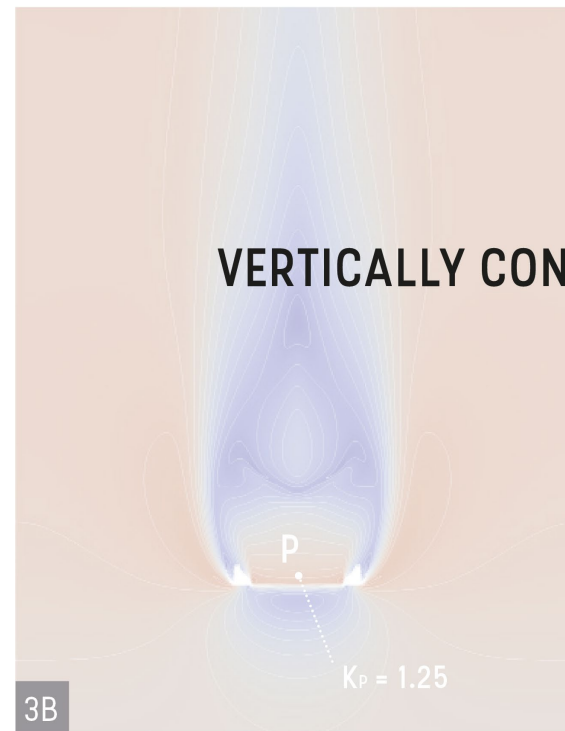
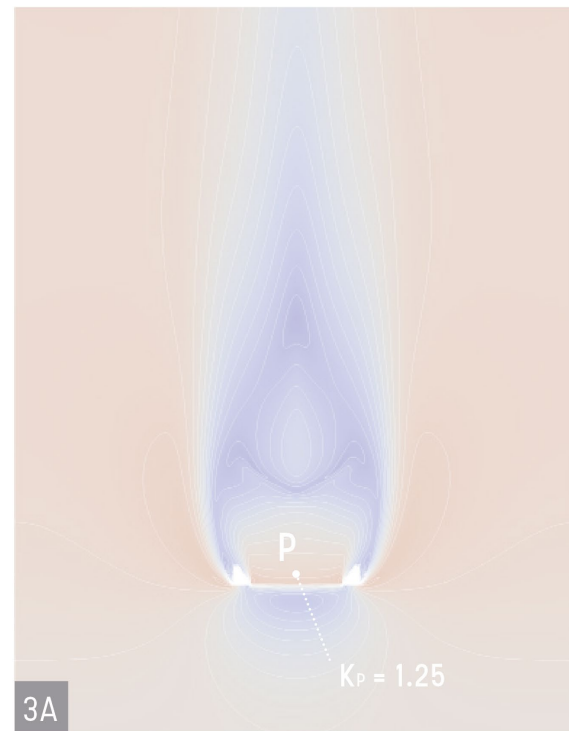
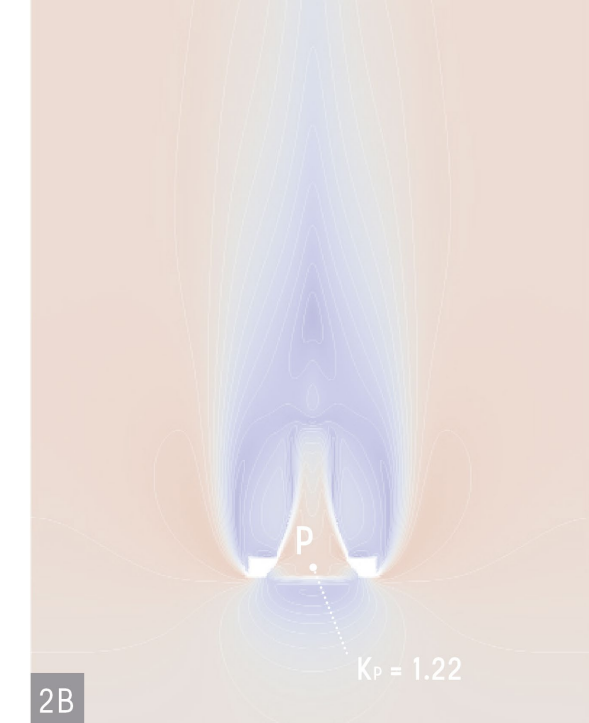
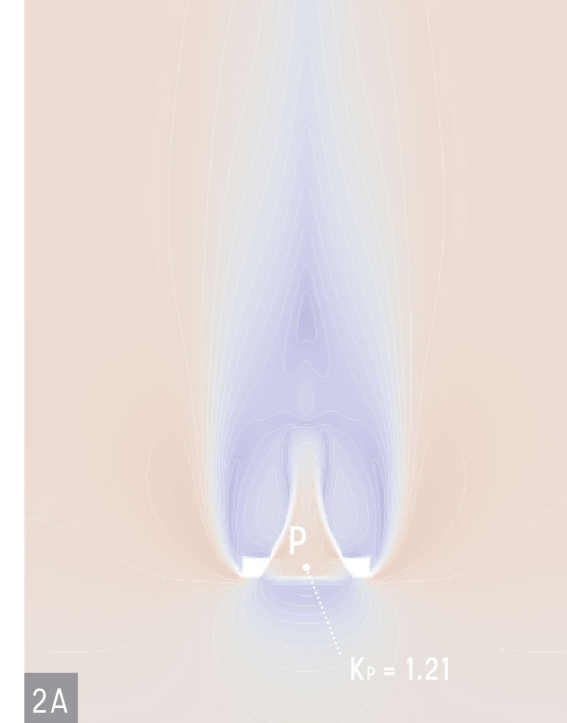
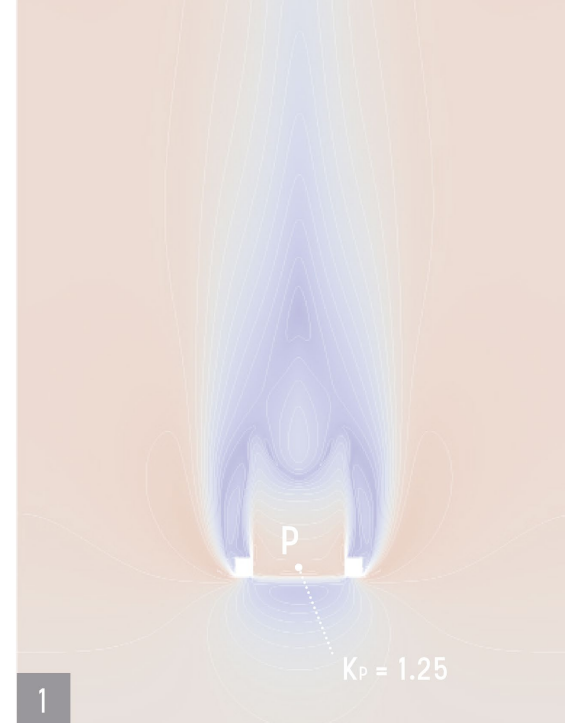


0 AMPLIFICATION FACTOR (plane $h=1.75m$)

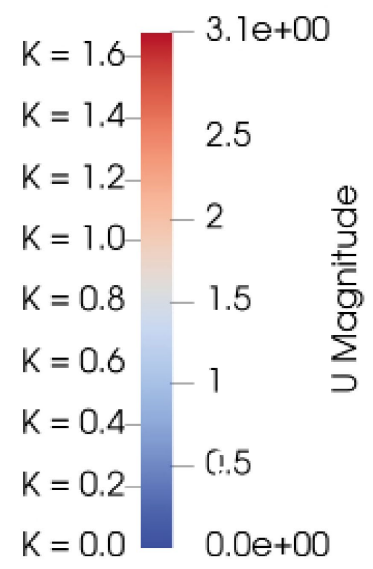




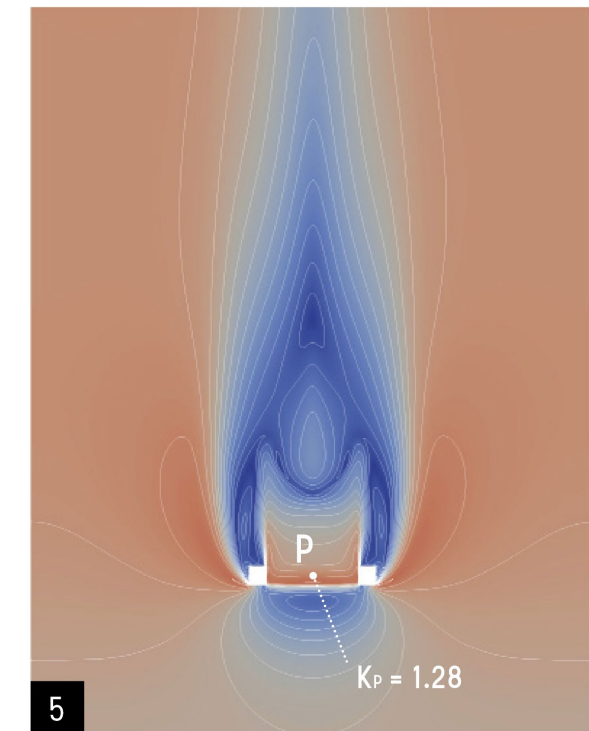
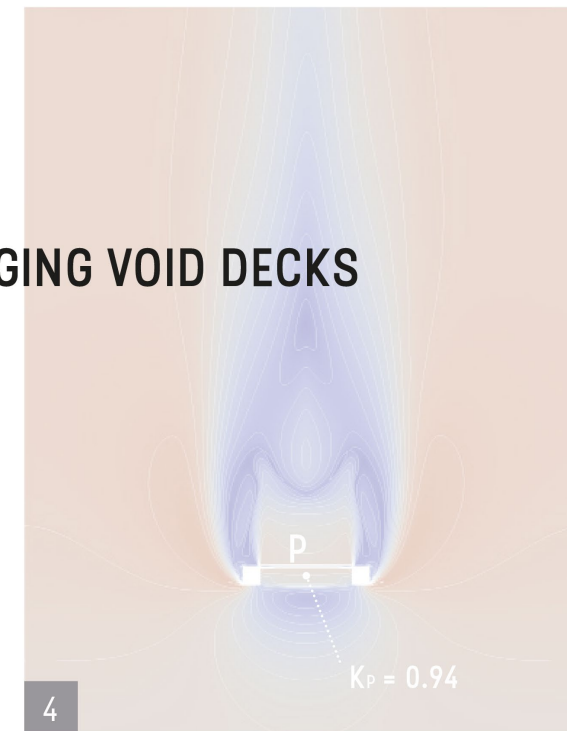
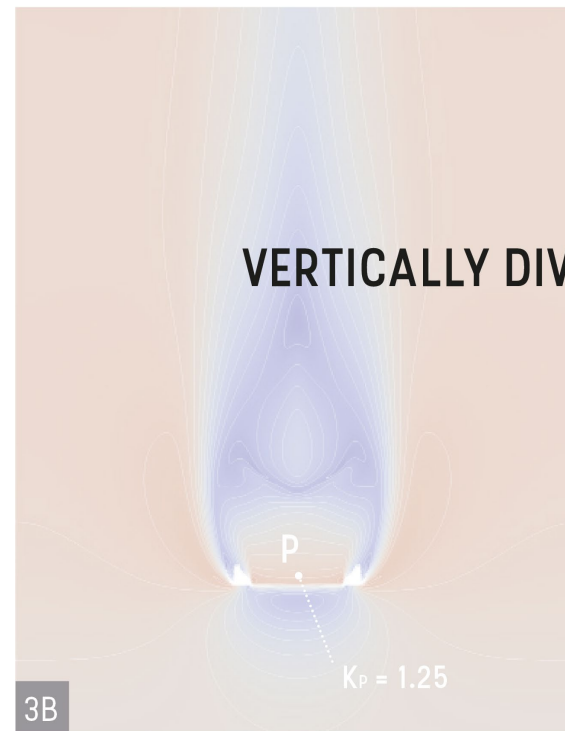
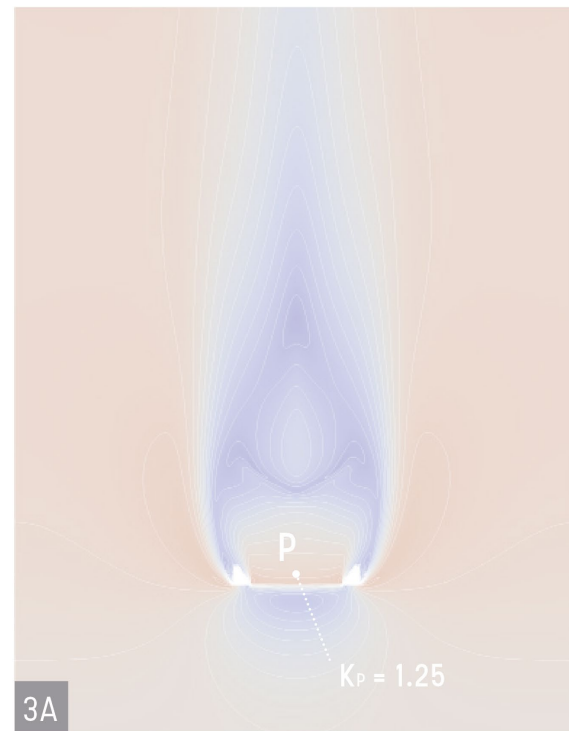
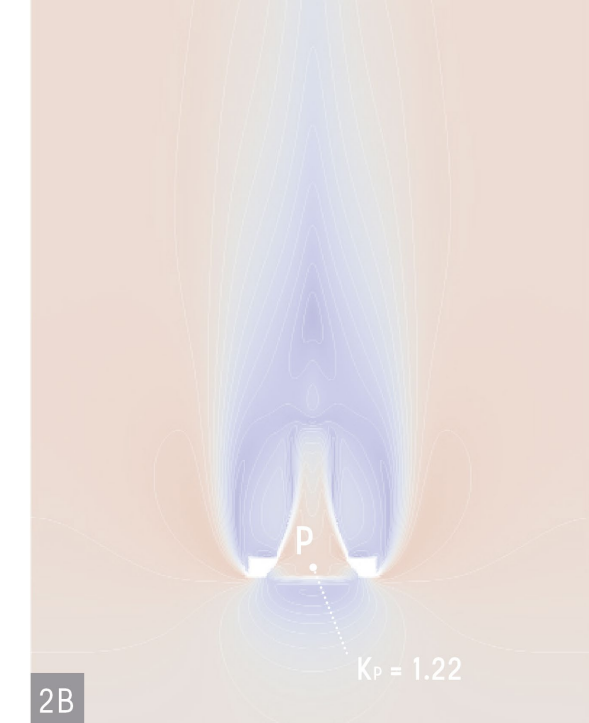
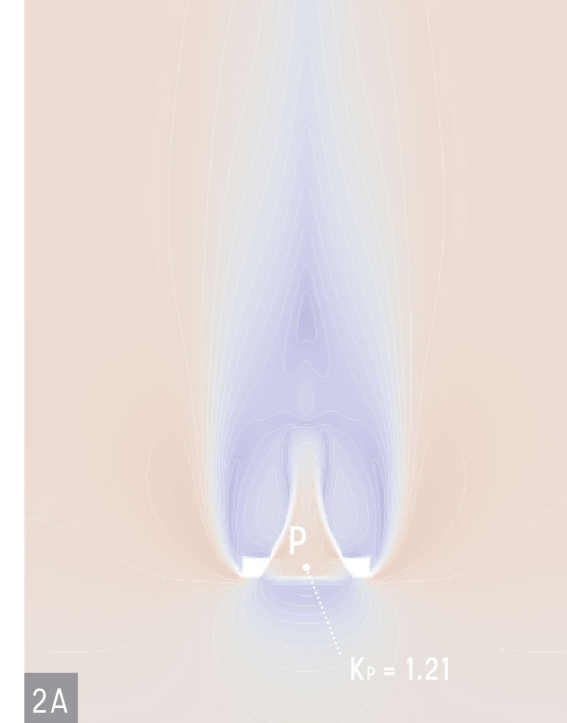
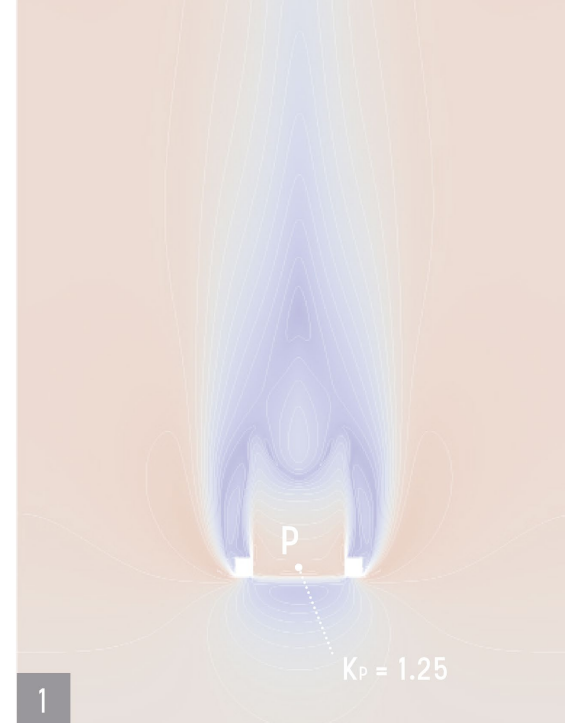
0 AMPLIFICATION FACTOR (plane $h=1.75m$)



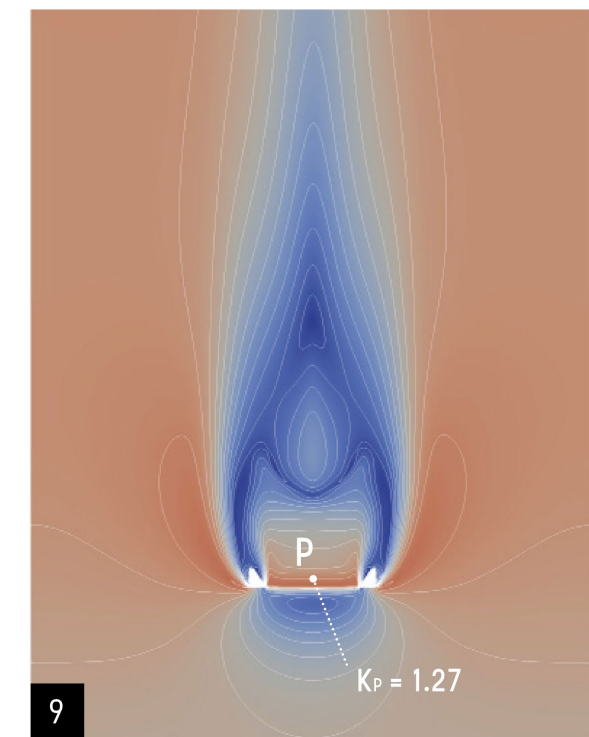
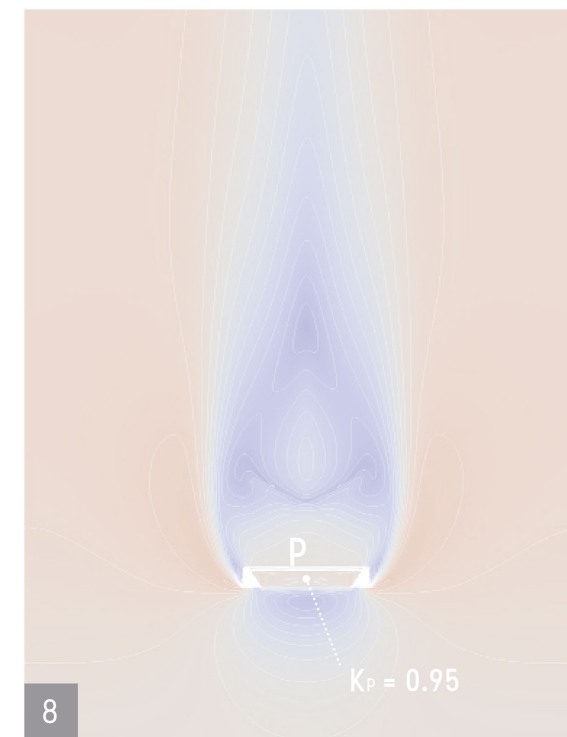
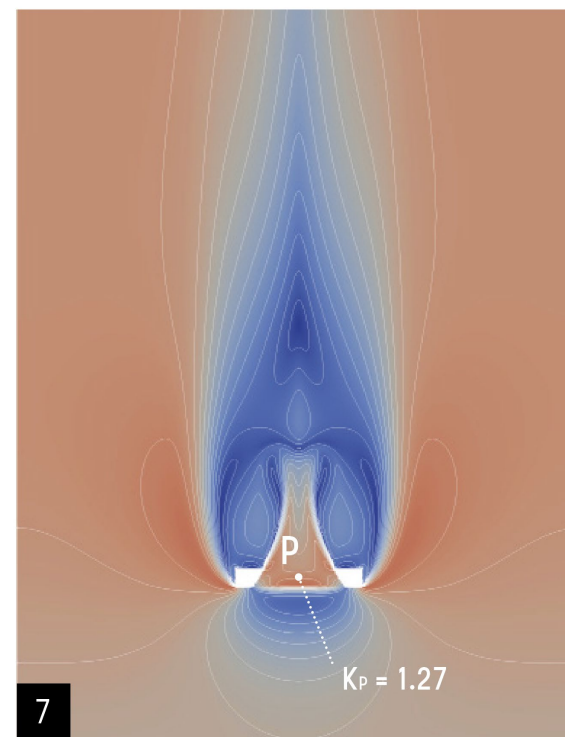
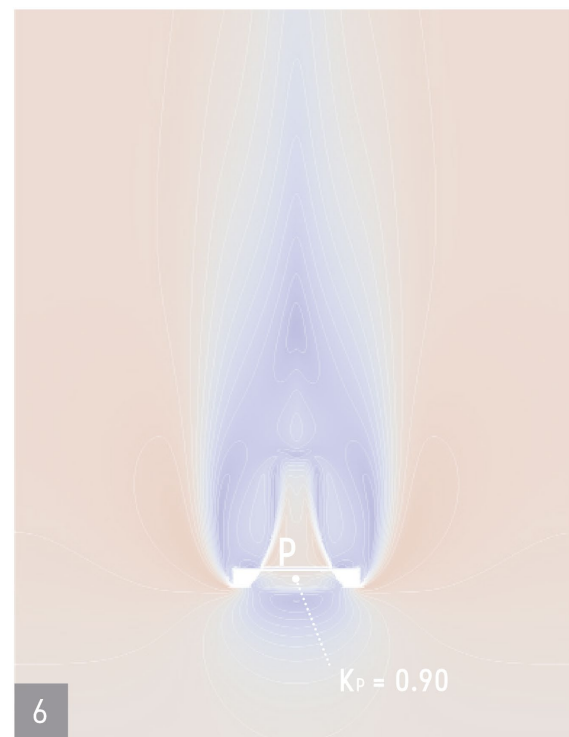
VERTICALLY CONVERGING VOID DECKS

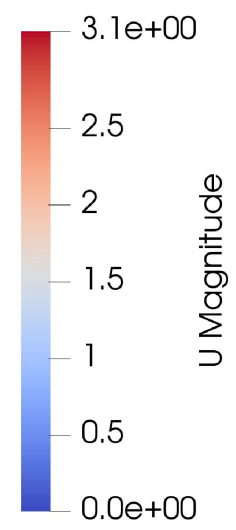


0 AMPLIFICATION FACTOR (plane $h=1.75m$)

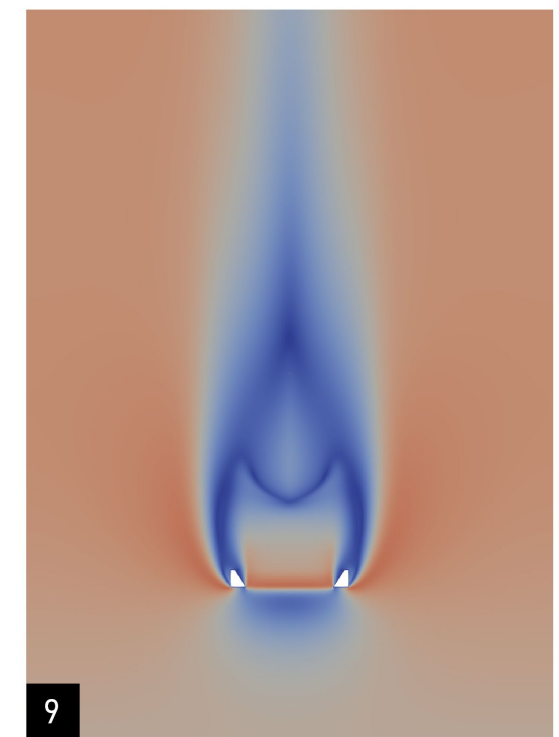
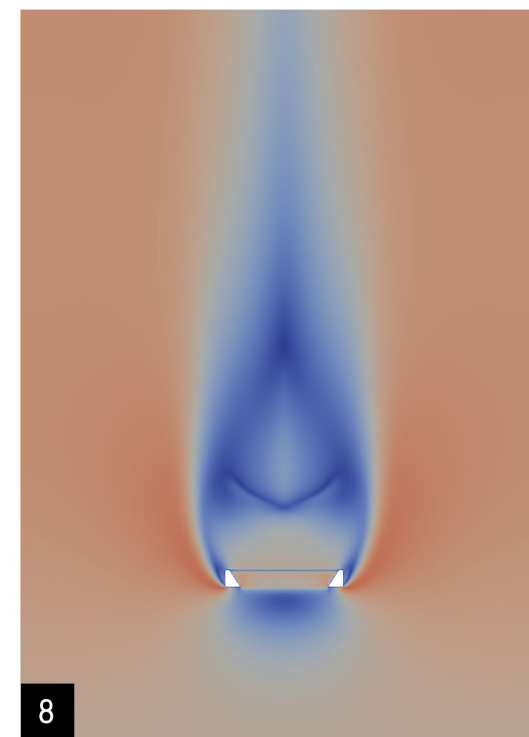
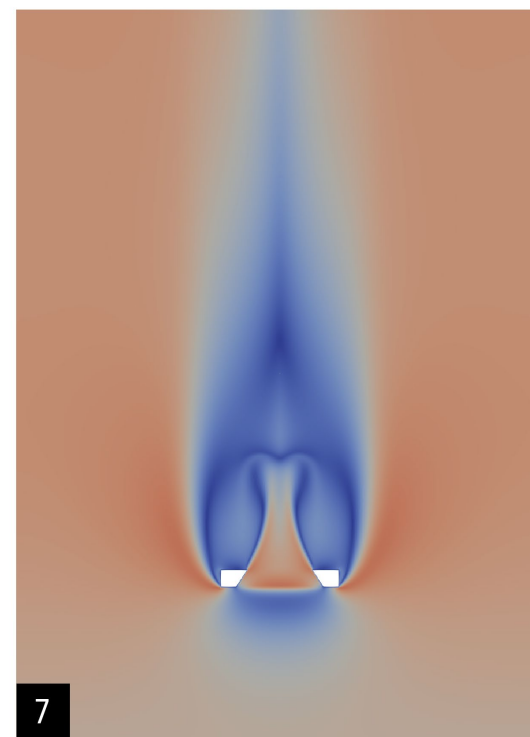
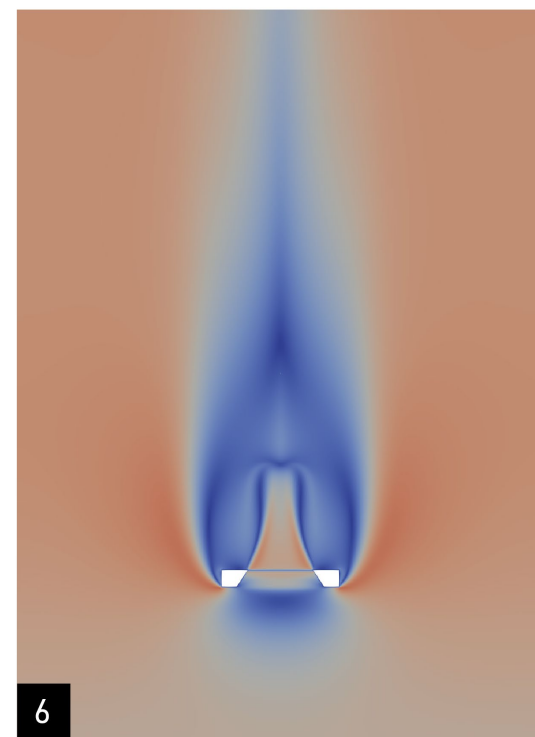
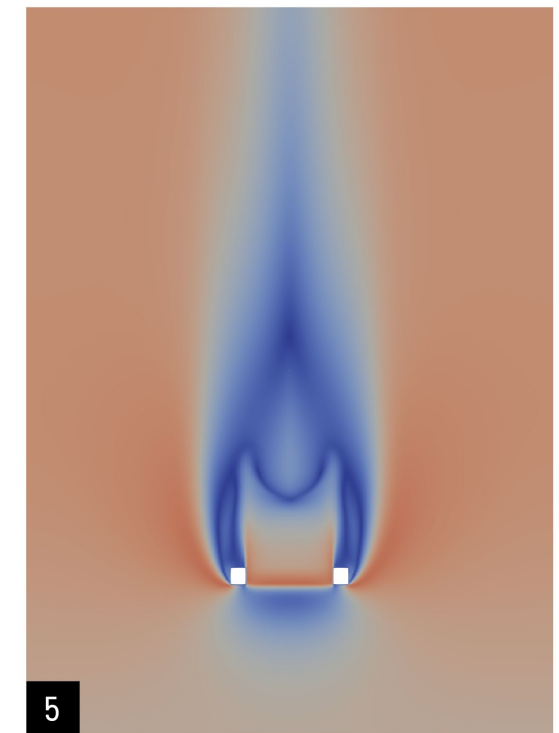
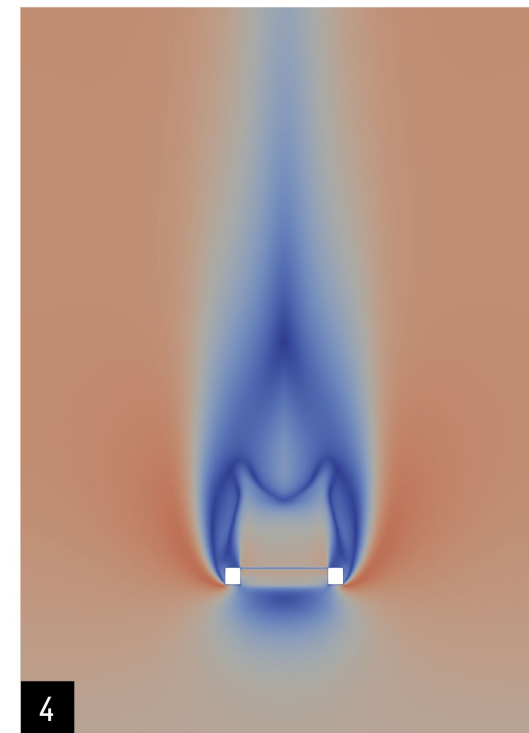
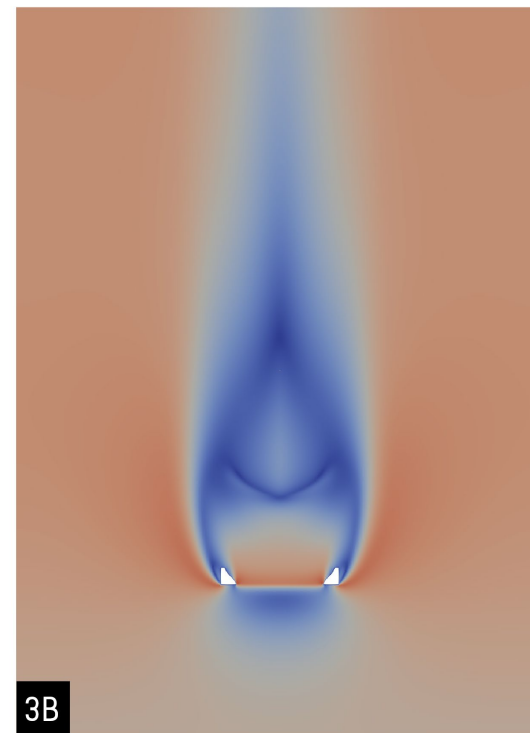
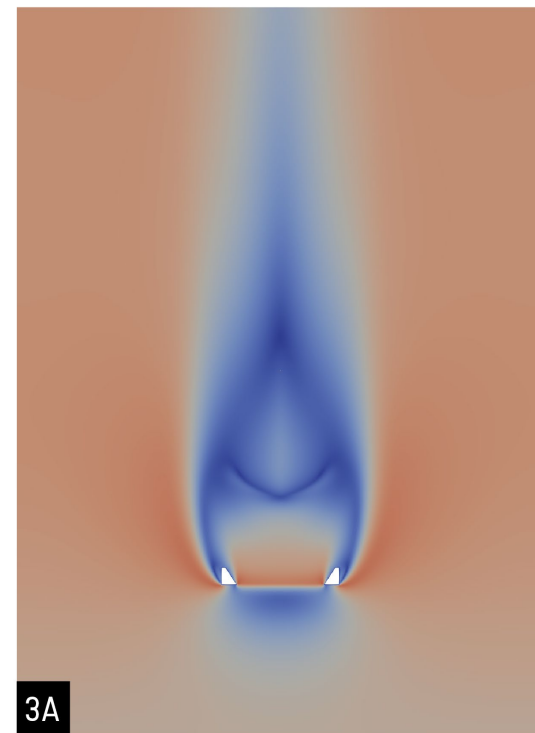
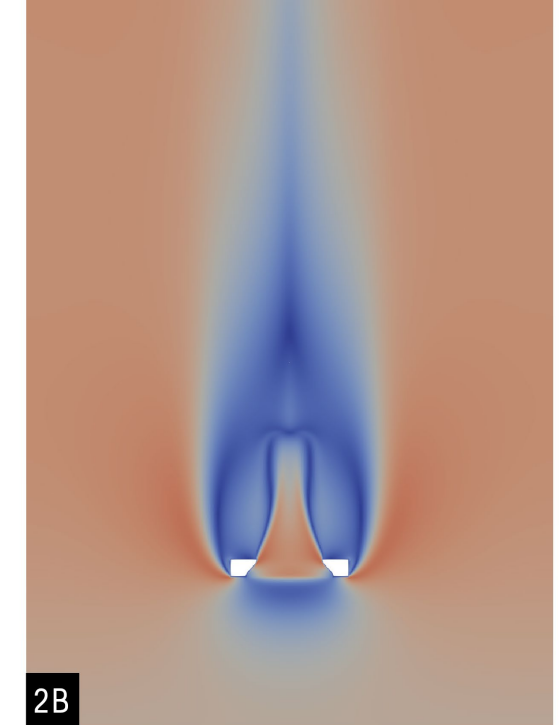
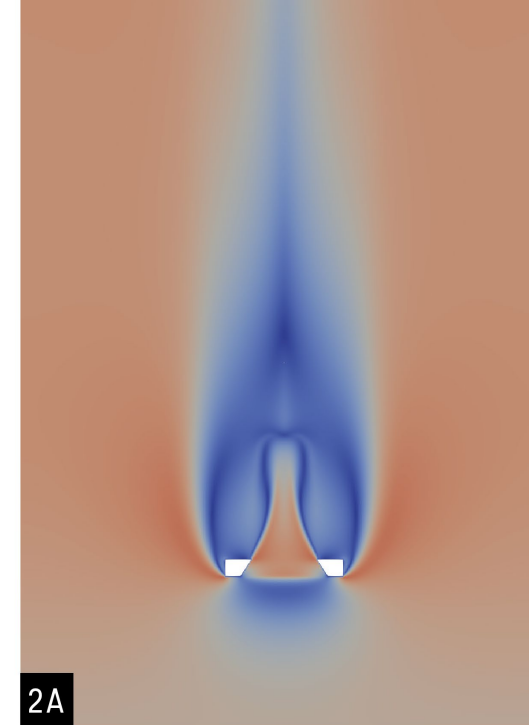
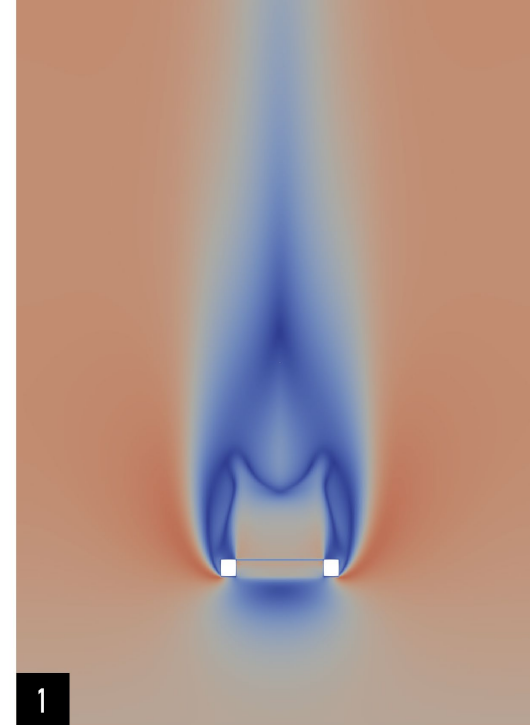


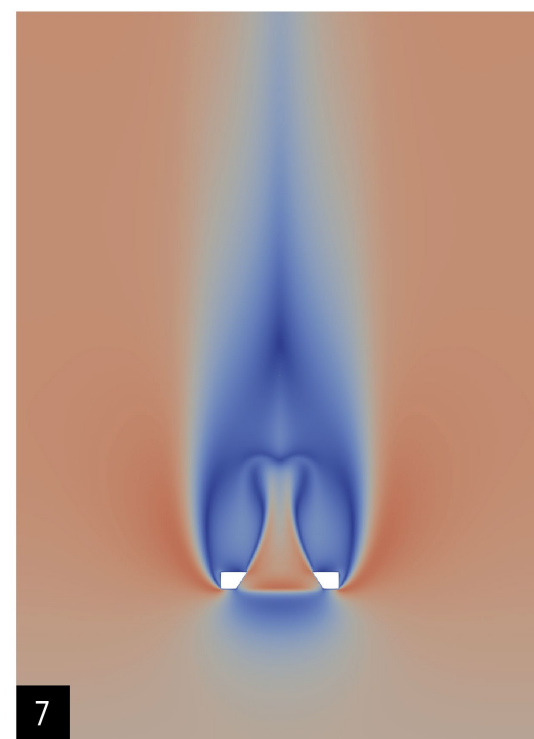
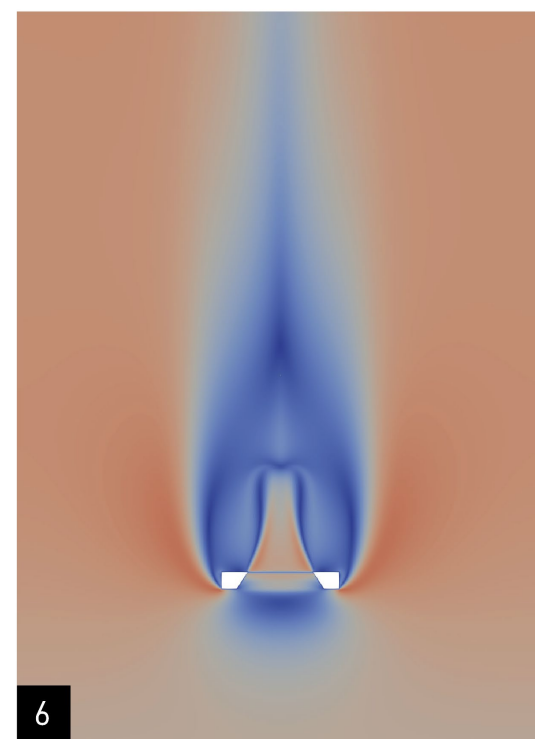
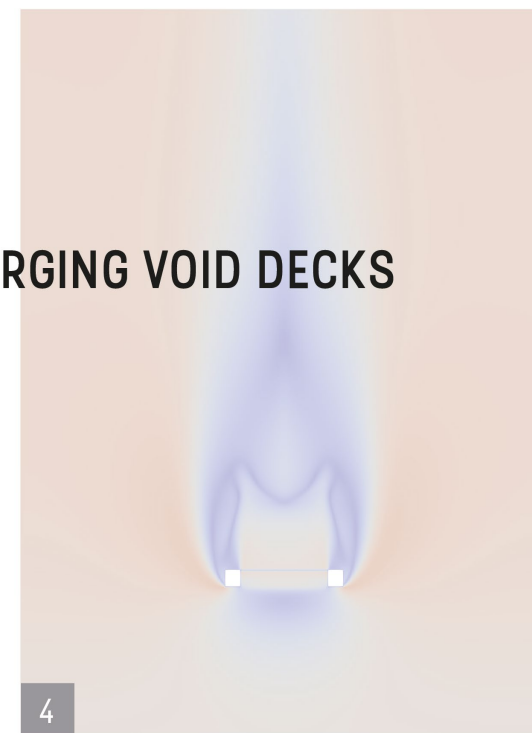
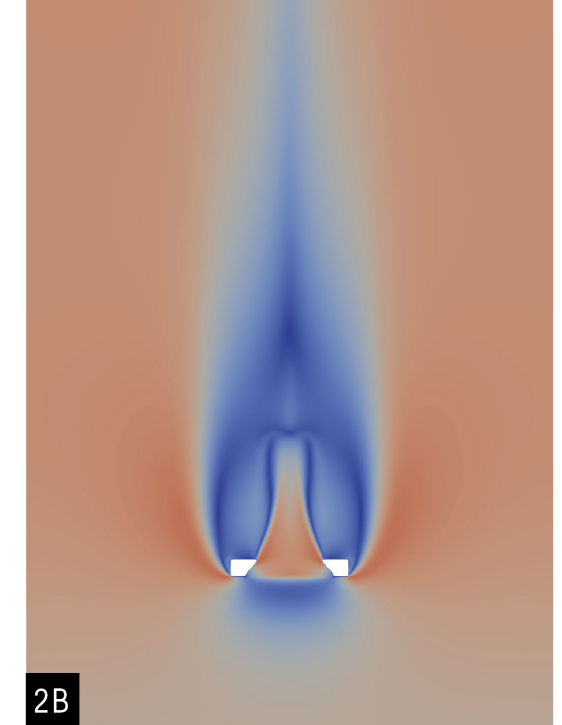
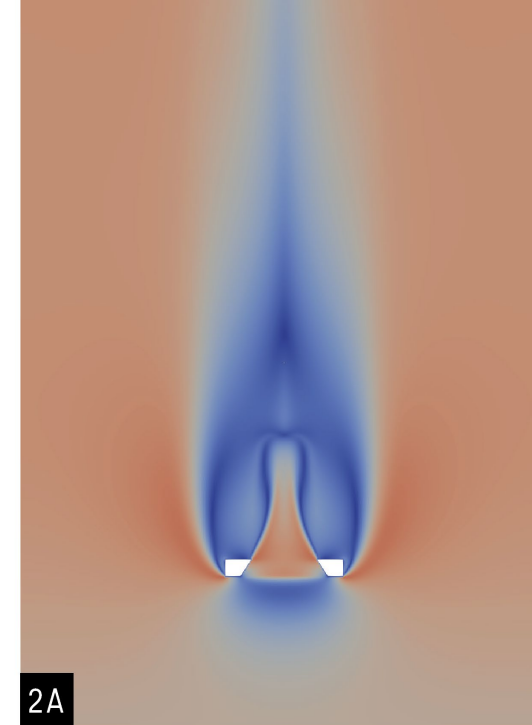
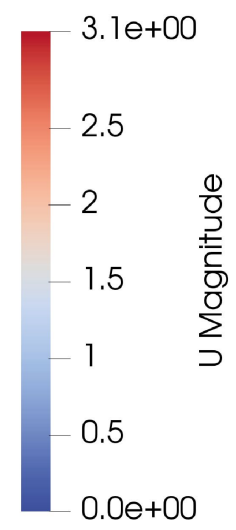
VERTICALLY DIVERGING VOID DECKS



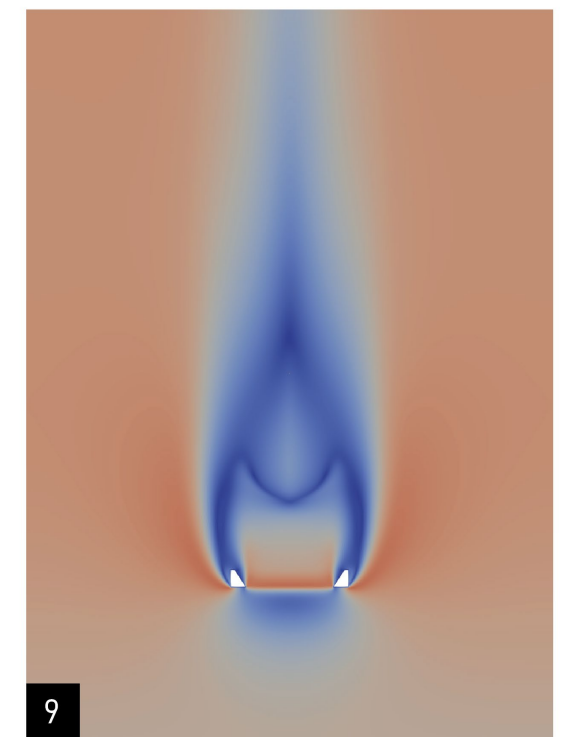
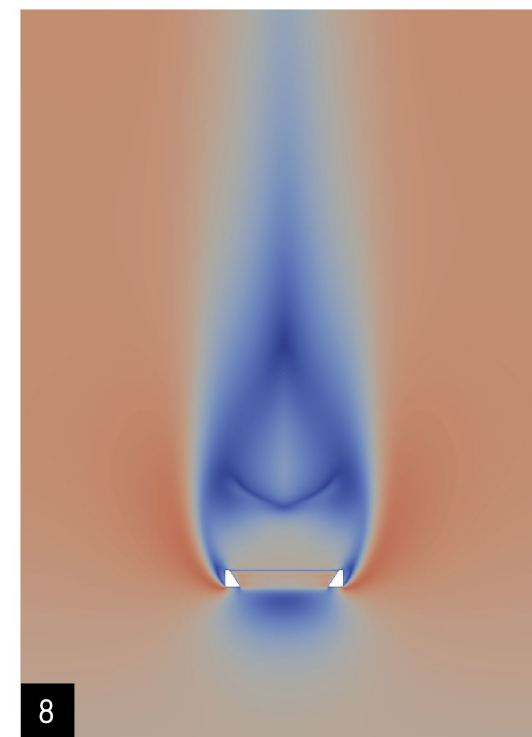
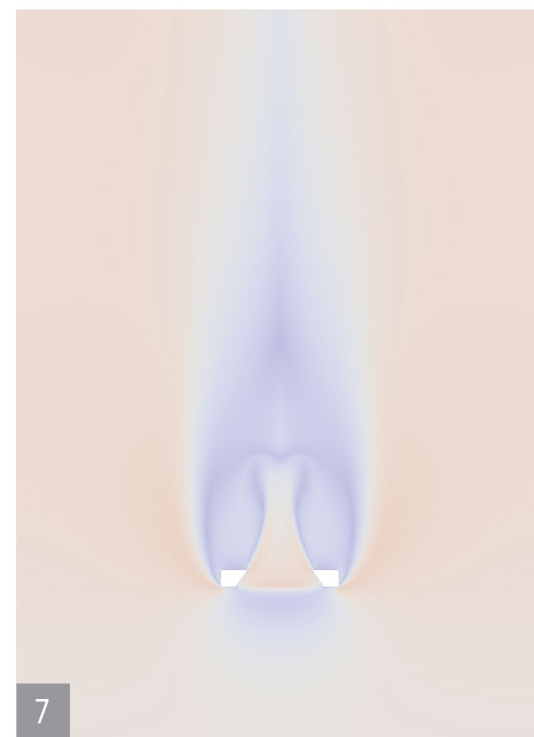
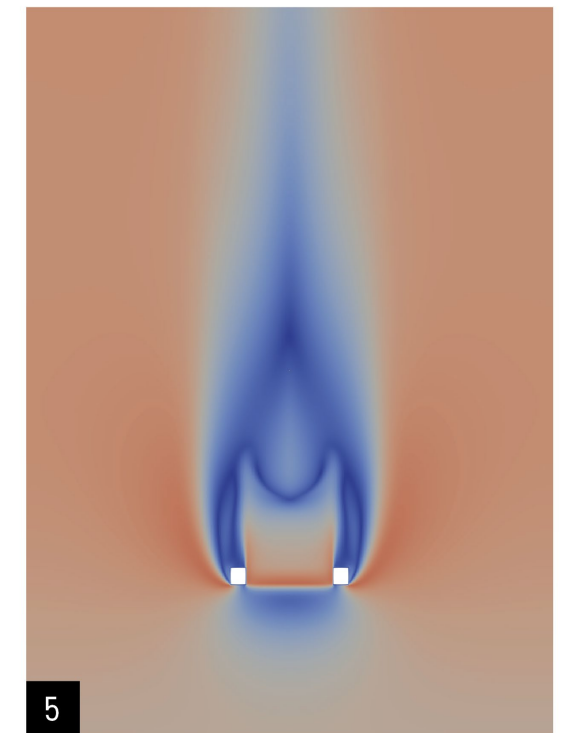
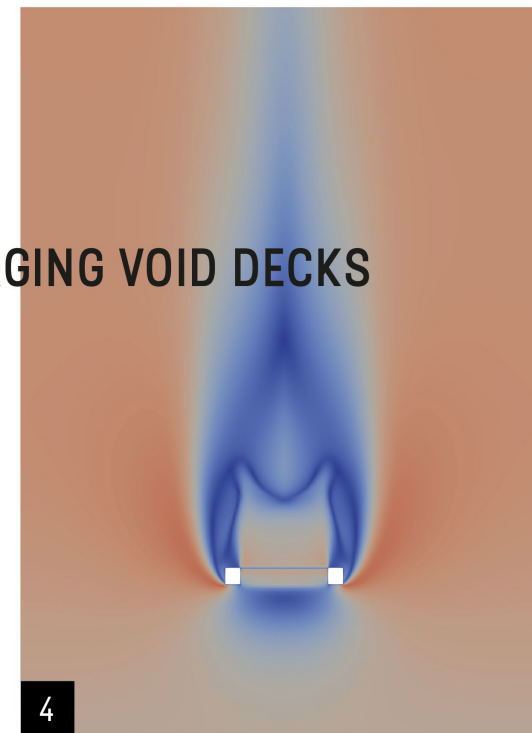
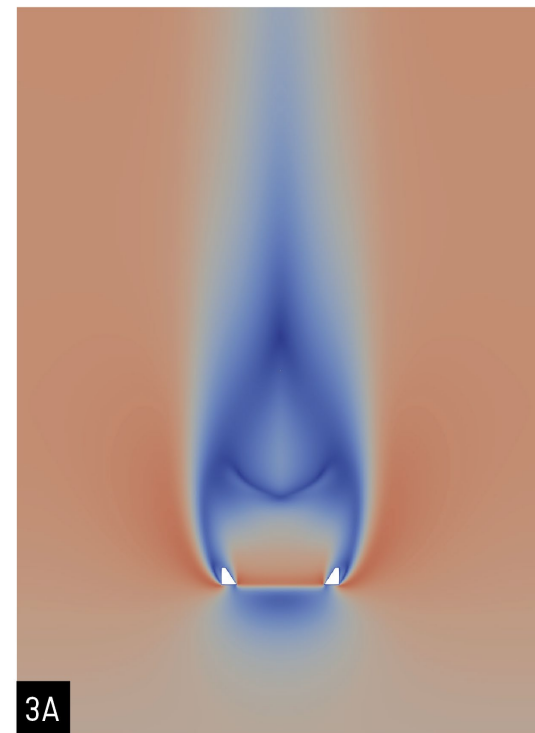
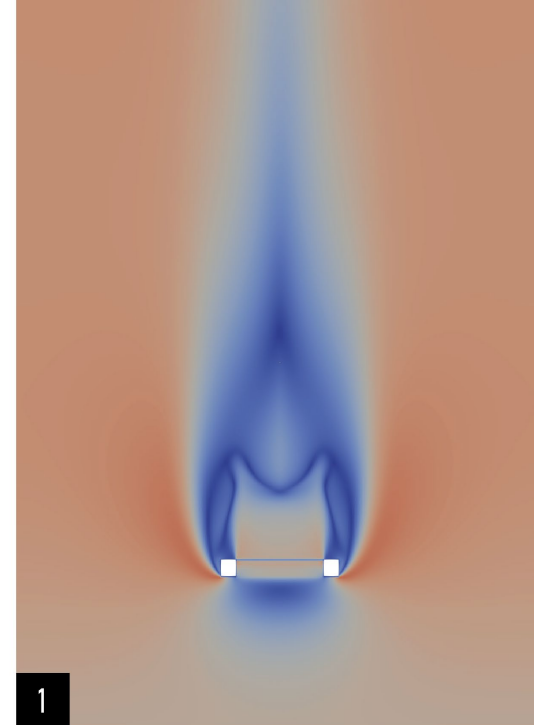
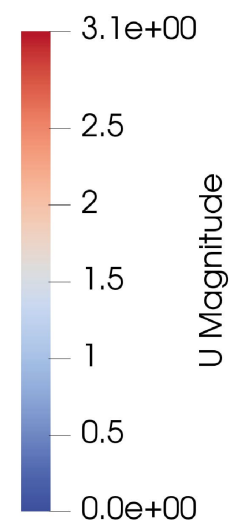


horizontal plane at pedestrian height



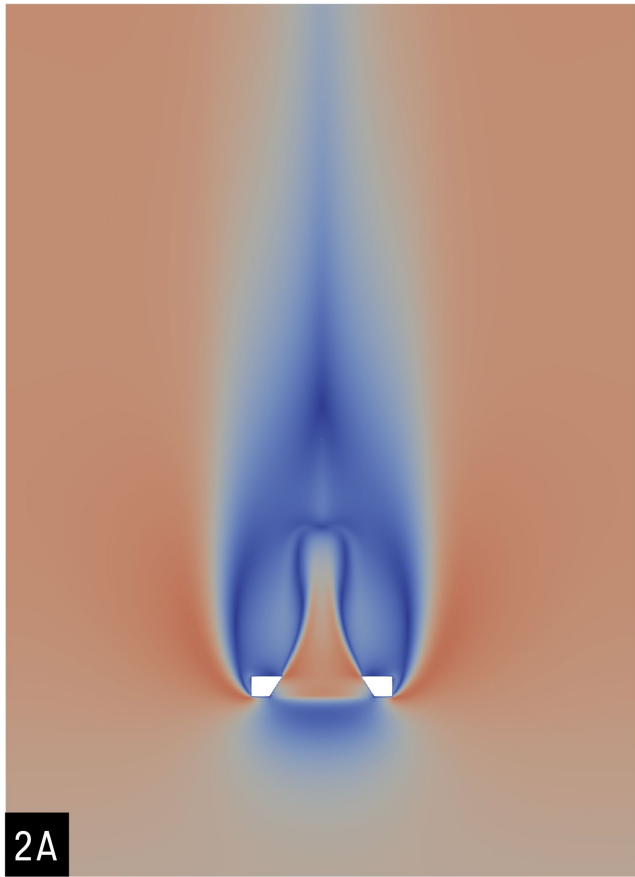


HORIZONTALLY CONVERGING VOID DECKS

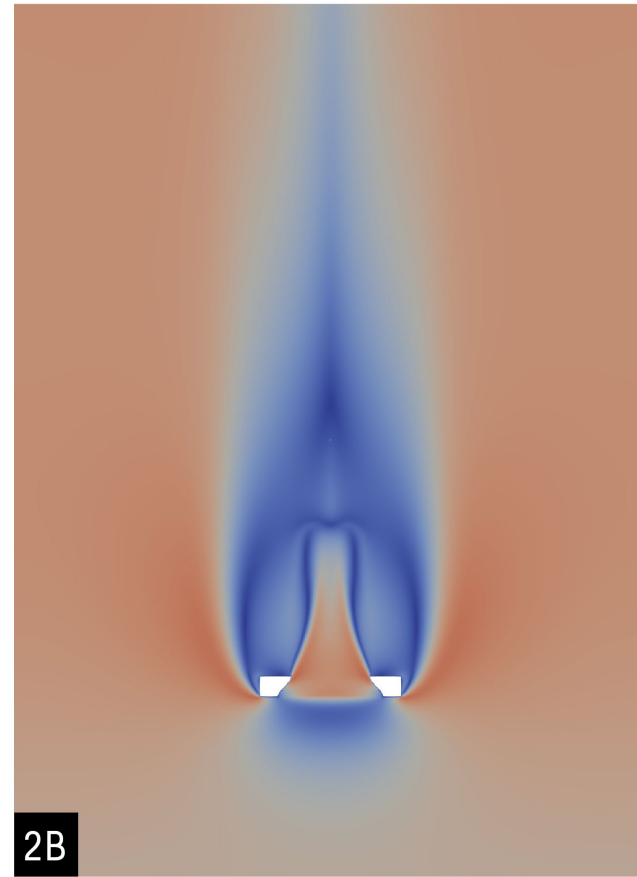


HORIZONTALLY DIVERGING VOID DECKS

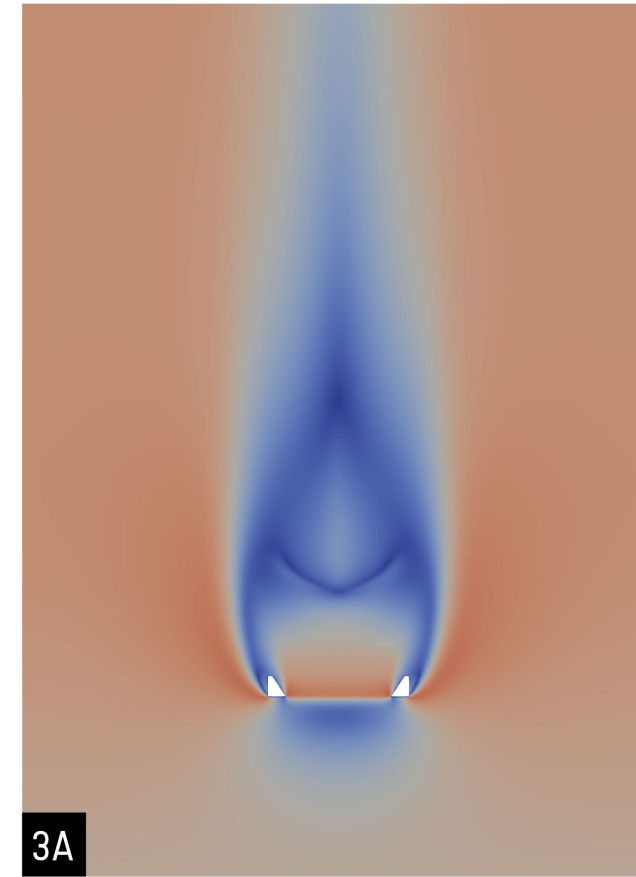
STRAIGHT VS. CURVED WALLS



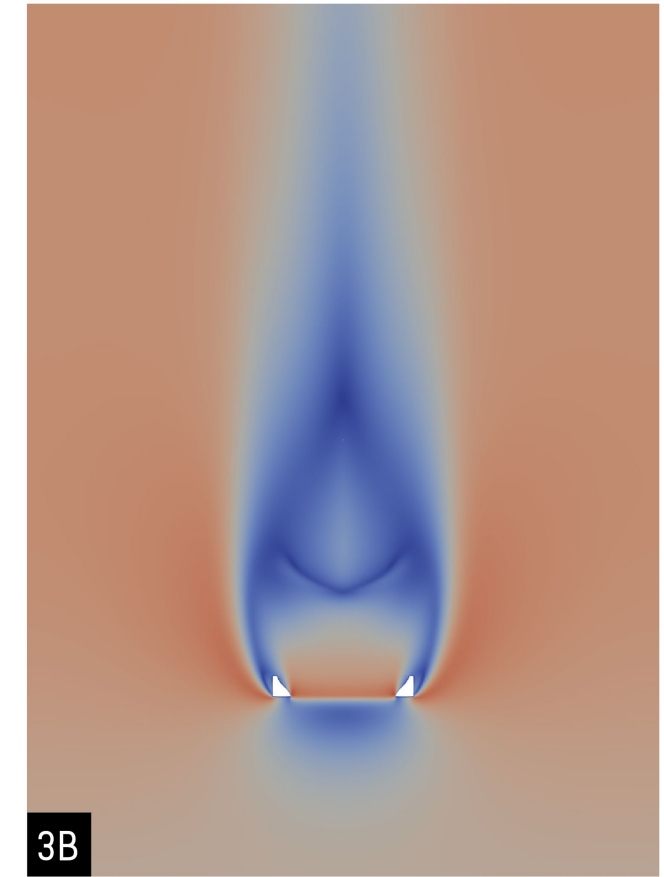
HORIZONTALLY CONVERGING VOID
STRAIGHT TAPER



HORIZONTALLY CONVERGING VOID
CURVED TAPER



HORIZONTALLY DIVERGING VOID
STRAIGHT TAPER



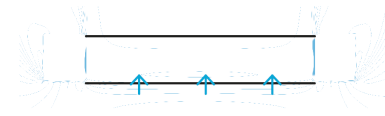
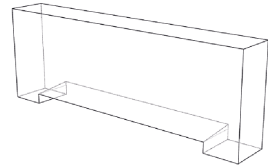
HORIZONTALLY DIVERGING VOID
CURVED TAPER

IMPLICATIONS

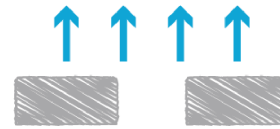
DESCRIPTION OF FLOW PATTERN

VARIANT	INSIDE VOID DECK	DOWNSTREAM OF VOID DECK	AMPLIFICATION FACTOR AT CENTRE OF VOID DECK	SUGGESTIONS WITH REGARD TO URBAN PLANNING
1	 <p>no significant velocity gradients inside void deck (steep gradient right before entry of void deck)</p>	 <p>even spread of accelerated flow along length</p>	 <p>$K > 1 \Rightarrow$ urban ventilation \uparrow due to presence of building with void deck</p>	 <p>adjacent walking route along building</p>
2A	 <p>steepest velocity gradient at middle of void deck (entry); more gradual change along edges of void deck walls</p>	 <p>funnel-shaped area of accelerated flow</p>	 <p>$K > 1 \Rightarrow$ urban ventilation \uparrow due to presence of building with void deck</p>	 <p>direct accelerated flow towards target</p>
2B	 <p>steepest velocity gradient at middle of void deck (entry); more gradual change along edges of void deck walls</p>	 <p>funnel-shaped area of accelerated flow</p>	 <p>$K > 1 \Rightarrow$ urban ventilation \uparrow due to presence of building with void deck</p>	 <p>direct accelerated flow towards target</p>
3A	 <p>largest velocity gradients at edges of void deck walls (also steep gradient right before entry of void deck)</p>	 <p>even spread of accelerated flow along length</p>	 <p>$K > 1 \Rightarrow$ urban ventilation \uparrow due to presence of building with void deck</p>	 <p>adjacent walking route along building</p>
3B	 <p>largest velocity gradients at edges of void deck walls (also steep gradient right before entry of void deck)</p>	 <p>even spread of accelerated flow along length</p>	 <p>$K > 1 \Rightarrow$ urban ventilation \uparrow due to presence of building with void deck</p>	 <p>adjacent walking route along building</p>
4	 <p>steepest velocity gradient upon flow exit from void deck</p>	 <p>even spread of accelerated flow along length</p>	 <p>$K < 1 \Rightarrow$ urban ventilation \downarrow due to presence of building with void deck</p>	 <p>not suitable for microclimate enhancement inside void deck</p>

5



steepest velocity gradient upon flow entry in void deck



even spread of accelerated flow along length

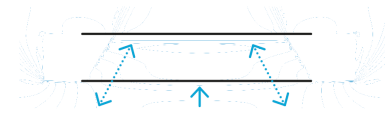
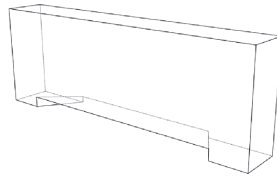


$K > 1 \Rightarrow$ urban ventilation \uparrow due to presence of building with void deck

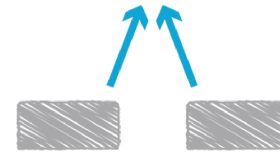


adjacent walking route along building

6



steepest velocity gradients at entry and along edges of void deck walls



funnel-shaped area of accelerated flow

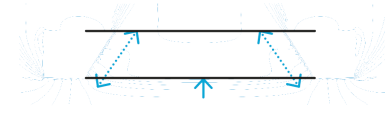
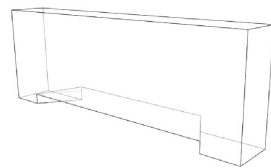


$K < 1 \Rightarrow$ urban ventilation \downarrow due to presence of building with void deck

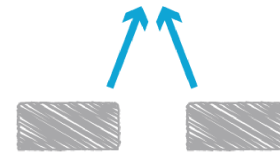


not suitable for microclimate enhancement inside void deck

7



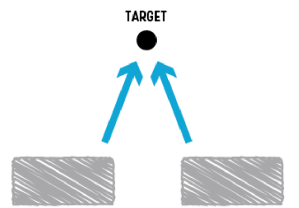
steepest velocity gradient right before entry; inside void deck steepest along edges of void deck walls



funnel-shaped area of accelerated flow

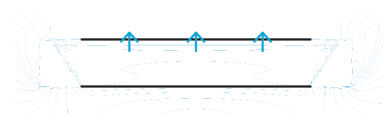
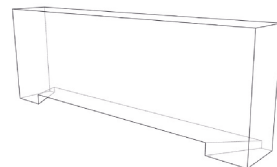


$K > 1 \Rightarrow$ urban ventilation \uparrow due to presence of building with void deck



direct accelerated flow towards target

8



steepest velocity gradient upon flow exit from void deck; smaller gradient inside void deck



even spread of accelerated flow along length

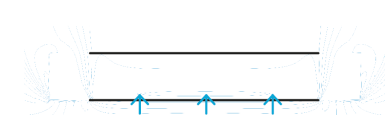
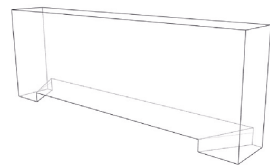


$K < 1 \Rightarrow$ urban ventilation \downarrow due to presence of building with void deck



not suitable for microclimate enhancement inside void deck

9



steepest velocity gradient upon flow entry in void deck



even spread of accelerated flow along length

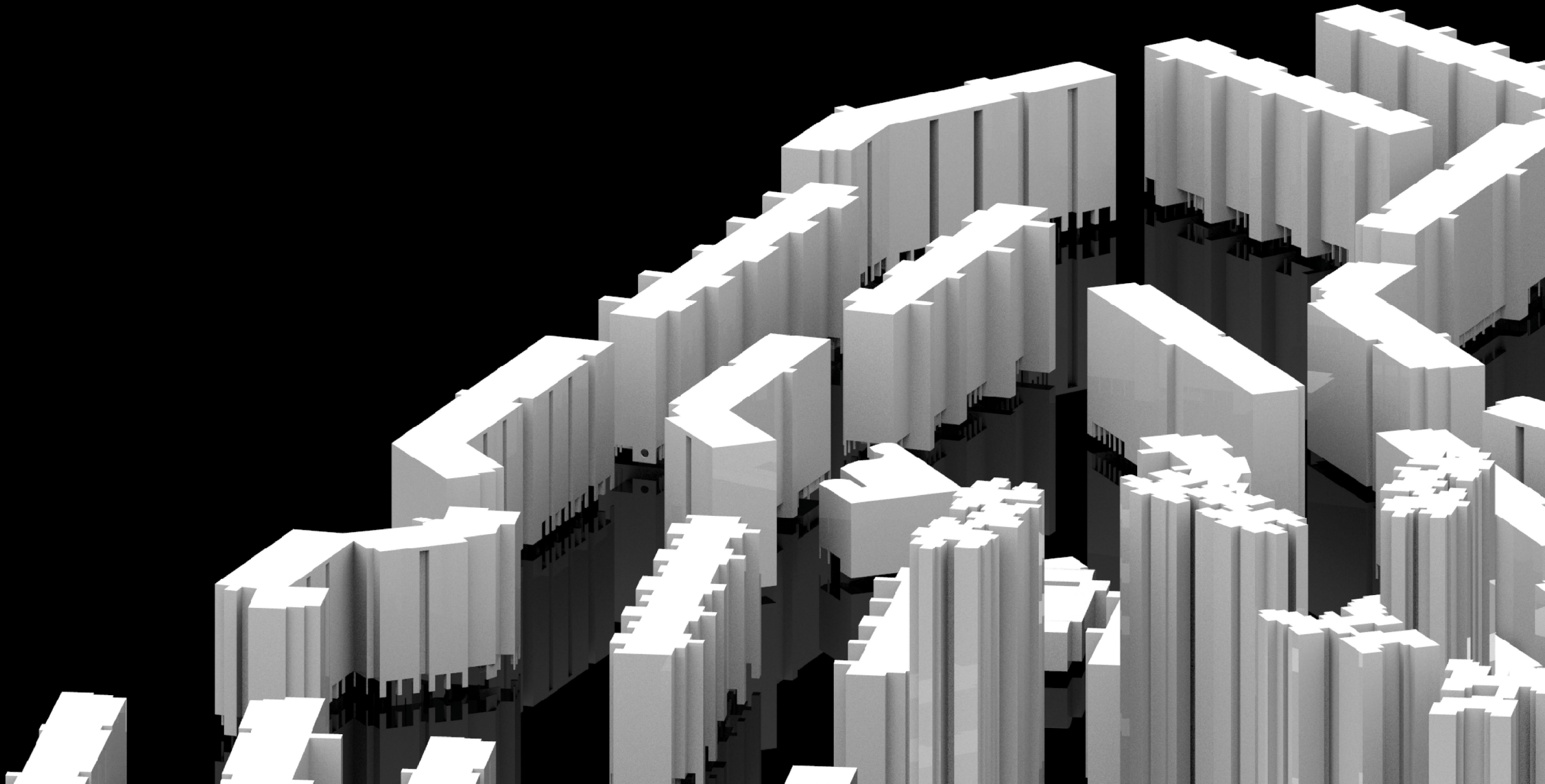


$K > 1 \Rightarrow$ urban ventilation \uparrow due to presence of building with void deck



adjacent walking route along building

FROM BUILDING TO URBAN SCALE



CURRENT ACTIVITY PATTERN



1

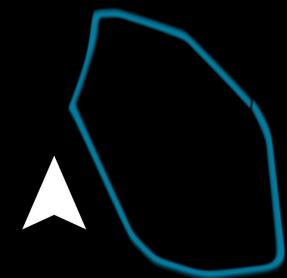


2



3

cutting plane: h = 1.75m



Firefly park

Ulu Pandan Park Connector

shopping / market area

primary school area

- running & cycling trail
- sports field / outdoor gym
- playground
- frequent outdoor seating area (restaurant / café)
- occasional outdoor seating area (void deck)
- B bus stop
- MRT MRT station

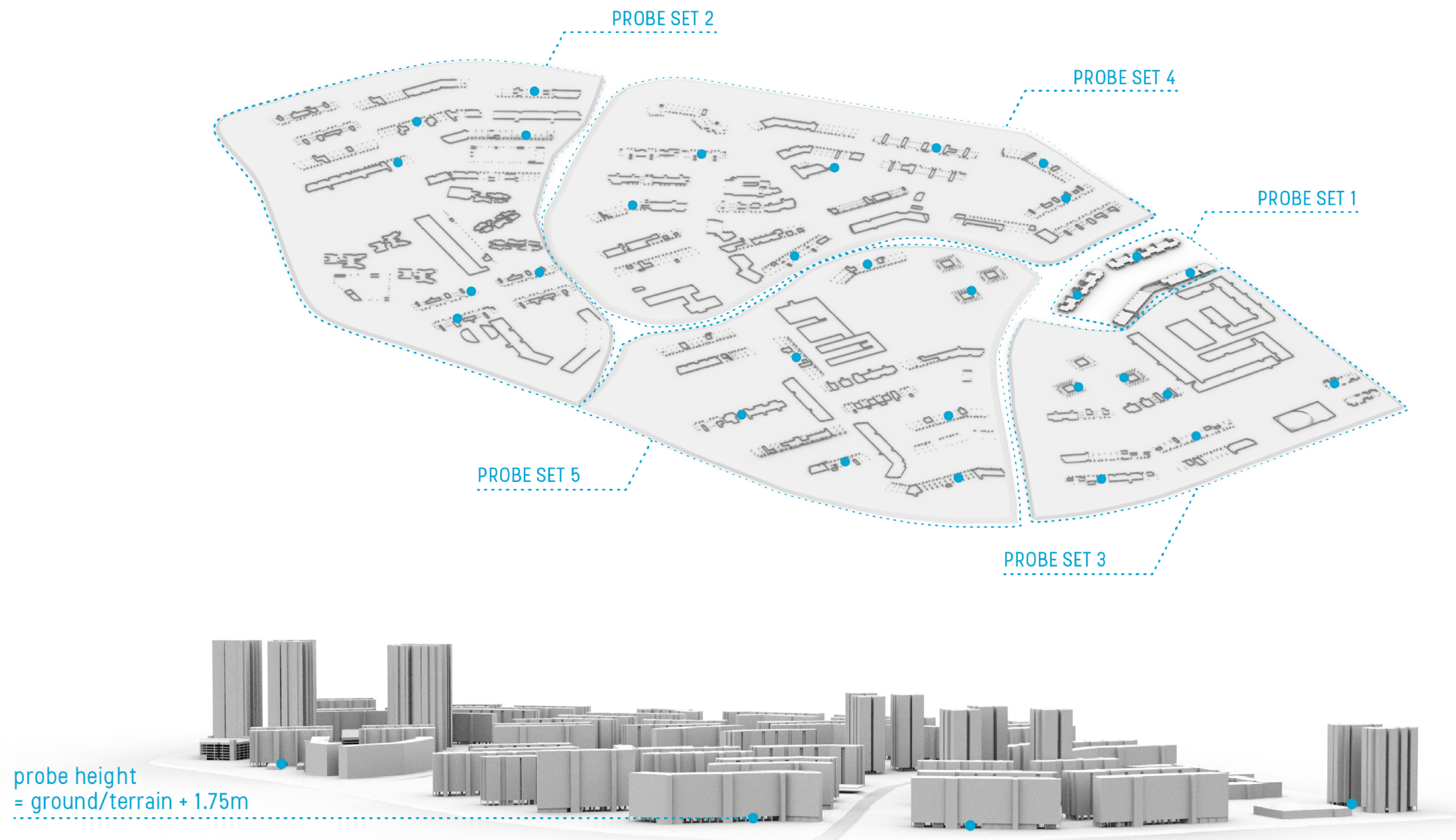


4

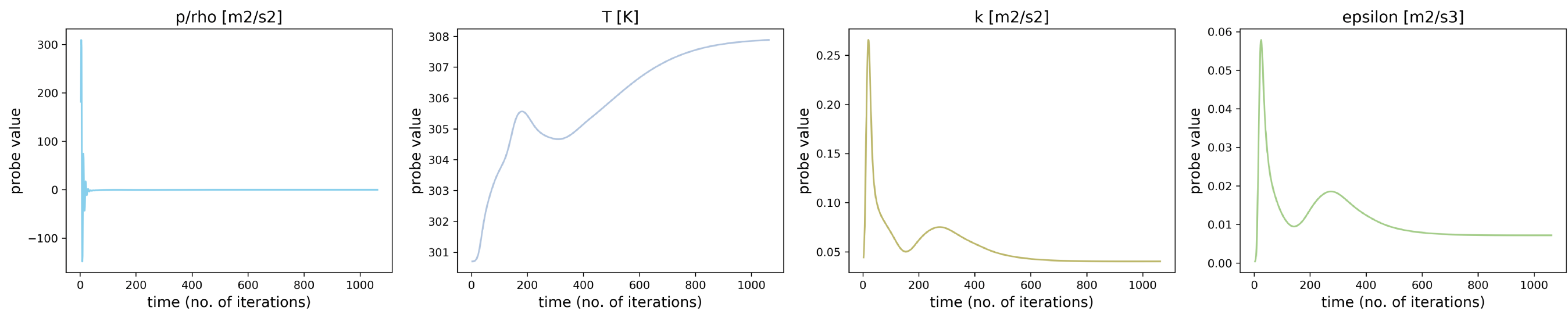


5

MONITORING PROBES IN VOID DECKS

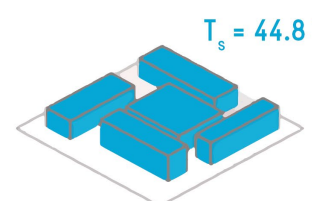


example: convergence at probe 13 (probe set 3)





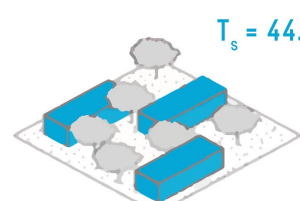
LOCAL CLIMATE ZONES IN STUDY AREA



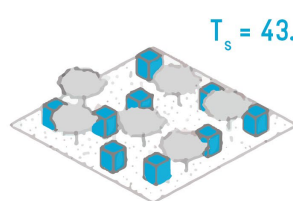
LCZ 2
compact mid-rise



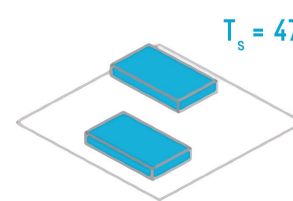
LCZ 4
open high-rise



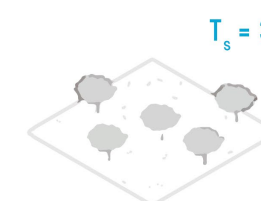
LCZ 5
open mid-rise



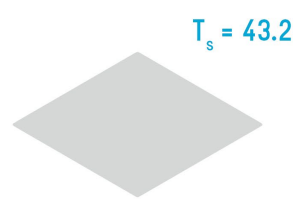
LCZ 6
open low-rise



LCZ 8
large low-rise



LCZ B
scattered trees



LCZ E
bare rock or paved

NORTHEAST MONSOON: PREVAILING WIND FROM N



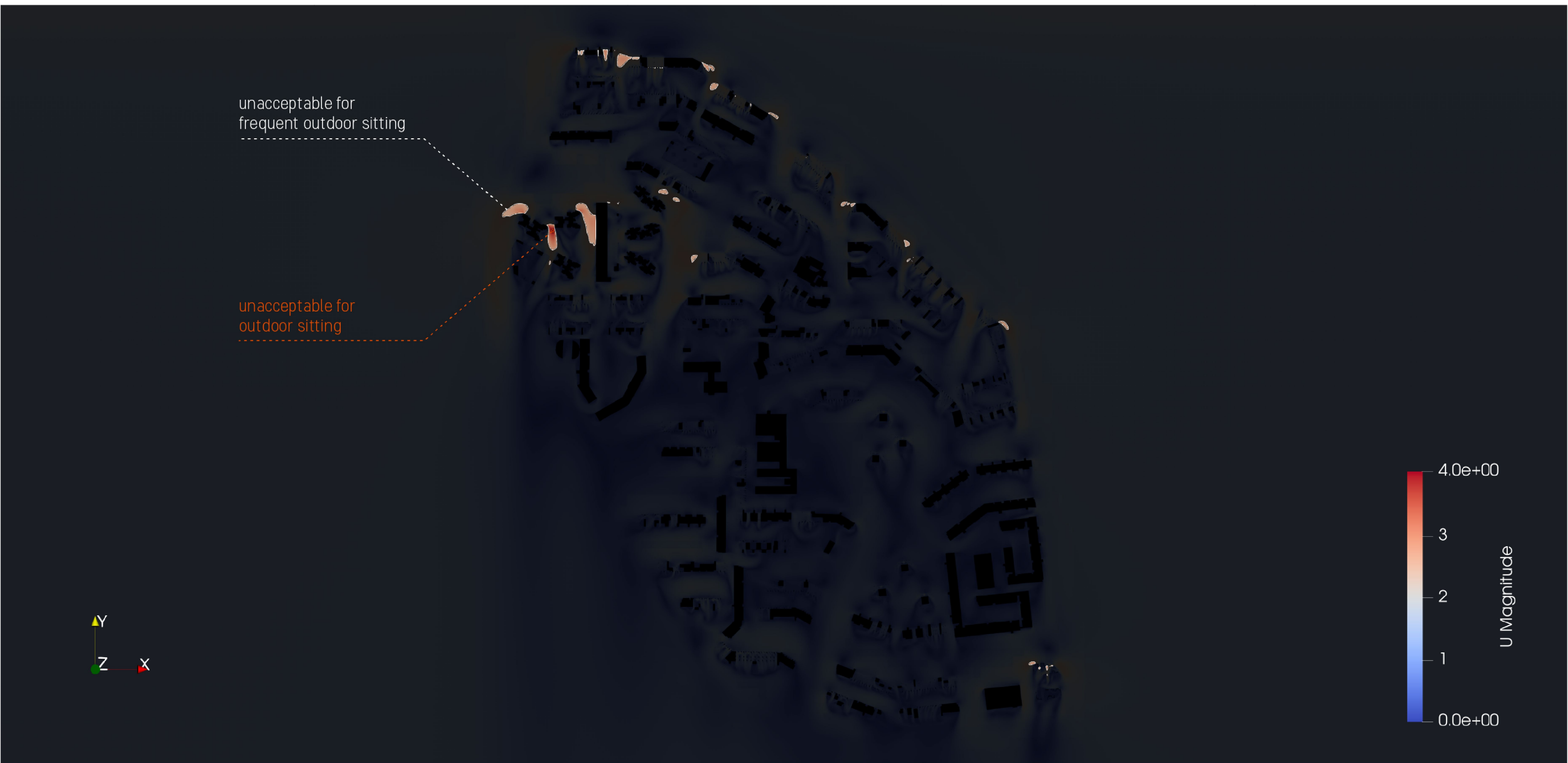
U RESULTS AT PEDESTRIAN HEIGHT

NORTHEAST MONSOON: PREVAILING WIND FROM N



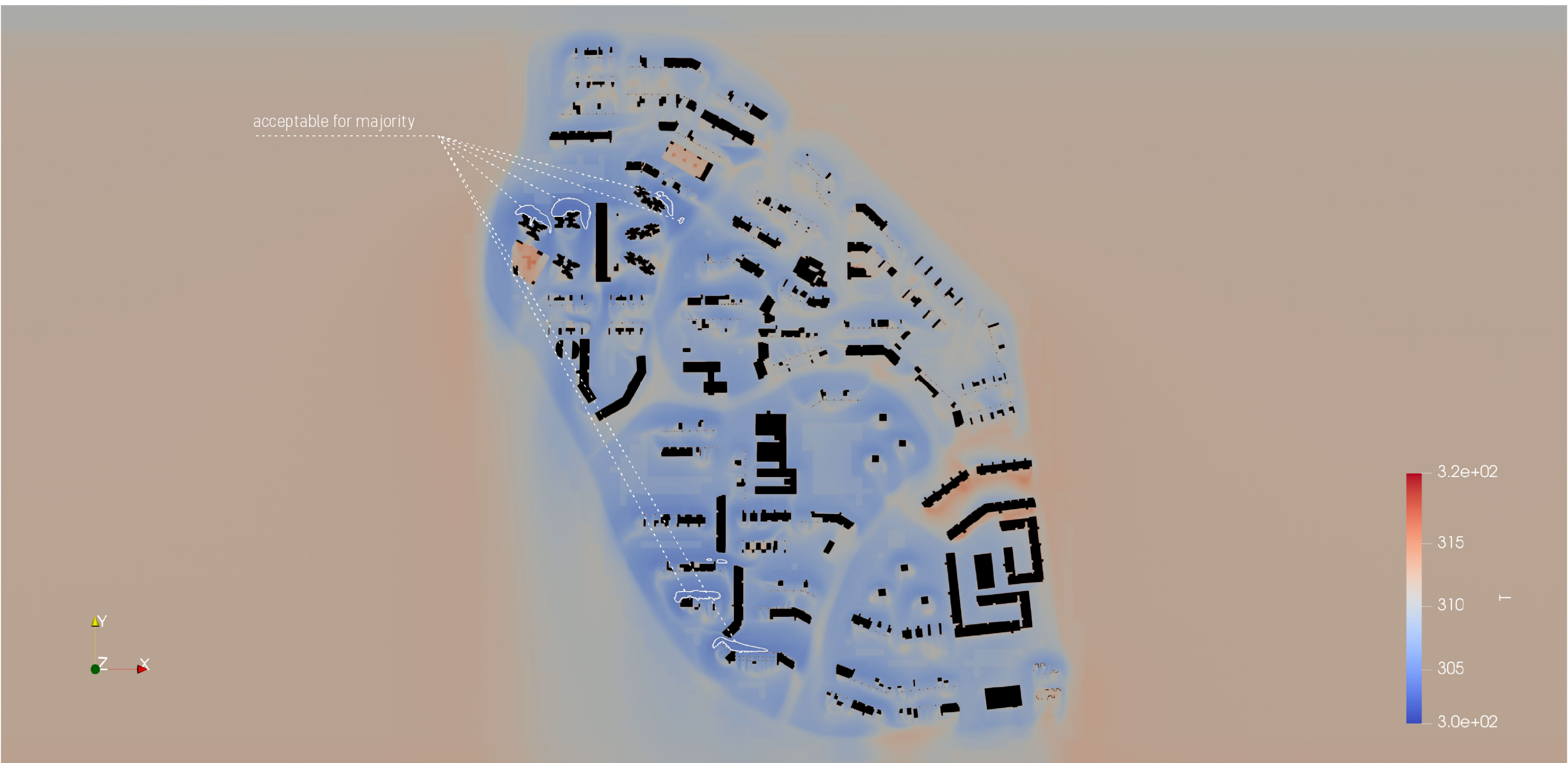
U RESULTS AT PEDESTRIAN HEIGHT

NORTHEAST MONSOON: PREVAILING WIND FROM N



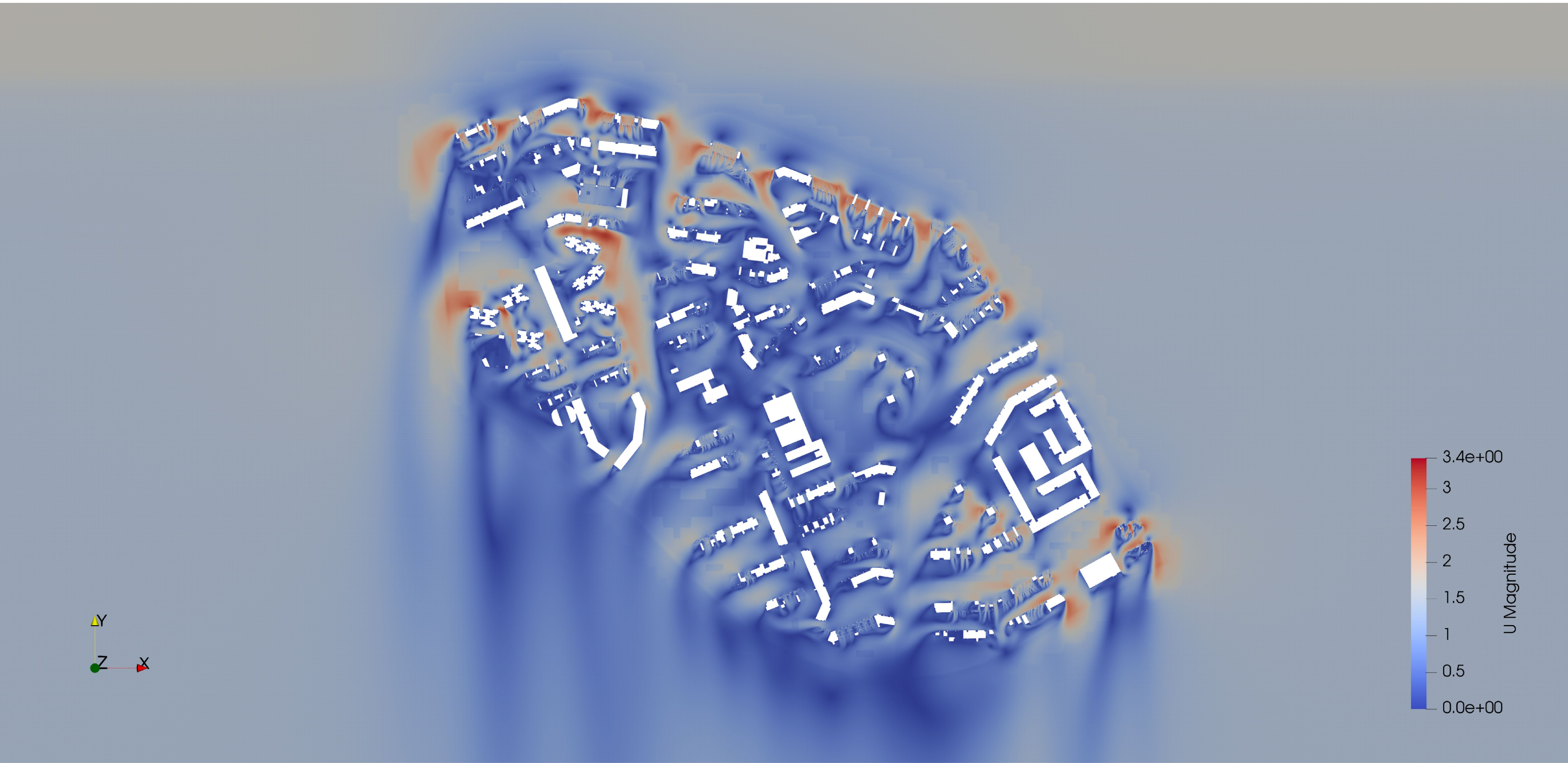
PEDESTRIAN WIND COMFORT: UNACCEPTABLE AREAS FOR FREQUENT & OCCASIONAL OUTDOOR SITTING
[2.5 m/s < U ≤ 4.0 m/s] and [4.0 m/s < U ≤ 6.0 m/s]

NORTHEAST MONSOON: PREVAILING WIND FROM N



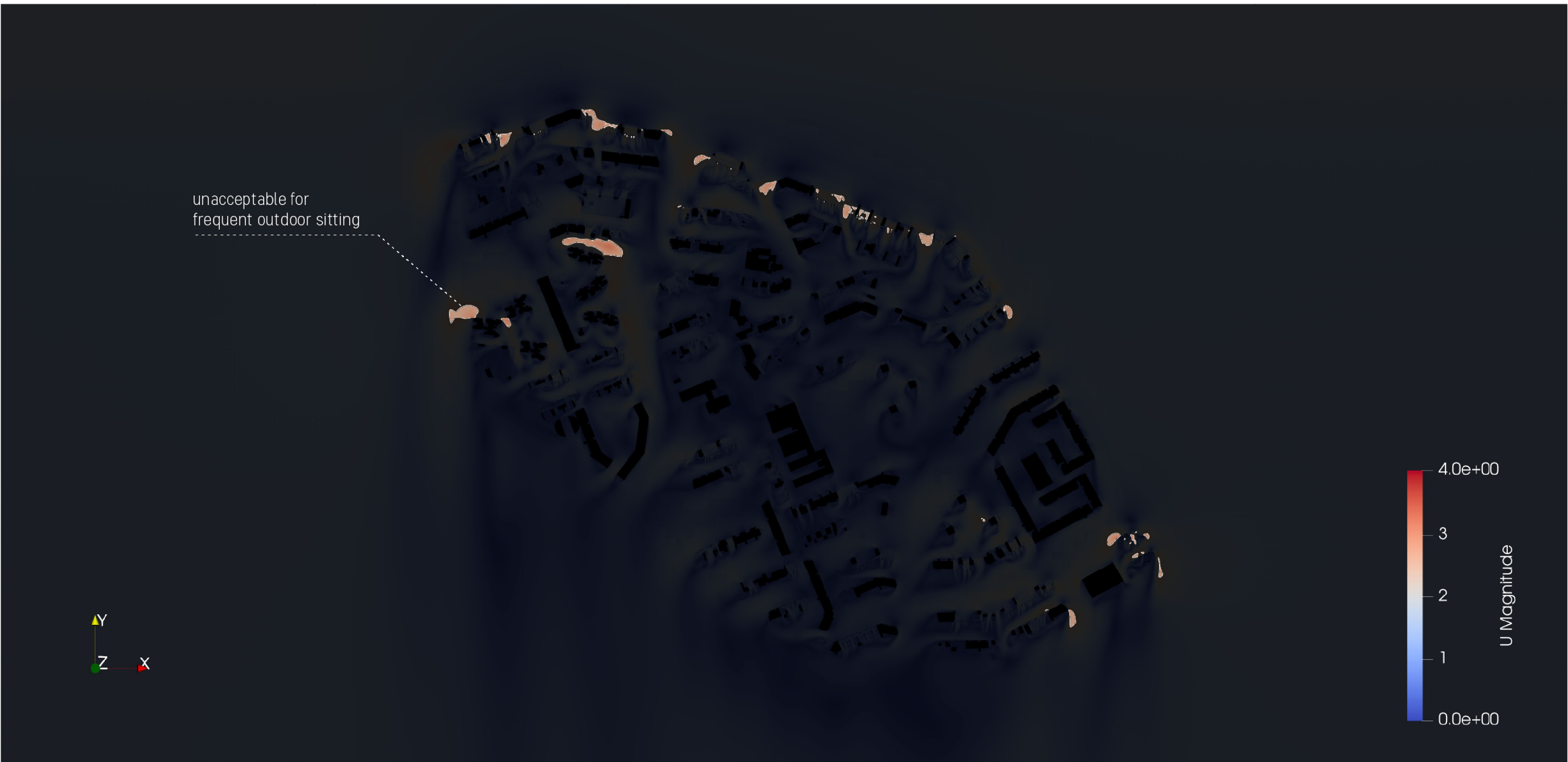
OUTDOOR THERMAL COMFORT: THERMALLY ACCEPTABLE & UNCOMFORTABLY HOT AREAS
[$24\text{ }^{\circ}\text{C} < \text{THI} \leq 31\text{ }^{\circ}\text{C}$] and [$\text{THI} > 31\text{ }^{\circ}\text{C}$]

NORTHEAST MONSOON: PREVAILING WIND FROM NNE



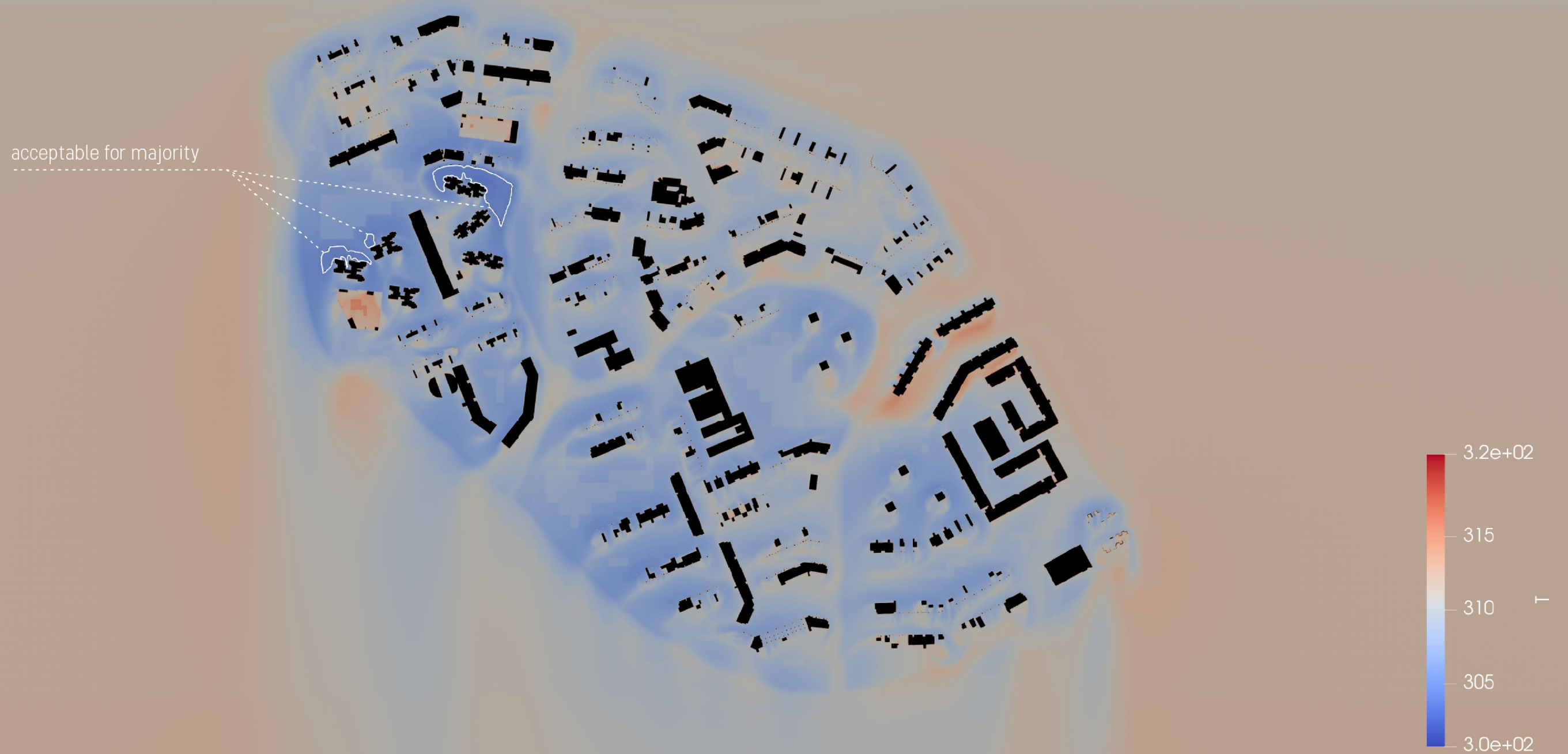
U RESULTS AT PEDESTRIAN HEIGHT

NORTHEAST MONSOON: PREVAILING WIND FROM NNE



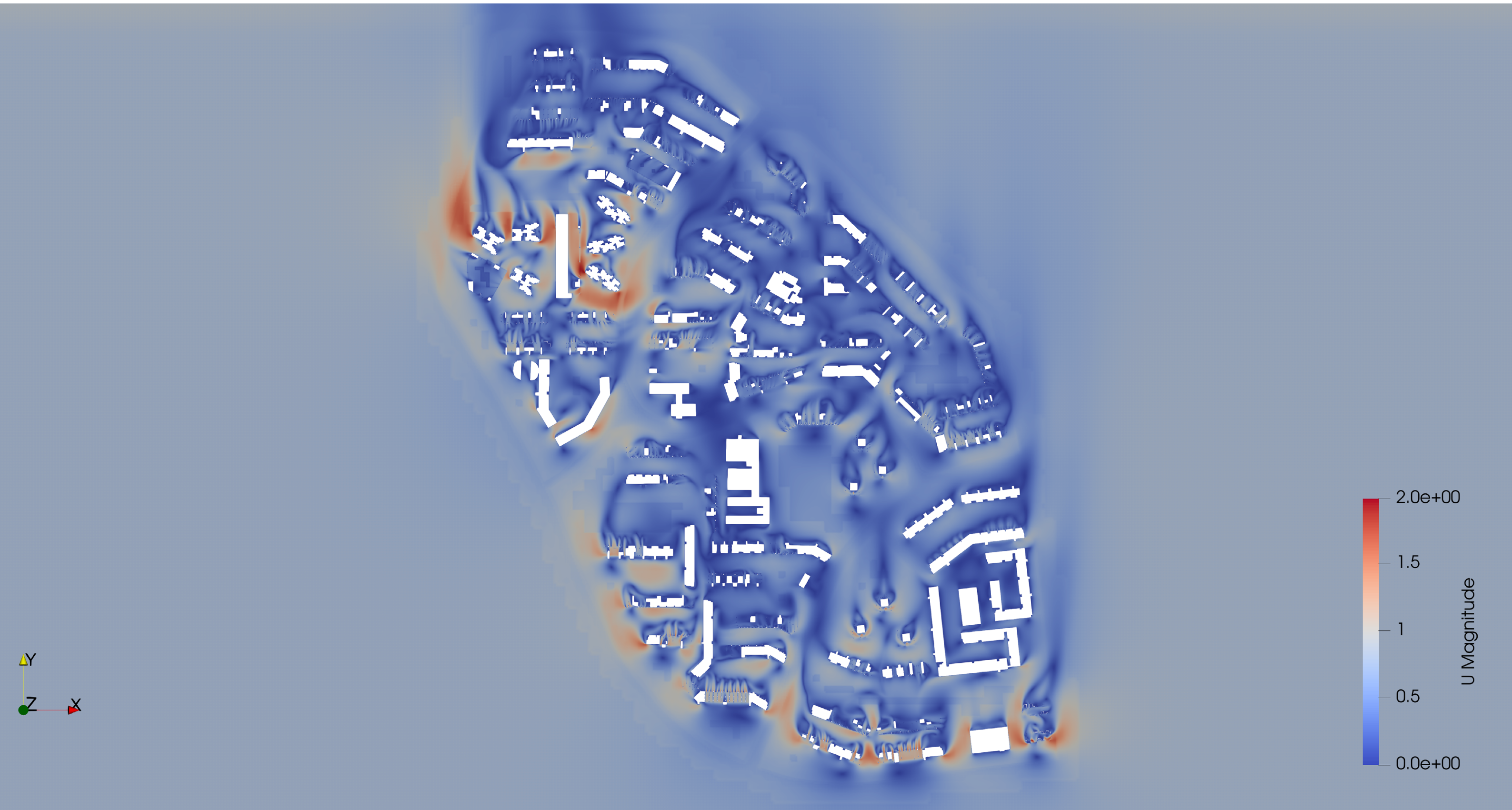
PEDESTRIAN WIND COMFORT: UNACCEPTABLE AREAS FOR FREQUENT OUTDOOR SITTING
[2.5 m/s < U ≤ 4.0 m/s]

NORTHEAST MONSOON: PREVAILING WIND FROM NNE



OUTDOOR THERMAL COMFORT: THERMALLY ACCEPTABLE & UNCOMFORTABLY HOT AREAS
[$24\text{ }^{\circ}\text{C} < \text{THI} \leq 31\text{ }^{\circ}\text{C}$] and [$\text{THI} > 31\text{ }^{\circ}\text{C}$]

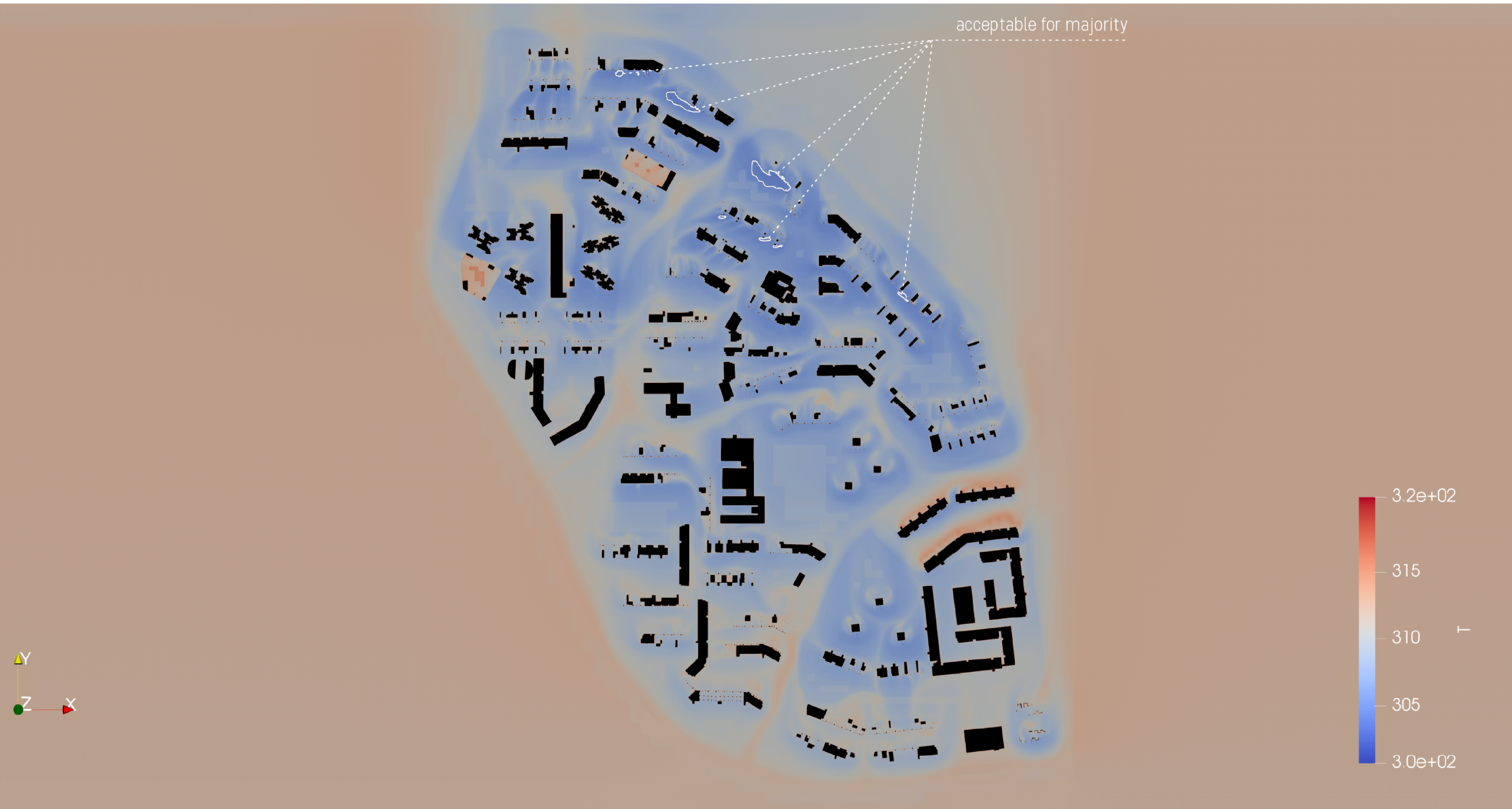
SOUTHWEST MONSOON: PREVAILING WIND FROM S



U RESULTS AT PEDESTRIAN HEIGHT
PEDESTRIAN WIND COMFORT: **ACCEPTABLE FOR ALL ASSESSED OUTDOOR ACTIVITIES**

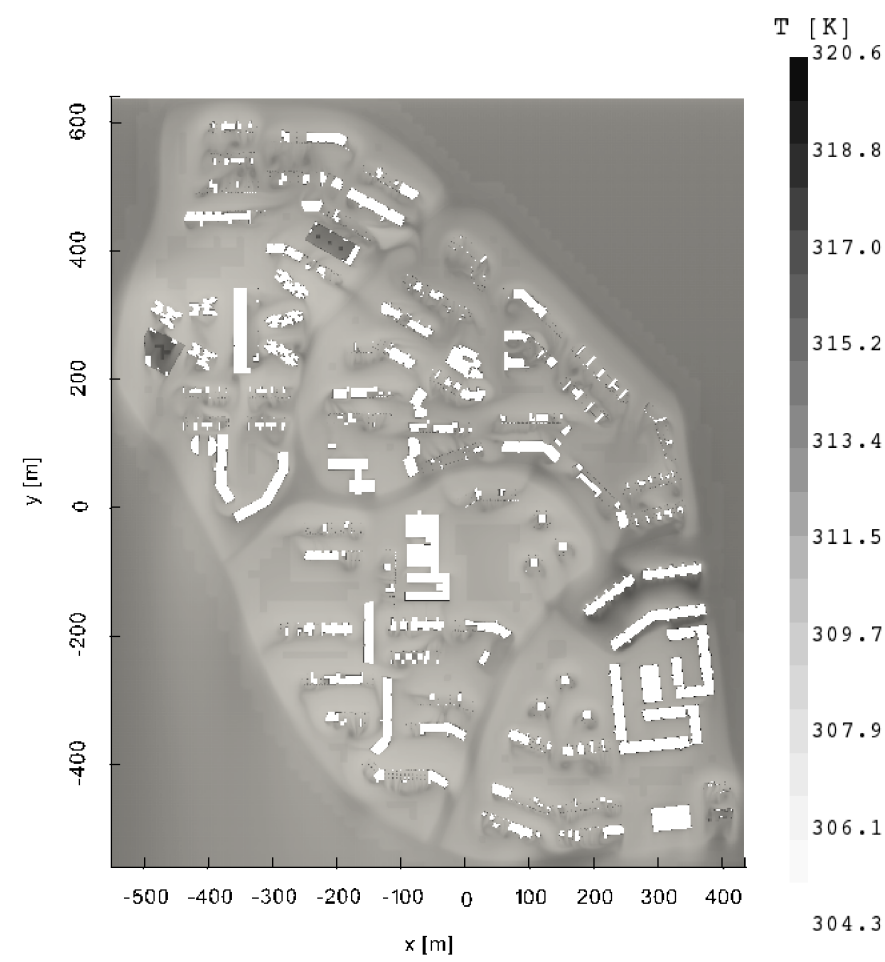
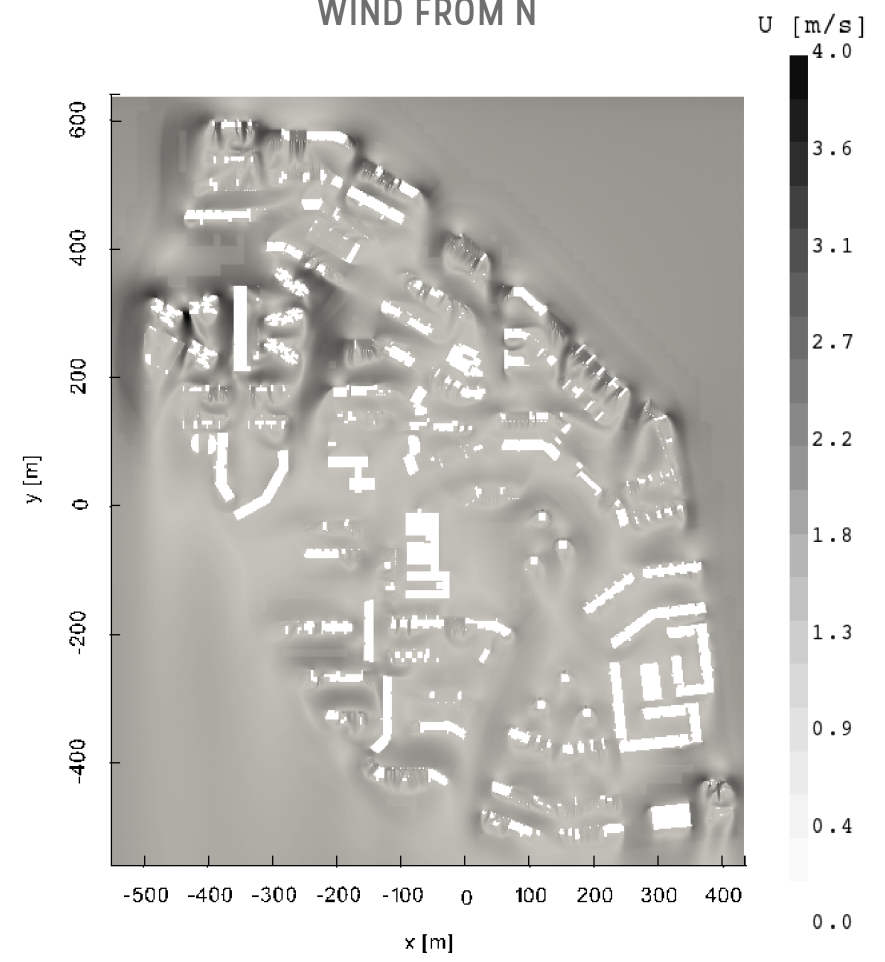


SOUTHWEST MONSOON: PREVAILING WIND FROM S

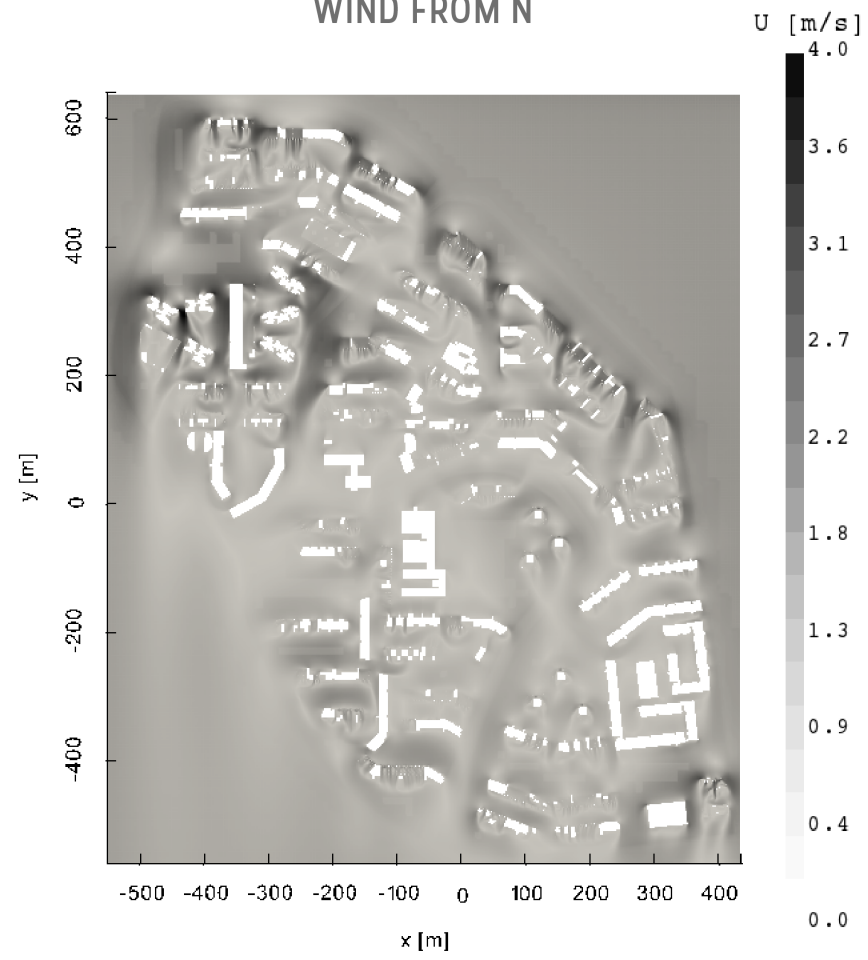


OUTDOOR THERMAL COMFORT: THERMALLY ACCEPTABLE & UNCOMFORTABLY HOT AREAS
[24 °C < THI ≤ 31 °C] and [THI > 31 °C]

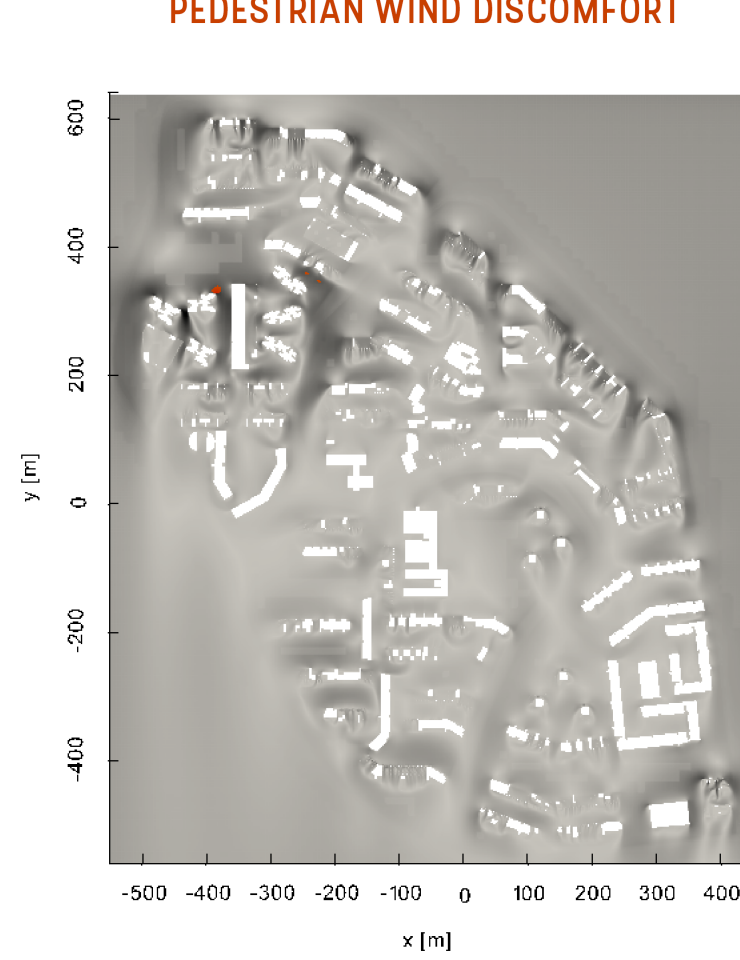
WIND FROM N



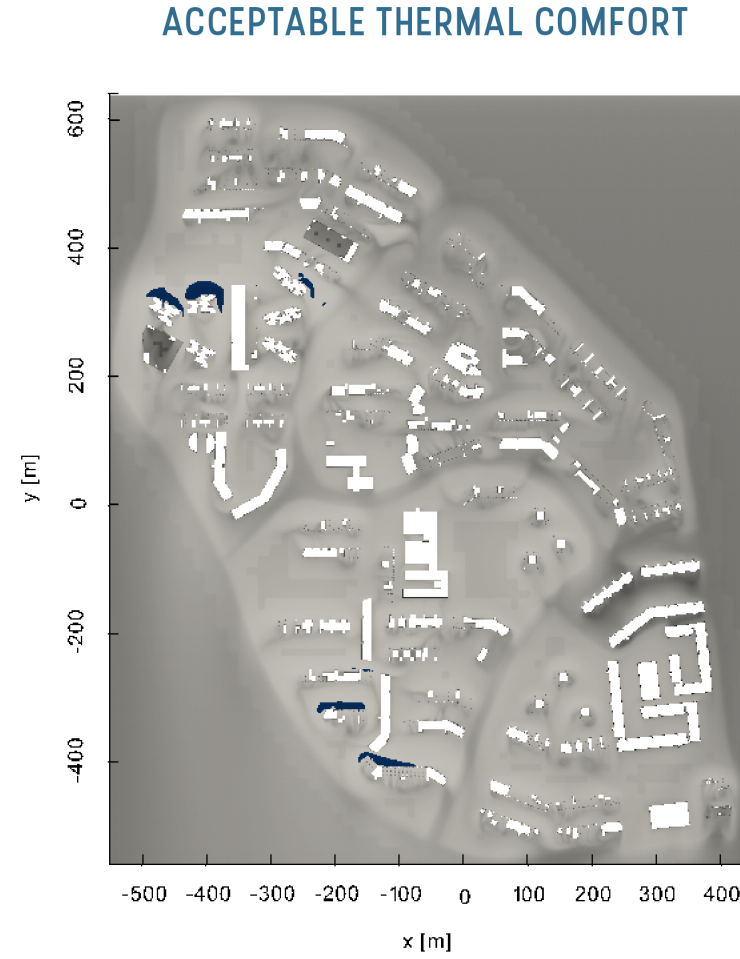
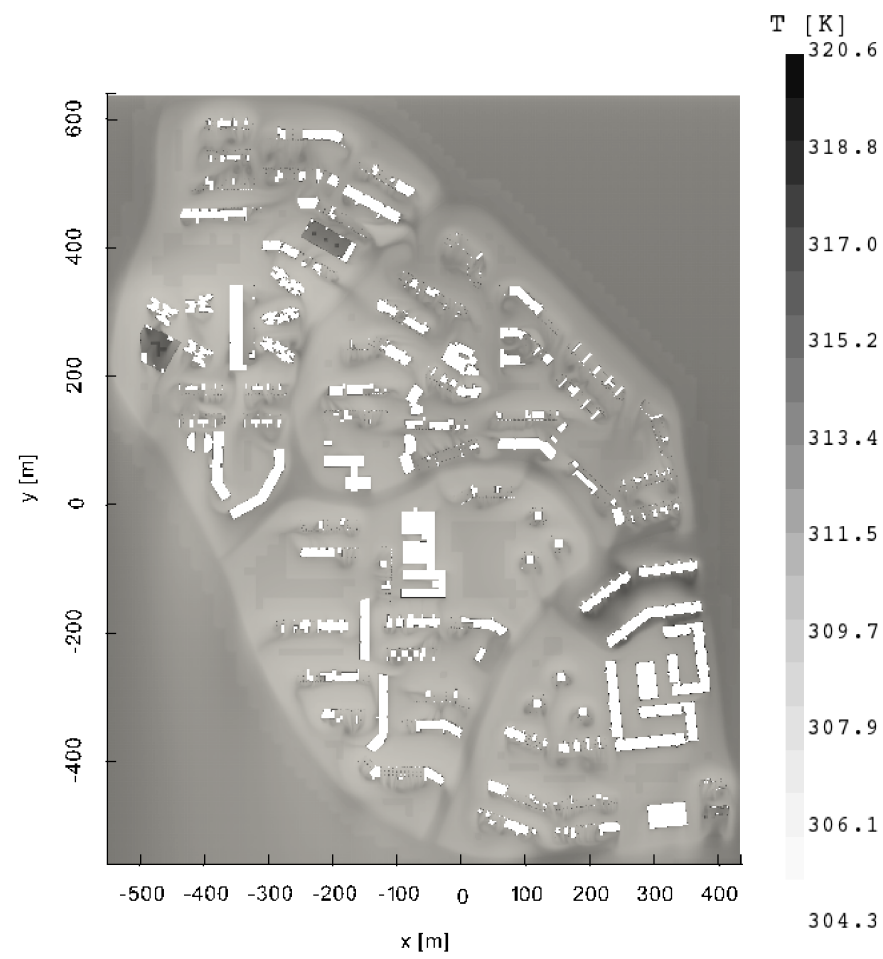
WIND FROM N



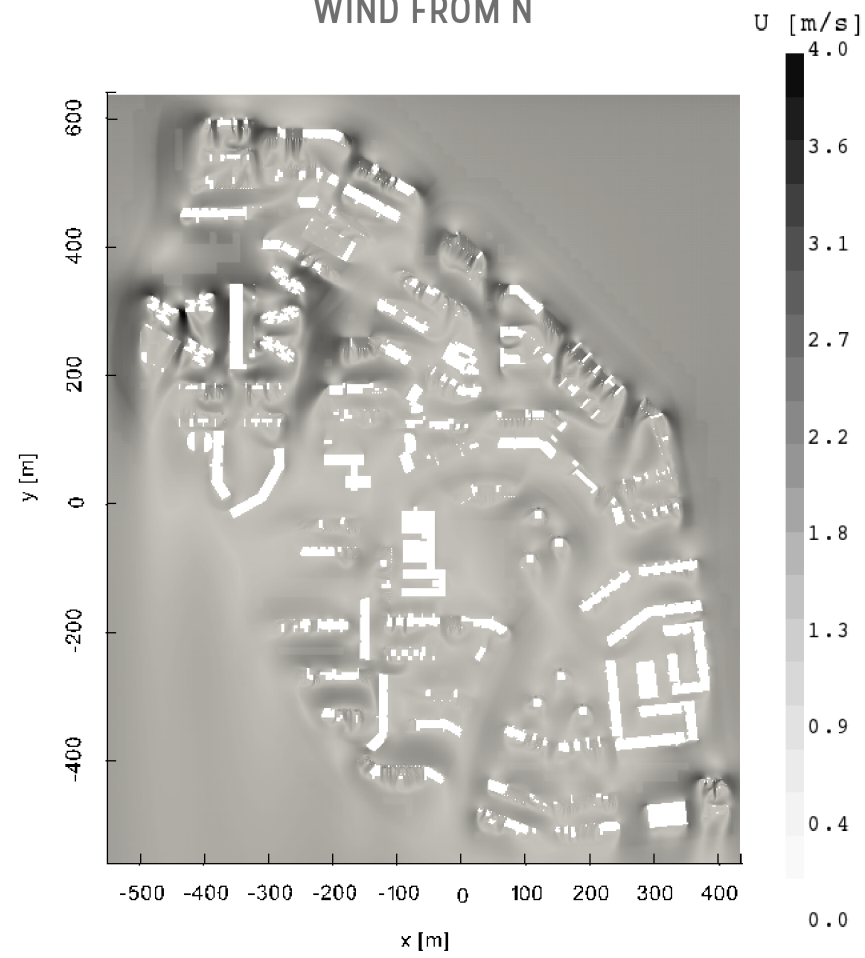
PEDESTRIAN WIND DISCOMFORT



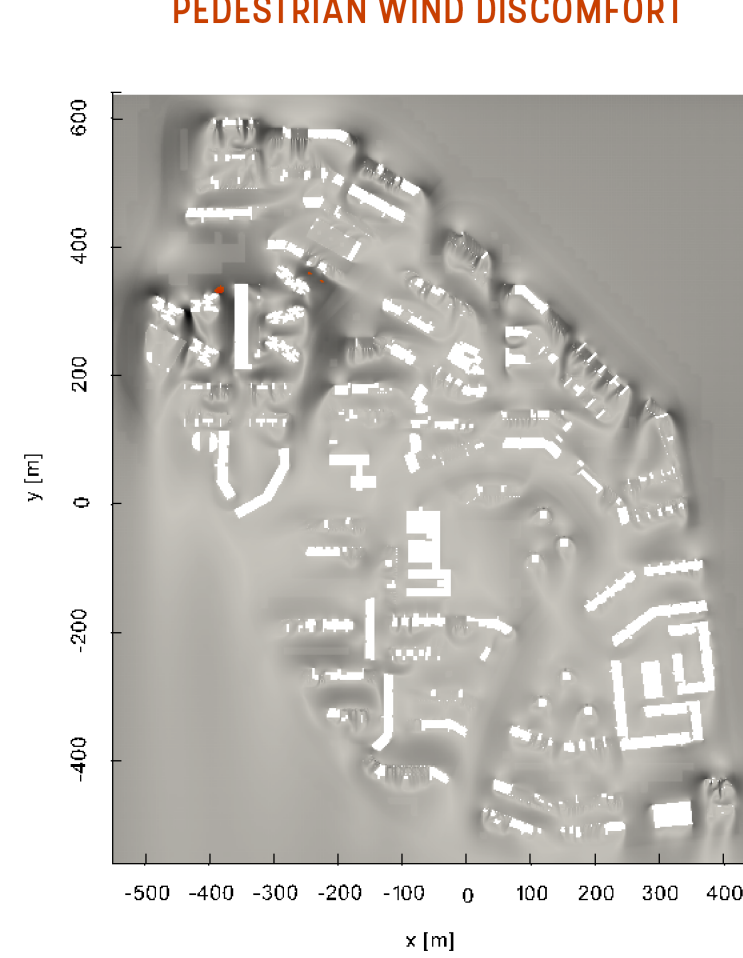
ACCEPTABLE THERMAL COMFORT



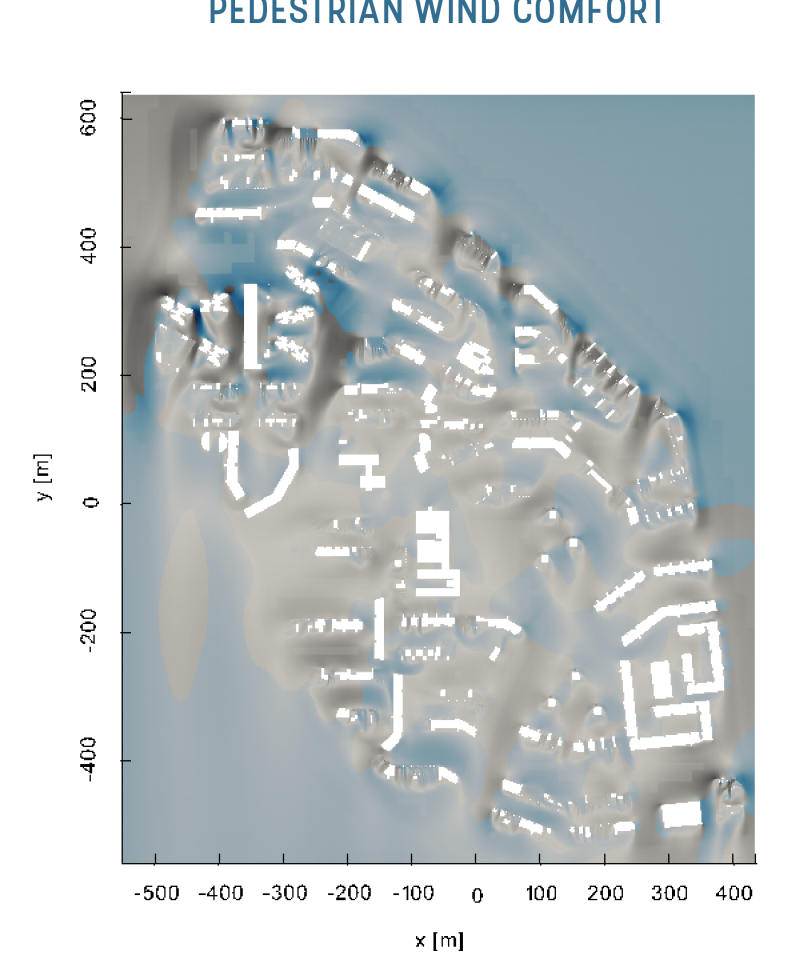
WIND FROM N



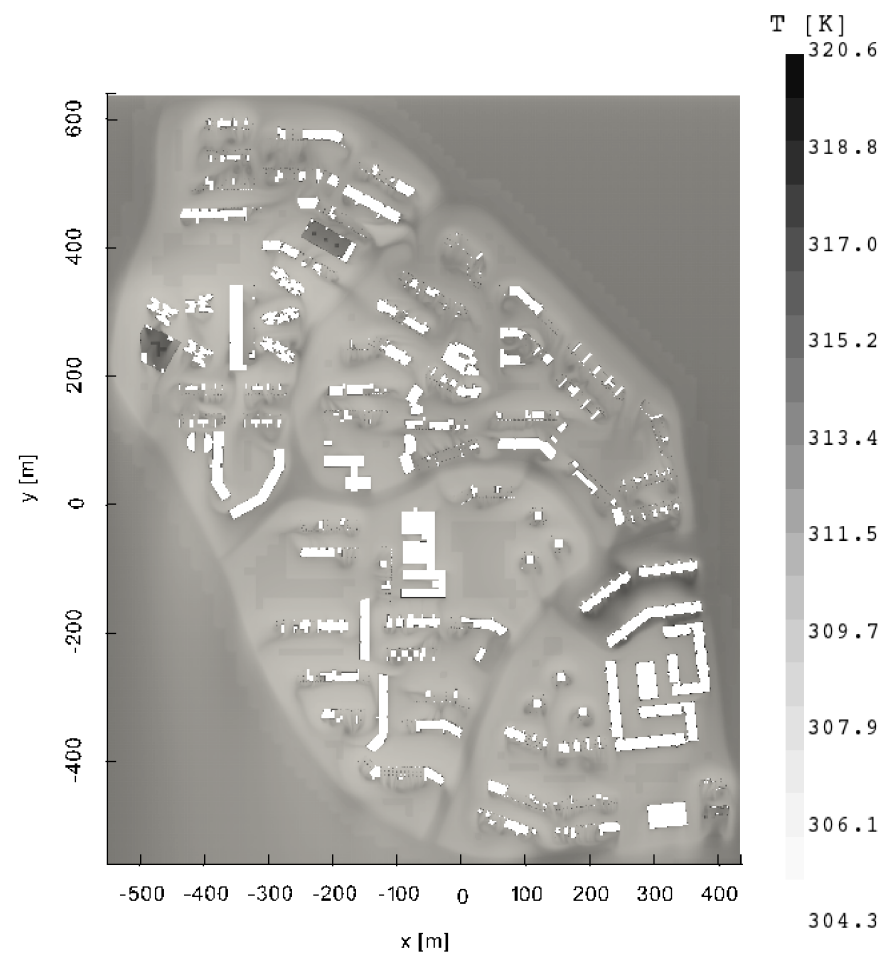
PEDESTRIAN WIND DISCOMFORT



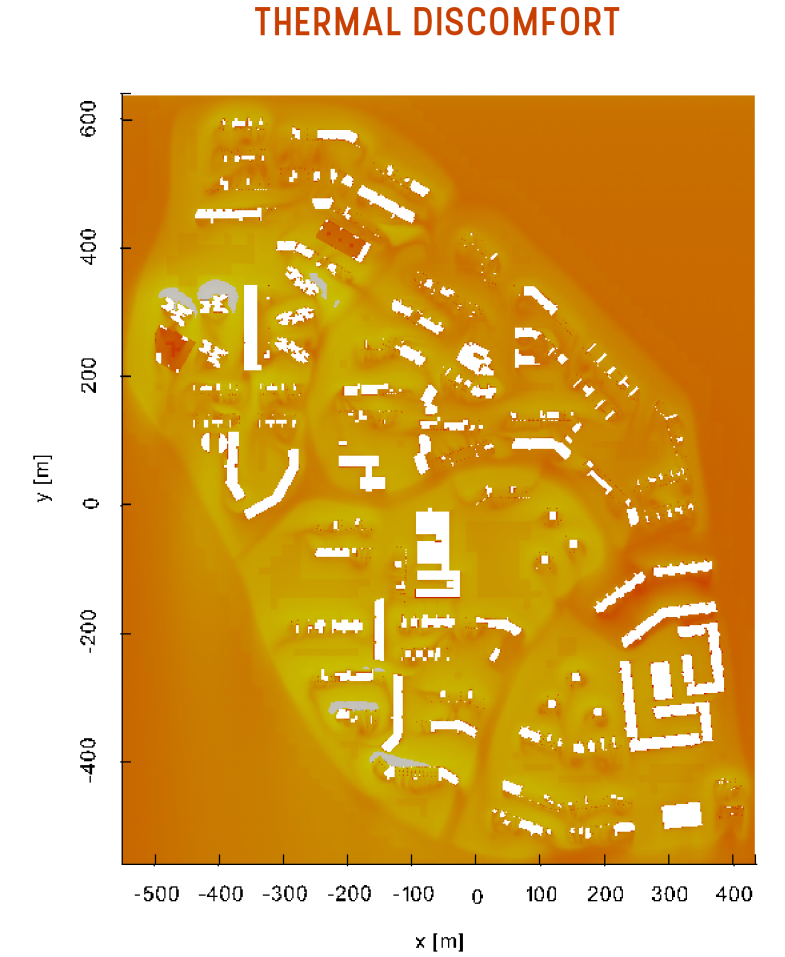
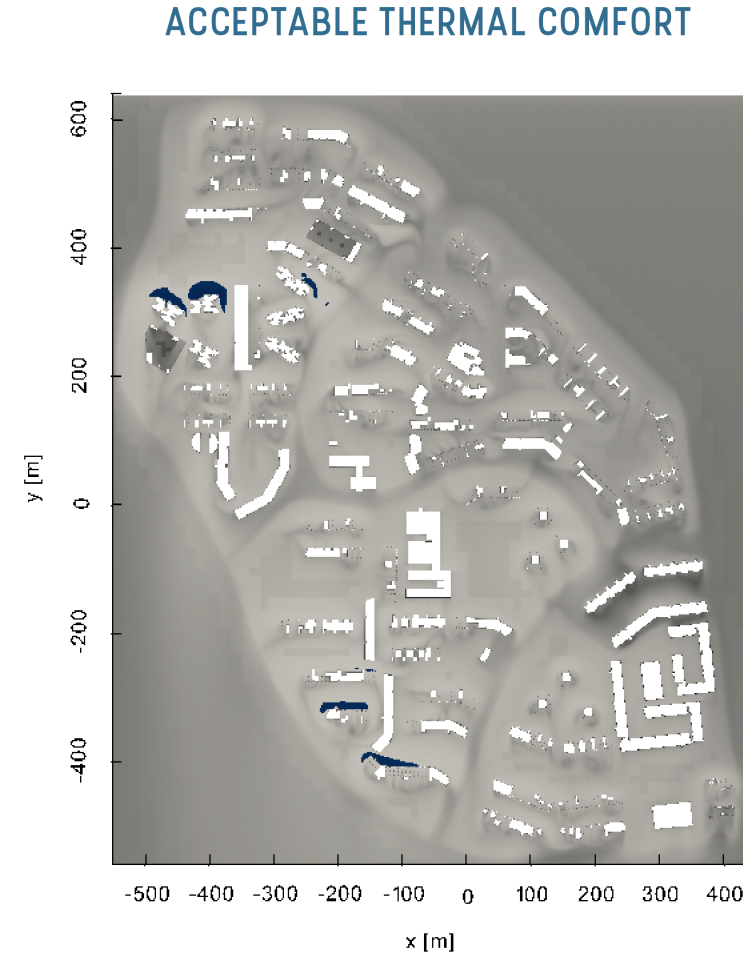
PEDESTRIAN WIND COMFORT



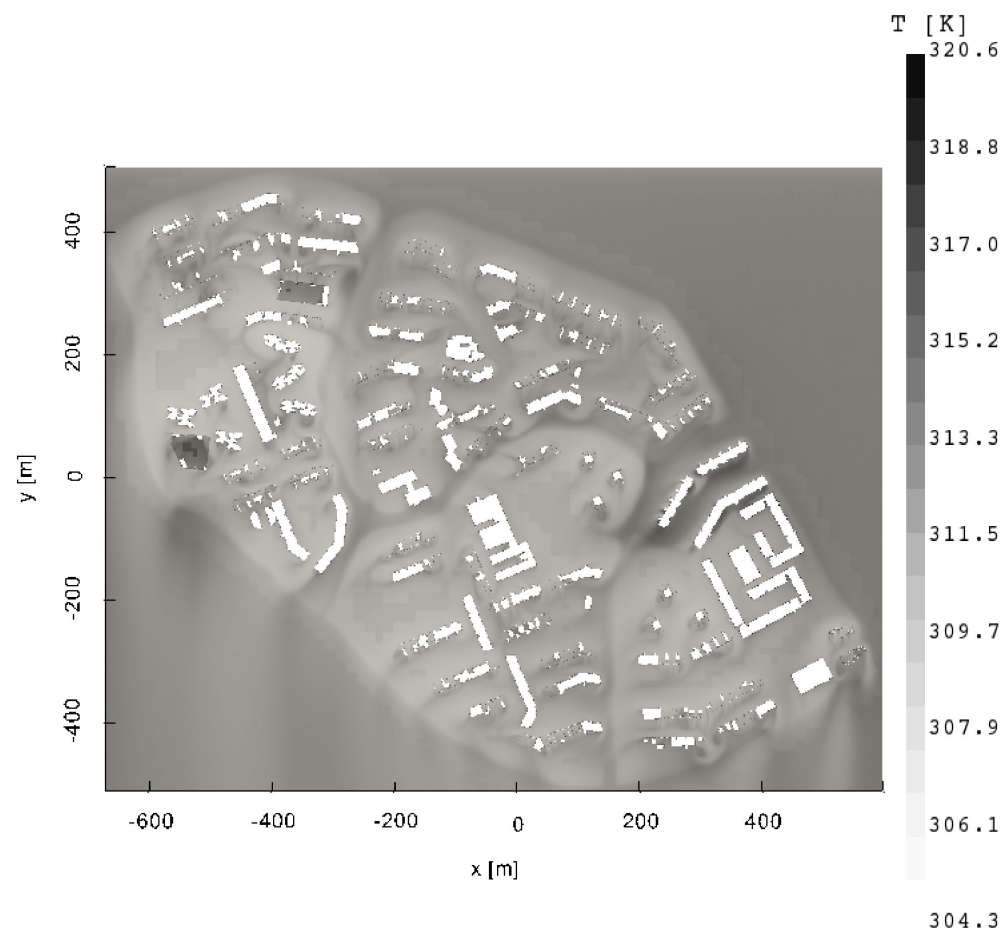
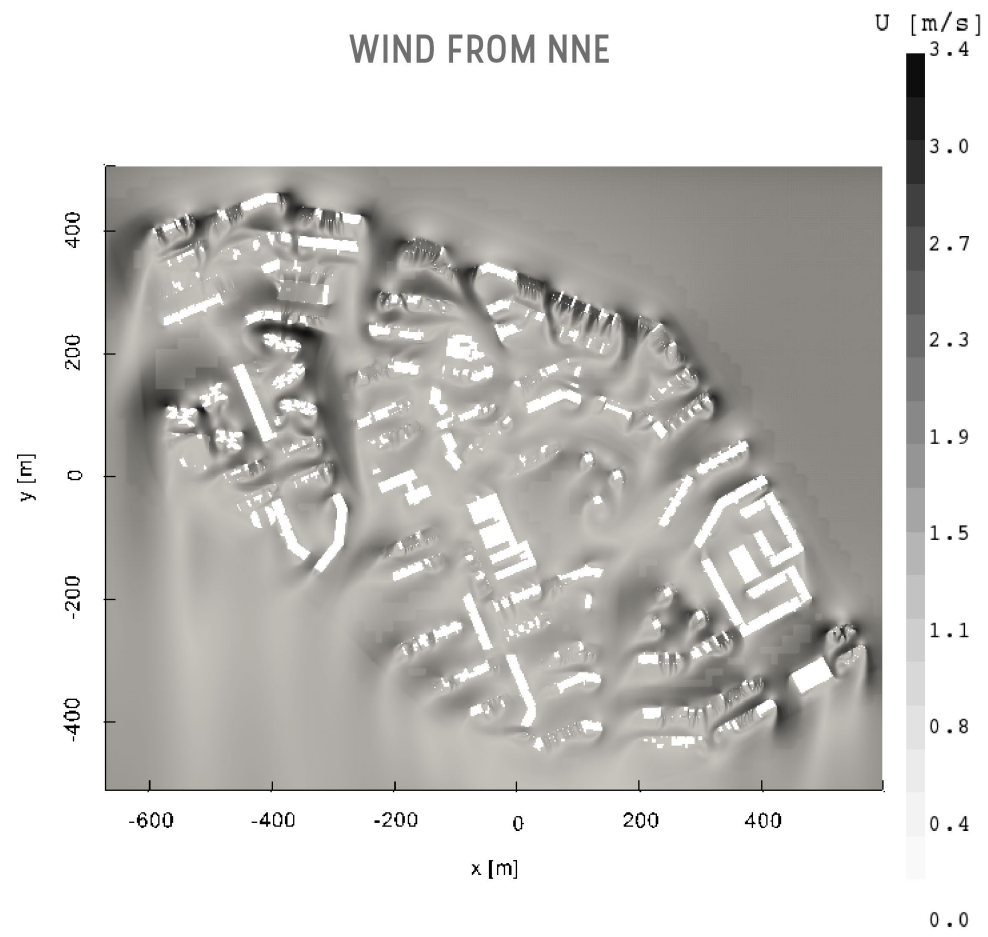
ACCEPTABLE THERMAL COMFORT



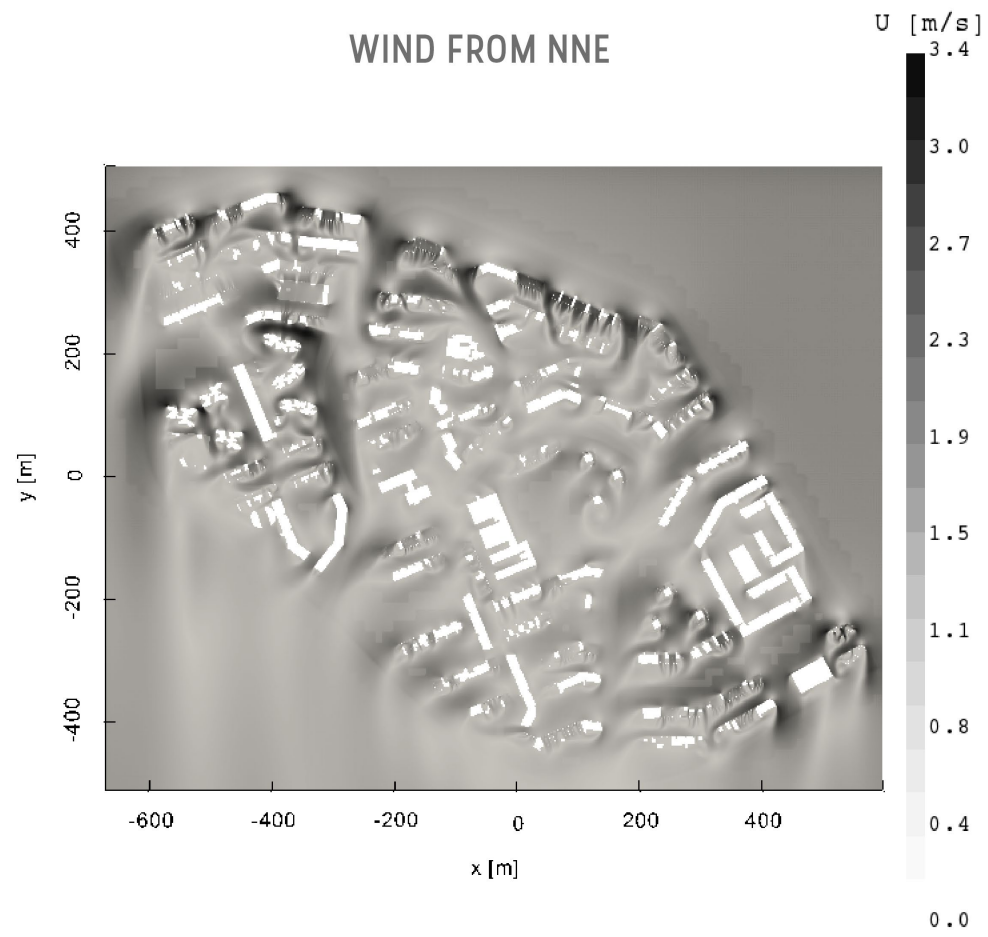
THERMAL DISCOMFORT



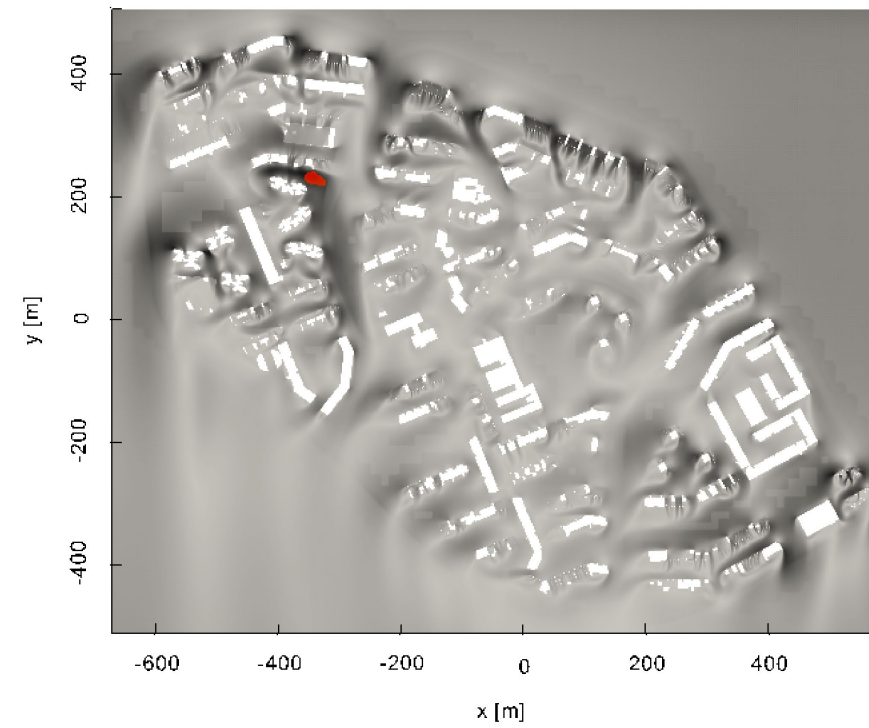
WIND FROM NNE



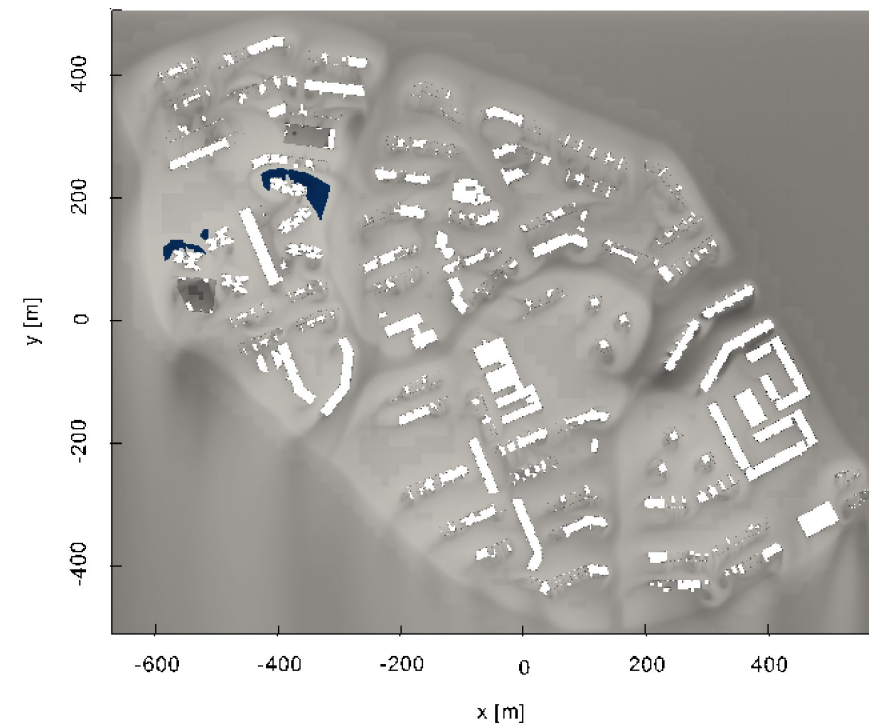
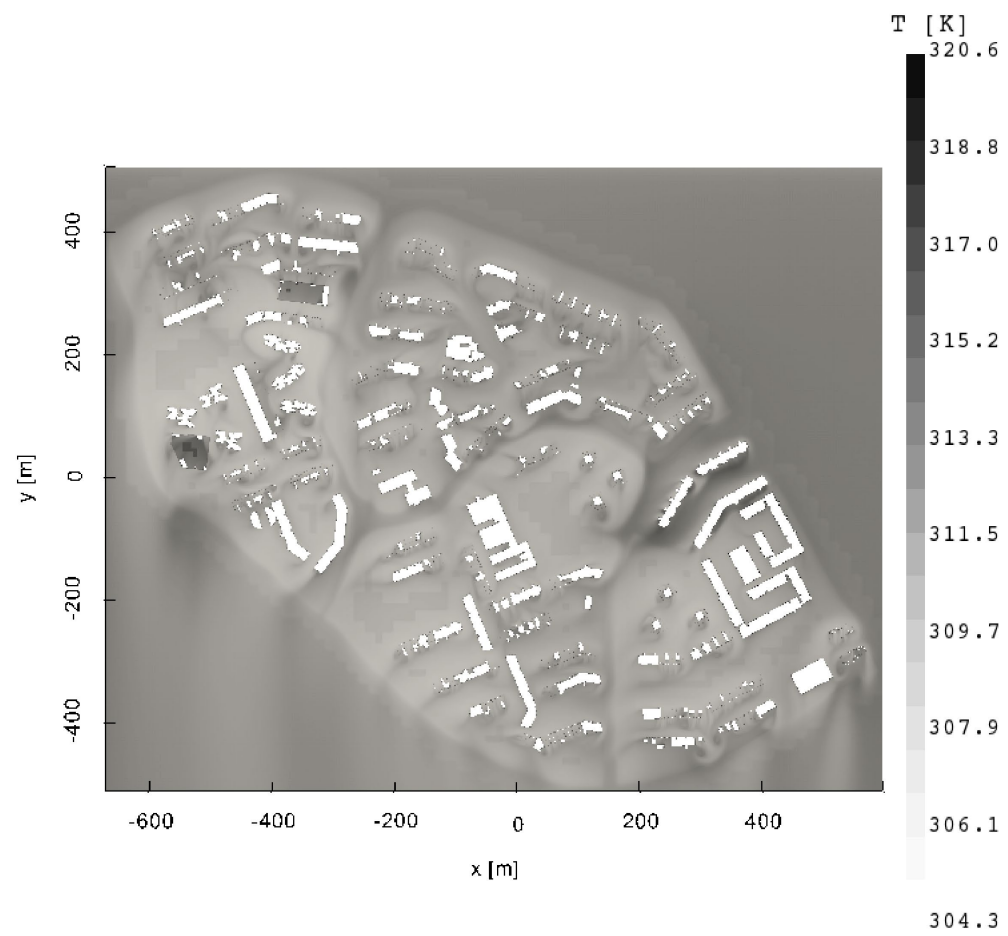
WIND FROM NNE



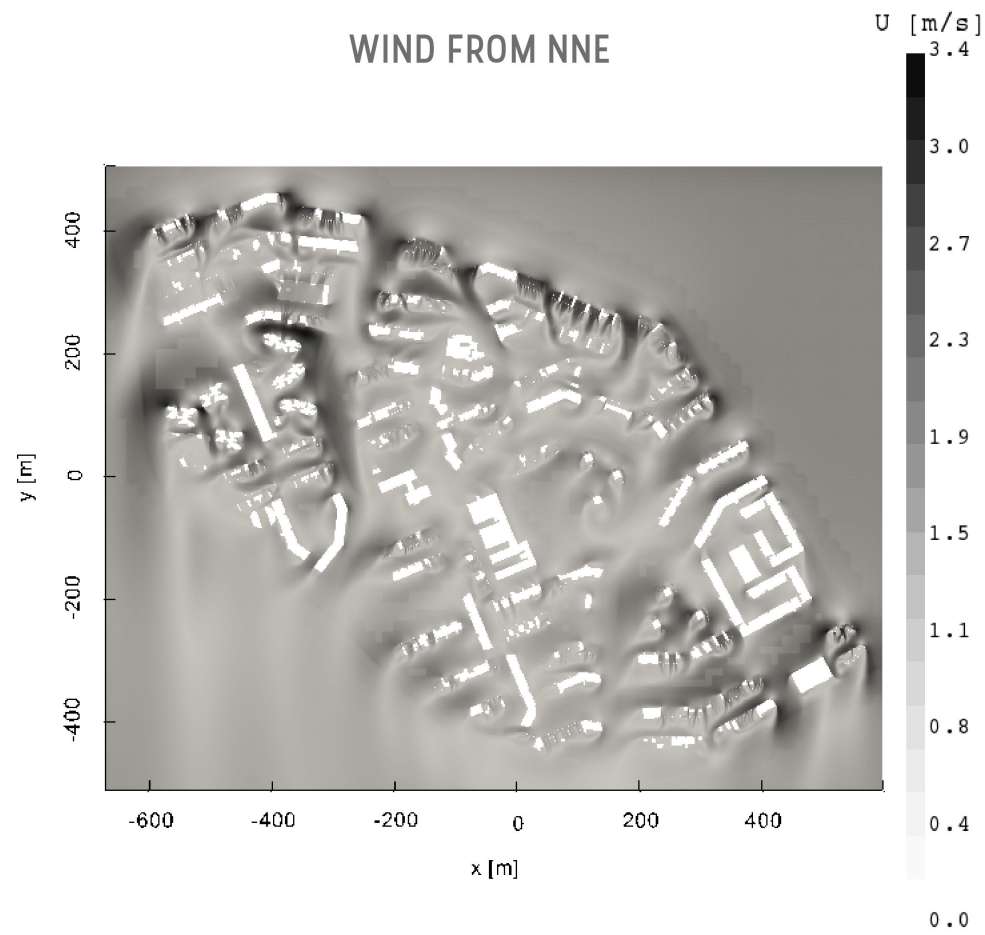
PEDESTRIAN WIND DISCOMFORT



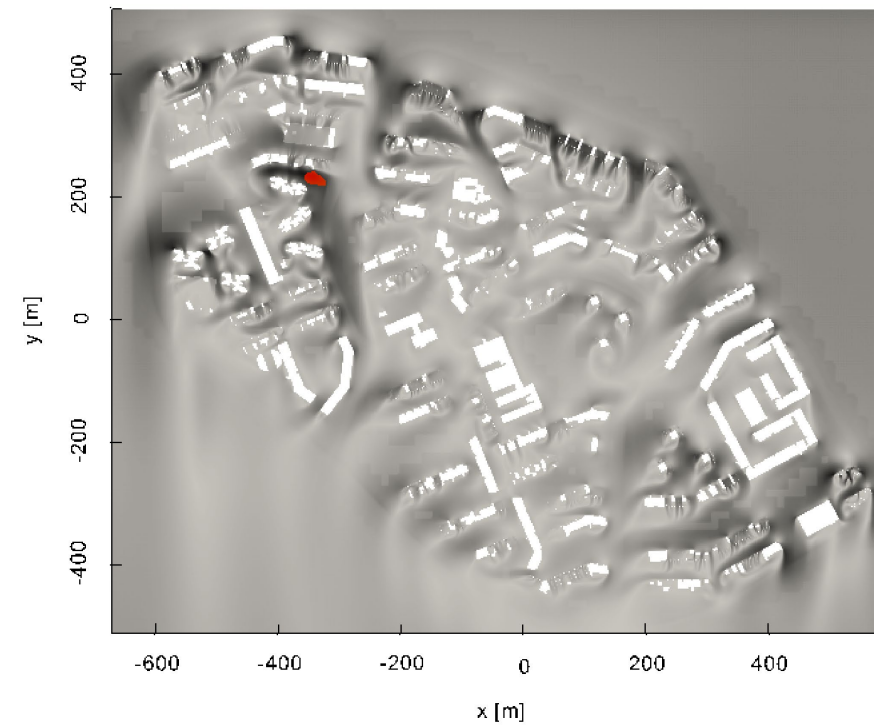
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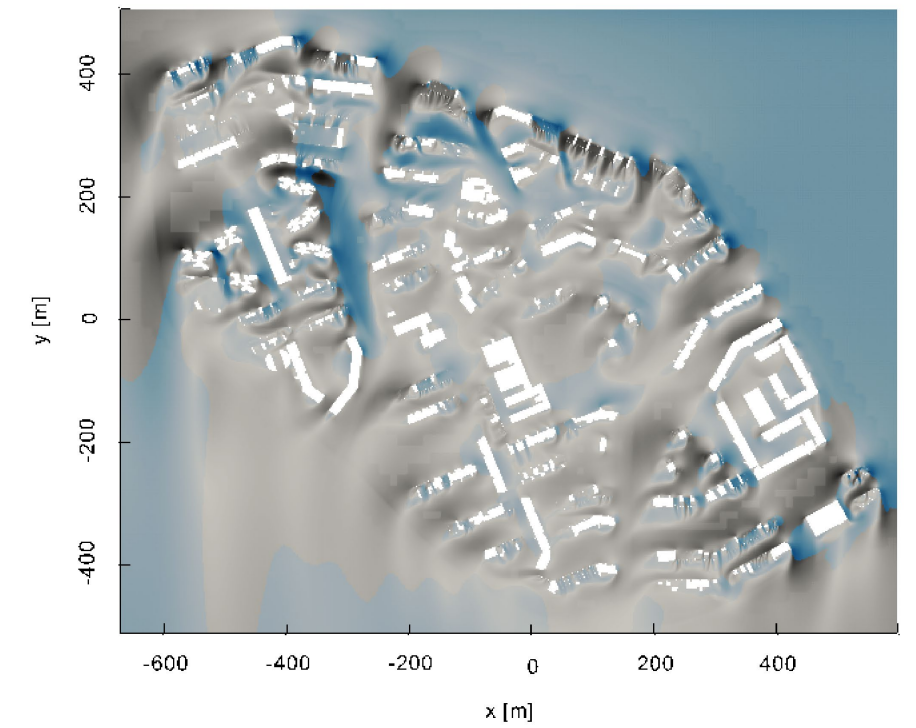
WIND FROM NNE



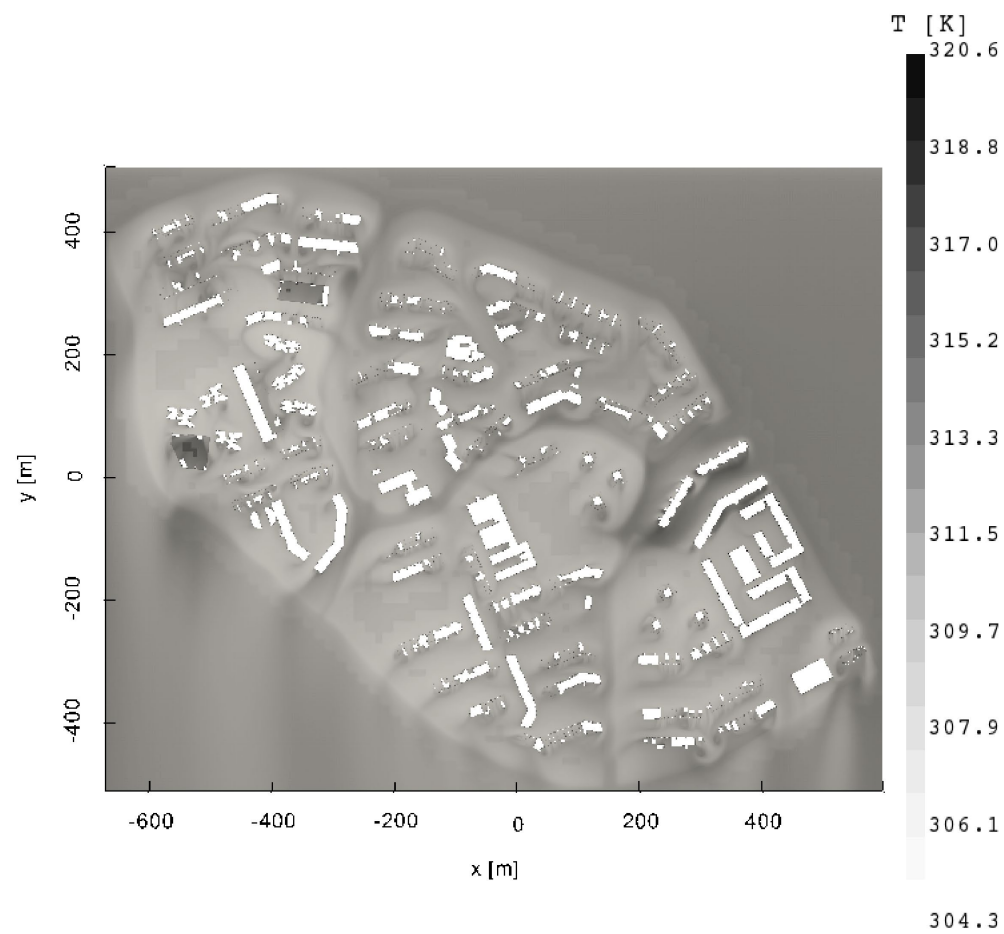
PEDESTRIAN WIND DISCOMFORT



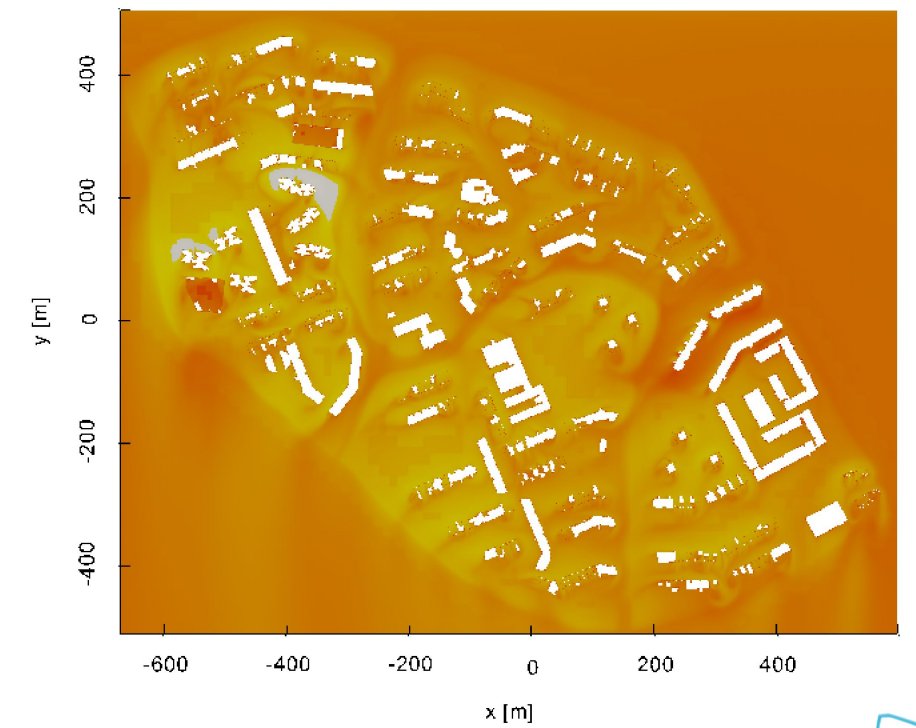
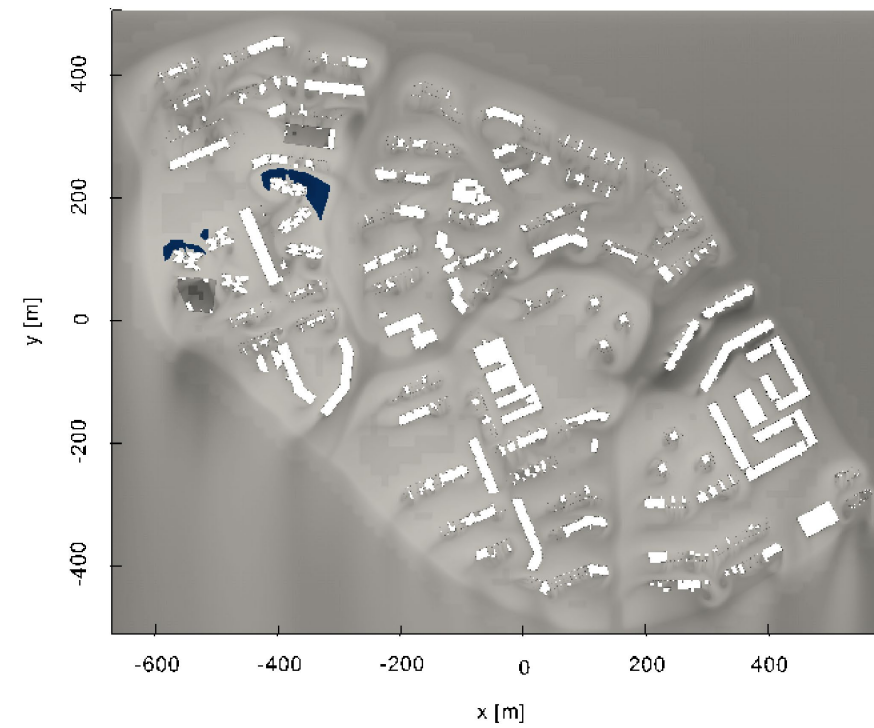
PEDESTRIAN WIND COMFORT



ACCEPTABLE THERMAL COMFORT

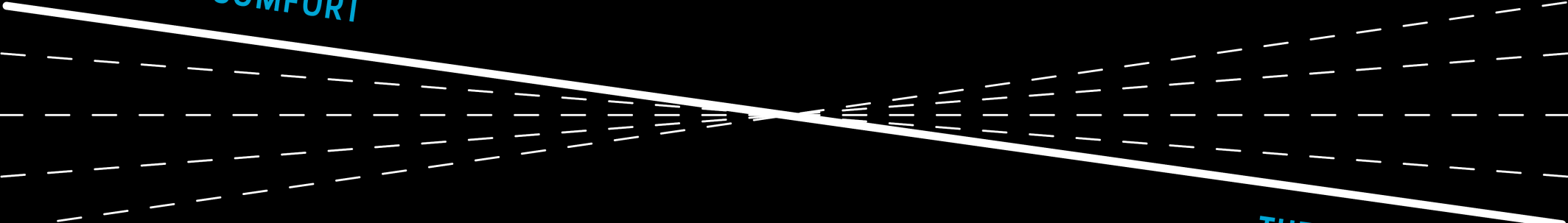


THERMAL DISCOMFORT



STRONG IMBALANCE

PEDESTRIAN COMFORT



THERMAL COMFORT

INTERVENTION



PARAMETRIC VOID DECK MODEL – URBAN SCALE

Parametric_URBAN MODEL simplified.3dm (131 MB) - Rhino 6 Educational (131 Days Remaining) - [Perspective]

File Edit View Curve Surface Solid Mesh Dimension Transform Tools Analyze Render Panels Help

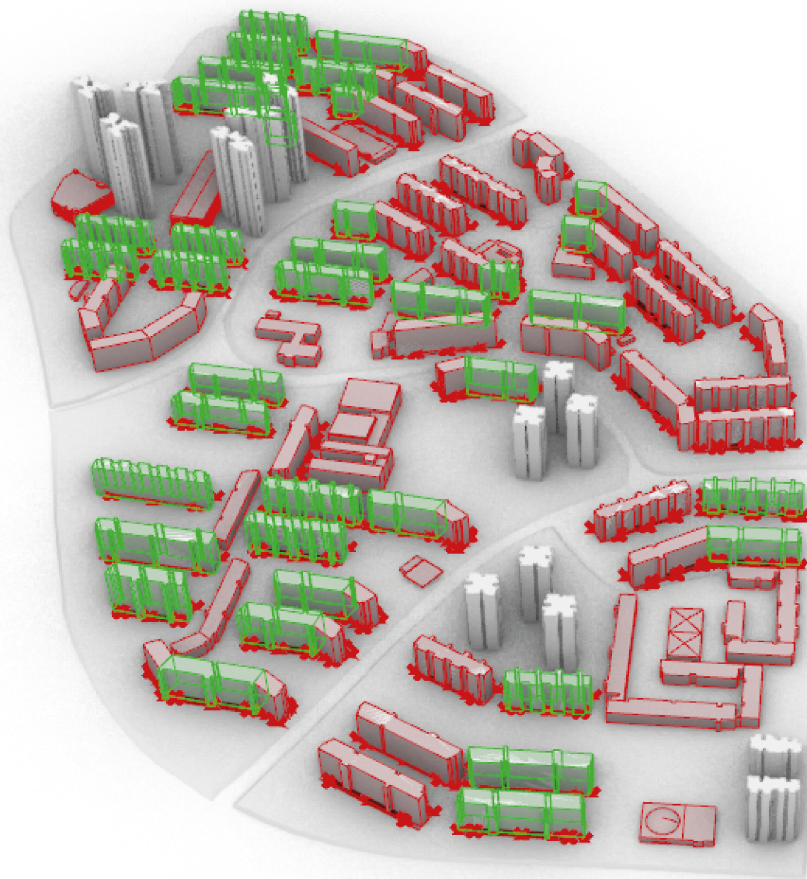
Display mode set to "Arctic".

Command:

Standard CPlanes Set View Display Select Viewport Layout Visibility Transform Curve Tools Surface Tools Solid To

Location Nodes Materials Metrics

Perspective



Perspective Top Front Right

☒ End ☒ Near ☒ Point ☒ Mid ☒ Cen ☒ Int ☒ Perp ☒ Tan ☐ Quad ☐ Knot ☒ Vertex ☐ Project ☐ Disable

CPlane x -1080.383 y 204.098 z 0.000 Meters Default Grid Snap Ortho Planar Osnap SmartTrack Gumball Record History Filter Absolute tolerance: 0.001

Grasshopper - Parametric_URBAN MODEL simplified

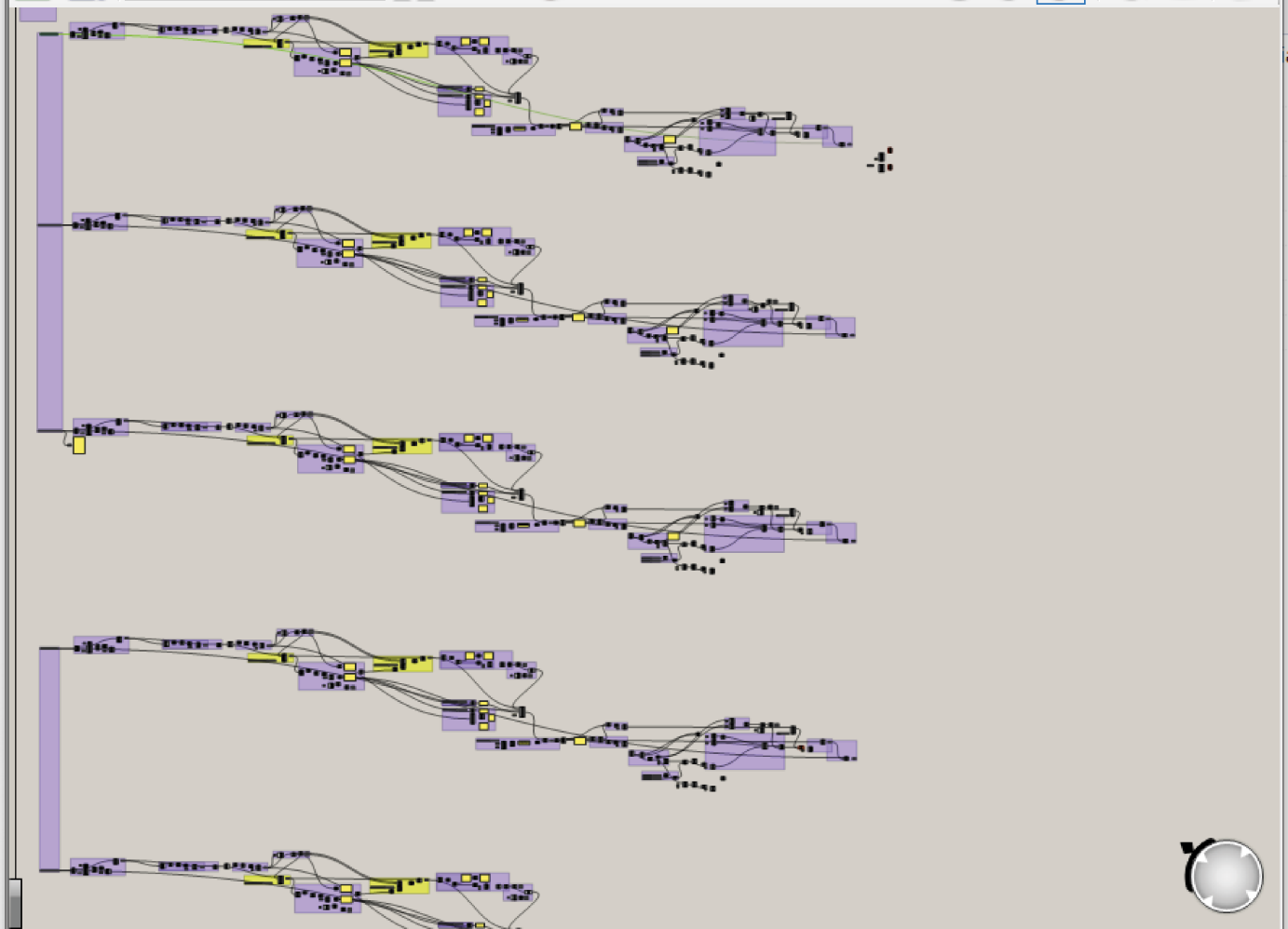
File Edit View Display Solution Help

Parametric_URBAN MODEL simplified

Pm Math Set Vec Crv Srf Msh Int Tms Dis Honeybee DIVA 4 Archsim Fly L K L S A E

Geometry Primitive Input Util

5% 1.0.0007

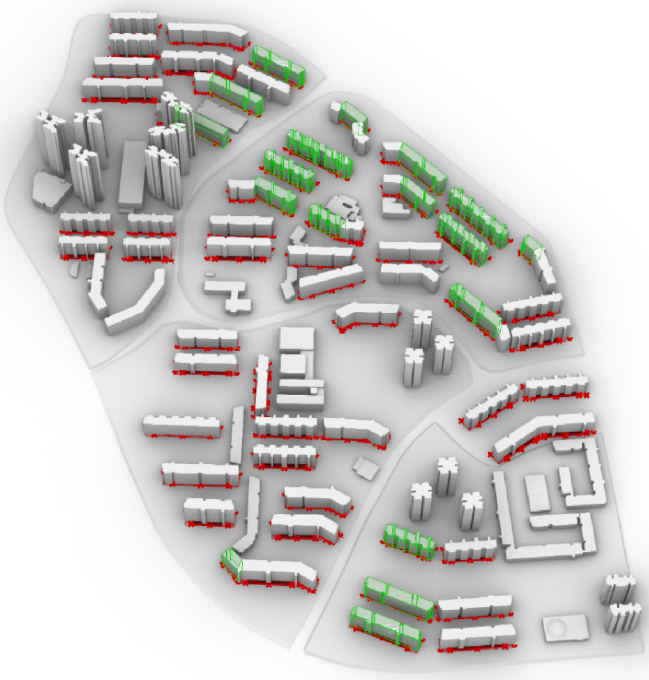


URBAN-SCALE VOID DECK GEOMETRY INTERVENTION

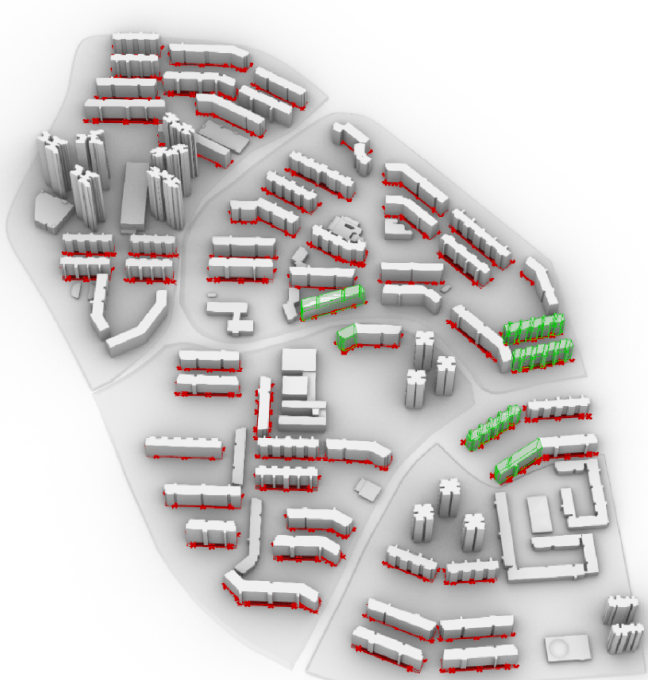
BUILDING GROUPS



BUILDING GROUP 1: buildings perpendicular to wind from N/S



BUILDING GROUP 2: buildings perpendicular to wind from NNE/NE (long blocks)



BUILDING GROUP 5: buildings perpendicular to wind from NW/SE



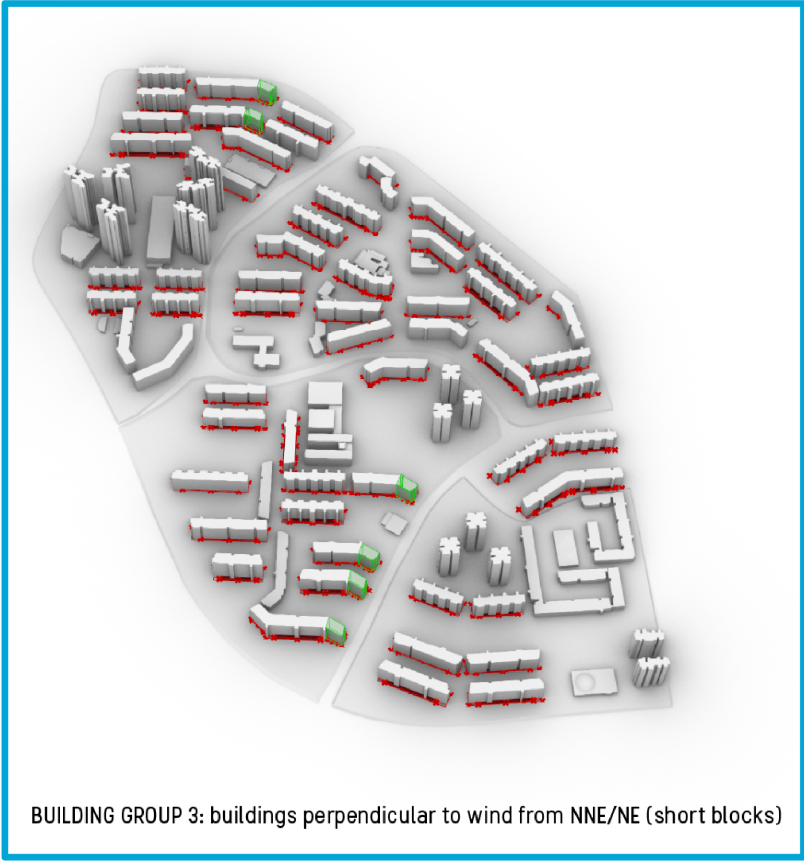
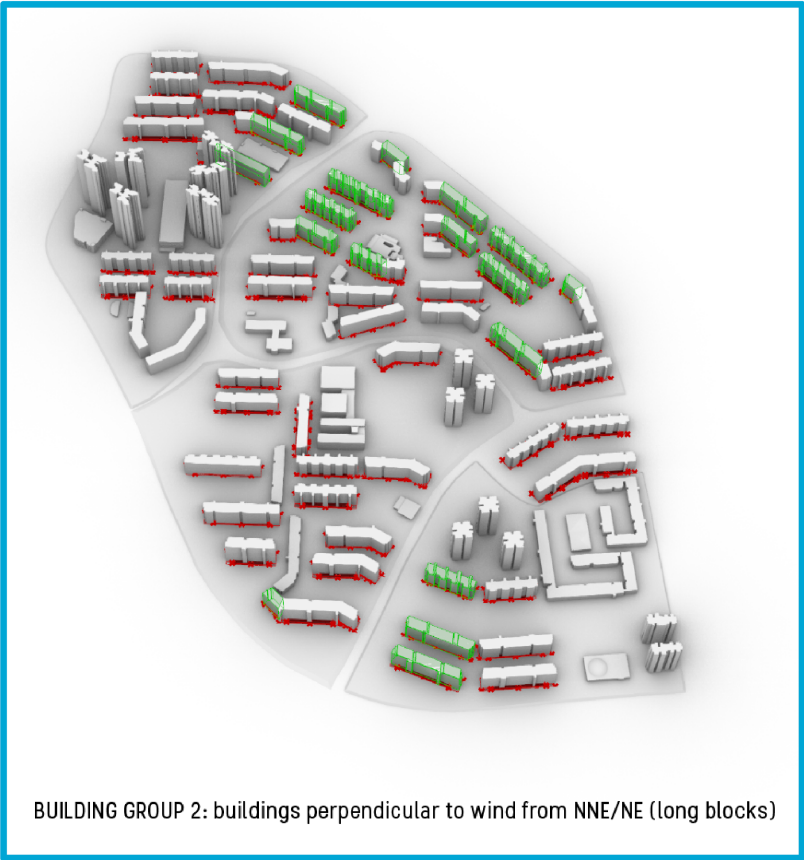
BUILDING GROUP 3: buildings perpendicular to wind from NNE/NE (short blocks)

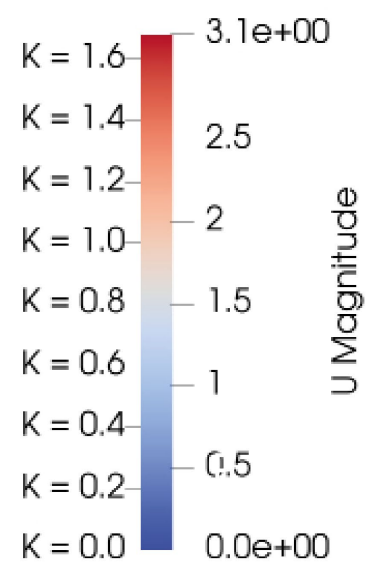


BUILDING GROUP 4: buildings perpendicular to wind from E/W

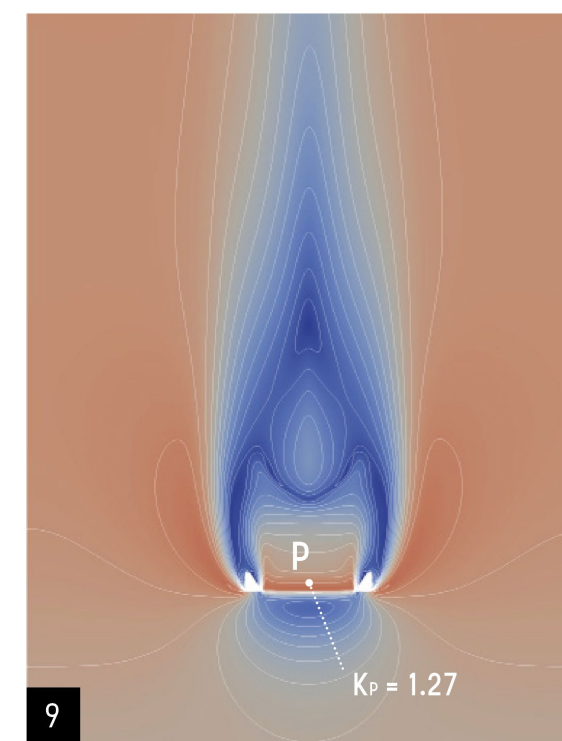
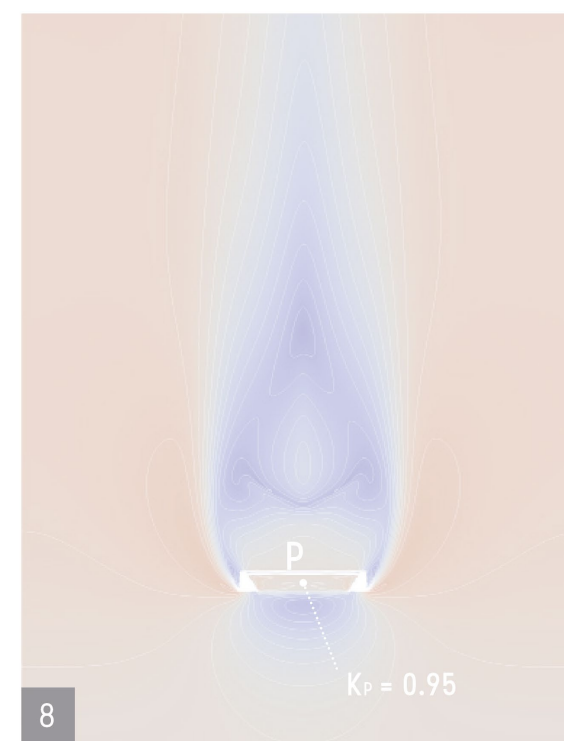
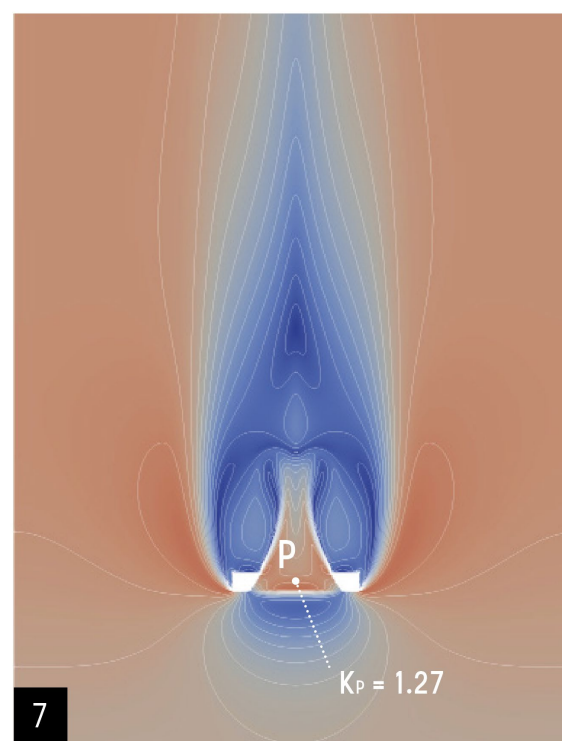
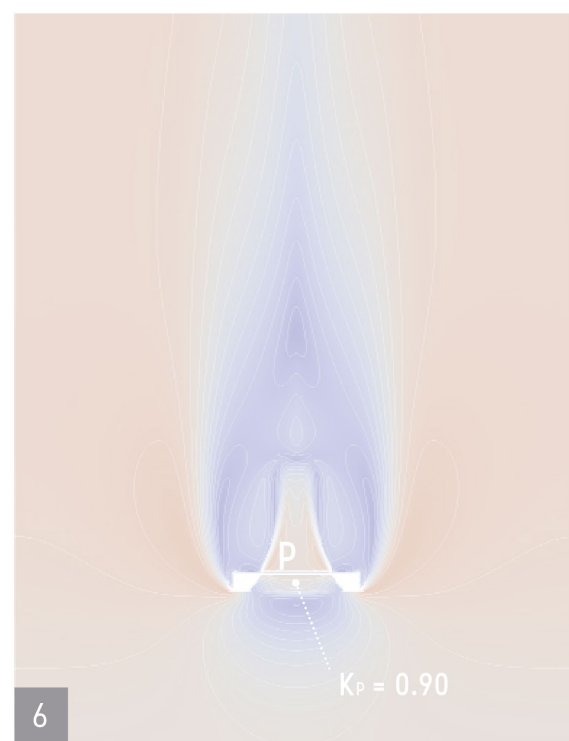
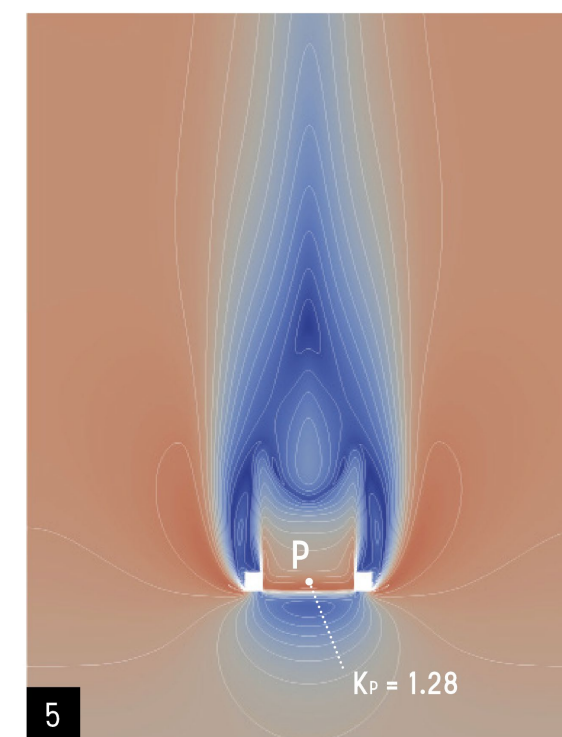
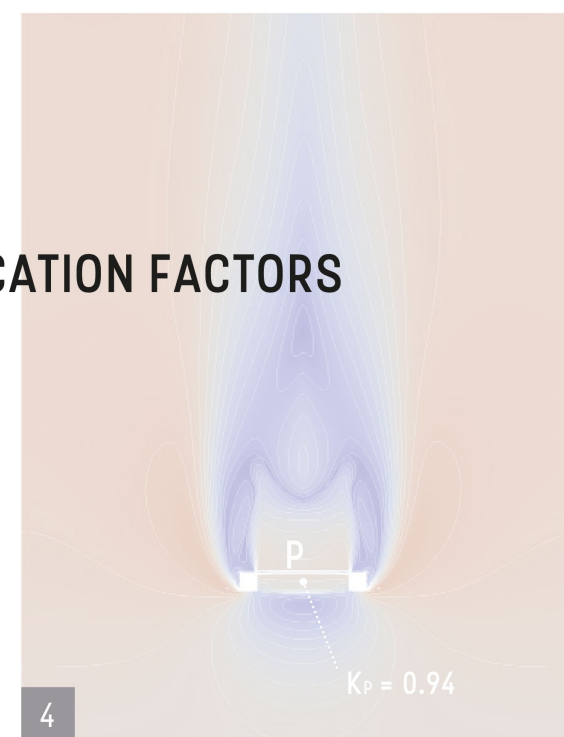
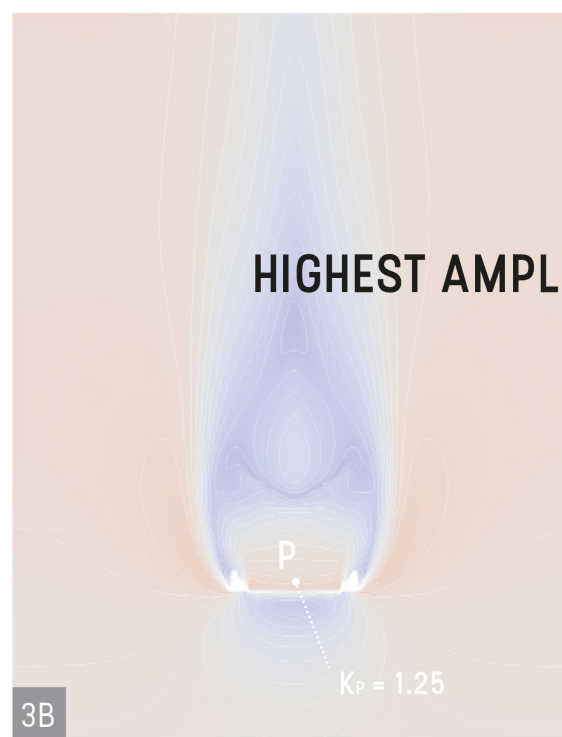
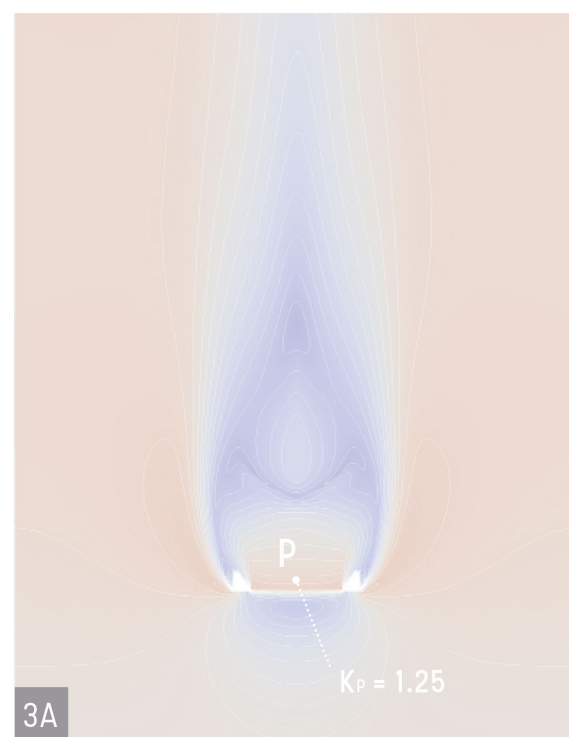
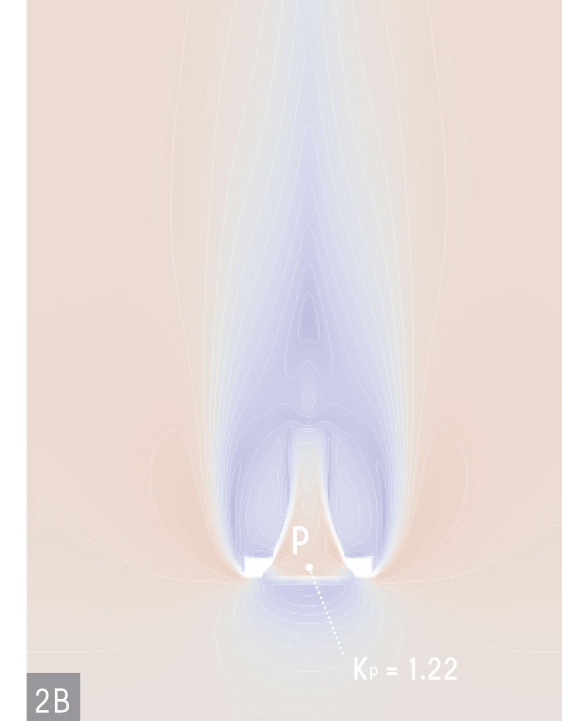
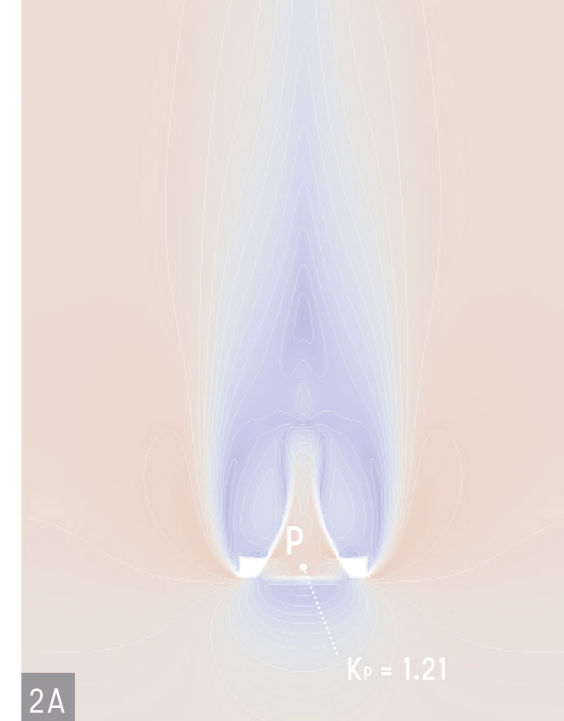
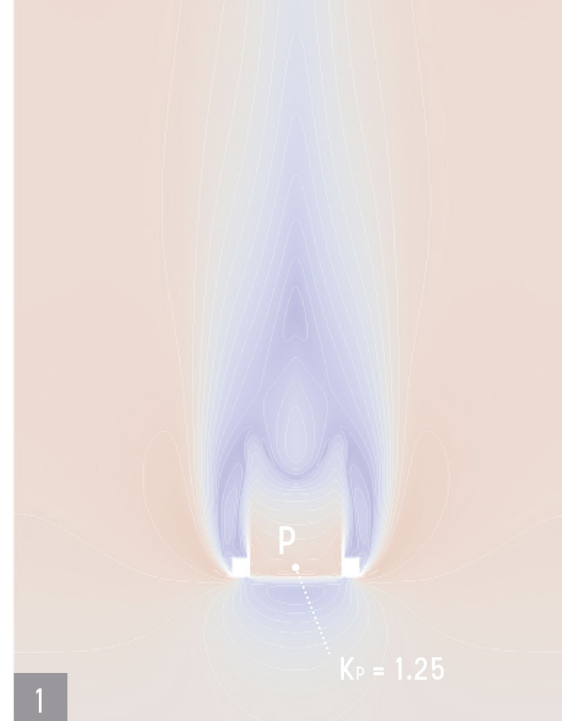
URBAN-SCALE VOID DECK GEOMETRY INTERVENTION

FOCUS BUILDING GROUPS

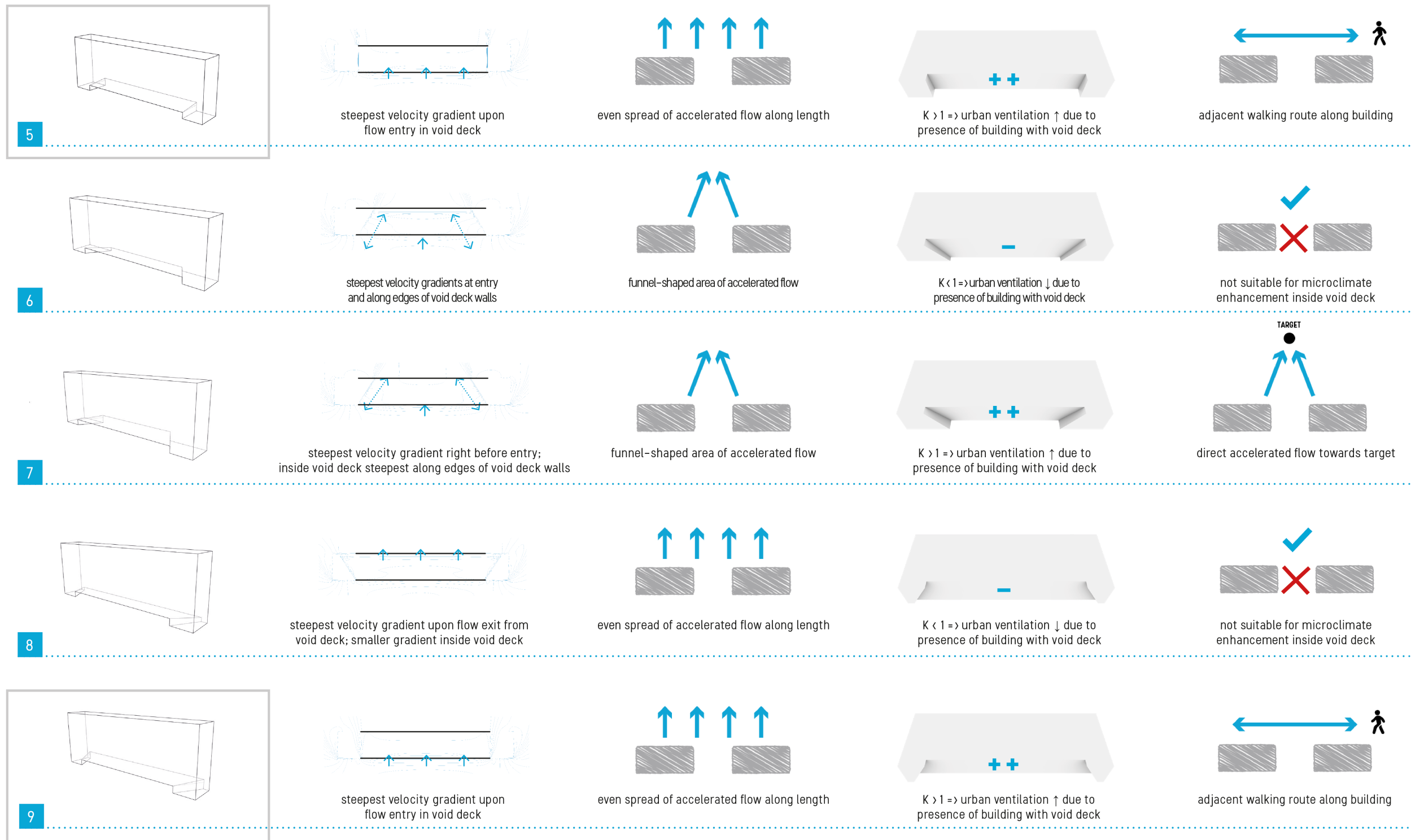




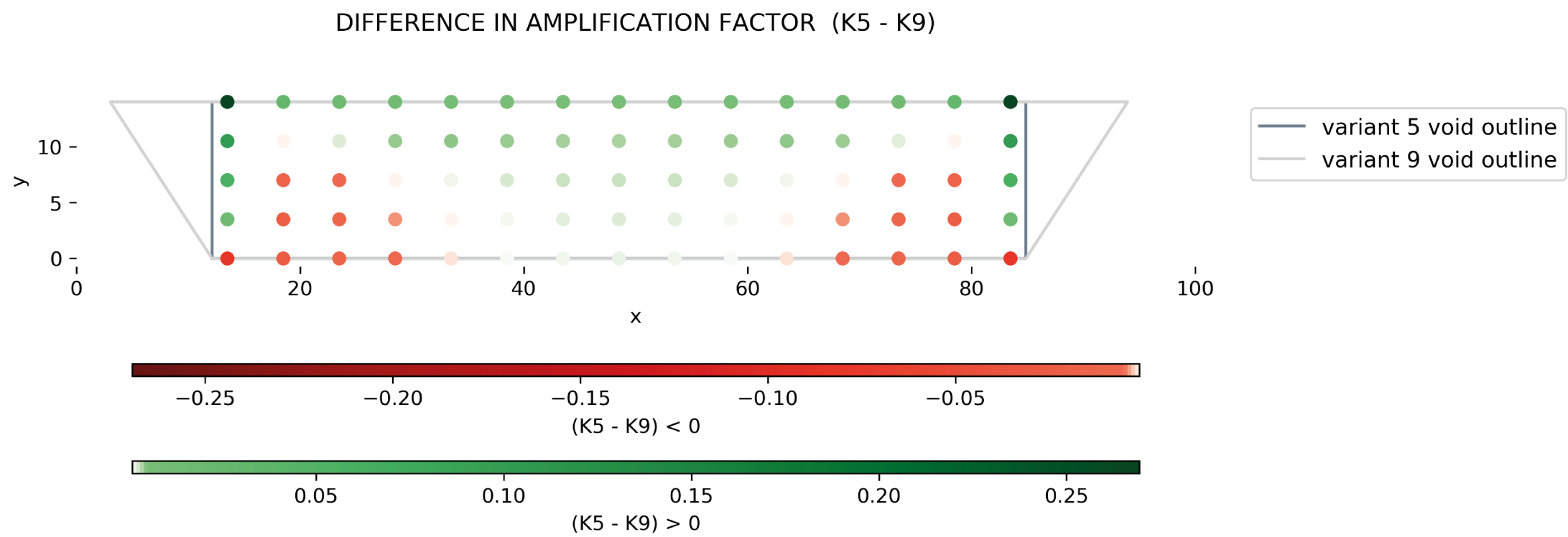
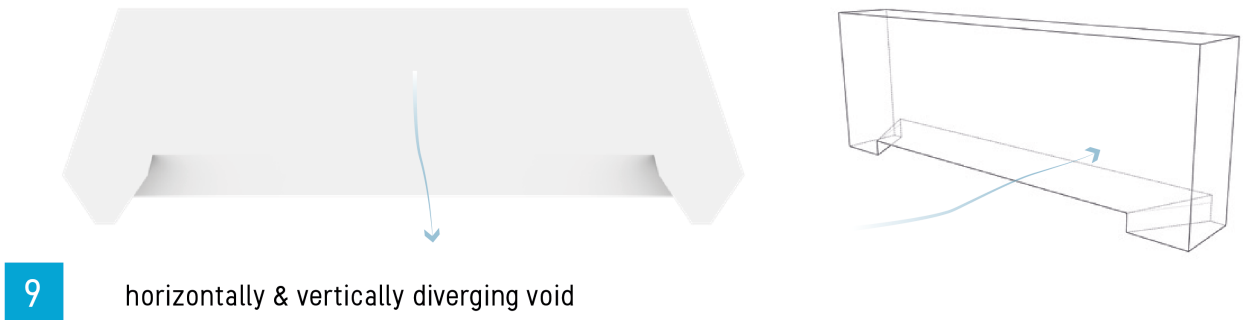
0 AMPLIFICATION FACTOR (plane h=1.75m)



HIGHEST AMPLIFICATION FACTORS



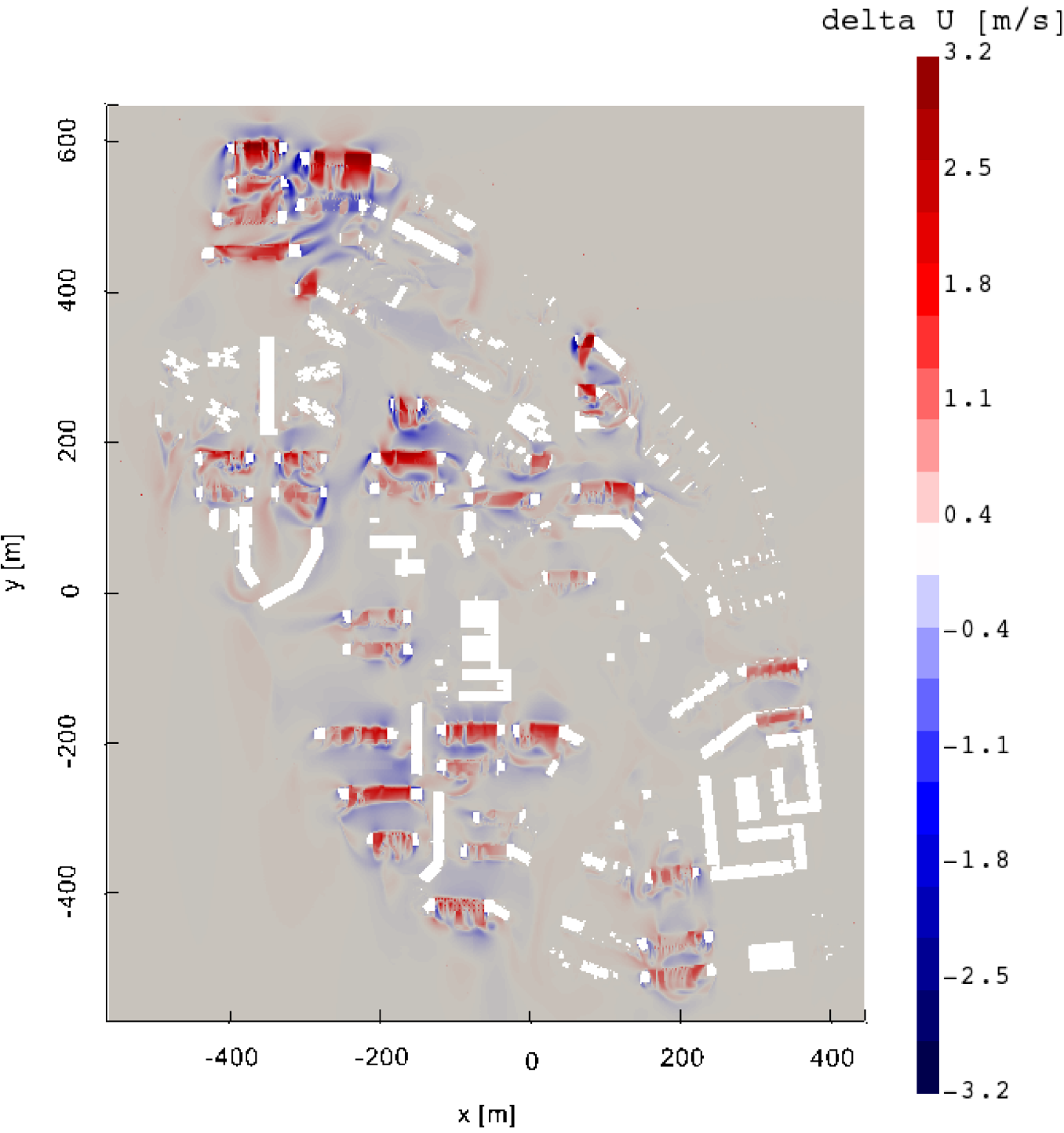
GEOMETRY FOR INTERVENTION



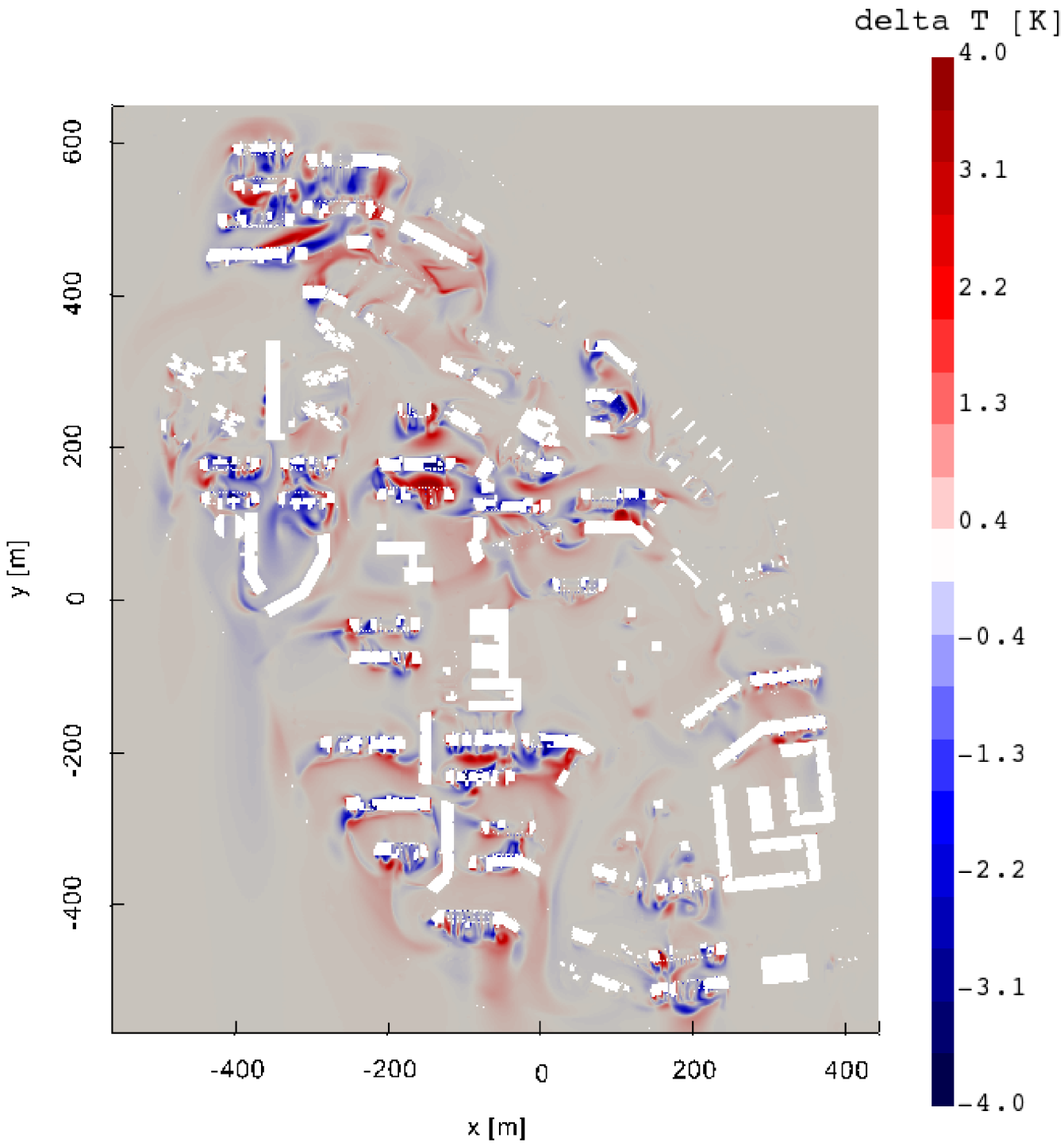
URBAN-SCALE VOID DECK GEOMETRY INTERVENTION



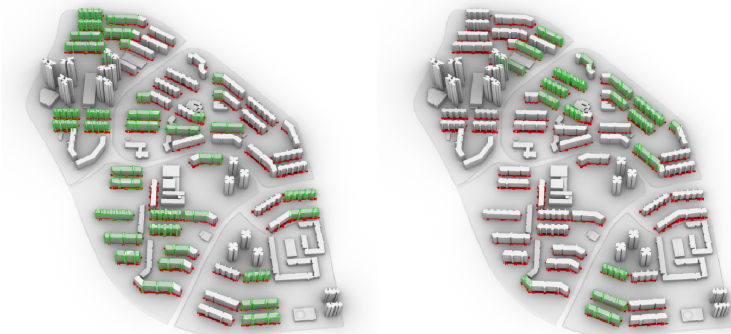
EFFECT ON VELOCITY



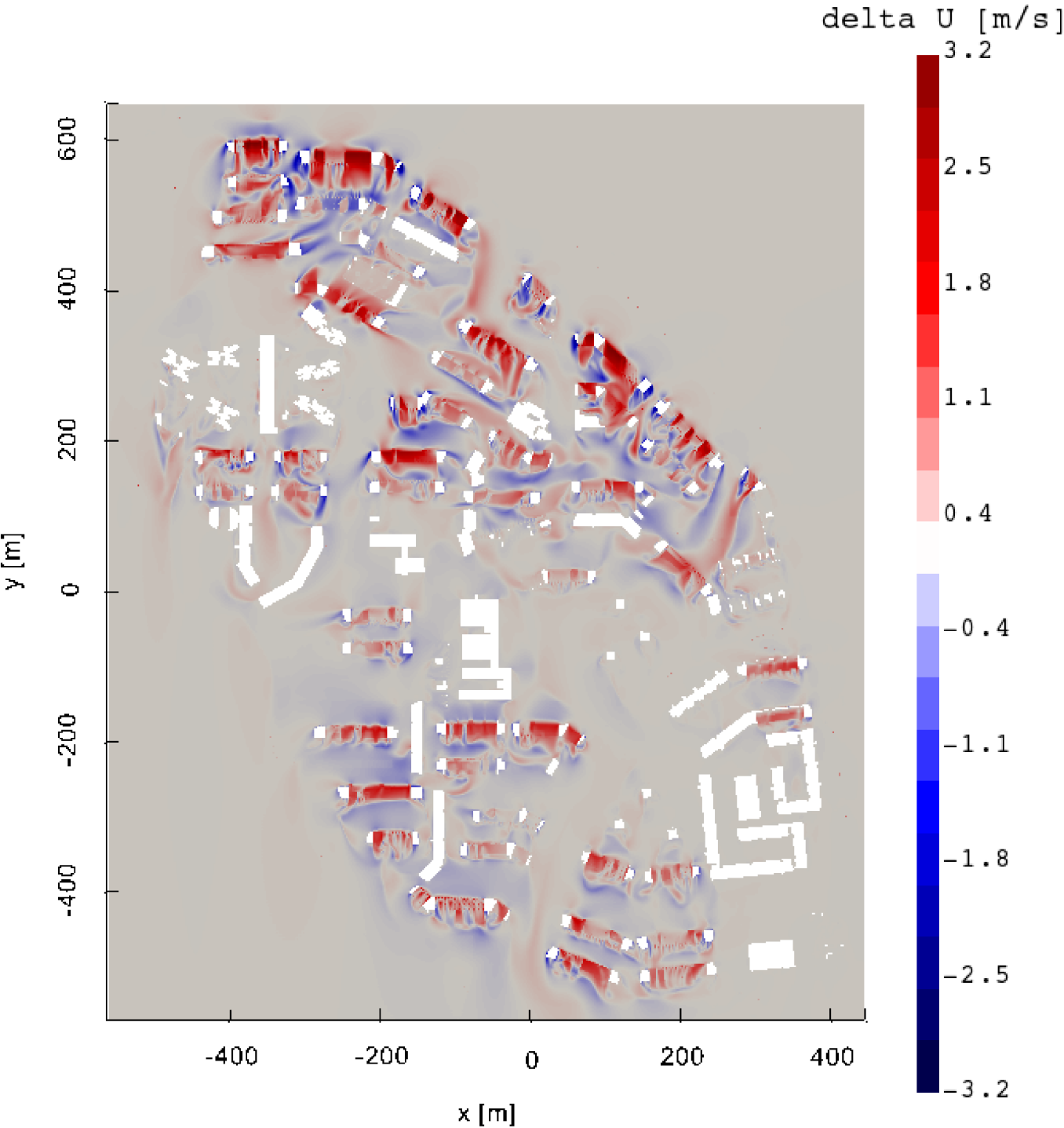
EFFECT ON TEMPERATURE



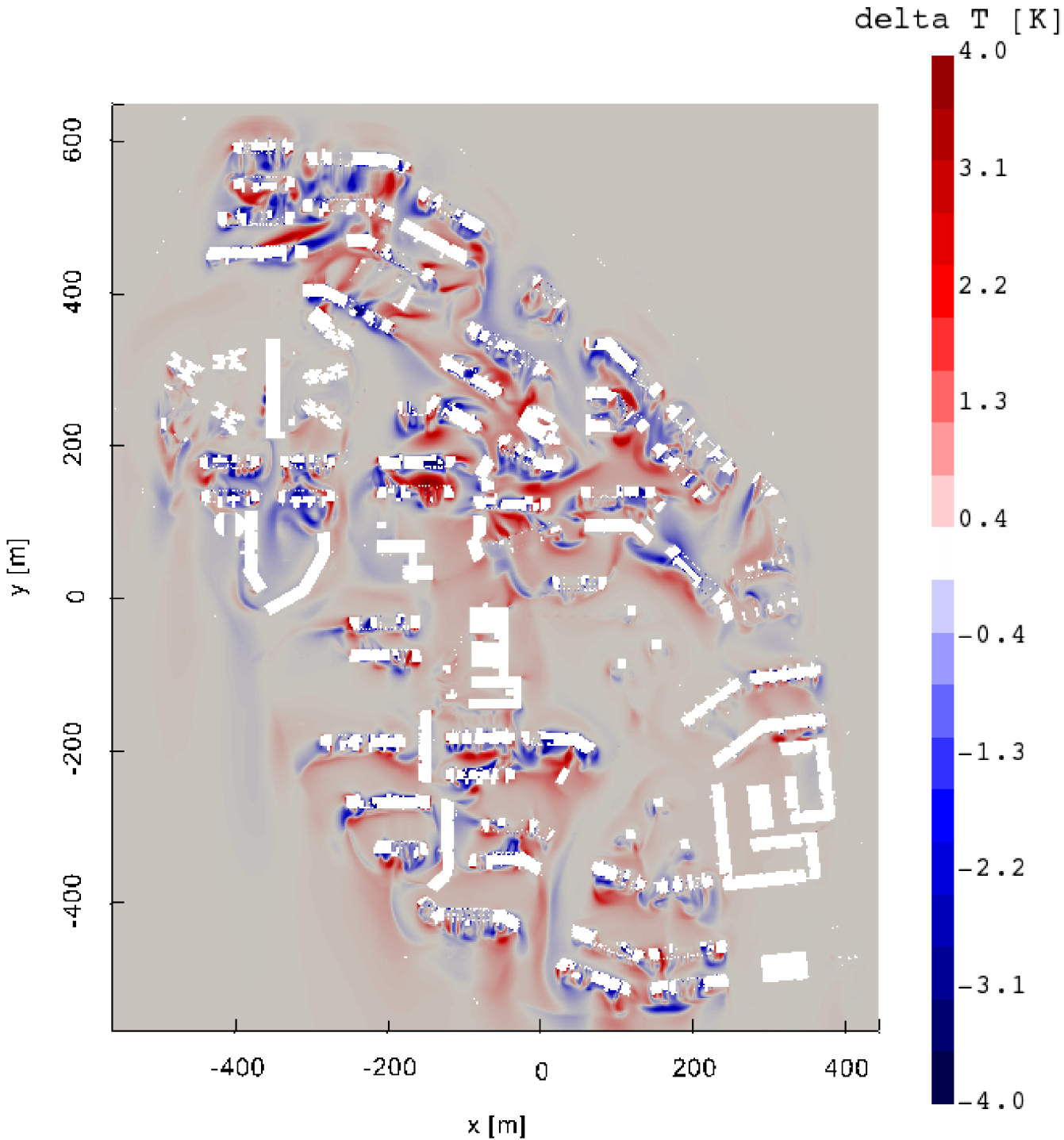
URBAN-SCALE VOID DECK GEOMETRY INTERVENTION



EFFECT ON VELOCITY



EFFECT ON TEMPERATURE

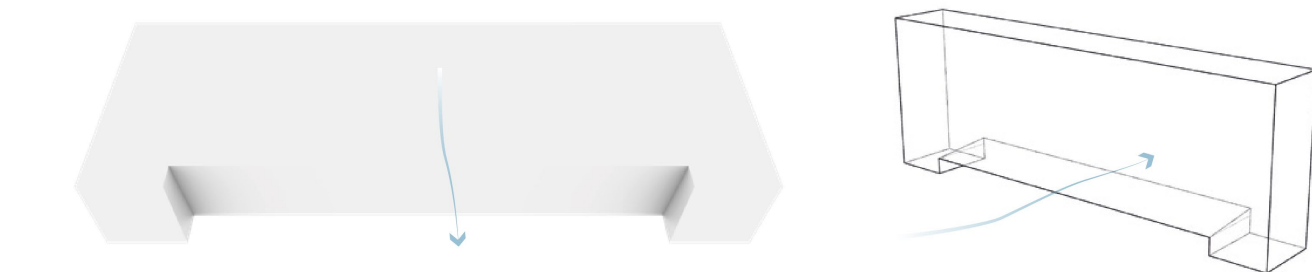


MAIN RESEARCH QUESTION:

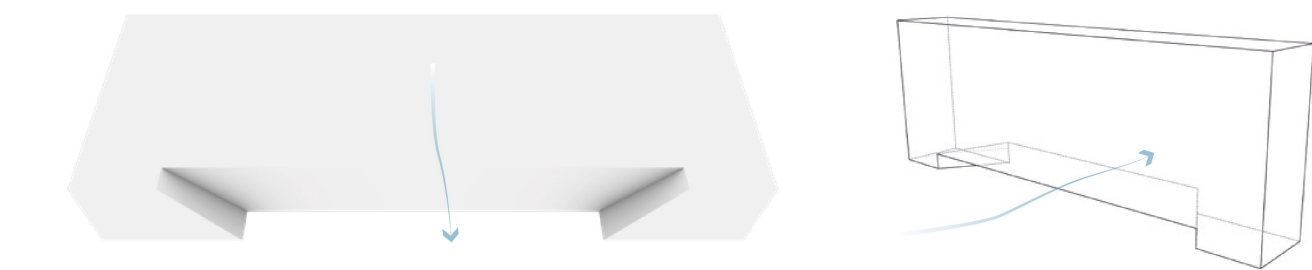
How can the geometry design of void decks be optimized to enhance urban ventilation for outdoor thermal comfort in Singapore while ensuring good pedestrian comfort?

-● Void decks affect flow pattern, magnitude and direction of wind velocity
=> also temperature distribution
(locally inside void decks & in between buildings)
-● We can optimize geometry of void decks to amplify wind speed as desired
(all tested geometries except vertically converging void decks showed $K > 1$
=> good potential for wind speed – and thus convective surface heat transfer – enhancement)

HOW?



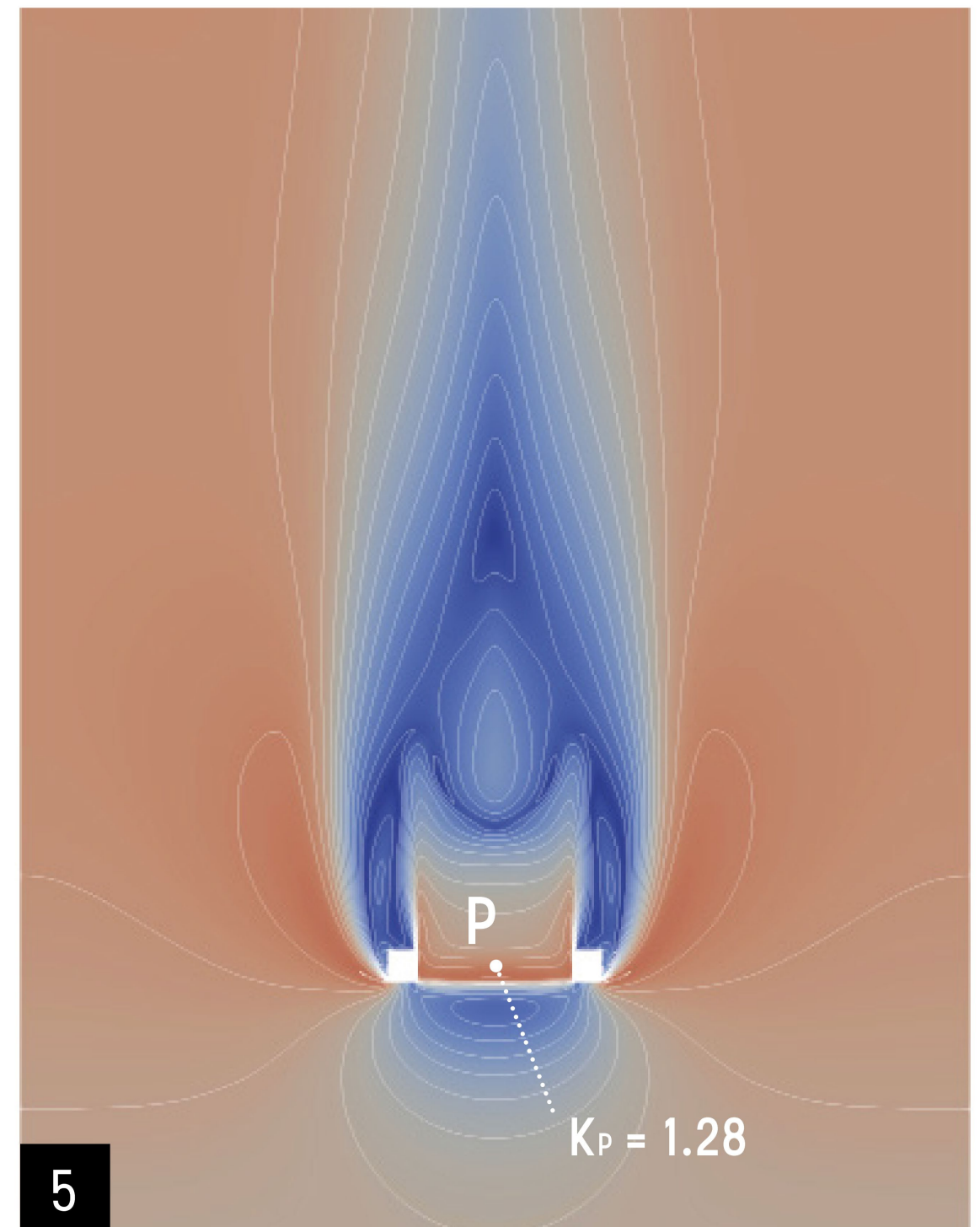
5 vertically diverging void



7 horizontally converging & vertically diverging void



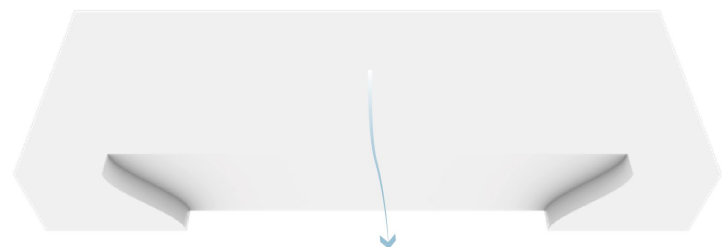
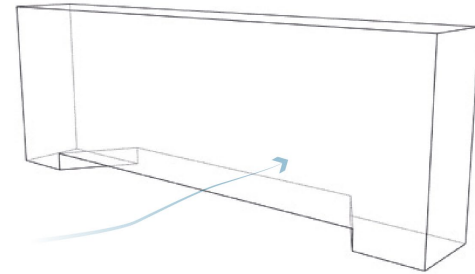
9 horizontally & vertically diverging void



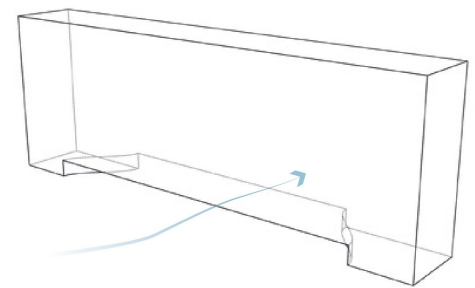
.....● Apply vertically diverging geometry for highest amplification effect in void deck



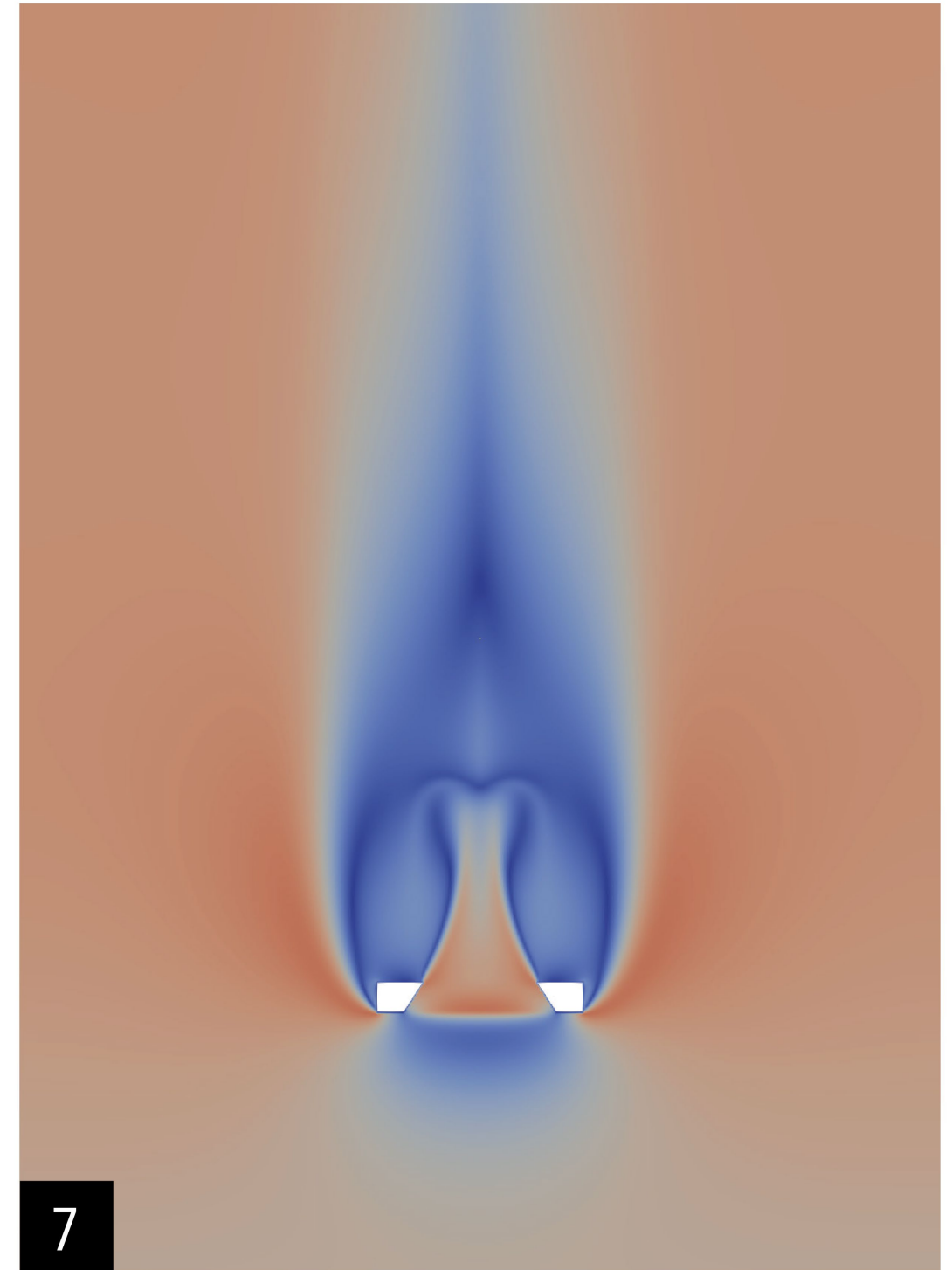
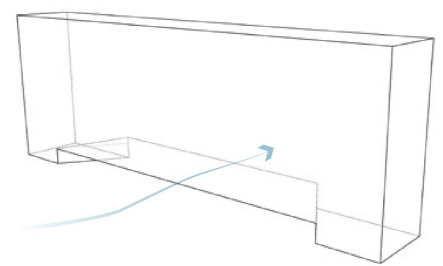
2A horizontally converging void (straight taper)



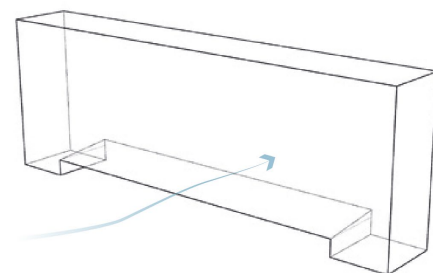
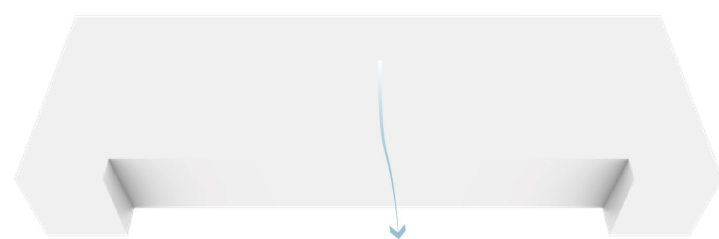
2B horizontally converging void (curved taper)



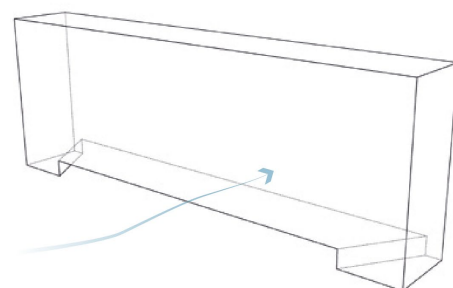
7 horizontally converging & vertically diverging void



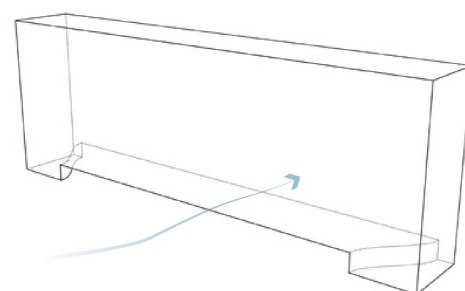
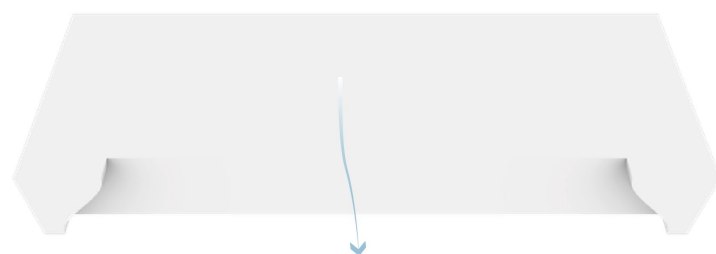
- Apply horizontally converging geometry and/or small void deck elements to direct flow towards location with high ventilation demand (e.g. sports field)



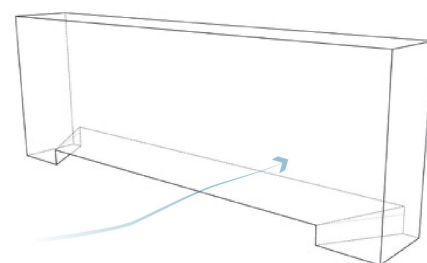
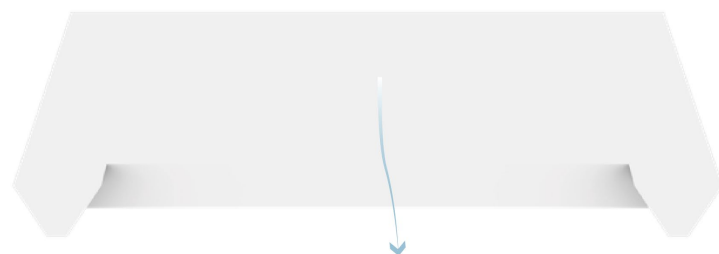
5 vertically diverging void



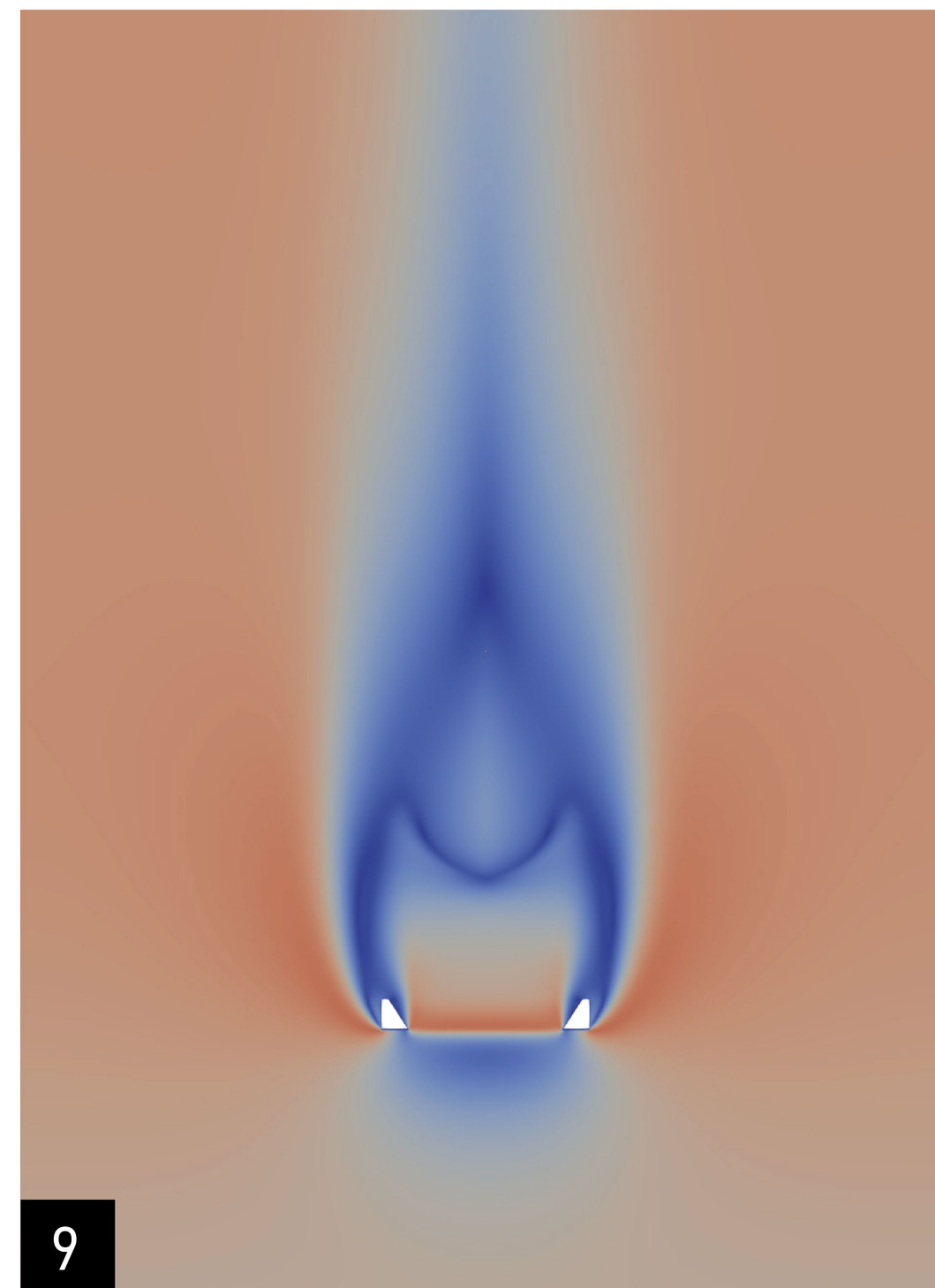
3A horizontally diverging void (straight taper)



3B horizontally diverging void (curved taper)



9 horizontally & vertically diverging void



9

.....● Apply horizontally diverging geometry for more evenly spread region of accelerated flow along void length (e.g. adjacent walking routes)

-● Apply wind speed-amplifying void deck geometries in combination with other urban cooling strategies to enhance outdoor thermal comfort in SG (e.g. tall buildings' downdraught effect, evaporative cooling, high-SRI materials)
-● Use workflow based on combination of parametric design & CFD simulation tools to test variants and make better wind-informed design decisions

COMPUTATIONAL DESIGN & SIMULATION WORKFLOW
FOR URBAN WIND MICROCLIMATE ENHANCEMENT



1

PARAMETRIC SMALL-SCALE TESTS

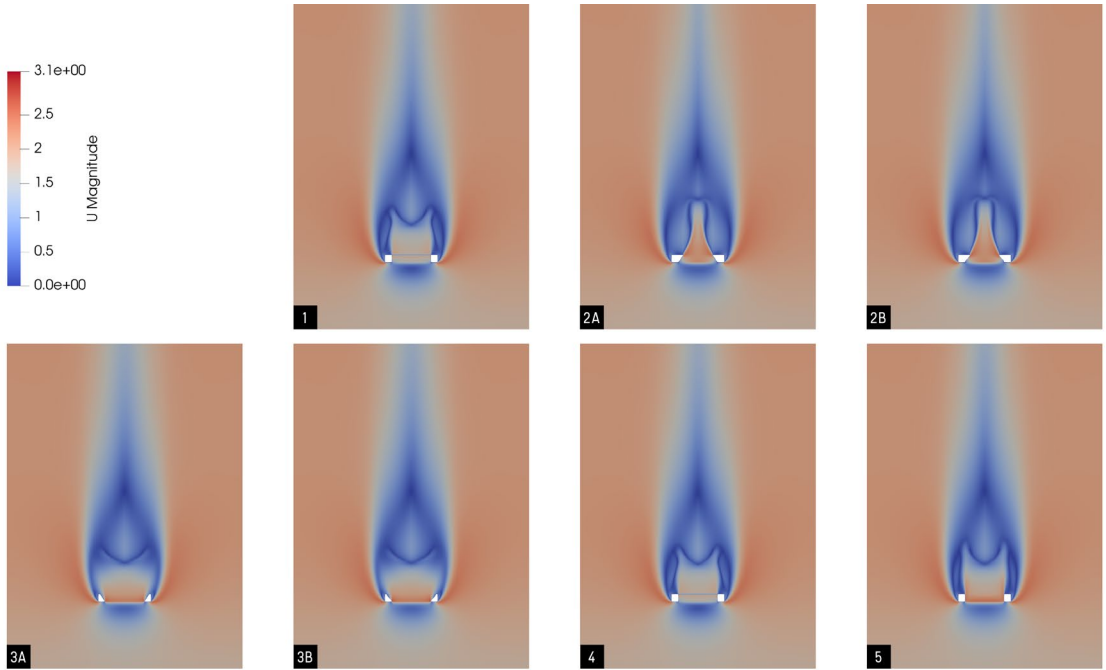
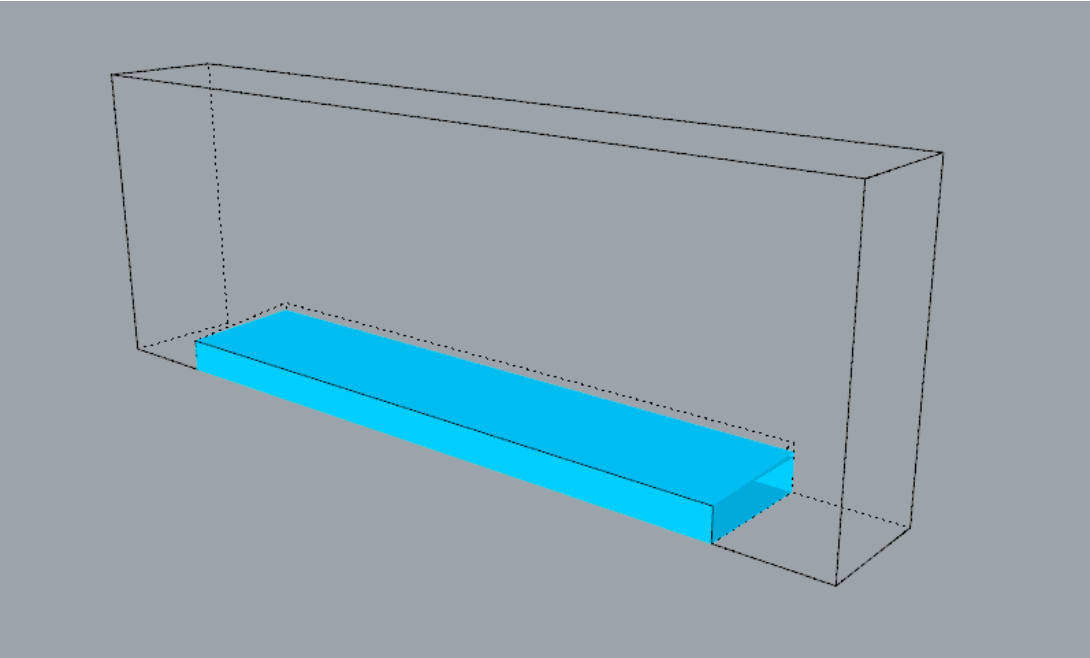
Perform simple CFD-tests on
parametric single-building model

COMPUTATIONAL DESIGN & SIMULATION WORKFLOW FOR URBAN WIND MICROCLIMATE ENHANCEMENT

1

PARAMETRIC SMALL-SCALE TESTS

Perform simple CFD-tests on
parametric single-building model



DESCRIPTION OF FLOW PATTERN				
VARIANT	INSIDE VOID DECK	DOWNSTREAM OF VOID DECK	AMPLIFICATION FACTOR AT CENTRE OF VOID DECK	SUGGESTIONS WITH REGARD TO URBAN PLANNING
4				
5				
6				
7				
8				

COMPUTATIONAL DESIGN & SIMULATION WORKFLOW
FOR URBAN WIND MICROCLIMATE ENHANCEMENT



1

PARAMETRIC SMALL-SCALE TESTS

Perform simple CFD-tests on
parametric single-building model

2

PARAMETRIC LARGE-SCALE INTERVENTION

Apply modifications to building groups
in parametric urban model

COMPUTATIONAL DESIGN & SIMULATION WORKFLOW FOR URBAN WIND MICROCLIMATE ENHANCEMENT

1

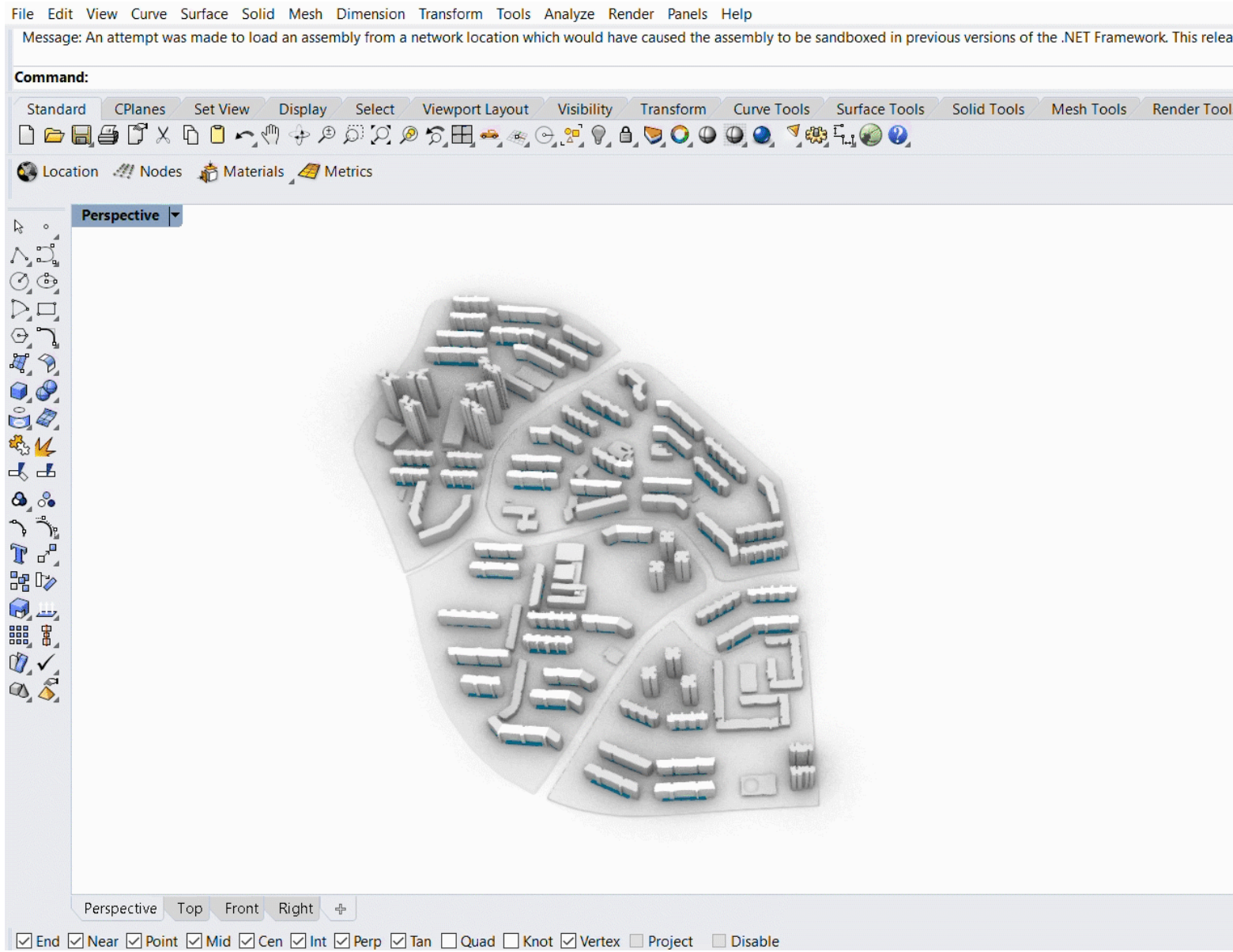
PARAMETRIC SMALL-SCALE TESTS

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URBAN INTERVENTION CFD-SIMULATION

Perform urban intervention CFD-simulation and
analyze results

COMPUTATIONAL DESIGN & SIMULATION WORKFLOW
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```
smoothSolver: Solving for epsilon, Initial residual = 0
smoothSolver: Solving for k, Initial residual = 5.
ExecutionTime = 25.14 s  ClockTime = 25 s
smoothSolver: Solving for Ux, Initial residual = 0
smoothSolver: Solving for Uy, Initial residual = 2
smoothSolver: Solving for Uz, Initial residual = 0
GAMG: Solving for p, Initial residual = 0.0010761
timeStepContinuityErrorsUy, sum local = 645189
smoothSolver: Solving for epsilon, Initial residual = 0
smoothSolver: Solving for k, Initial residual = 4.
ExecutionTime = 25.22 s  ClockTime = 25 s
smoothSolver: Solving for Ux, Initial residual = 0
smoothSolver: Solving for Uy, Initial residual = 2
smoothSolver: Solving for Uz, Initial residual = 0
GAMG: Solving for p, Initial residual = 0.00105182
timeStepContinuityErrorsUy, sum local = 1507086
```

```
View  Insert  Cell  Kernel  Widgets  LaTeX_envs  Help  Trusted  Python 3
[Icons] [Run] [Code]
vertical=True,
position_x=0.9,
position_y=0.1,
n_colors=20)

# BAD COMFORT (unacceptable for some outdoor activities):
discomfort_pedestrianthreshold = clippedU.threshold([2.5001, 15.000]) # U > 2.5 m/s
discomfort_thermalthreshold = clippedT.threshold([305.001, 330.000]) # T_air > 305.0 K
# GOOD COMFORT (acceptable for all outdoor activities):
comfort_pedestrianthreshold = clippedU.threshold([0.000, 2.500]) # U <= 2.5 m/s
comfort_thermalthreshold = clippedT.threshold([285.000, 305.000]) # T_air <= 305.0 K

#

# plotter set-up (create 2 subplots): bad pedestrian vs. good thermal comfort
plotter = pv.Plotter(shape=(1, 2), window_size=[3000,2500], border=False)
plotter.set_background("w")
#plotter.add_mesh(Buildings, 'gray')
#plotter.add_mesh(mosque, 'gray')
#plotter.add_mesh(nursinghome, 'gray')
#plotter.add_mesh(parking, 'gray')
#plotter.add_mesh(schoolcommunitycentre, 'gray')
#plotter.add_mesh(supermarket, 'gray')
#plotter.add_mesh(terrainislands, 'gray')
pv.set_plot_theme("document")

# -----

# upper left subplot: U (bad pedestrian comfort)
plotter.subplot(0, 0)

plotter.add_mesh(clippedU, scalars=U_scalars, title='U [m/s]', scalar_bar_args=sargs, cmap="Greys")
#plotter.add_mesh(discomfort_pedestrianthreshold, title='U [m/s]', cmap="autumn_r") # bad=>red
plotter.show_bounds(xlabel='x [m]', ylabel='y [m]')
#plotter.add_text('PEDESTRIAN WIND DISCOMFORT', font='courier', font_size=9, position='upper_edge')
plotter.view_xy() # plot the xy-plane
plotter.enable_zoom_style() # enable to zoom in the image
```


COMPUTATIONAL DESIGN & SIMULATION WORKFLOW
FOR URBAN WIND MICROCLIMATE ENHANCEMENT

- 
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Perform simple CFD-tests on
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 - 2** **PARAMETRIC LARGE-SCALE INTERVENTION**
Apply modifications to building groups
in parametric urban model
 - 3** **URBAN INTERVENTION CFD-SIMULATION**
Perform urban intervention CFD-simulation and
analyze results
 - 4** **NON-PARAMETRIC LOCAL INTERVENTION**
Apply (non-parametric) modification at particular
location based on results from small-scale tests
and specific activity comfort requirements

COMPUTATIONAL DESIGN & SIMULATION WORKFLOW FOR URBAN WIND MICROCLIMATE ENHANCEMENT

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URBAN INTERVENTION CFD-SIMULATION

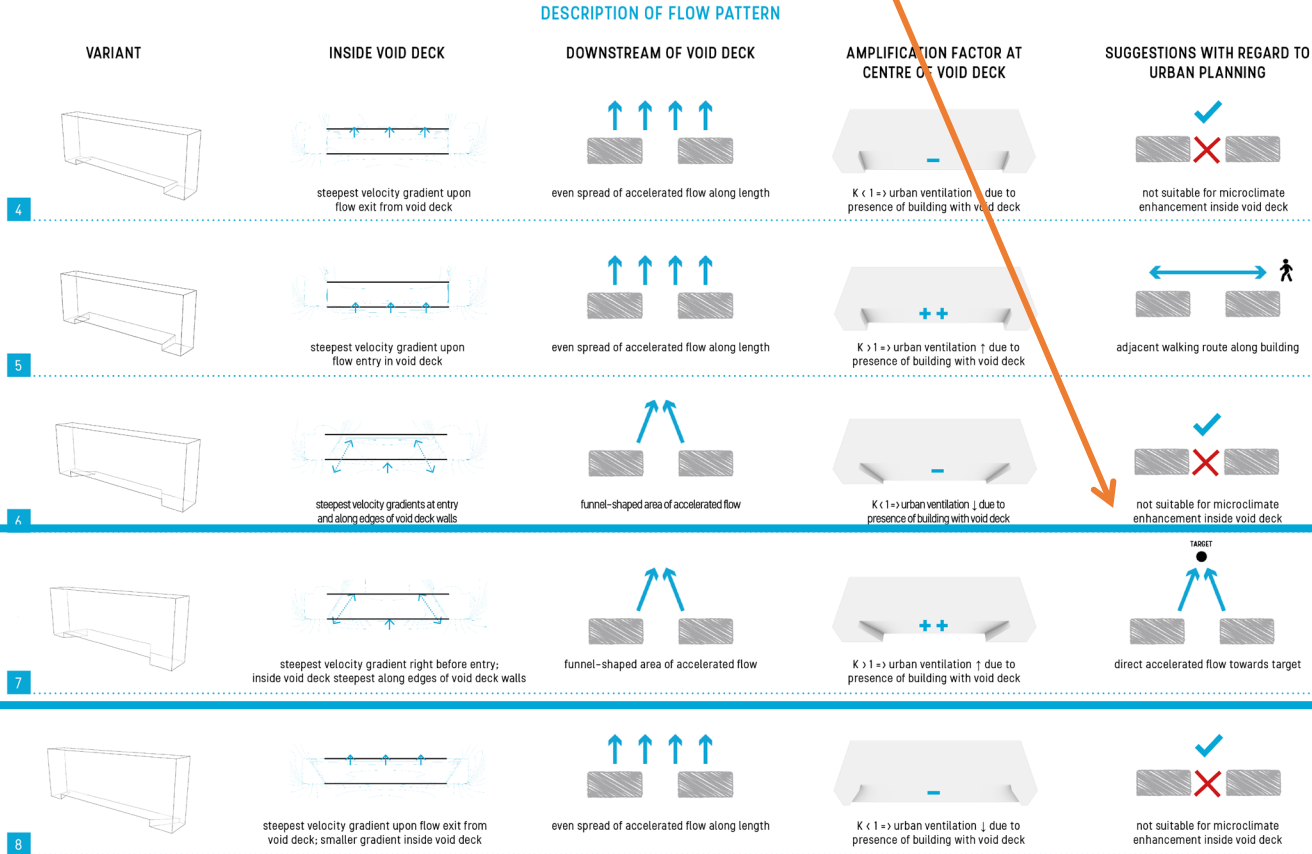
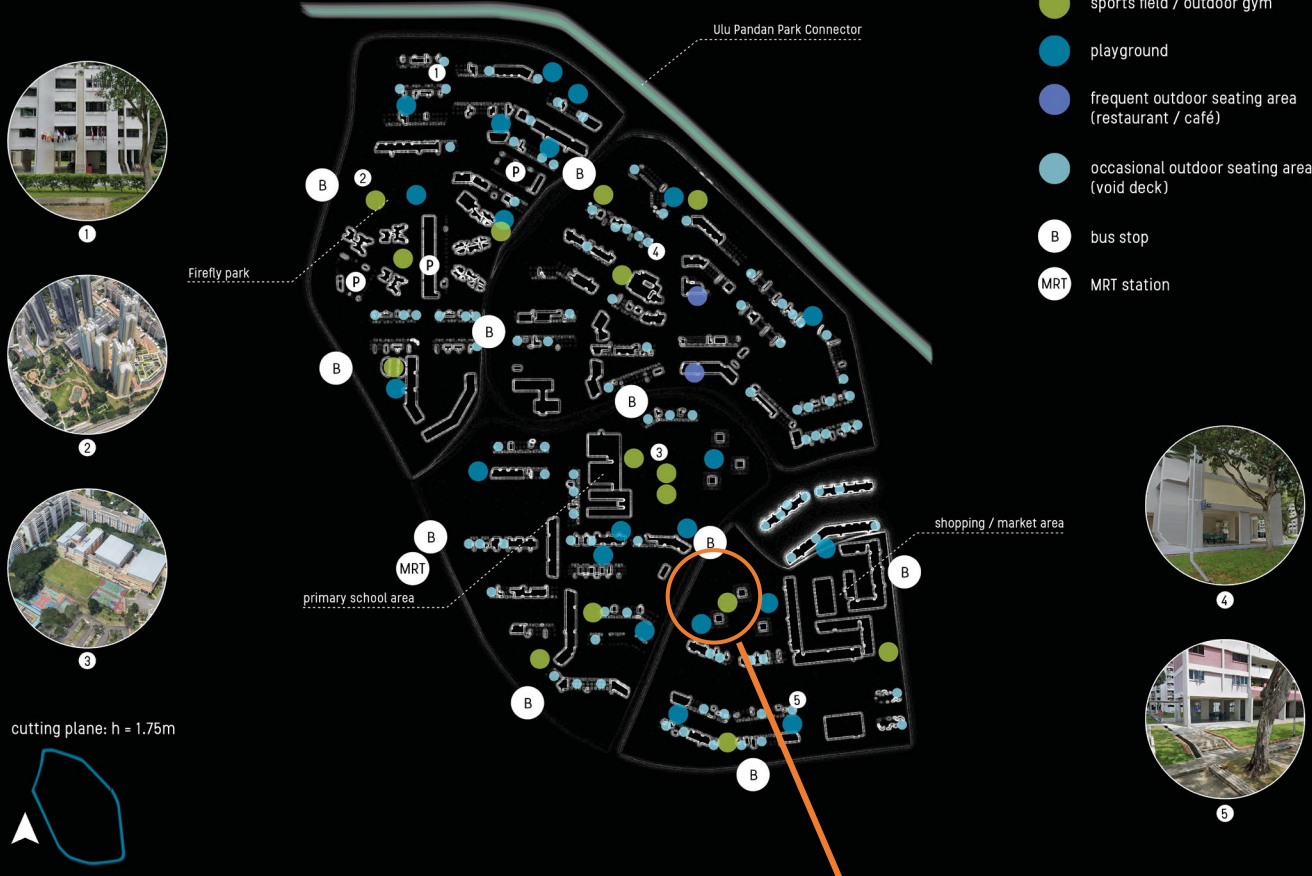
Perform urban intervention CFD-simulation and
analyze results

4

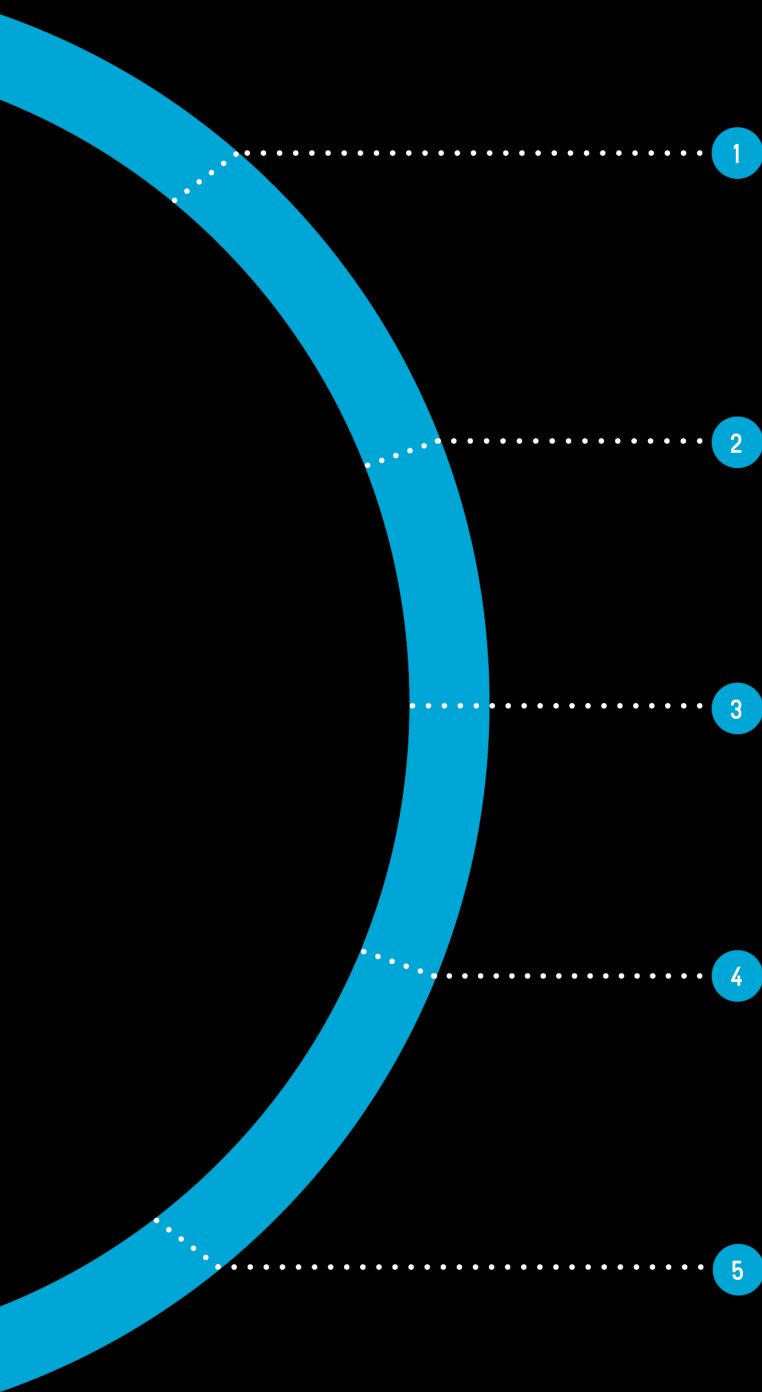
NON-PARAMETRIC LOCAL INTERVENTION

Apply (non-parametric) modification at particular
location based on results from small-scale tests
and specific activity comfort requirements

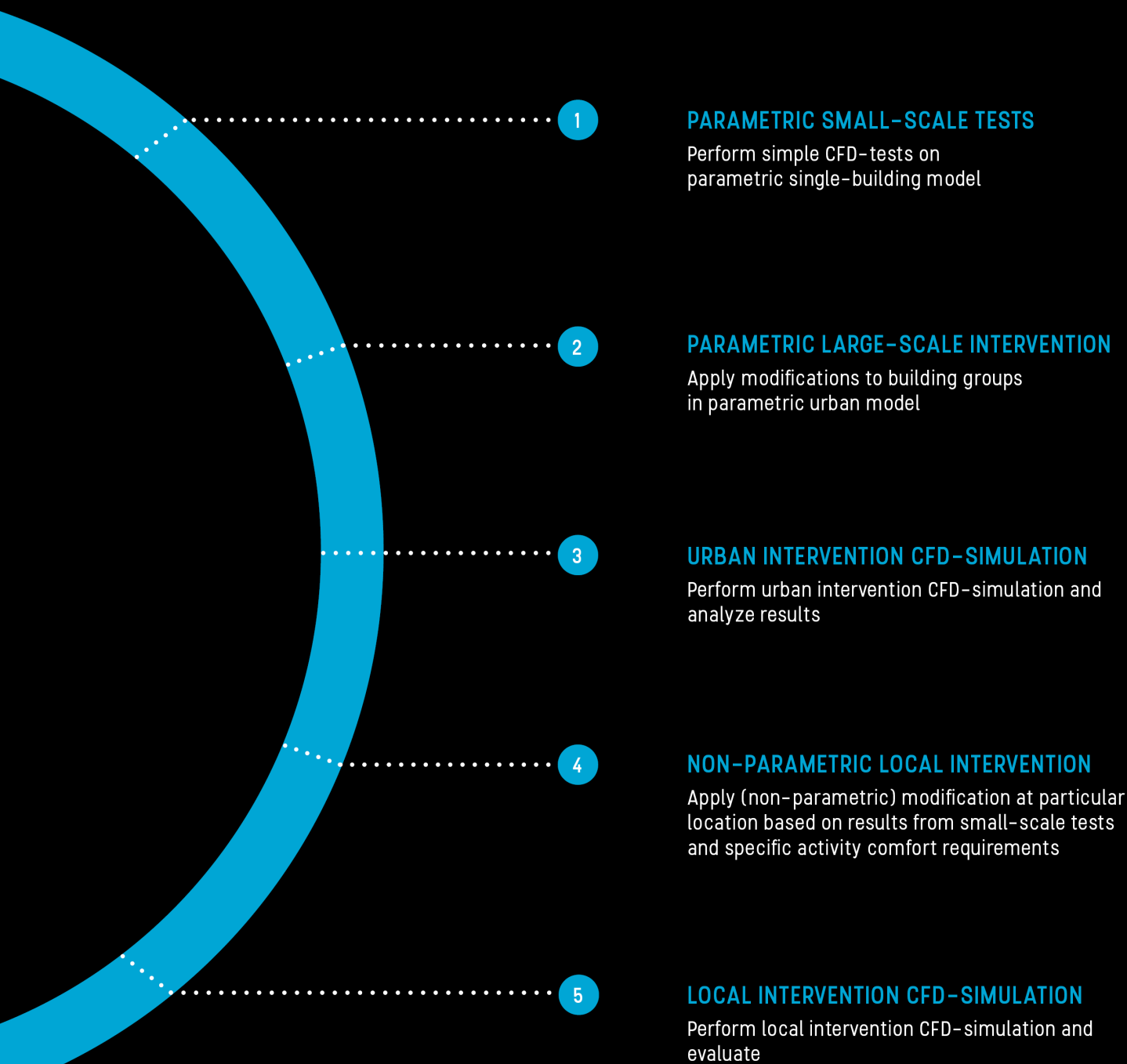
CURRENT ACTIVITY PATTERN



COMPUTATIONAL DESIGN & SIMULATION WORKFLOW
FOR URBAN WIND MICROCLIMATE ENHANCEMENT

- 
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Perform urban intervention CFD-simulation and
analyze results
 - 4** **NON-PARAMETRIC LOCAL INTERVENTION**
Apply (non-parametric) modification at particular
location based on results from small-scale tests
and specific activity comfort requirements
 - 5** **LOCAL INTERVENTION CFD-SIMULATION**
Perform local intervention CFD-simulation and
evaluate

COMPUTATIONAL DESIGN & SIMULATION WORKFLOW
FOR URBAN WIND MICROCLIMATE ENHANCEMENT



● Demonstrated workflow also applicable in optimization process of other building features that may affect the urban wind microclimate (e.g. canopies, building podia)

