Enhancing Urban Environmental Quality through Computational Fluid Dynamics: Case Studies and Methodologies in Green Infrastructure Design

hyphæ design laboratory
Ecological Design & Engineering

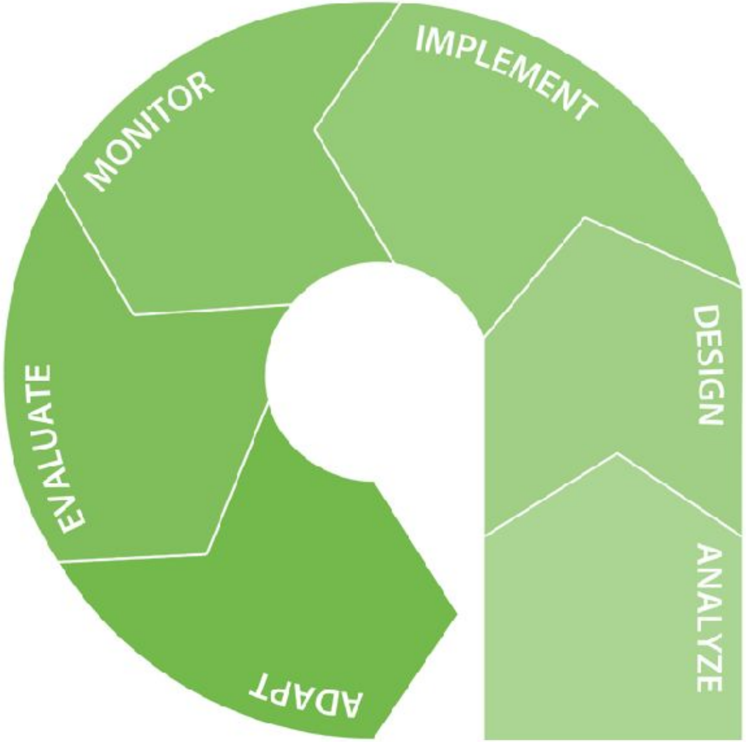
Daniel Fleischer, Lead Researcher
Juan Penaloza Gutierrez

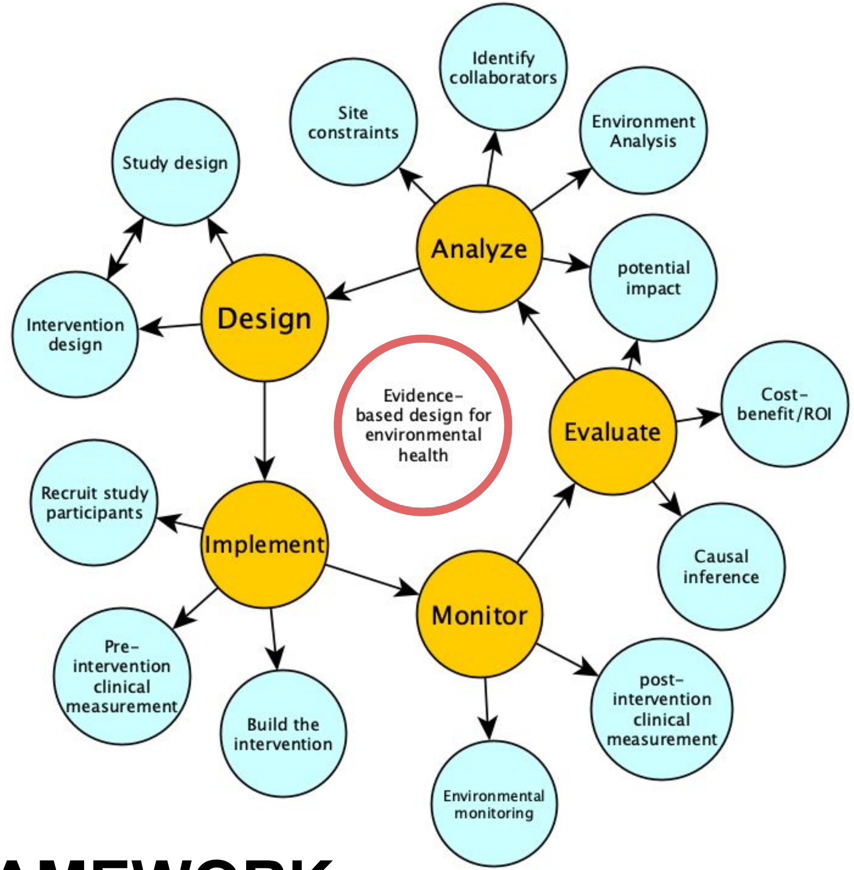
CMAS

Bay Area Air Quality Management District

NSF | America's SEED FUND

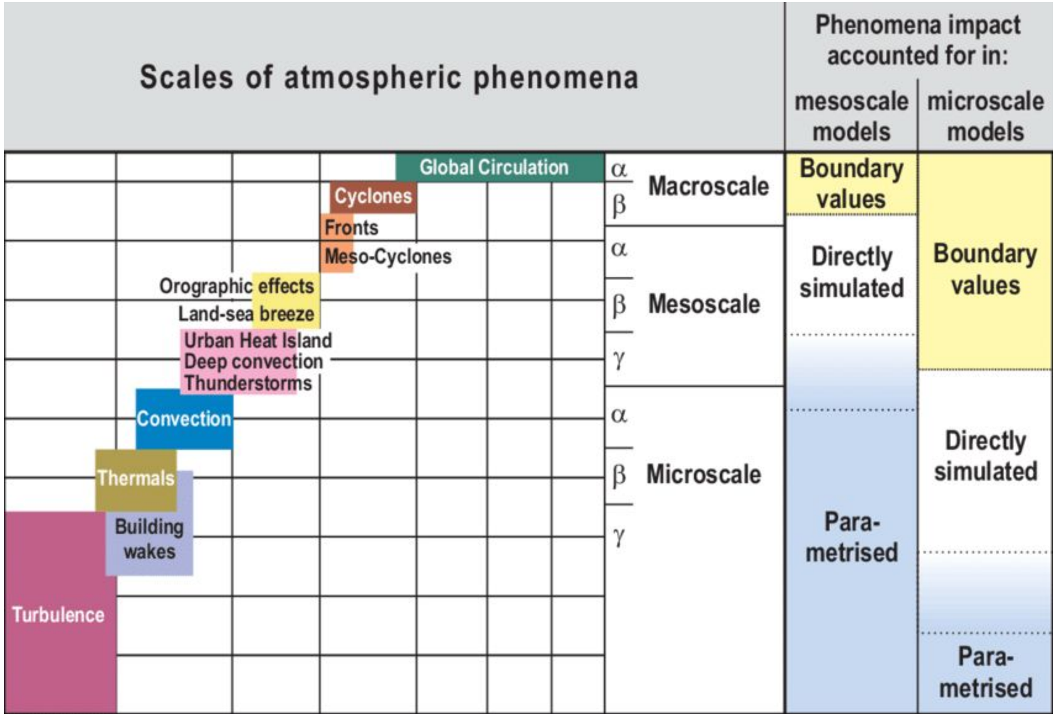
NIH National Institute of Environmental Health Sciences
Your Environment. Your Health.





ADAPT FRAMEWORK

Meso- and Micro-scale models



Scales of atmospheric phenomena (adopted from Schlünzen et al., 2011)

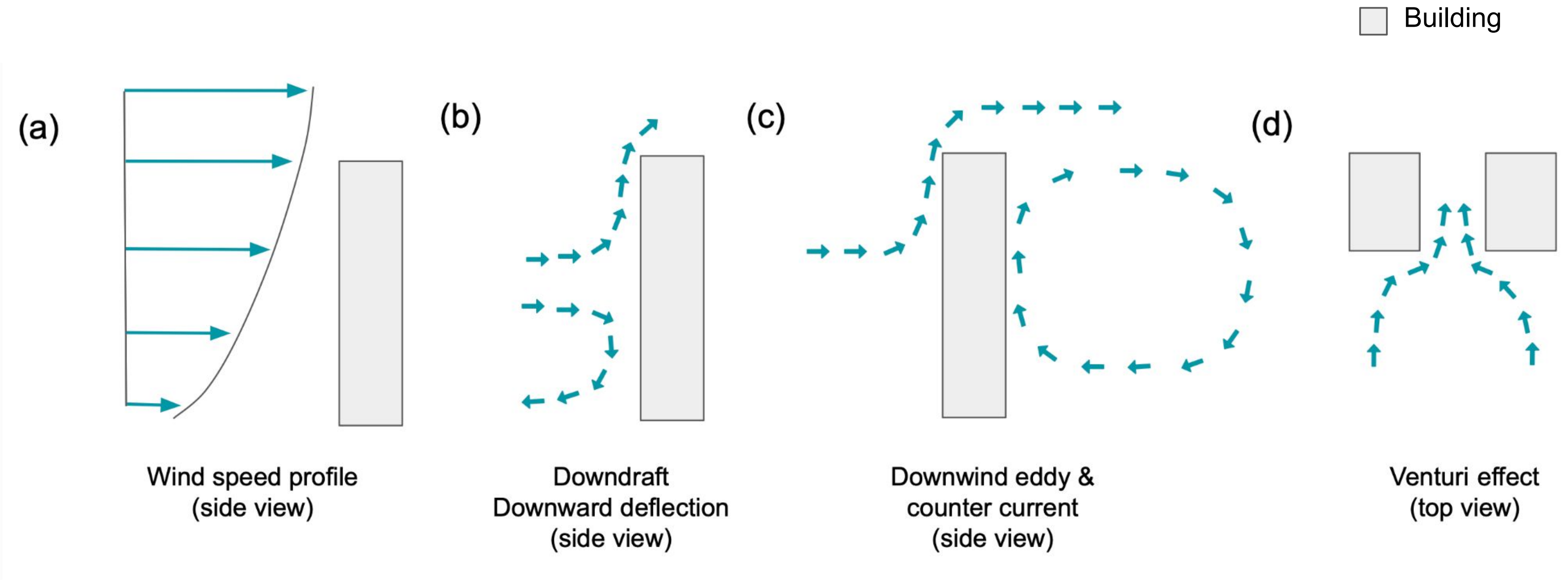


Figure. Basic urban wind effects by structures (e.g., buildings). (a) Wind profile upwind of the building. (b) Upward and downward deflection. (c) Downwind eddy and counter current. (d) Venturi effect (wind speed intensified by gap). Note that (a)-(c) corresponds to the side view of the building; in contrast (d) corresponds to a top view.

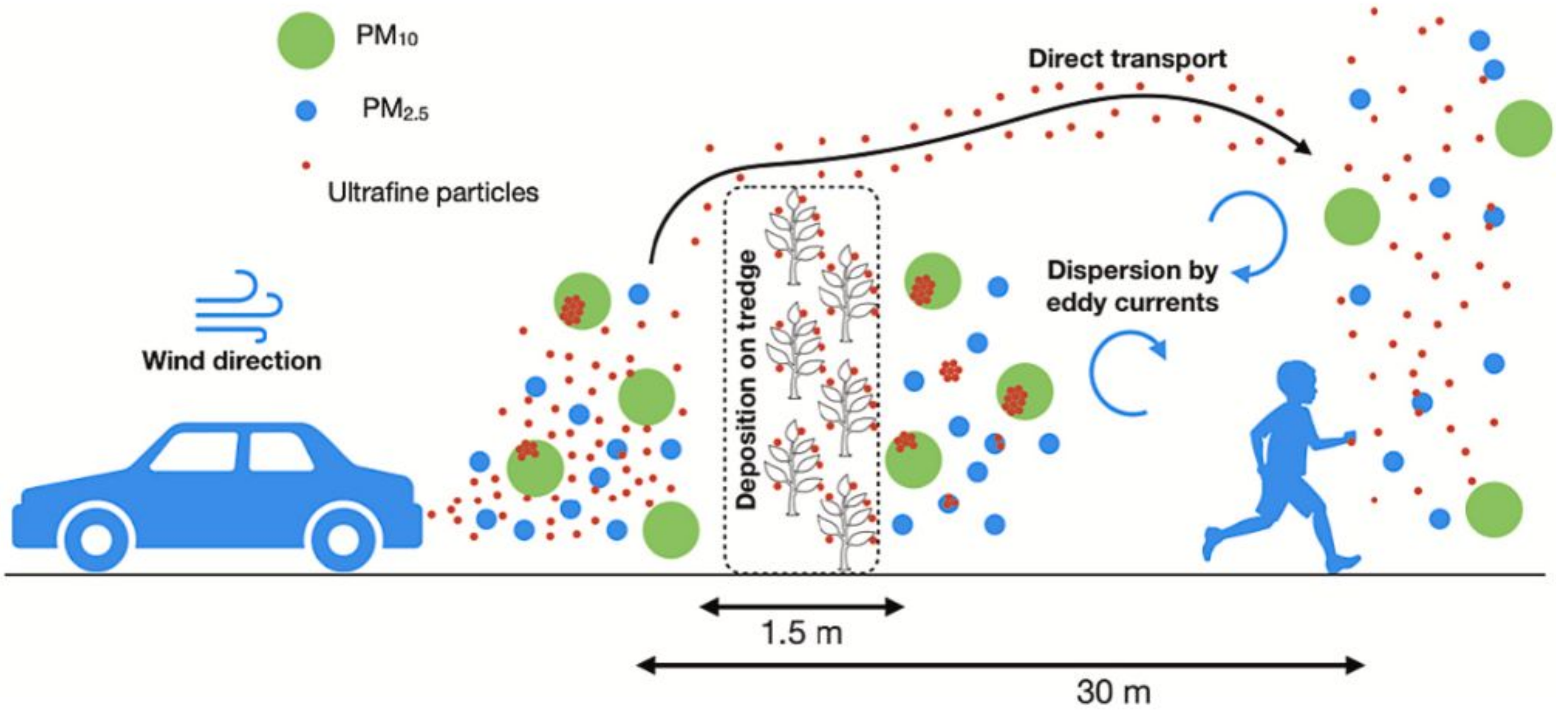


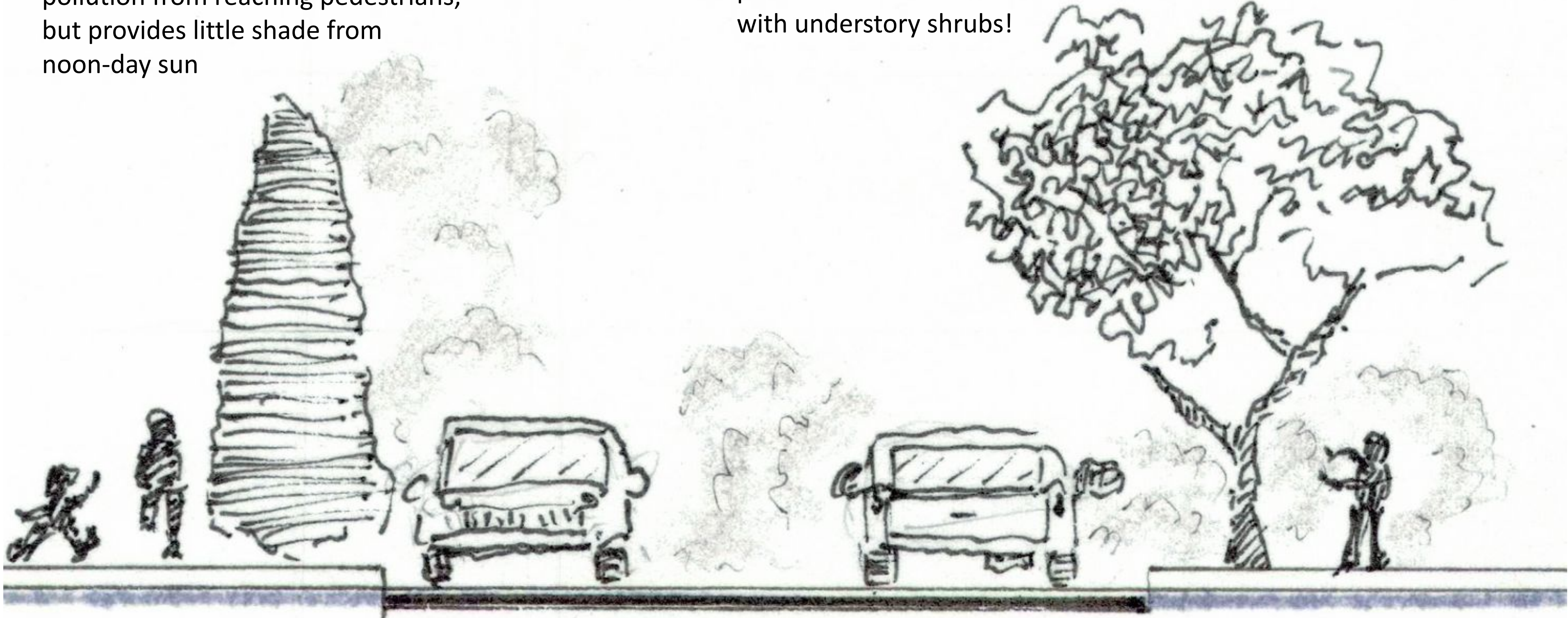
Figure. Basic urban effects by vegetation. PM deposition on leaves reduces downwind exposure. Figure retrieved from Sheikh et al., 2023: Efficacy of green infrastructure in reducing exposure to local, traffic-related sources of airborne particulate matter (PM).

Air pollution vs Heat benefits

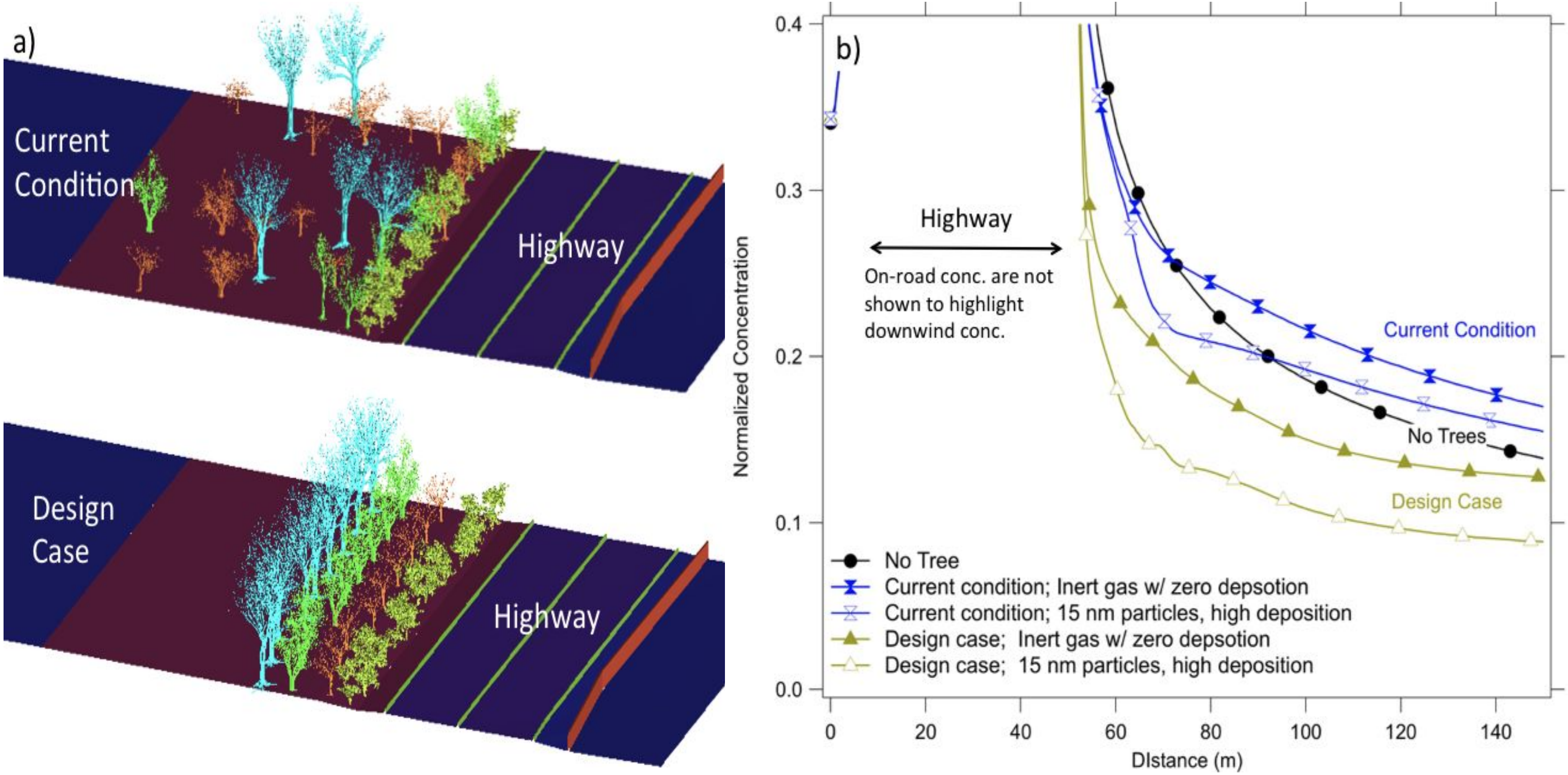
Heat and pollution benefits can be at cross-purposes depending on the location and the tree species, thus carefully matching species / form with location is required to maximize benefits and prevent harm!

This dense, conical conifer blocks pollution from reaching pedestrians, but provides little shade from noon-day sun

This canopy tree traps pollution at ground level, but provides good shade! Maybe it should be planted further from the road or be combined with understory shrubs!

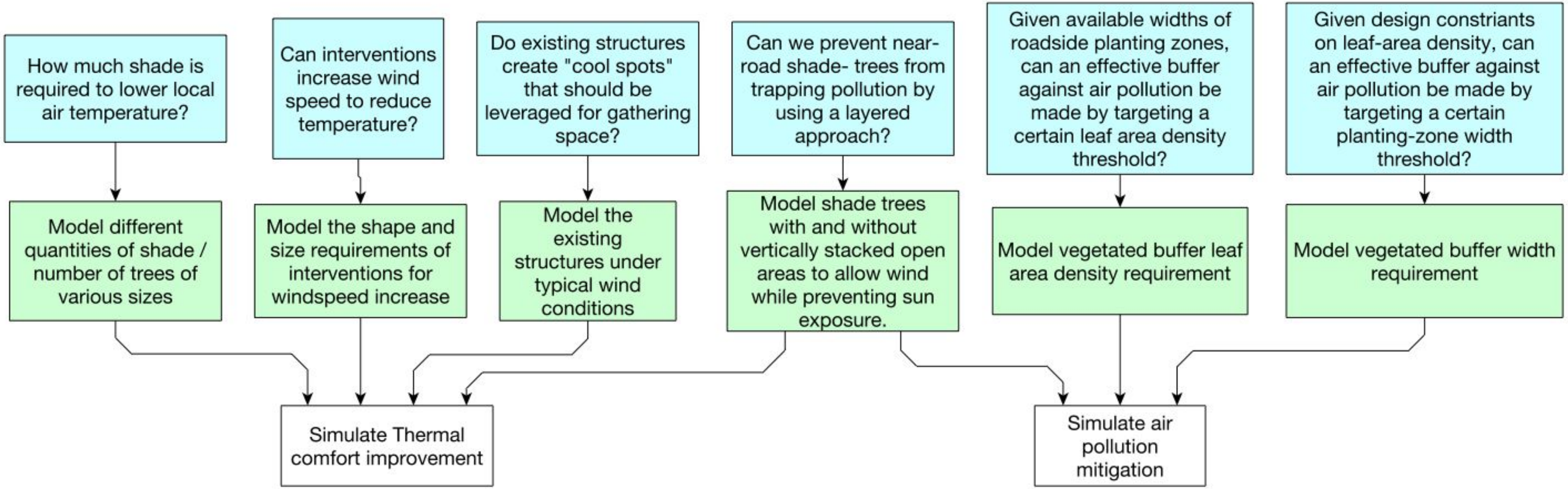


Tree placement can determine harms or benefits of trees WRT air pollution



Identical tree inventory results in worse air pollution than no trees when placed randomly, but improves air quality when placed in structured rows! (Figure produced by Dr. Max Zhang using CTAG)

Design Questions: Modelling



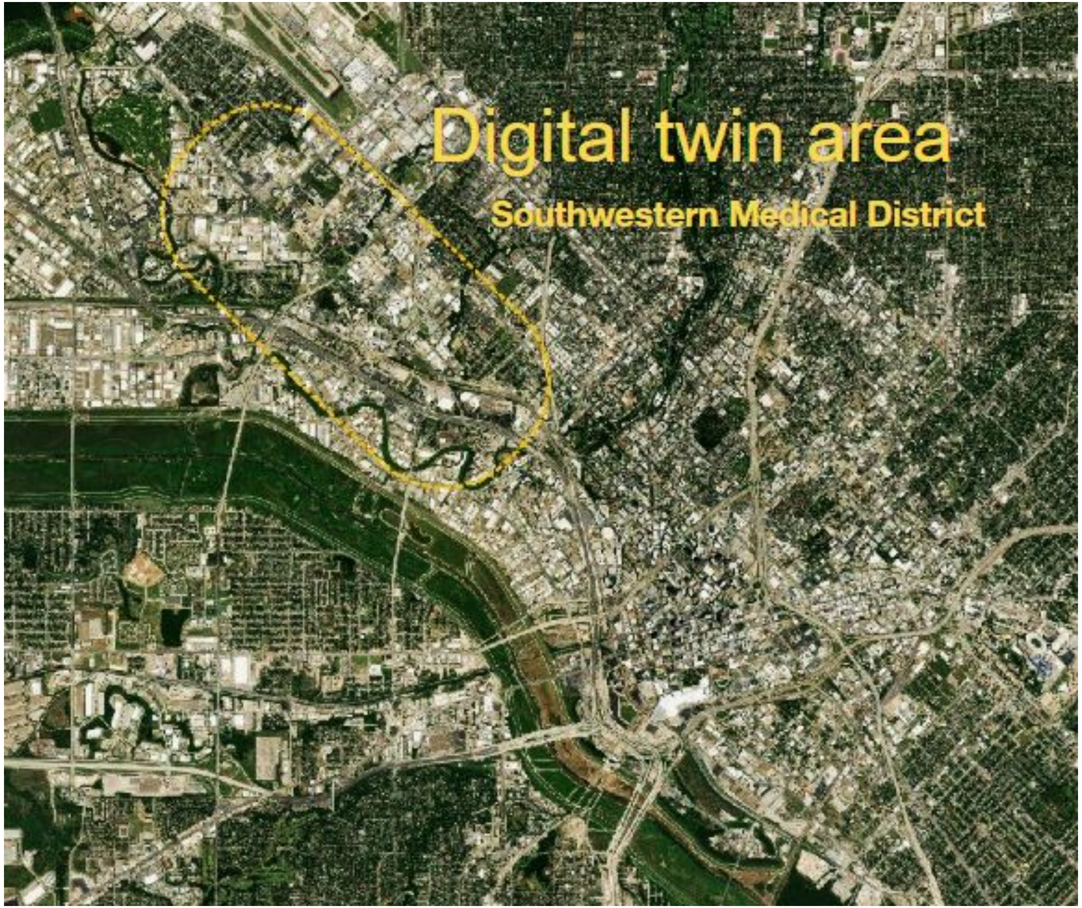
Harry Hines Corridor in Dallas' Southwestern Medical District

- 2 mile corridor through medical district
- To be completely re-landscaped
- Installed ~40 microclimate sensor (measuring wind speed, radiant temperature, air temperature and humidity)
- Simulations of existing and proposed conditions with SOLWEIG, ENVI-MET and OpenFOAM were used to evaluate design scenarios for thermal stress and air pollution
- Sensor data was used to validate the simulation results for thermal studies (but air pollution will be harder!)

Current Day: Aerial of Dallas

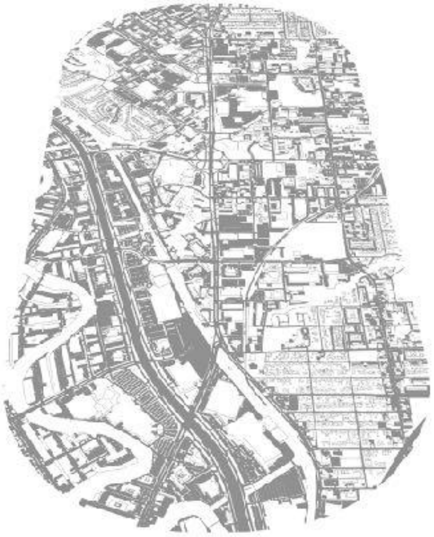
3D “digital twin”

3D Mapping



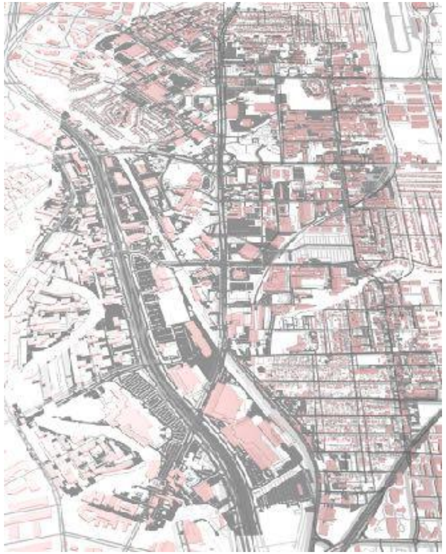
Existing data layers

Public
GIS



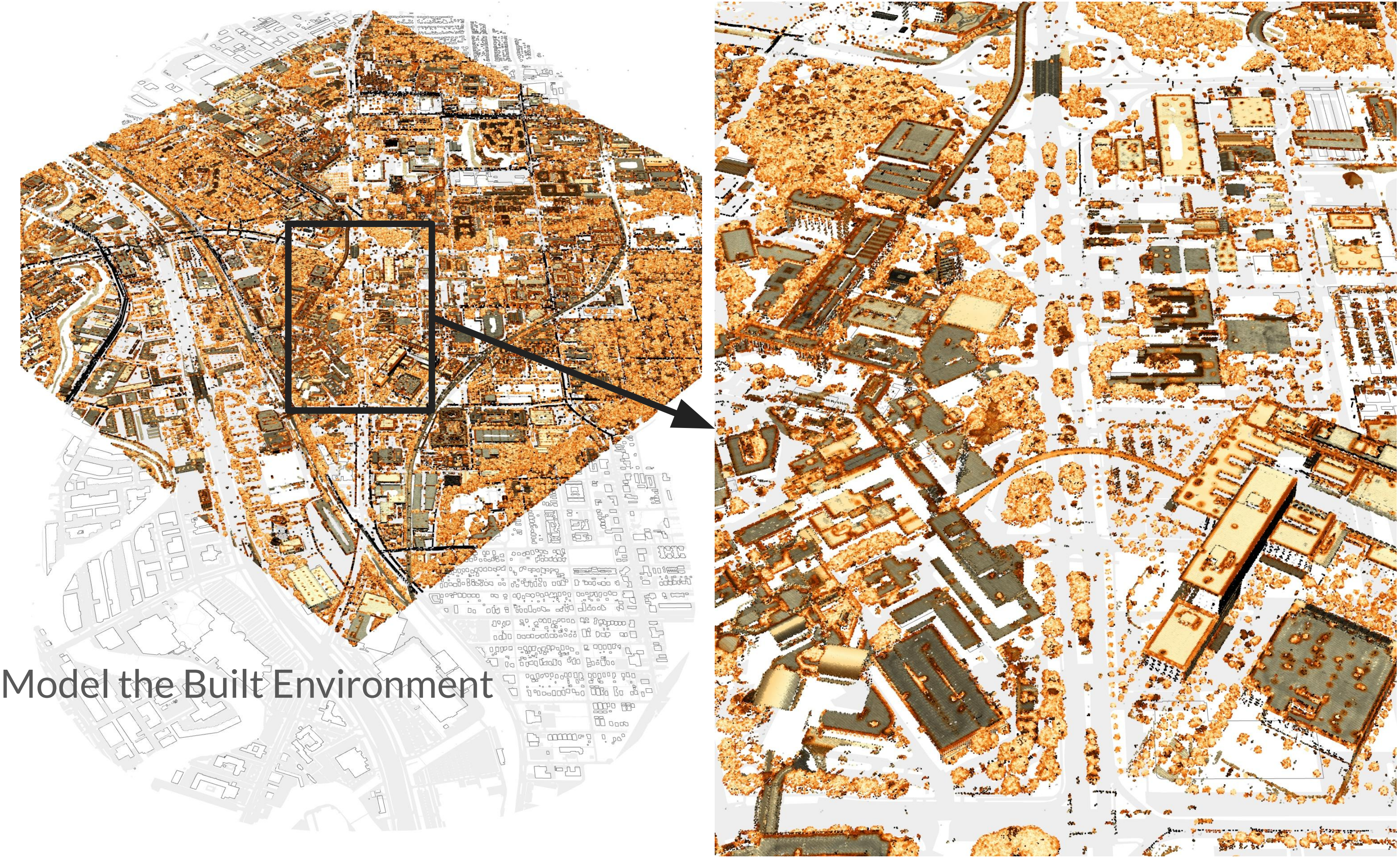
City GIS

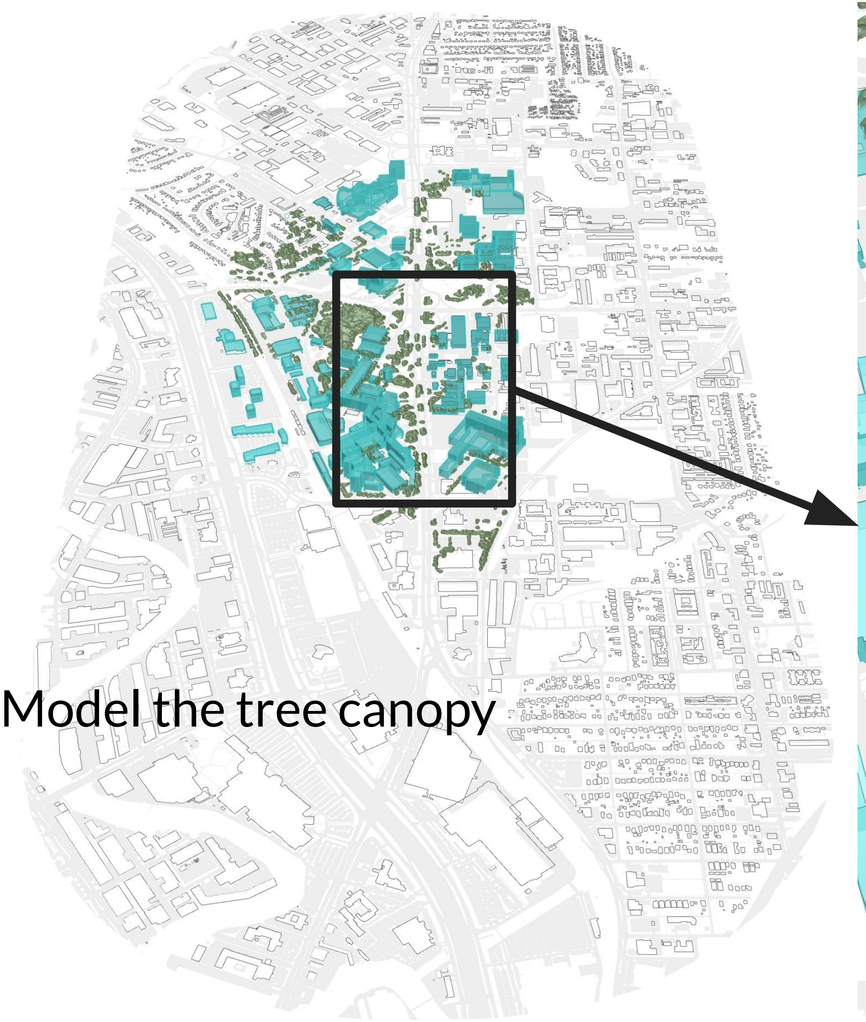
USGS Elevation



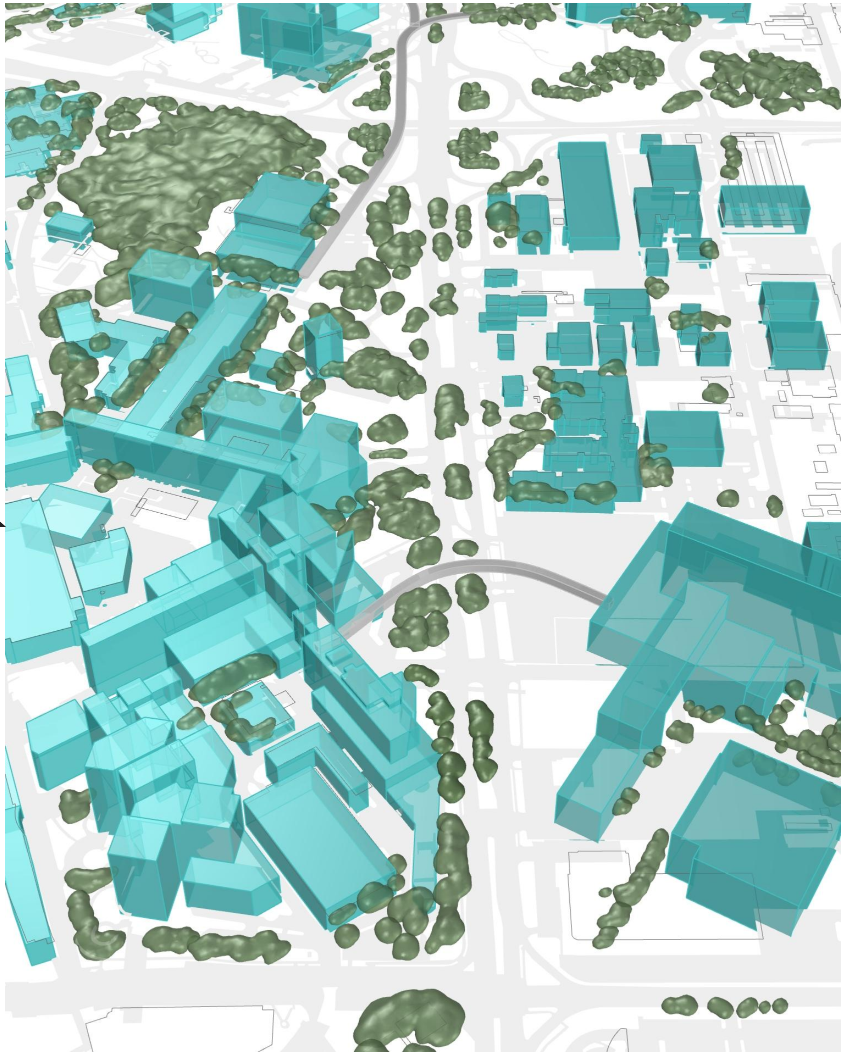
OpenStreetMap
/ Microsoft

Model the Built Environment

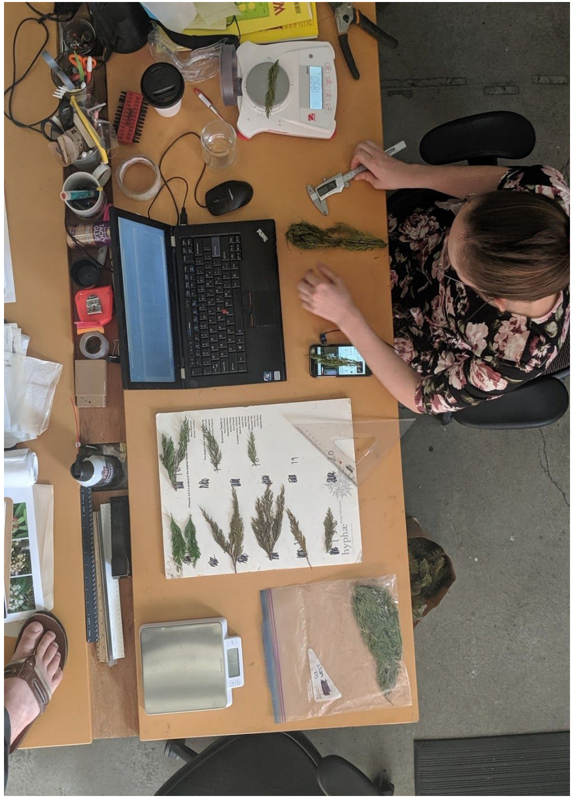


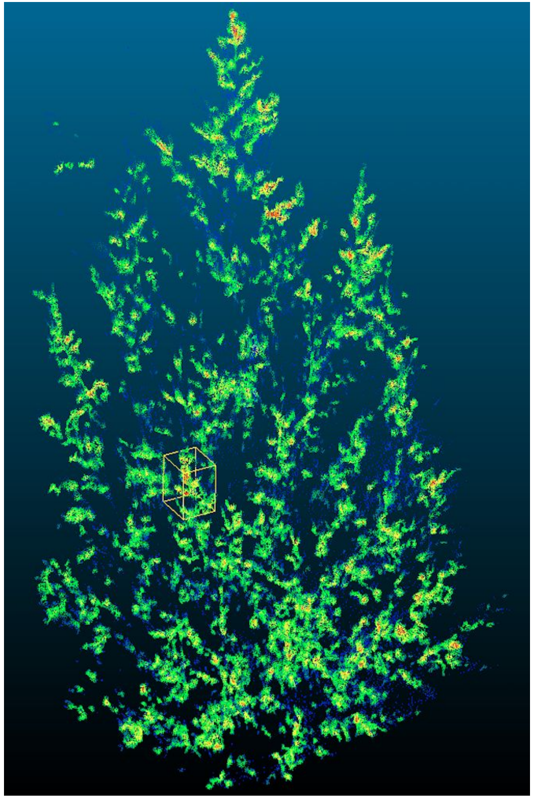


Model the tree canopy



Model Leaf Area Density - LAD

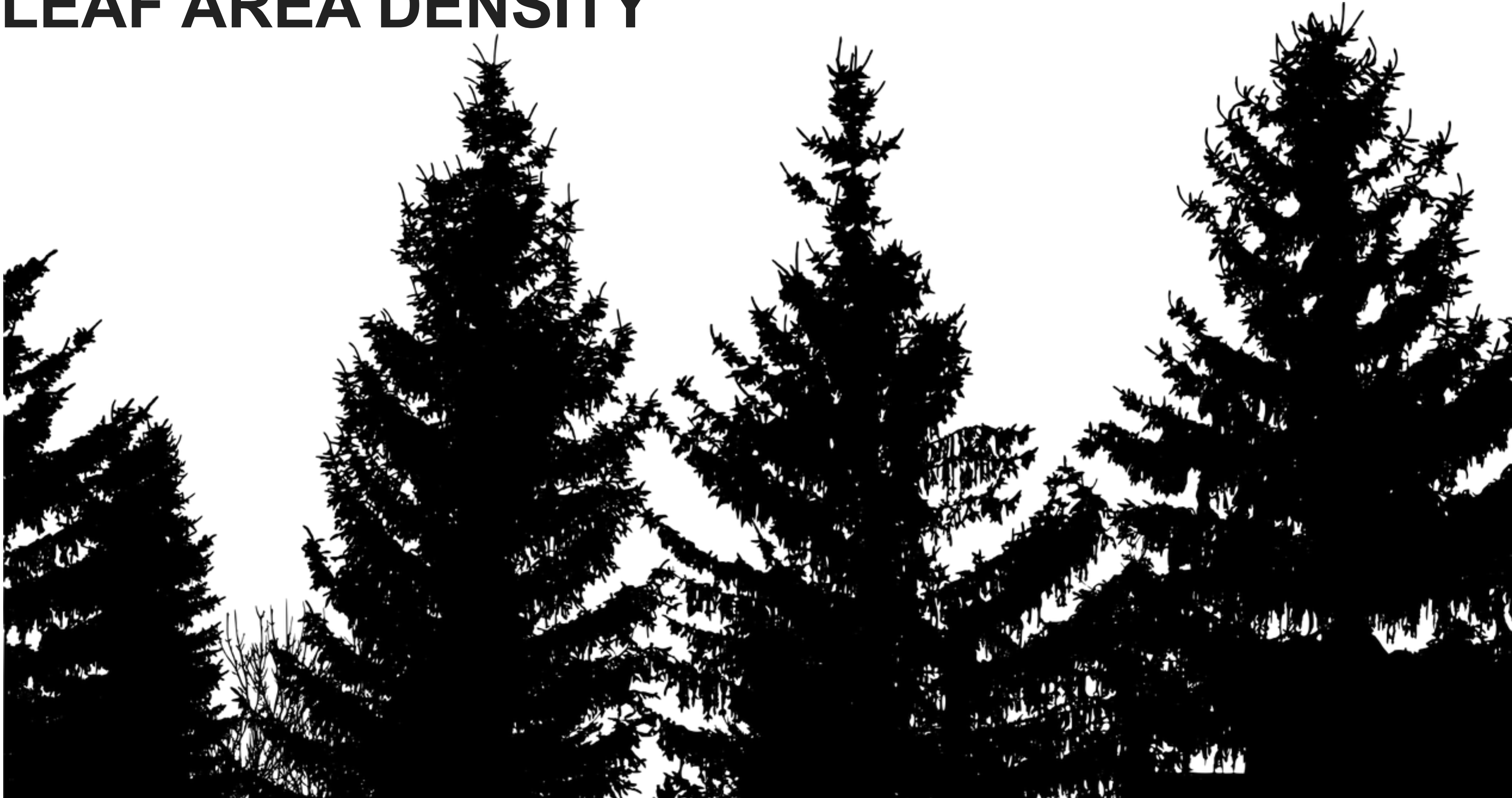




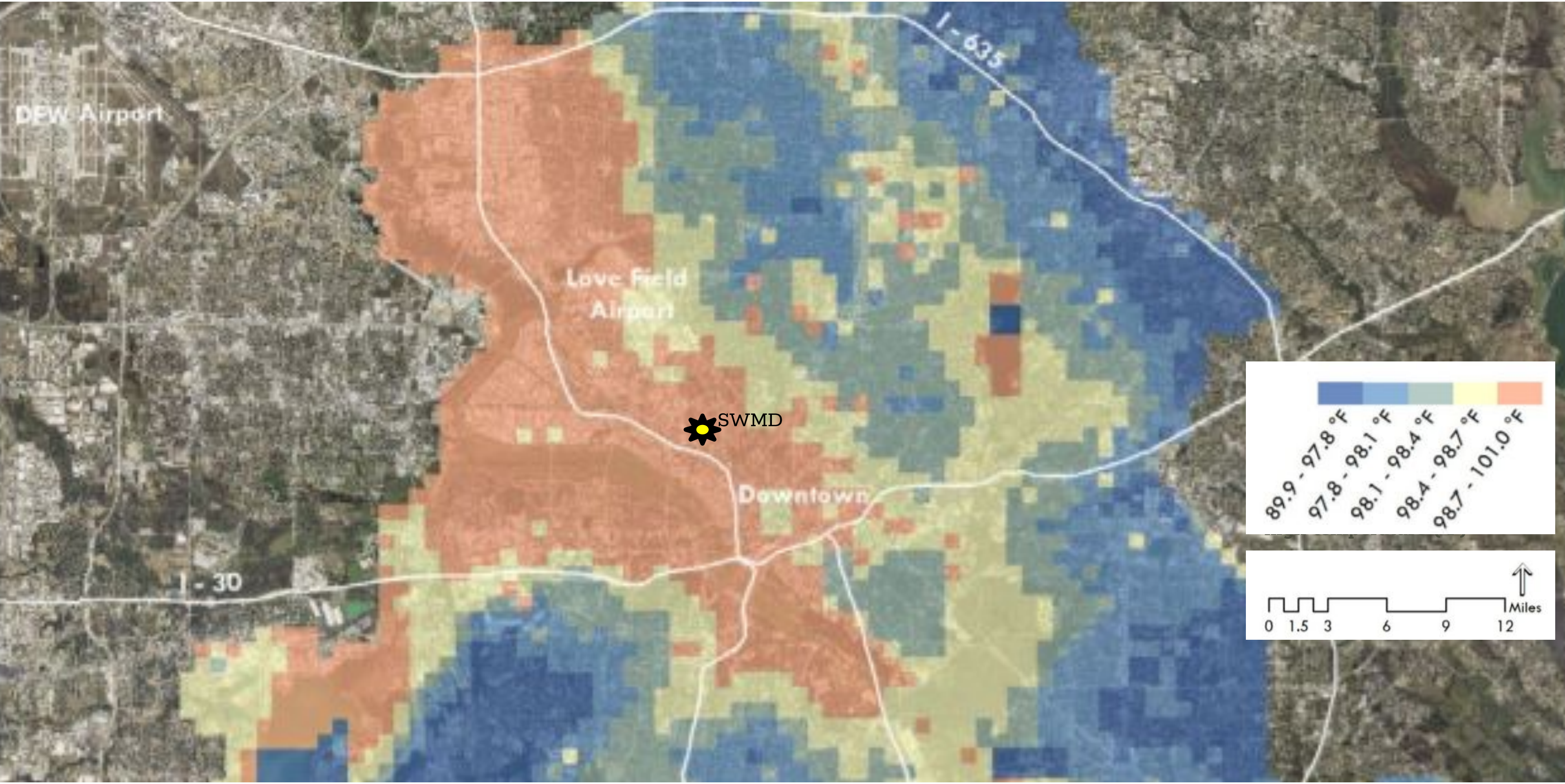
LAD Analysis

LEAF AREA DENSITY

LEAF AREA DENSITY



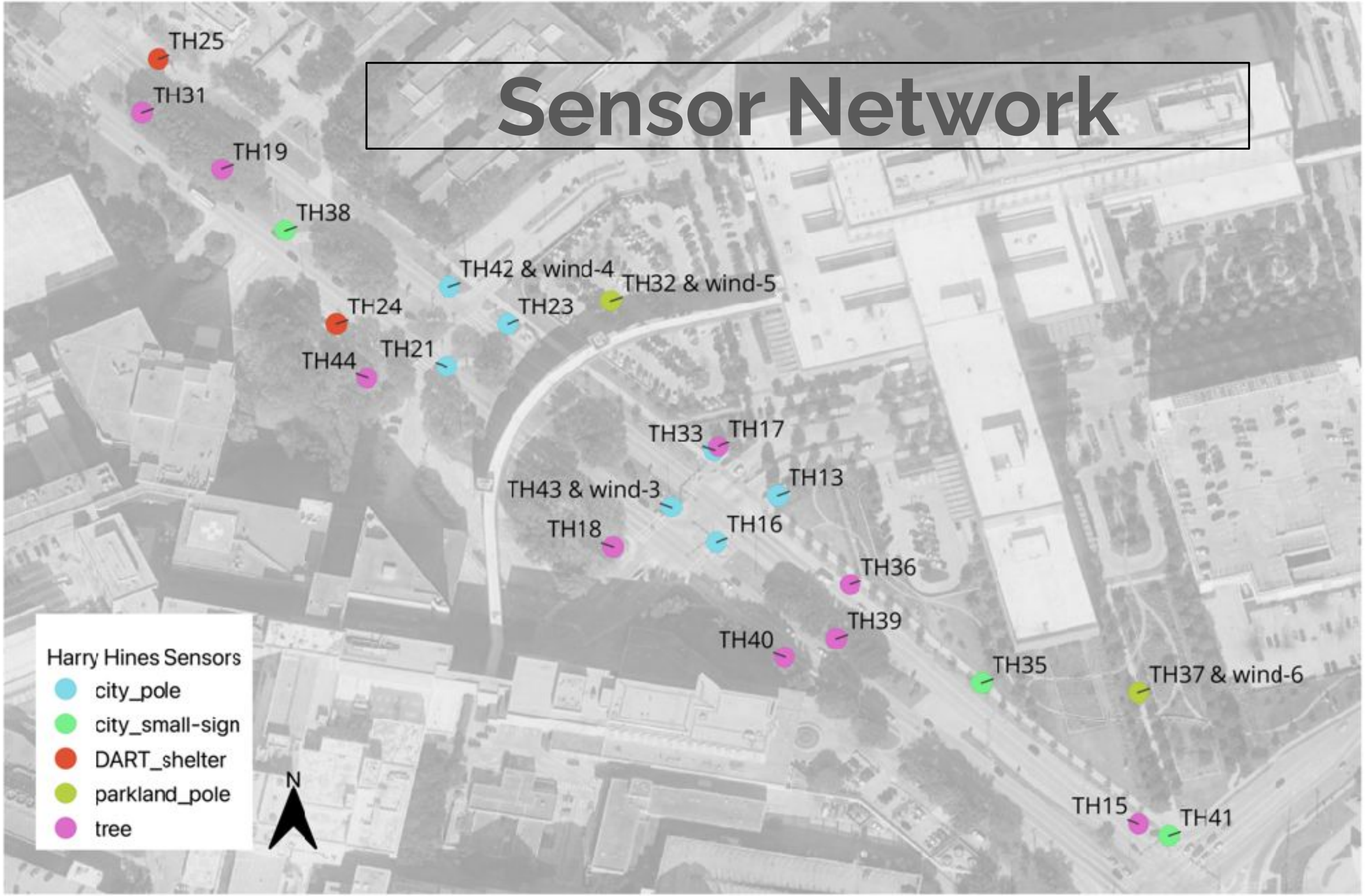
Defining SWMD environmental conditions



Satellite imagery can see trends over large areas and over time

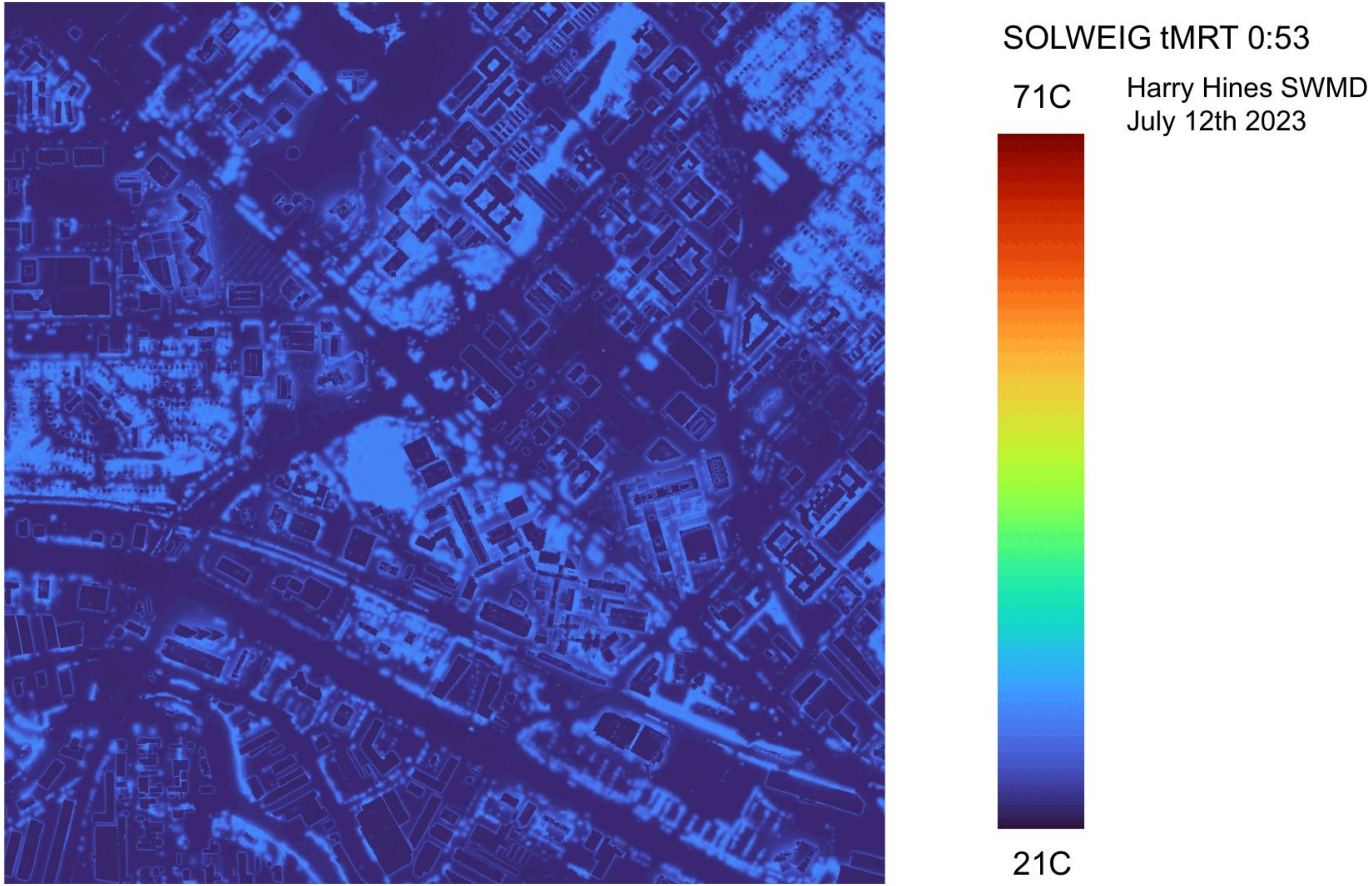
As of May 1st 2023 27 sensors were placed along Harry Hines from Butler to Medical District Drive

Sensor Network



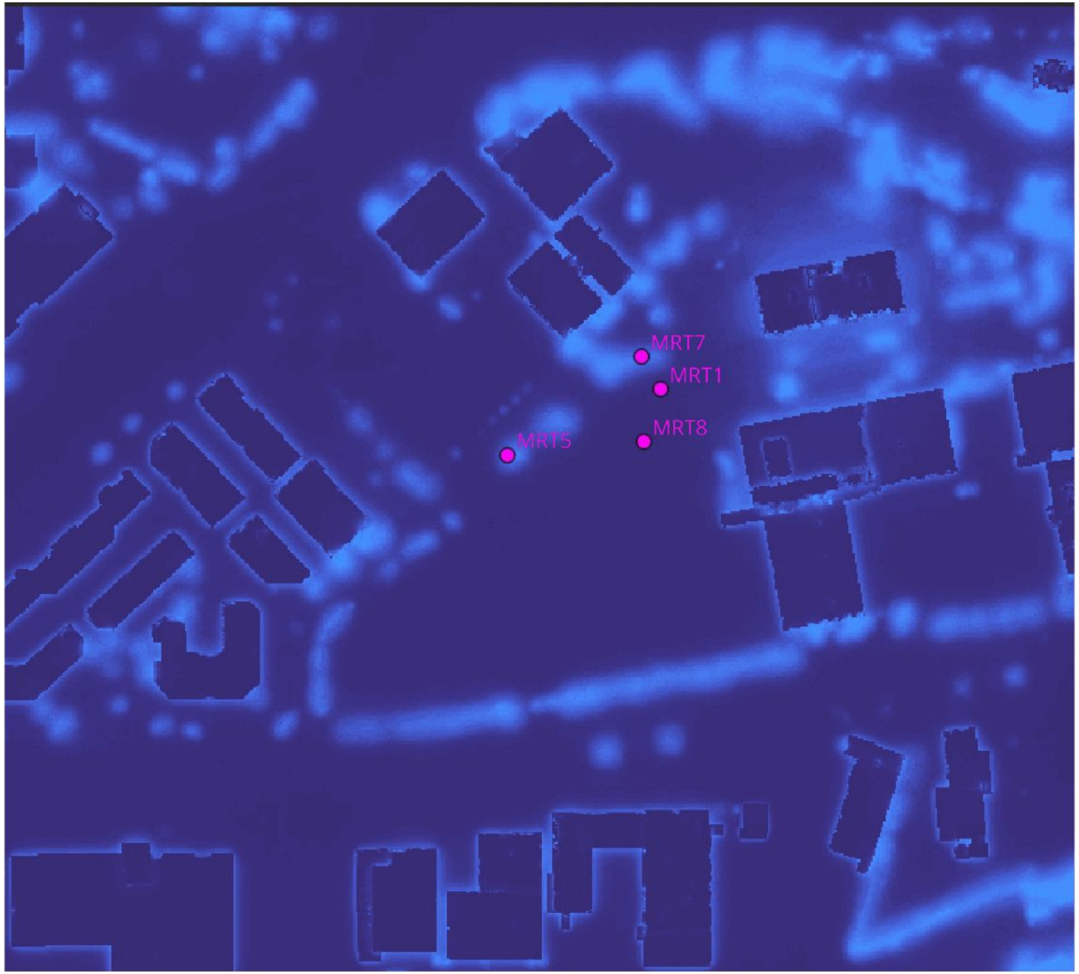
Harry Hines Corridor Texas Trees Foundation microclimate sensor map May 1st 2023

0 50 100 m


SOLWEIG tMRT 0:53
71C
21C
Harry Hines SWMD
July 12th 2023

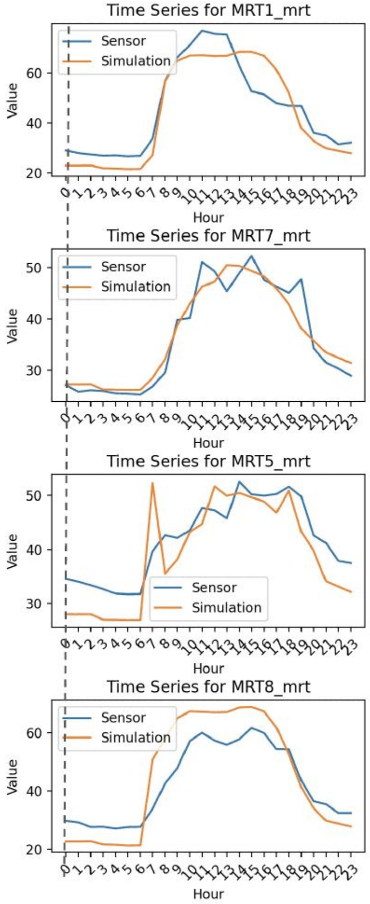
SOLWEIG tMRT 0:53

Pegasus Park
July 12th 2023



70C

21C



r^2 = **0.82** maybe off due to geopositioning and old lidar data (2018)

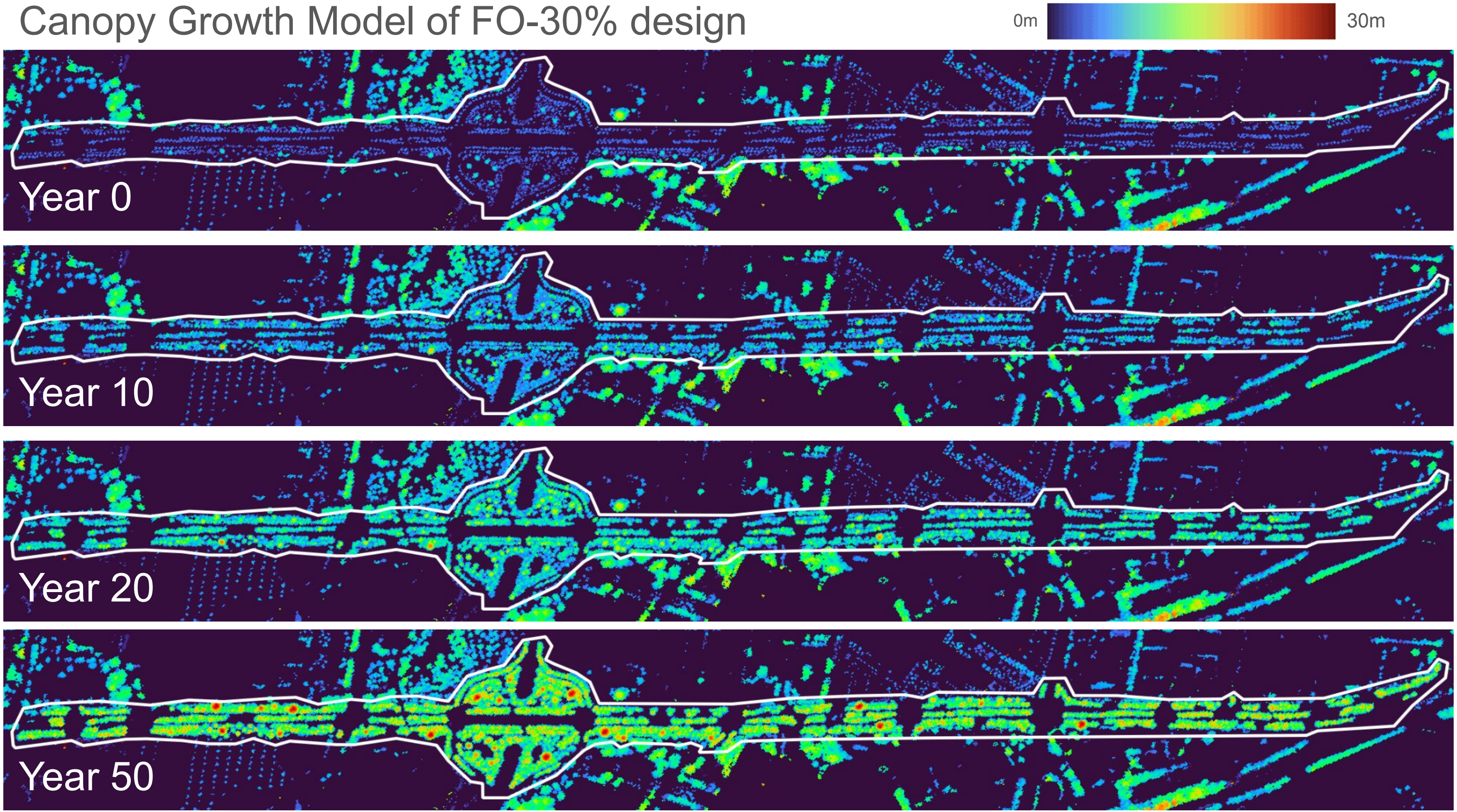
r^2 = **0.91** pretty close

r^2 = **0.45** maybe off due to geopositioning and old lidar data

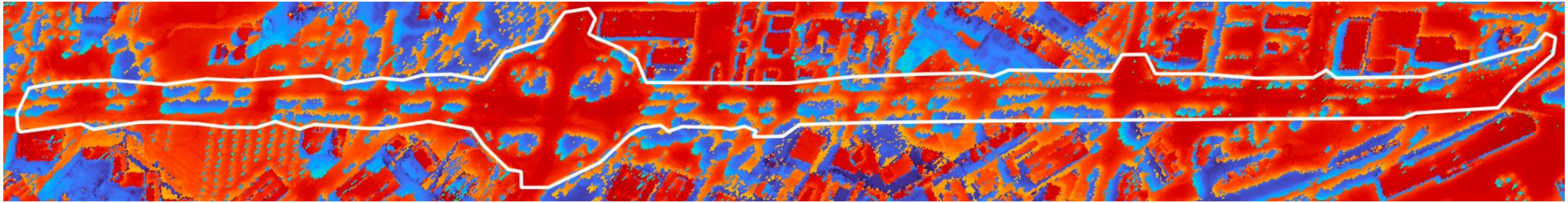
r^2 = **0.54** old lidar data: this small tree didn’t exist in the simulation

Sensors vs simulation: mean radiant temperature

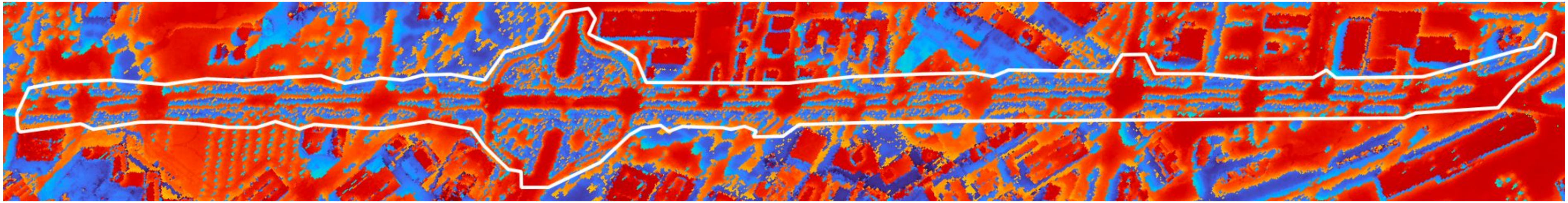
Canopy Growth Model of FO-30% design



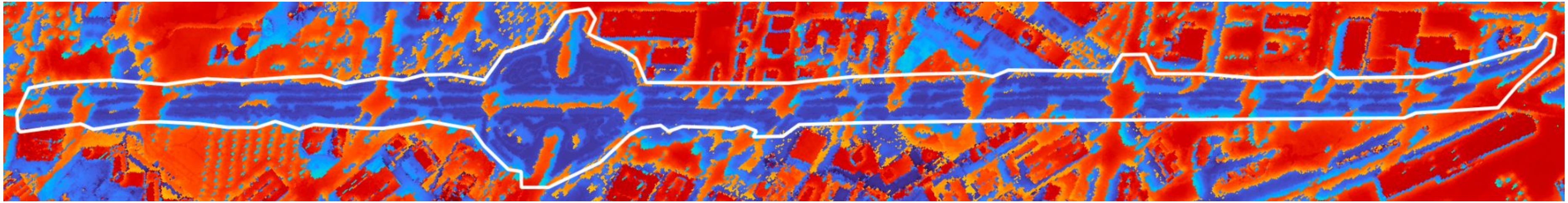
Existing Conditions vs FO 30% Summer Afternoon Mean Radiant Temperature, years 0 and 50



Existing Conditions: Average MRT = 66.76 C



FO 30% design Year 0: average MRT = 62.8 C (**4C cooling over existing conditions**)



FO 30% design Year 50: average MRT = 52.38 C (**14C cooling over existing conditions**)

Particulate dispersion CFD models

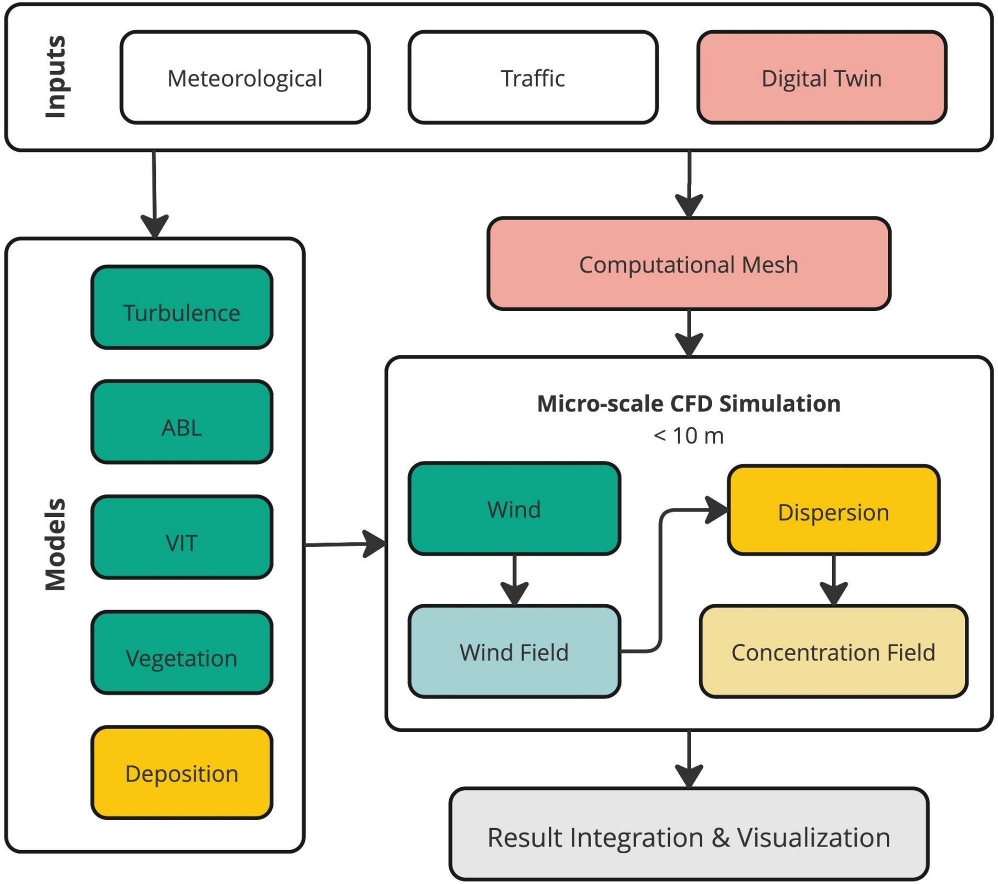
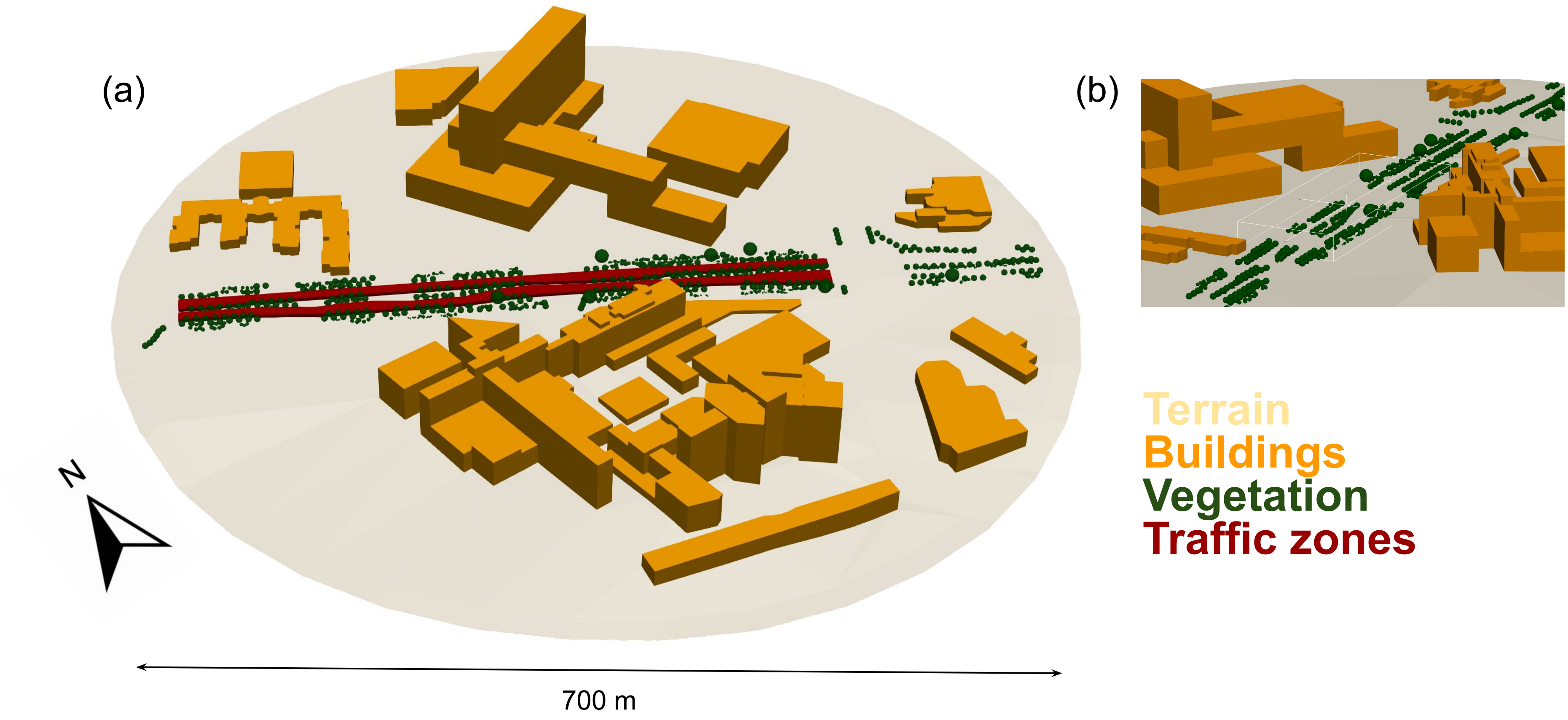


Figure. Schematic of proposed framework and models for urban CFD simulations.



(a)
(b)
N
700 m
Terrain
Buildings
Vegetation
Traffic zones

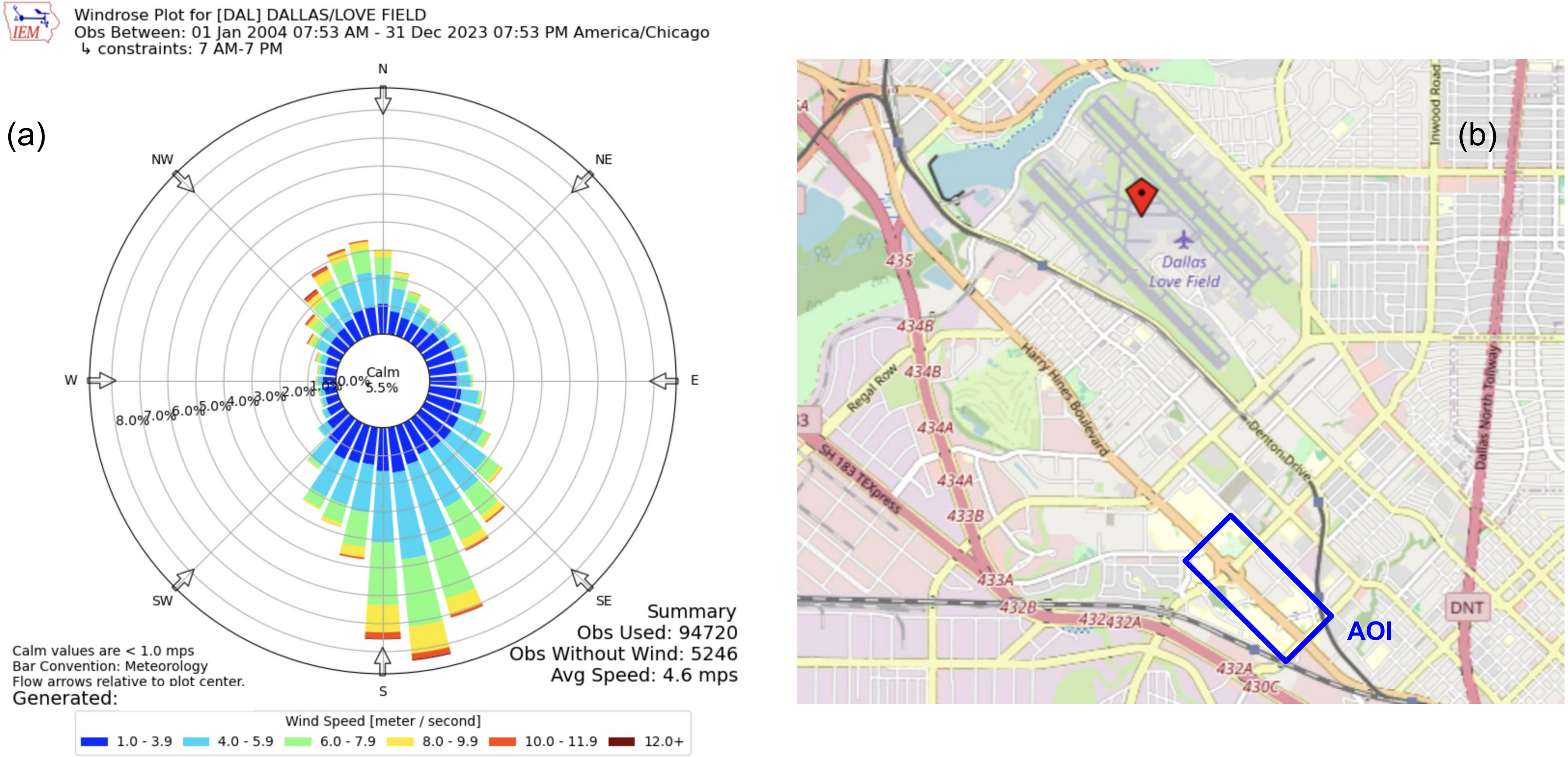
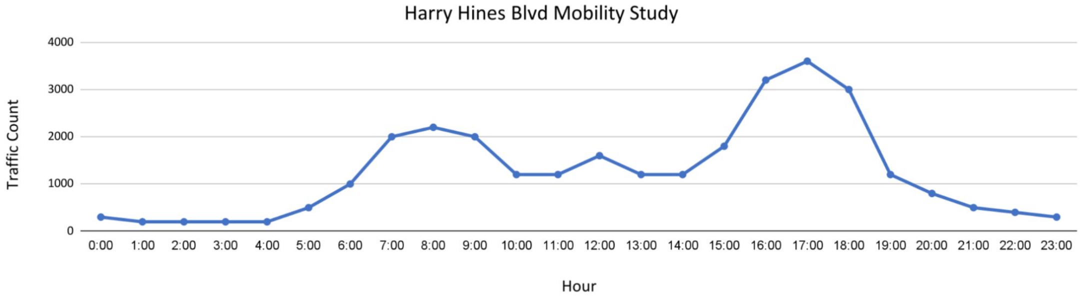


Figure. Windrose plot for Dallas Love Field in Dallas, TX (32.8 N, 96.8 S). (a) Windrose plot from January 2004 to December 2023. The data considered all months and was limited to a time range from 7 am to 8 pm. (b) Weather station site (Dallas Love Field) in Dallas, TX (32.8 N, 96.8 S). Area of interest (AOI) rectangle encloses both sites considered.

Mobility study & emissions

Alternatives: Street-Light
Emission factors: running exhaust, brake and tire wear (g/mile-veh) via emission inventory (e.g., EMFAC)
Vehicle categories: light-, medium-, and heavy-duty.



Traffic Parameters per Vehicle Category				
	PC	MD	HD	UNITS
percentage	92	2	6	%
frontal area	2	2.7	11.75	m2
drag coefficient	0.35	0.5	0.65	-
speed	15	15	15	m/s

Figure. Harry Hines Blvd. mobility study (hourly traffic count over 6 lanes).

Wind Model

Non-hydrostatic incompressible Reynolds-averaged continuity (mass conservation) and Navier-Stokes (momentum conservation) equations.

$$\frac{\partial \langle u_i \rangle}{\partial x_i} = 0$$

$$\frac{\partial \langle u_i \rangle}{\partial t} + \langle u_j \rangle \frac{\partial \langle u_i \rangle}{\partial x_j} = - \frac{1}{\rho} \frac{\partial \langle p \rangle}{\partial x_i} + \nu \frac{\partial^2 \langle u_i \rangle}{\partial x_j^2} - \frac{\partial \langle u_i' u_j' \rangle}{\partial x_j} + S_{veg,i}$$

Vegetation is represented as a porous medium (Darcy-Forchiemer)

Effects are proportional to the tree species (tree size, shape, and LAD).

Wind Model

Non-hydrostatic incompressible Reynolds-averaged continuity (mass conservation) and Navier-Stokes (momentum conservation) equations.

$$\frac{\partial \langle u_i \rangle}{\partial x_i} = 0$$

$$\frac{\partial \langle u_i \rangle}{\partial t} + \langle u_j \rangle \frac{\partial \langle u_i \rangle}{\partial x_j} = - \frac{1}{\rho} \frac{\partial \langle p \rangle}{\partial x_i} + \nu \frac{\partial^2 \langle u_i \rangle}{\partial x_j^2} - \frac{\partial \langle u'_i u'_j \rangle}{\partial x_j} + S_{veg,\, i}$$

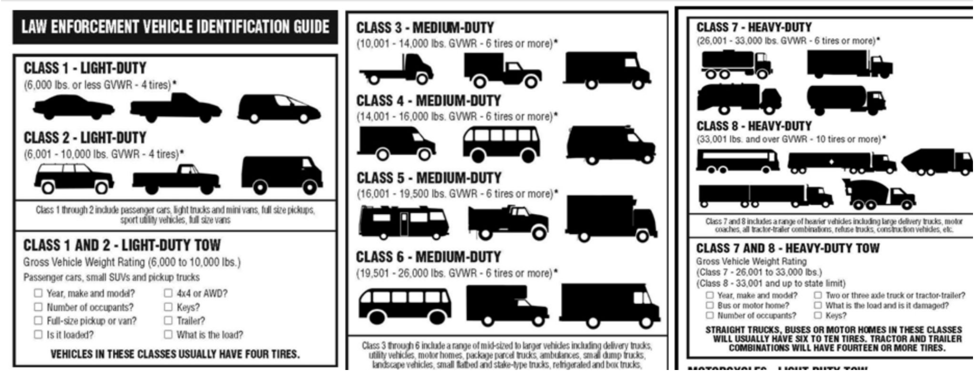
Turbulence closure is achieved via the standard k-epsilon turbulence model which requires solving two transport equations for turbulent kinetic energy (TKE) and TKE dissipation rate (epsilon).

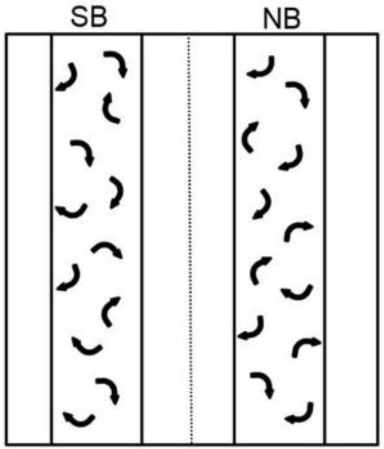
$$\frac{\partial k}{\partial t} + \langle u_j \rangle \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \varepsilon + S_{VIT}$$

Vehicle Induced Turbulence (VIT)

Turbulent kinetic energy is injected into a traffic region (Hashad et al., 2022; Tong et al., 2015; Steffens et al. 2012) instead of explicitly modeling vehicles in the domain to implicitly model vehicle-induced turbulence (VIT).

Vehicle categories: light-, medium-, and heavy-duty vehicles.





TKE method
Isotropic
No direction

$$S_{VIT} = U_i F_i \; / V_T$$

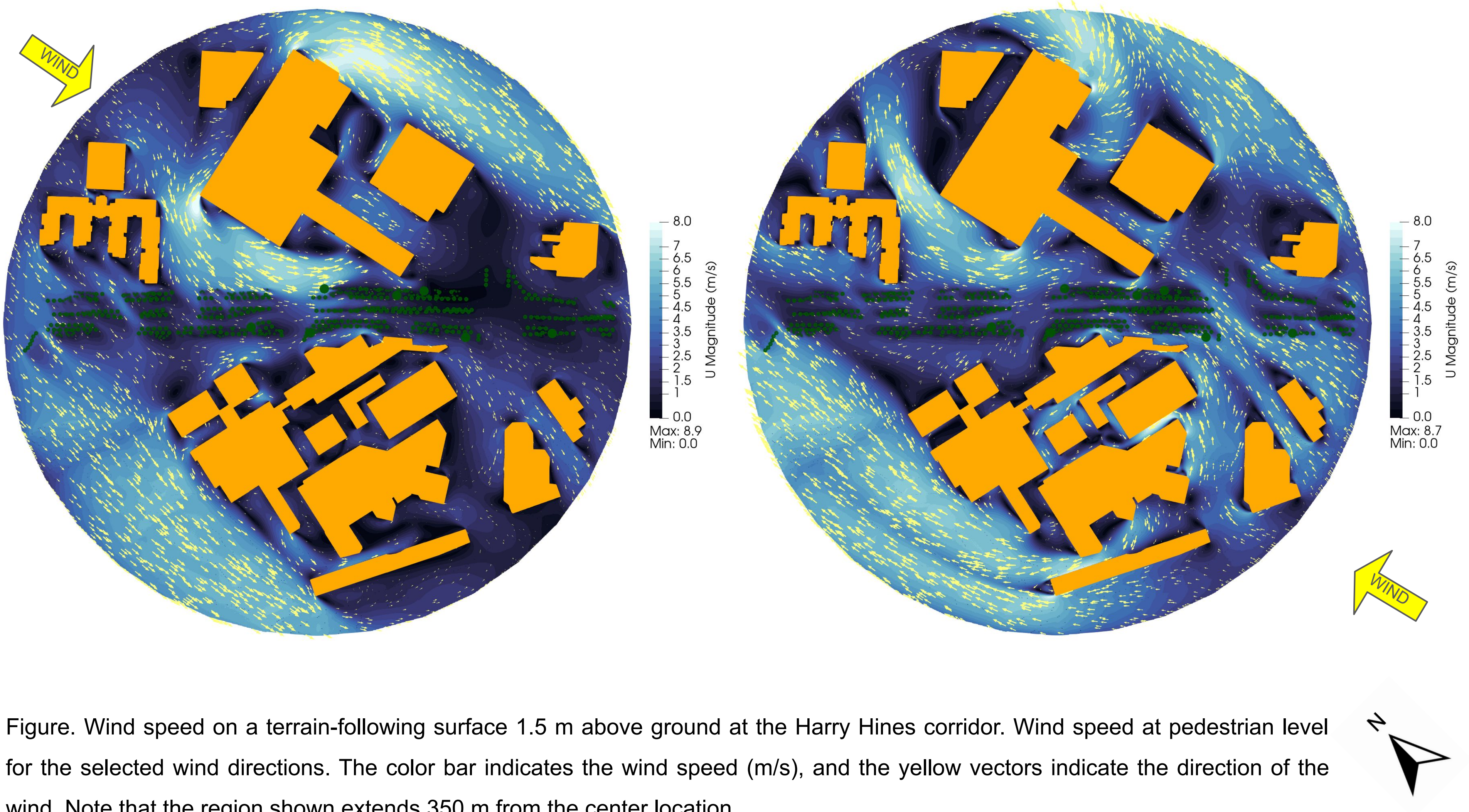
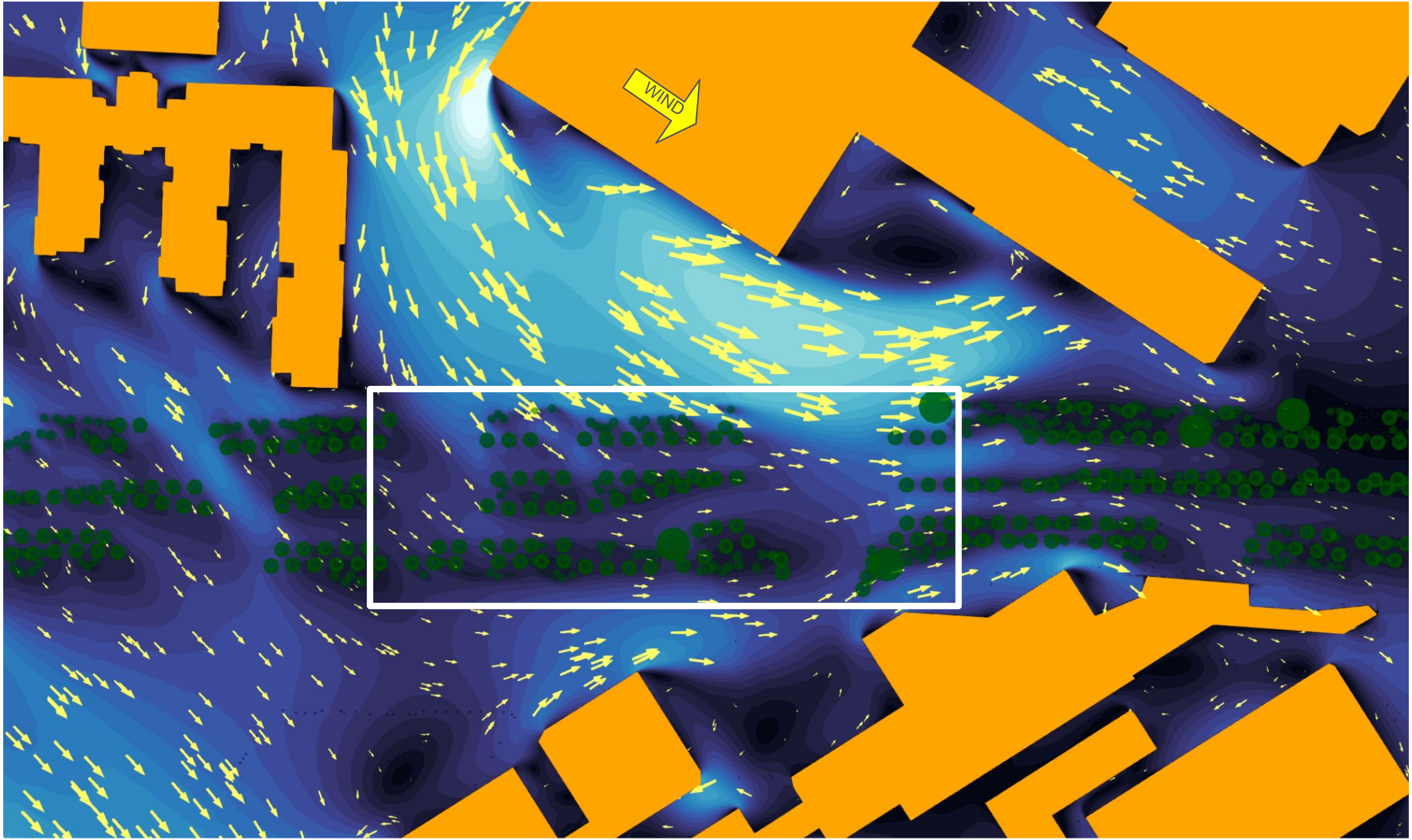


Figure. Wind speed on a terrain-following surface 1.5 m above ground at the Harry Hines corridor. Wind speed at pedestrian level for the selected wind directions. The color bar indicates the wind speed (m/s), and the yellow vectors indicate the direction of the wind. Note that the region shown extends 350 m from the center location.


WIND

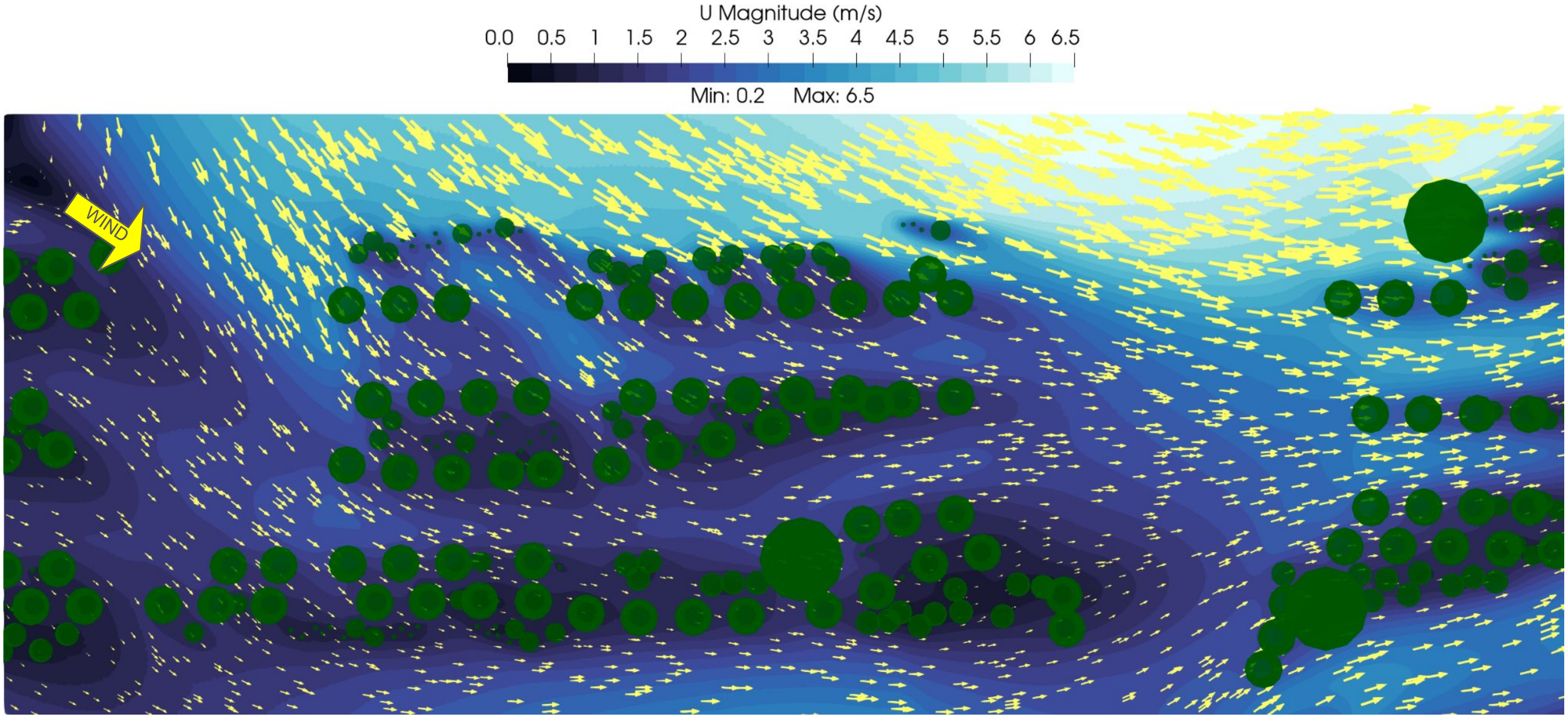
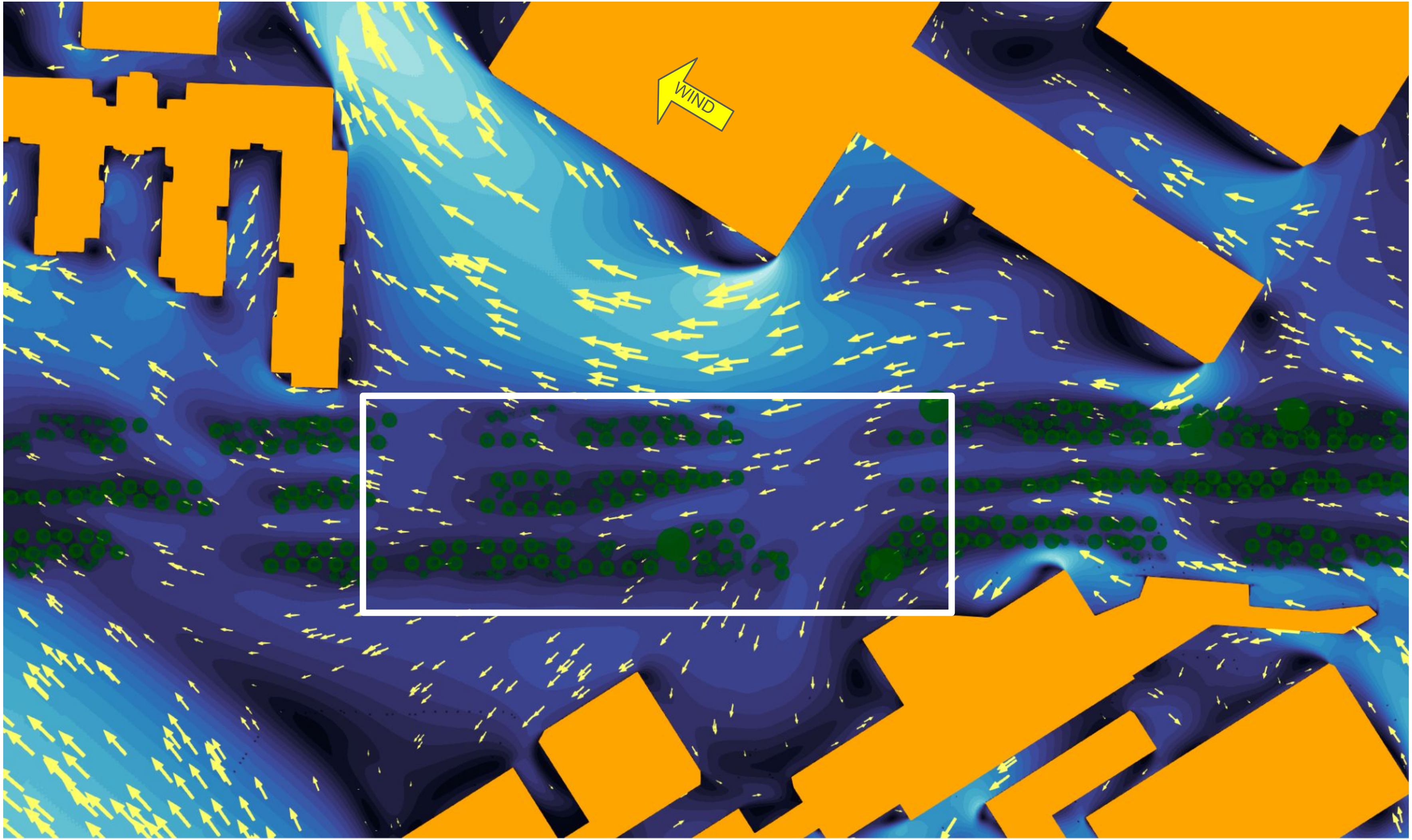


Figure. Wind speed on a terrain-following surface 1.5 m above ground at the Harry Hines corridor. Wind speed at pedestrian level (1.5 m above ground) for the selected wind directions. The color bar indicates the wind speed (m/s), and the yellow vectors indicate the direction of the wind flow. Note that the region shown extends 225 x 85 m.


WIND

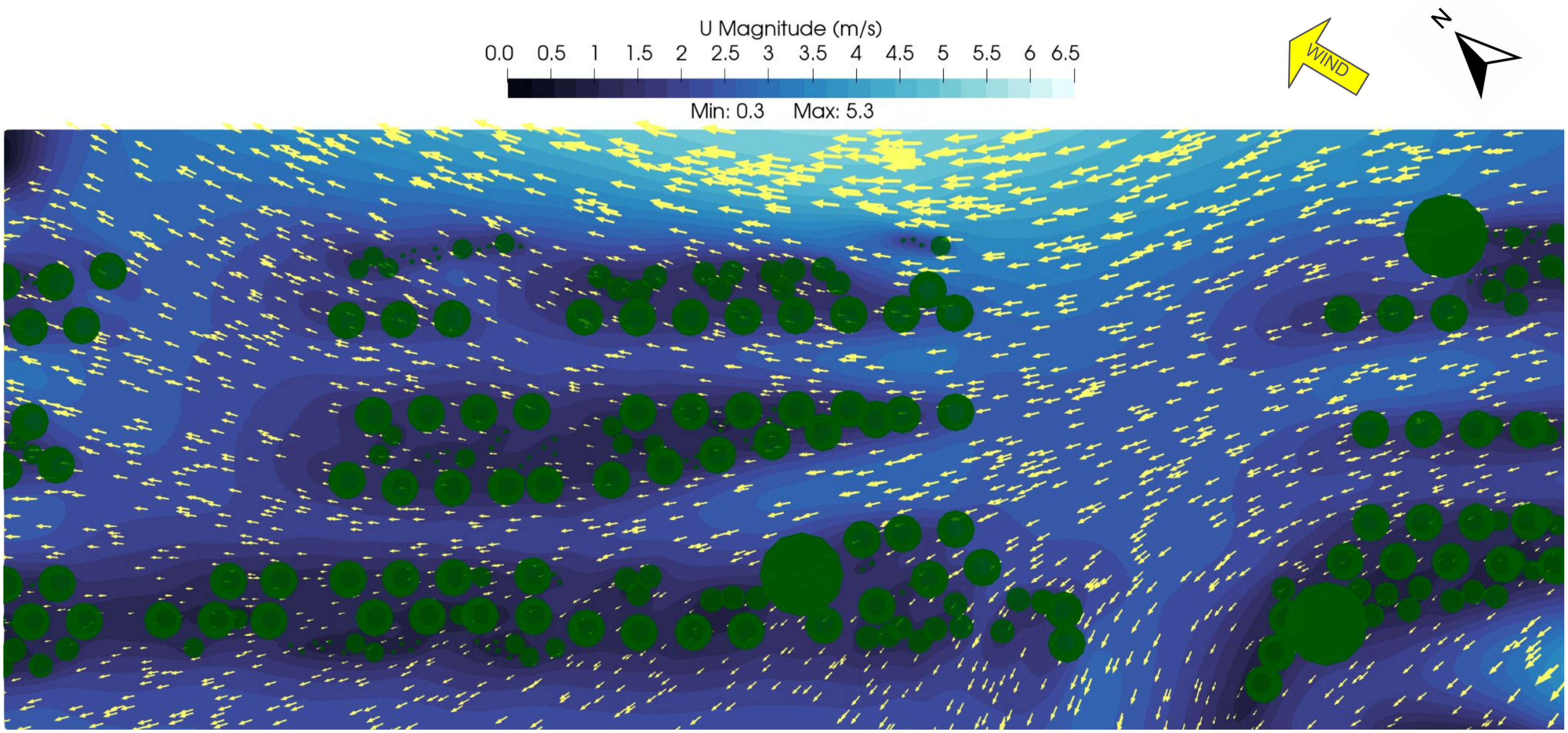


Figure. Wind speed on a terrain-following surface 1.5 m above ground at the Harry Hines corridor. Wind speed at pedestrian level (1.5 m above ground) for the selected wind directions. The color bar indicates the wind speed (m/s), and the yellow vectors indicate the direction of the wind flow. Note that the region shown extends 225 x 85 m.

Dispersion Model

Passive scalar transport based on the scalar-advection diffusion equation.

- The steady-state wind field is held static
- Background pollution is not considered
- Pollutant is released at a fixed rate over traffic volume
- Dry deposition (Zhang et al., 2001) on vegetation

$$\frac{\partial C_p}{\partial t} + \frac{\partial}{\partial x_i}\left(\langle u_i \rangle C_p\right) - \frac{\partial}{\partial x_i}\left(D_t \frac{\partial C_p}{\partial x_i}\right) = S_{em} + S_{dep}$$

$$S_{dep} = -LAD\ V_d\ C$$

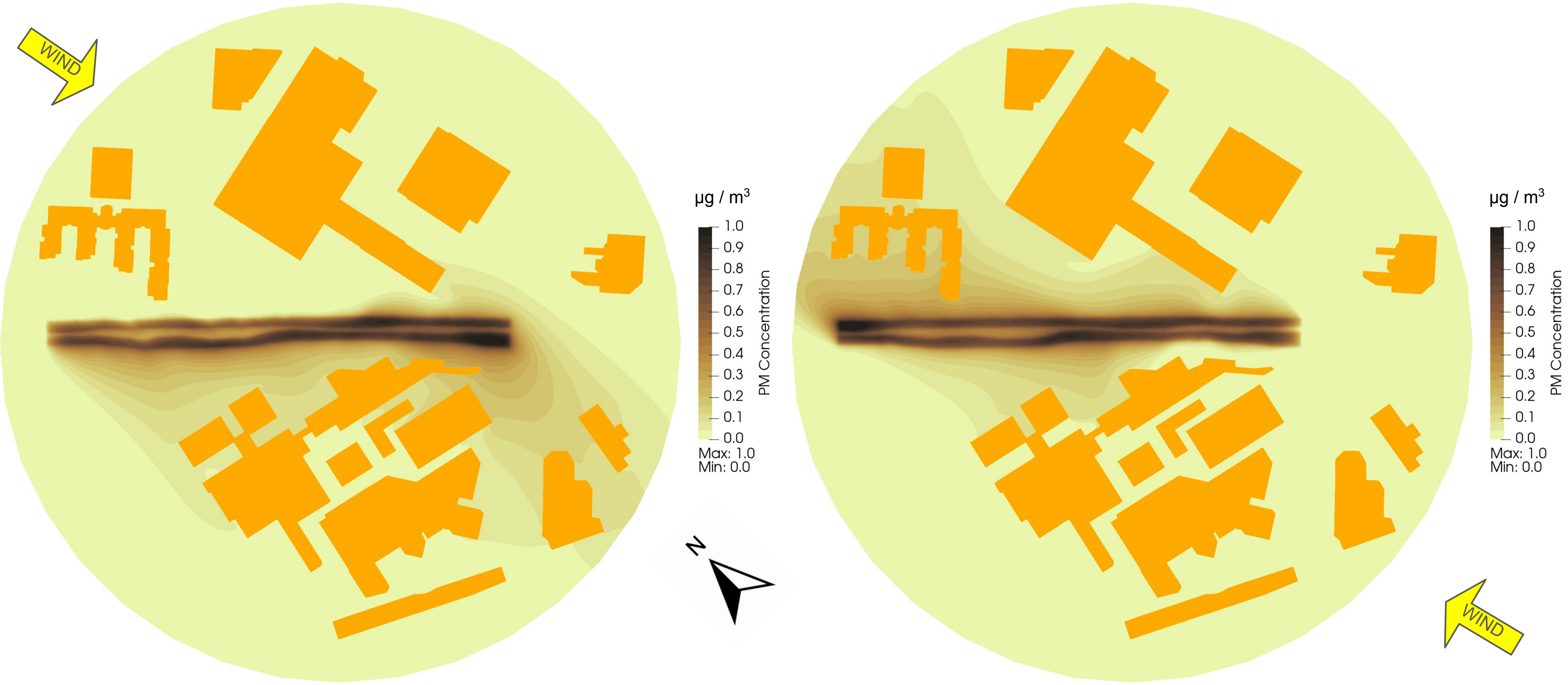
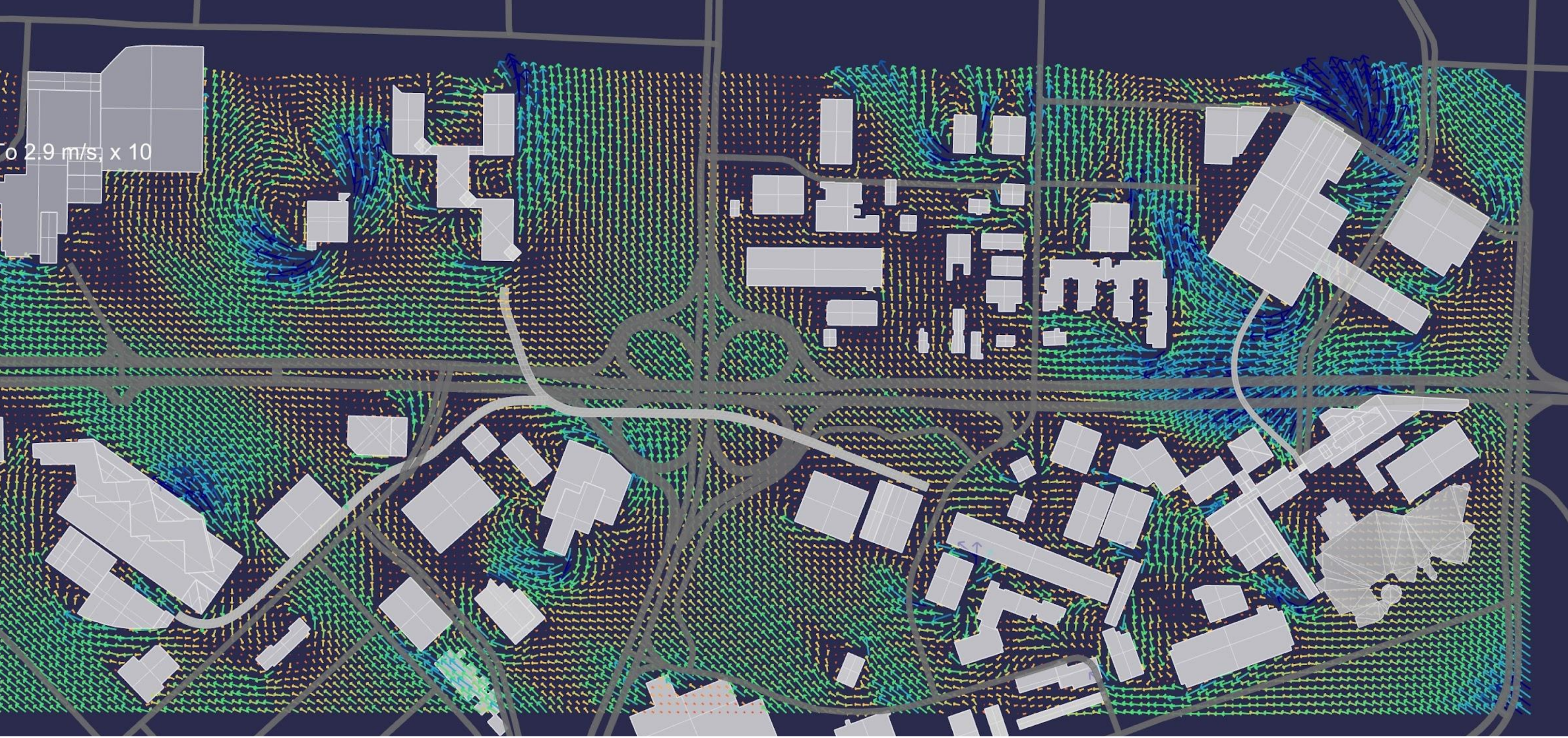
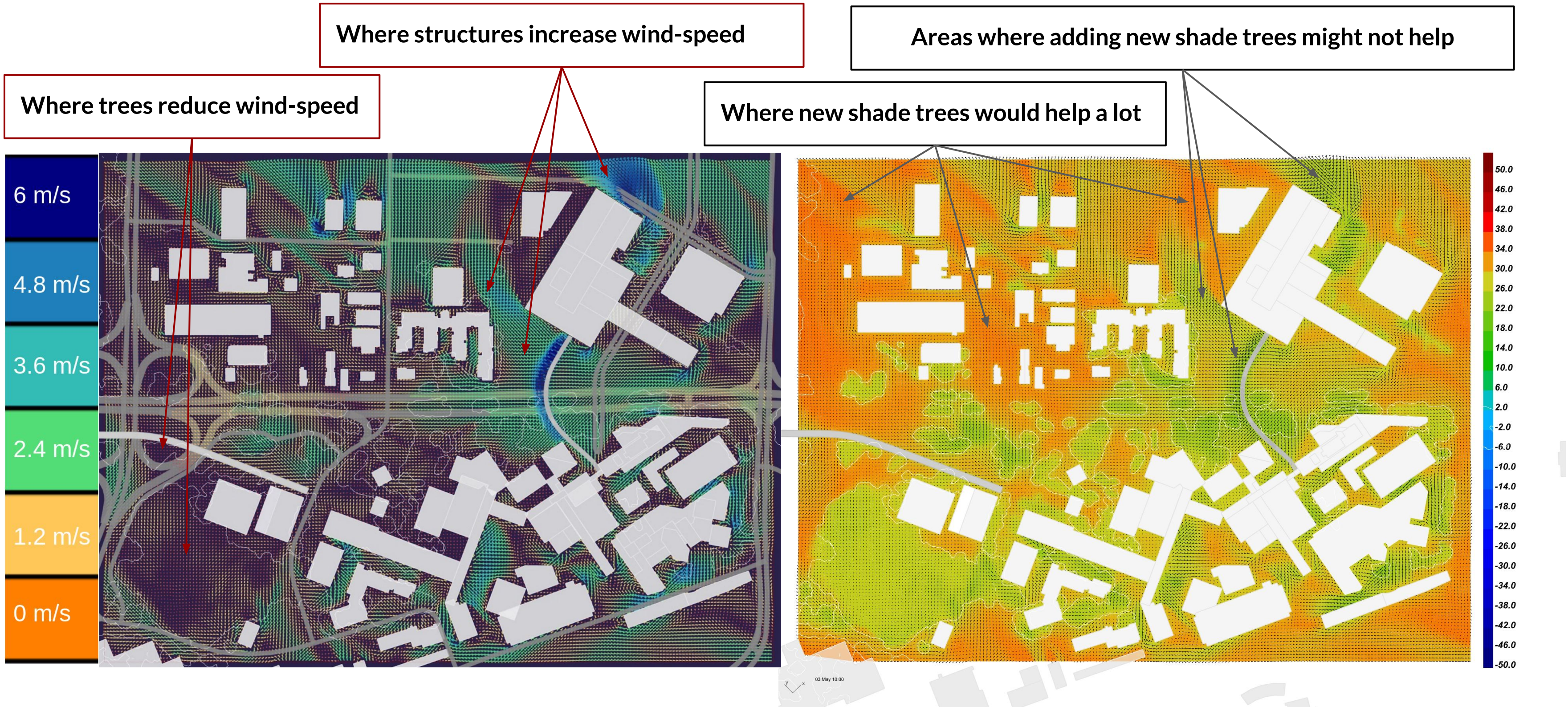


Figure. PM concentration on a terrain-following surface 1.5 m above ground at the Harry Hines corridor. PM2.5 concentration at pedestrian level for the selected wind directions. Note that the region shown extends 350 m from the center location.



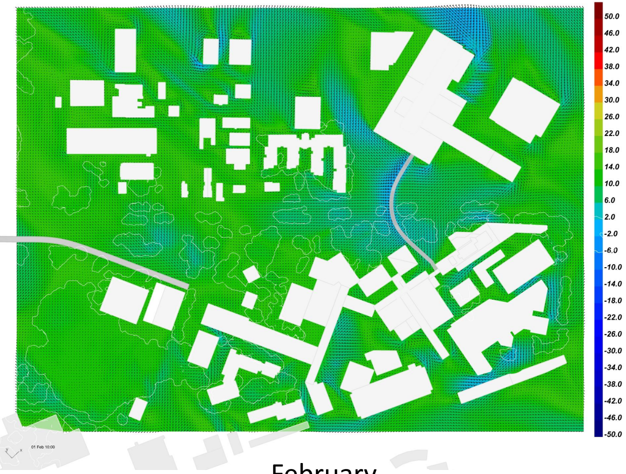
Microclimate Wind Study



Wind Flow Simulation

Thermal Comfort Simulation

Simulation of thermal comfort shows how trees can help (by shading) or hurt (by slowing wind)



February

May

August

Cold and warm season comfort dynamics are inverted, so sunny and slow-wind areas are most comfortable in the winter, while shady, fast-wind areas are most comfortable in the spring and summer. Built-environment planners can leverage this for seasonal programming.

Conclusions

- CFD simulation results heavily depend on the quality of inputs (meteorological, traffic, digital twin)
- More monitoring is needed to establish baselines
- Validation of the models will reinforce their weight
- hyphae is planning transient CFD simulations that are nested with meso-scale models (WRF)
- Other sources (e.g., stacks, fires, …)

© hyphae design laboratory