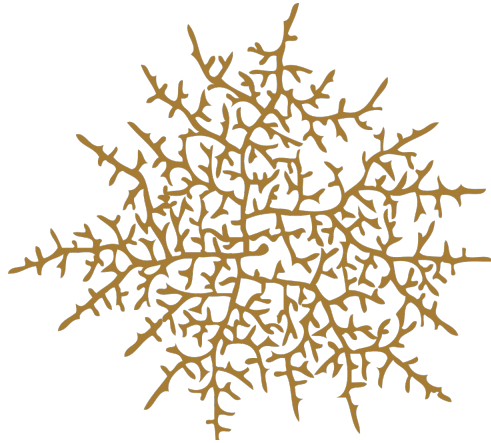
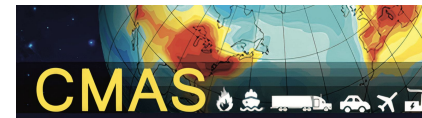


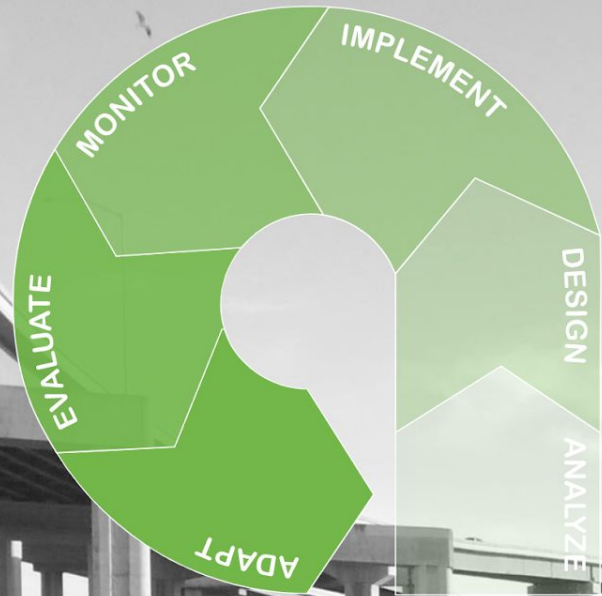
Enhancing Urban Environmental Quality through Computational Fluid Dynamics: Case Studies and Methodologies in Green Infrastructure Design



hyphæ design laboratory
Ecological Design & Engineering

Daniel Fleischer, Lead Researcher
Juan Penaloza Gutierrez





ADAPT



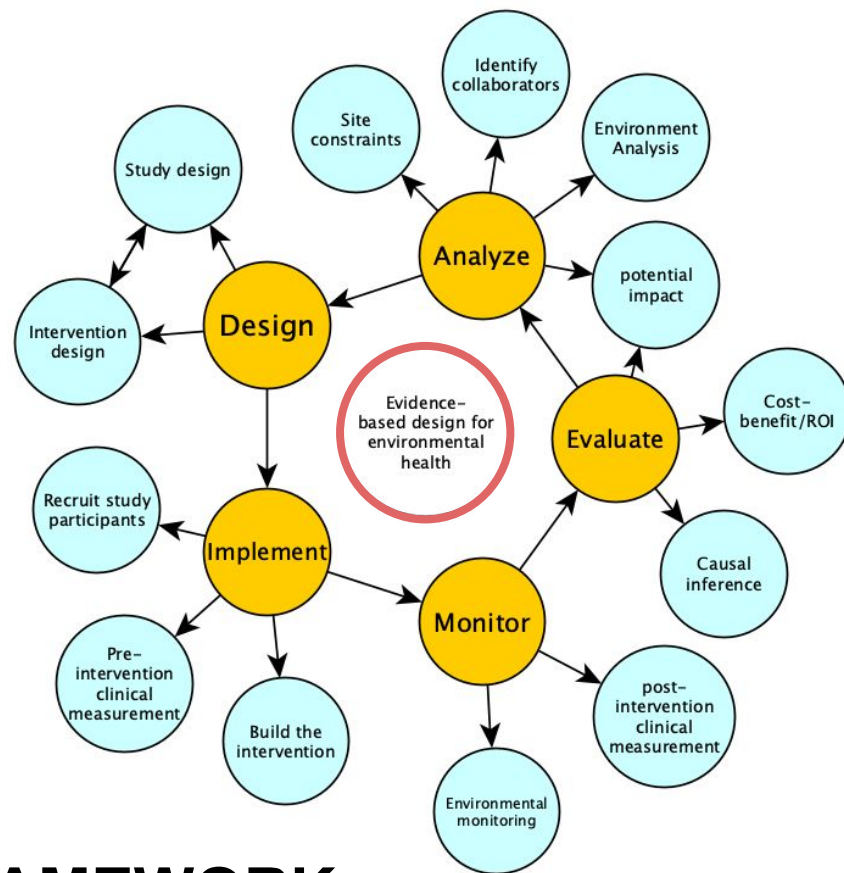
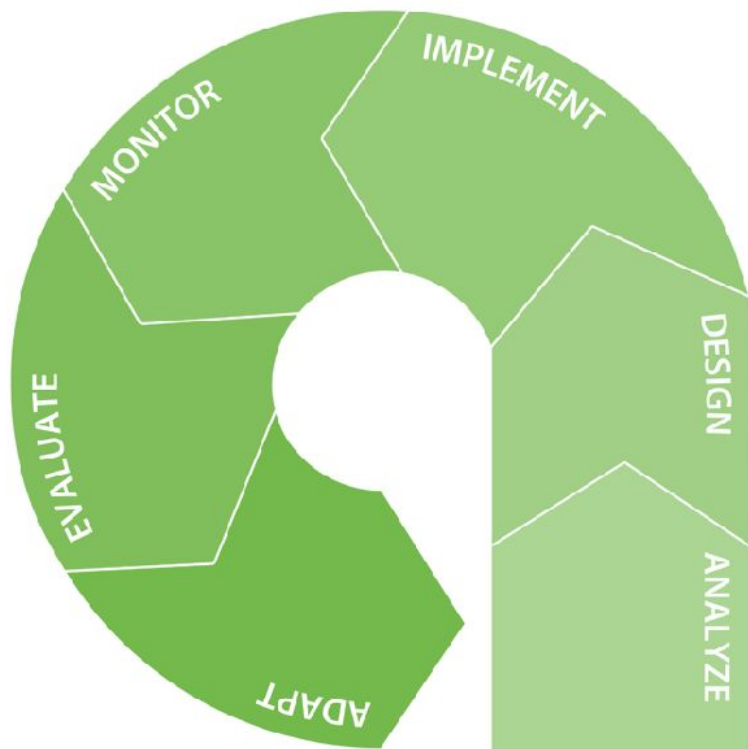
BAY AREA AIR QUALITY
MANAGEMENT DISTRICT



America's
SEED FUND



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



ADAPT FRAMEWORK



Meso- and Micro-scale models

Scales of atmospheric phenomena						Phenomena impact accounted for in:	
						mesoscale models	microscale models
				Global Circulation	α	Boundary values	Boundary values
			Cyclones		β		
			Fronts				
			Meso-Cyclones		α	Directly simulated	Boundary values
		Orographic effects			β		
		Land-sea breeze					
		Urban Heat Island			γ	Para-metrised	Directly simulated
		Deep convection					
		Thunderstorms					
	Convection				α		
	Thermals				β	Para-metrised	Directly simulated
	Building wakes				γ		
Turbulence						Para-metrised	Para-metrised

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

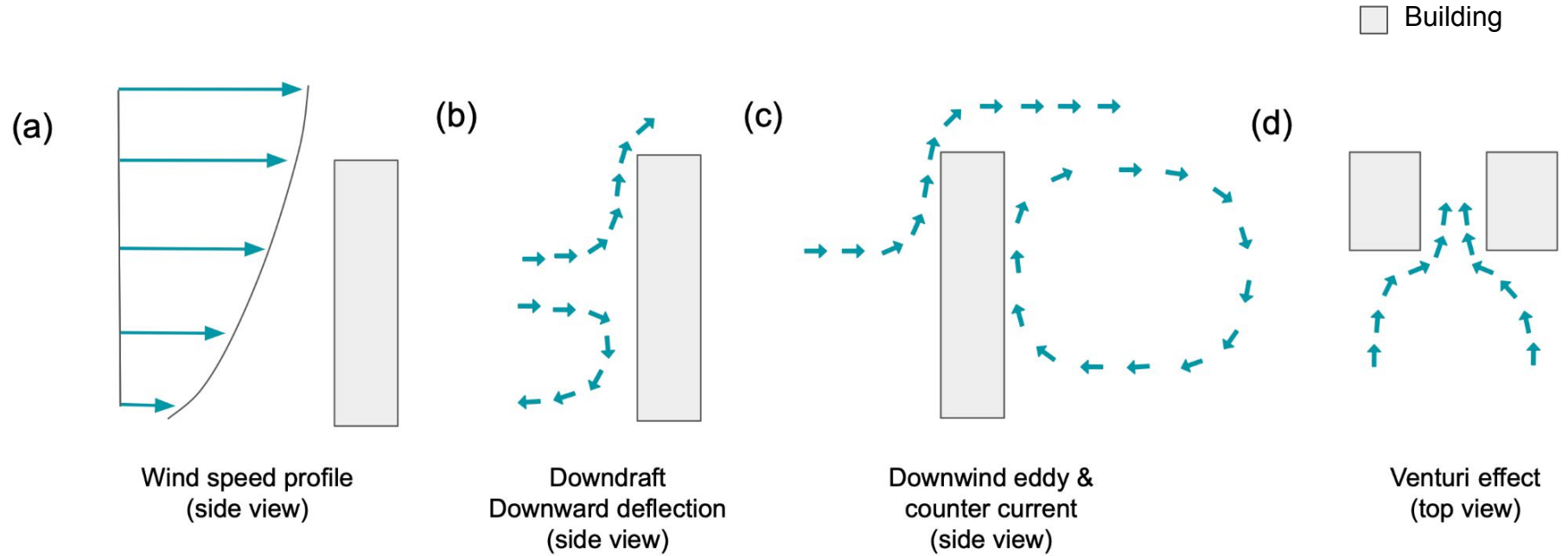


Figure. Basic urban wind effects by structures (e.g., buildings). (a) Wind profile upwind of the building. (b) Upward and downward deflection. (c) Downwind eddy and counter current. (d) Venturi effect (wind speed intensified by gap). Note that (a)-(c) corresponds to the side view of the building; in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

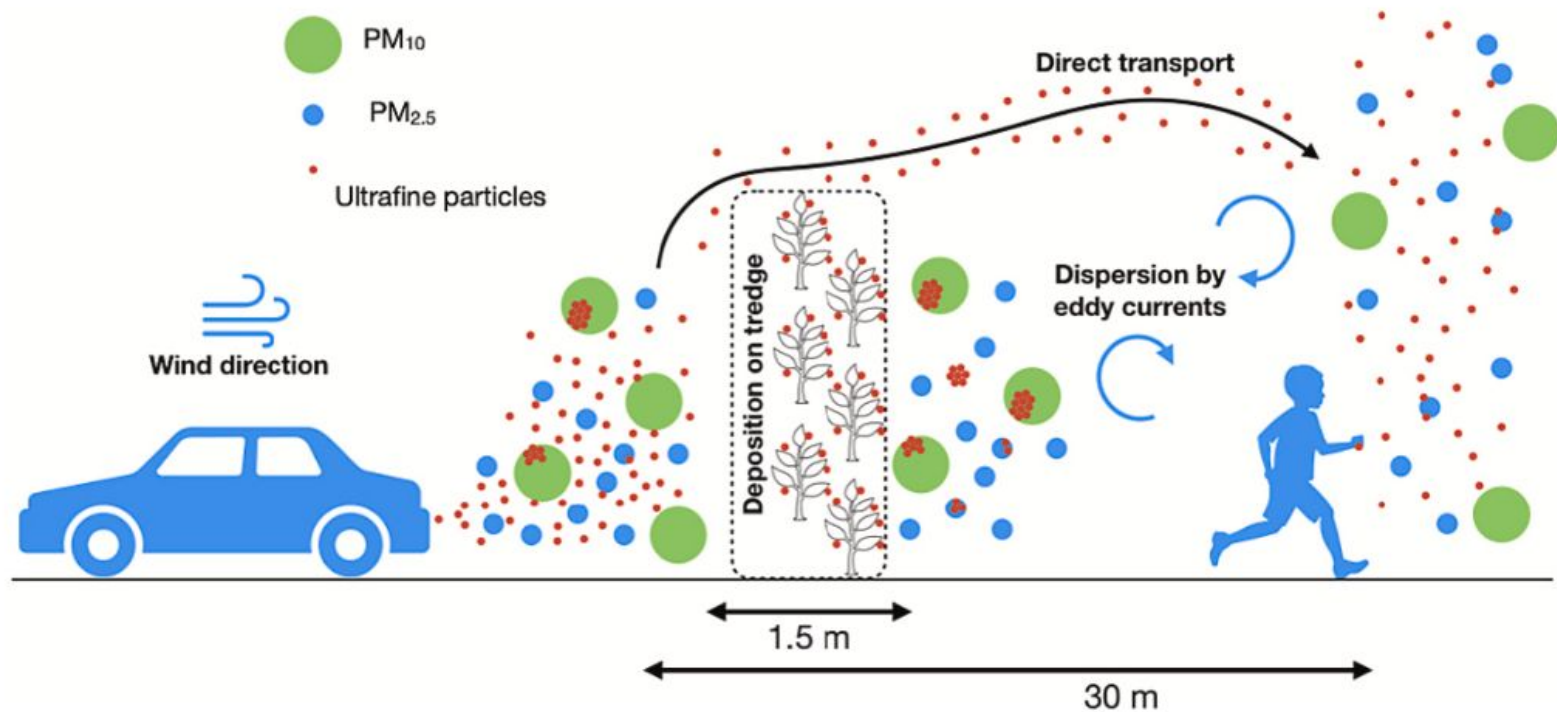


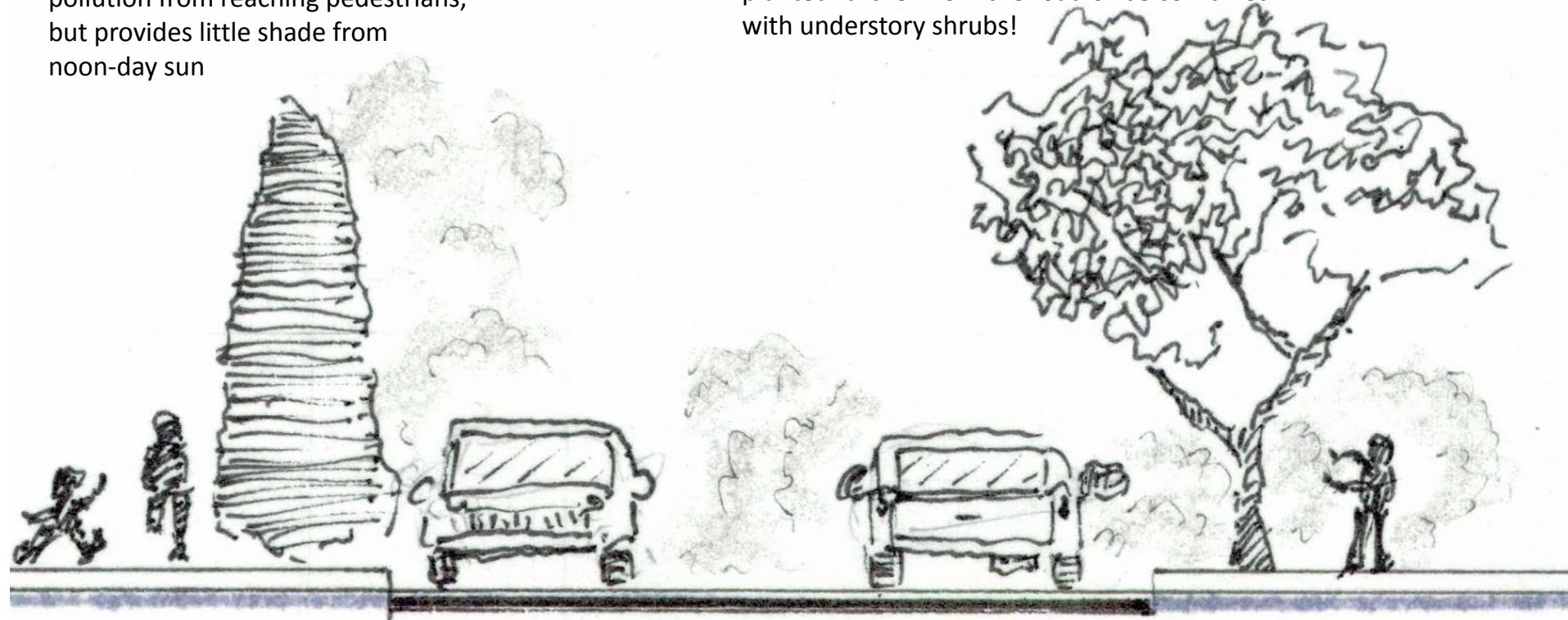
Figure. Basic urban effects by vegetation. PM deposition on leaves reduces downwind exposure. Figure retrieved from Sheikh et al., 2023: Efficacy of green infrastructure in reducing exposure to local, traffic-related sources of airborne particulate matter (PM).

Air pollution vs Heat benefits

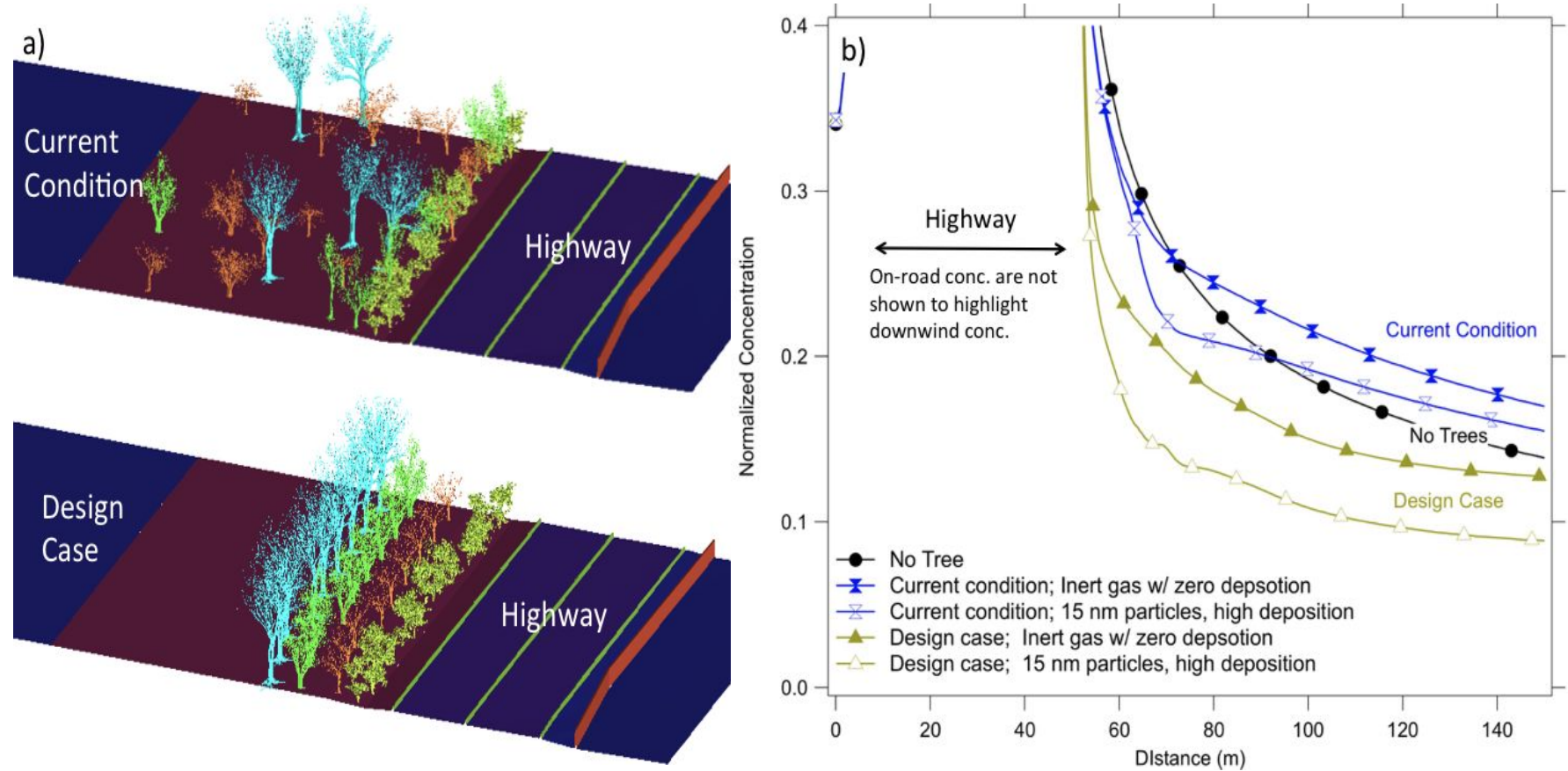
Heat and pollution benefits can be at cross-purposes depending on the location and the tree species, thus carefully matching species / form with location is required to maximize benefits and prevent harm!

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!

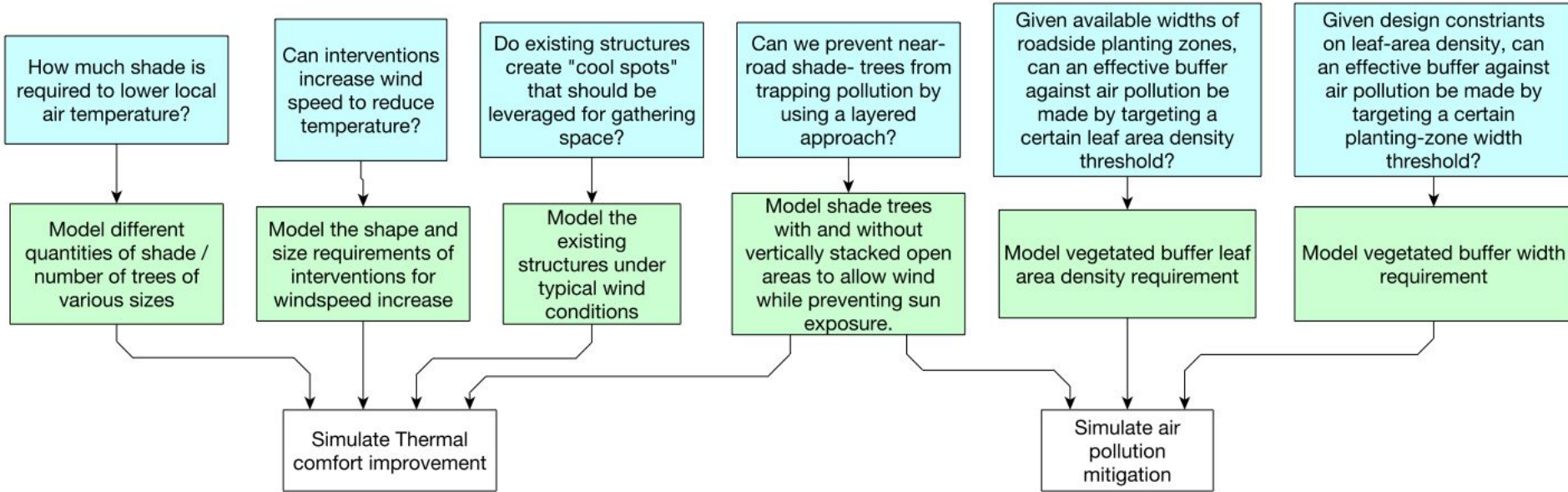


Tree placement can determine harms or benefits of trees WRT air pollution



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!)

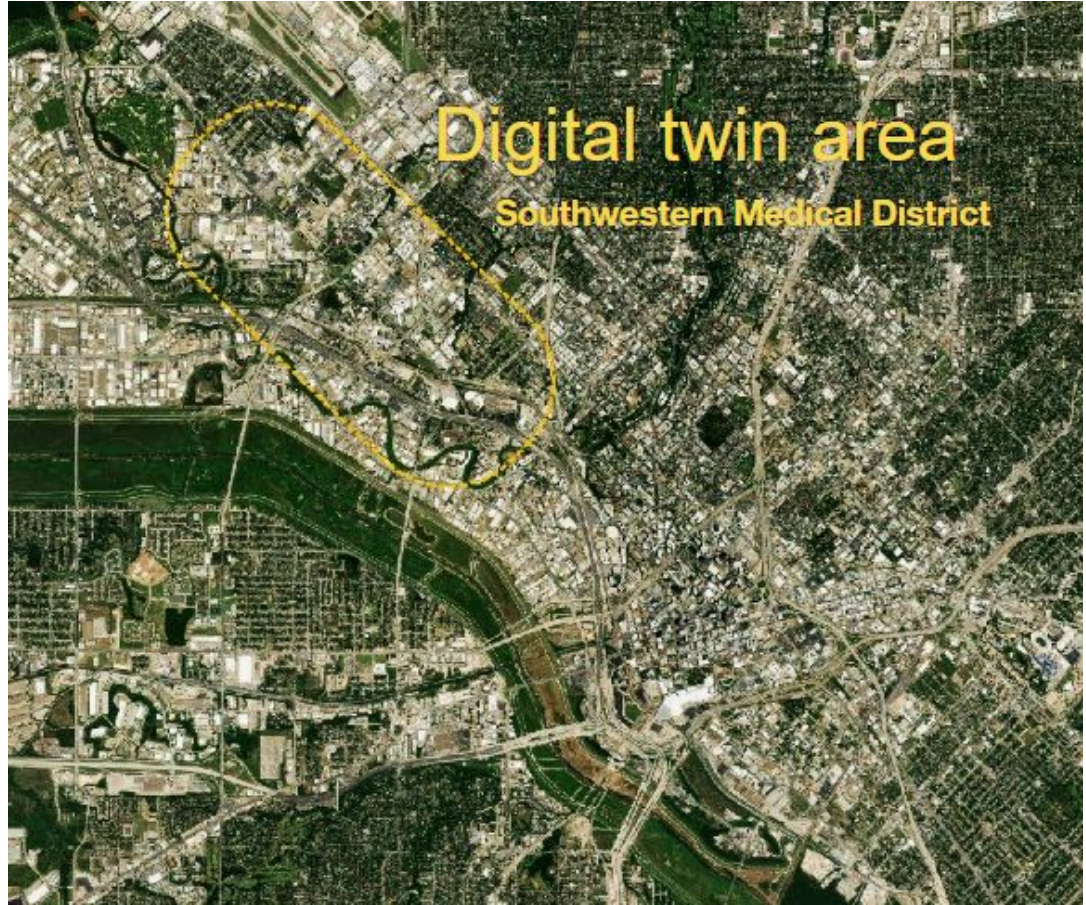


Current Day: Aerial of Dallas



3D “digital twin”

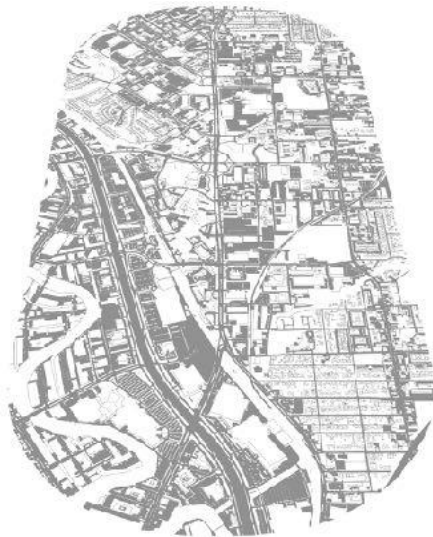
3D Mapping



Existing data layers



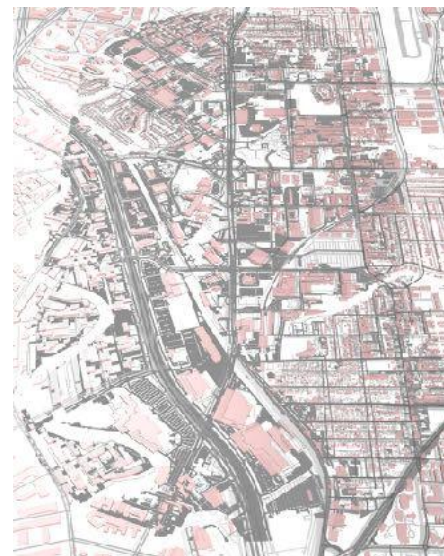
**Public
GIS**



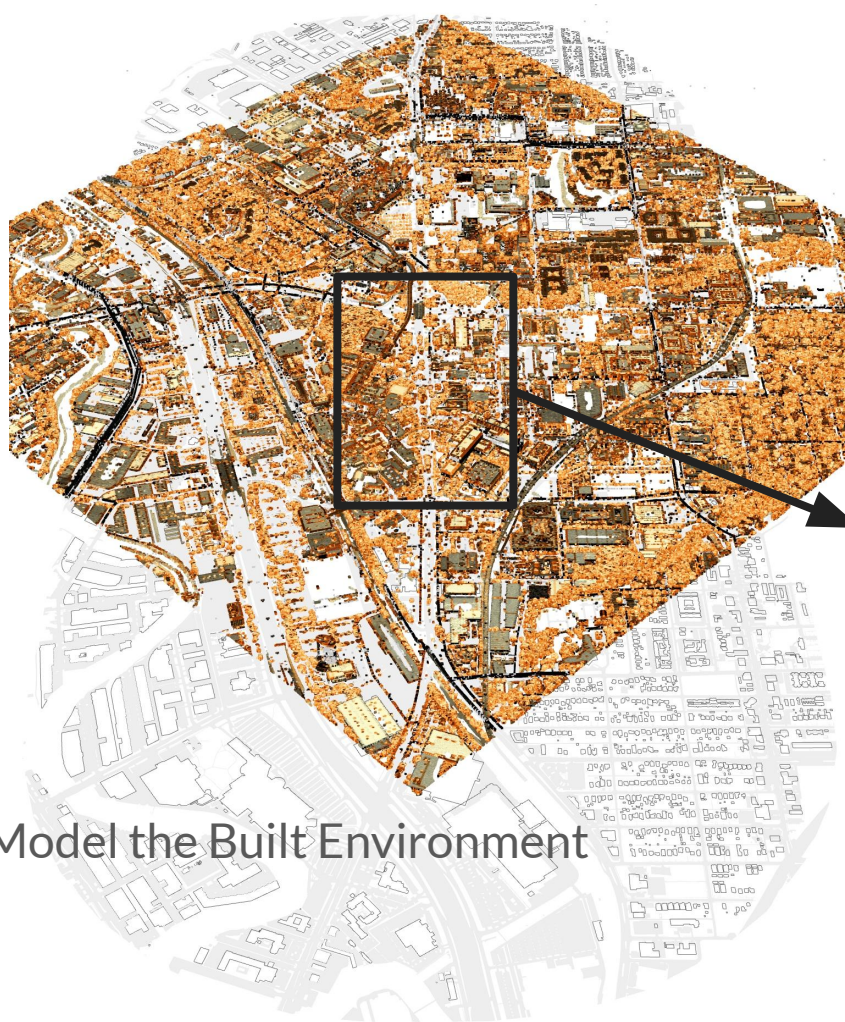
City GIS



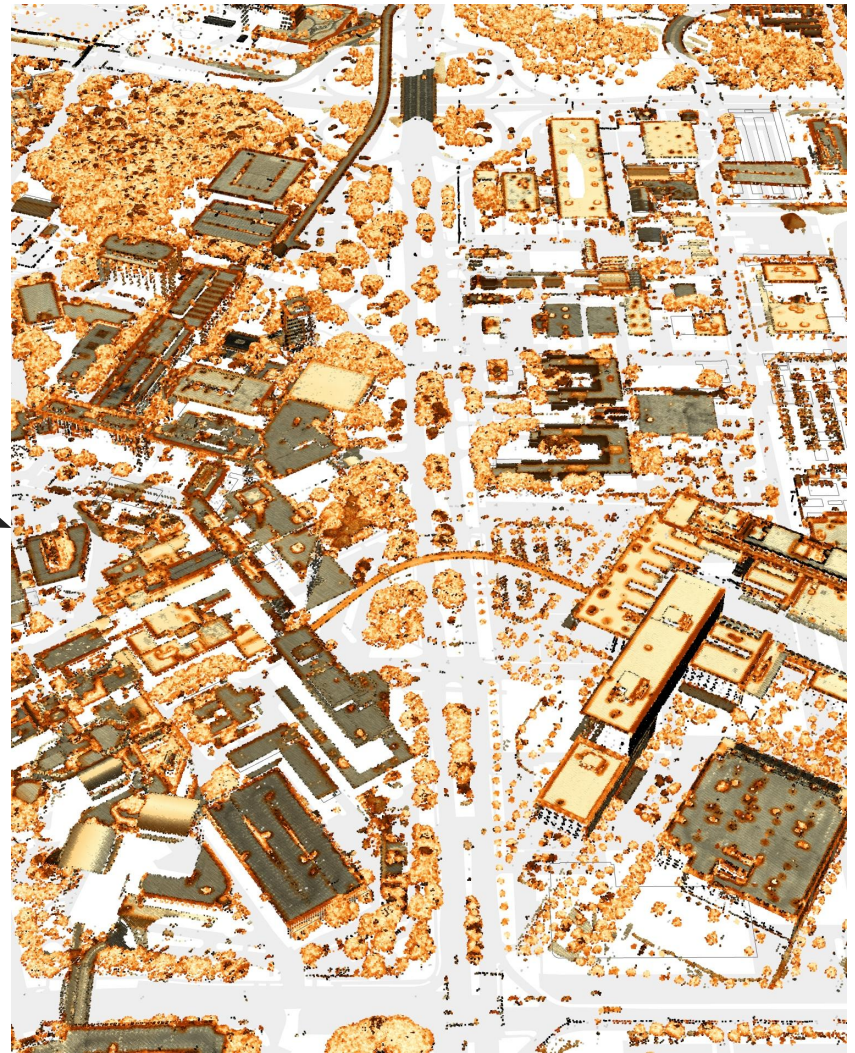
USGS Elevation



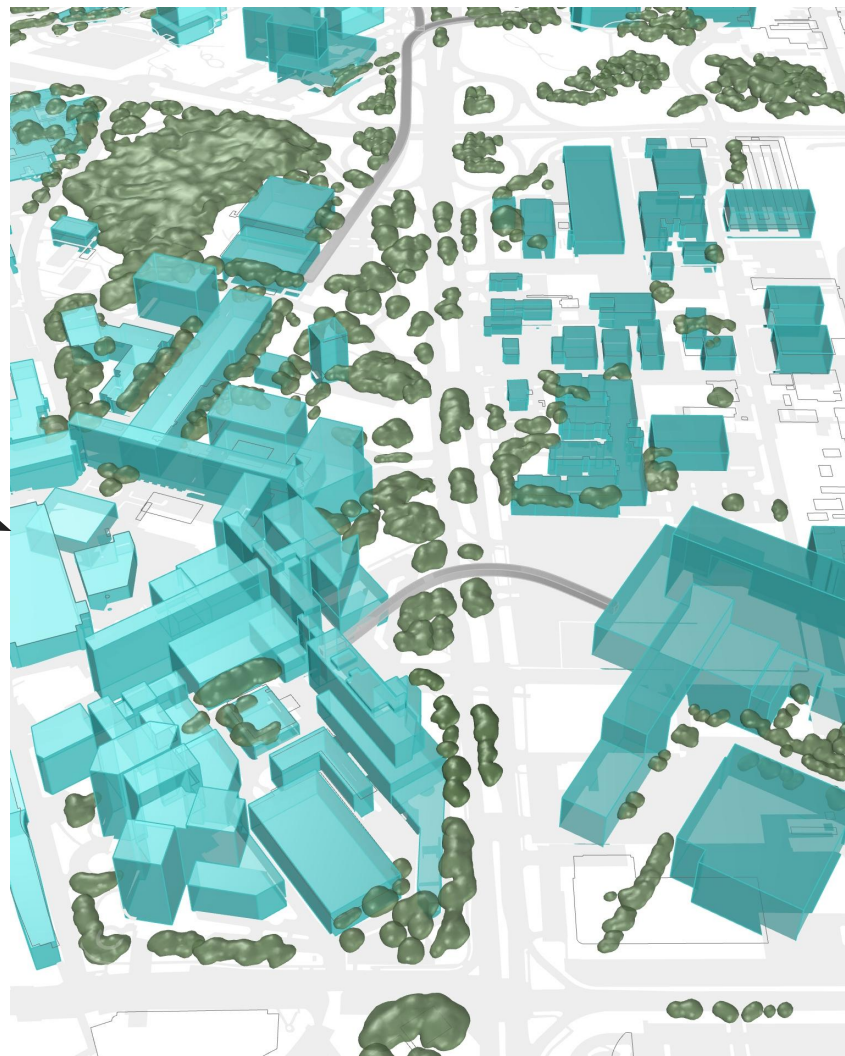
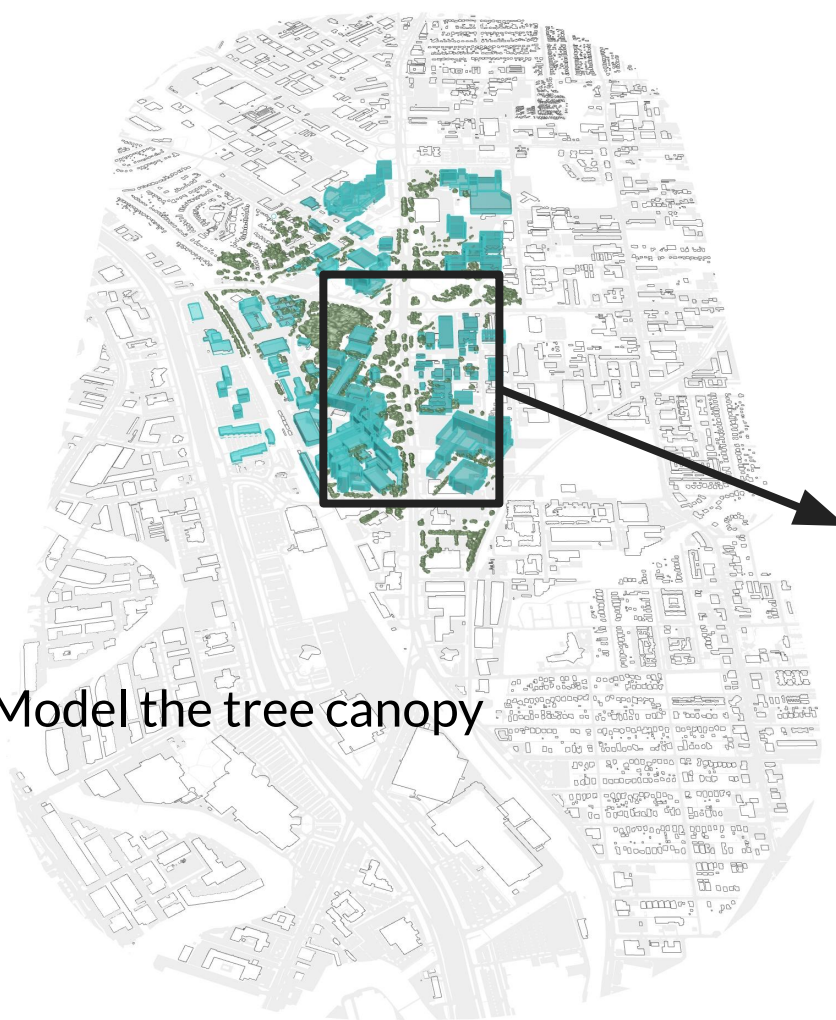
**OpenStreetMap
/ Microsoft**



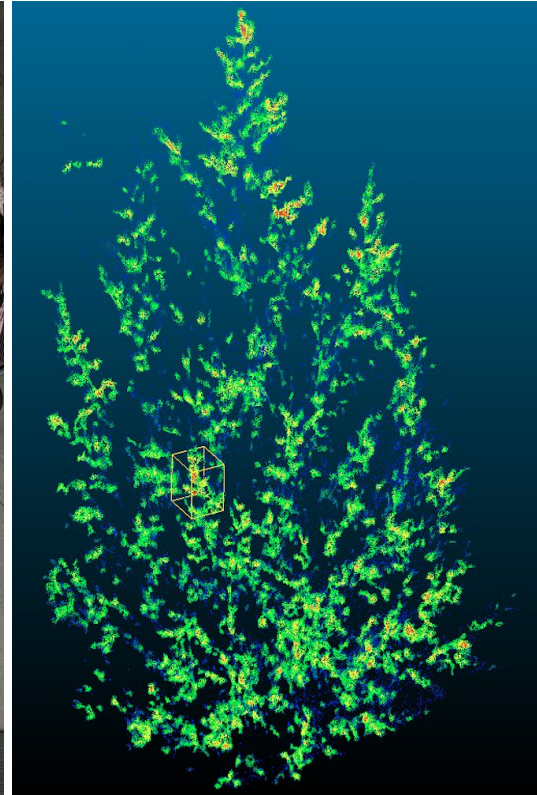
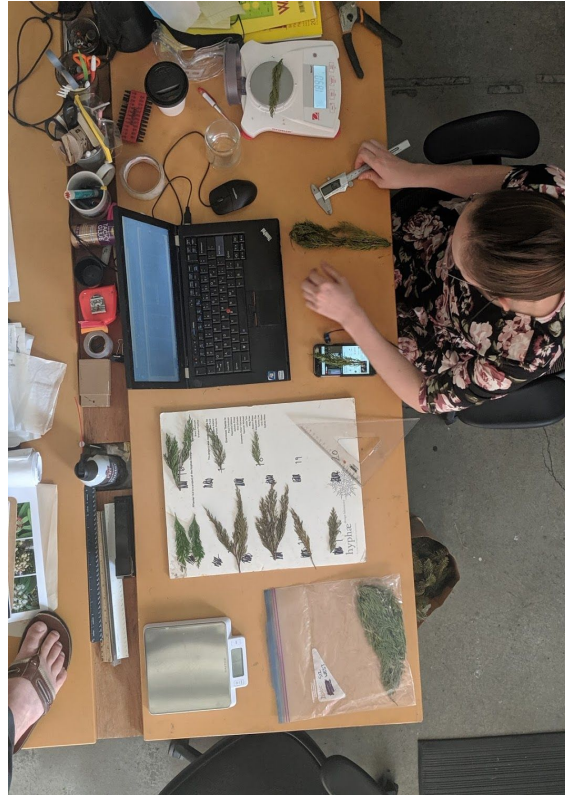
Model the Built Environment



Model the tree canopy



Model Leaf Area Density - LAD

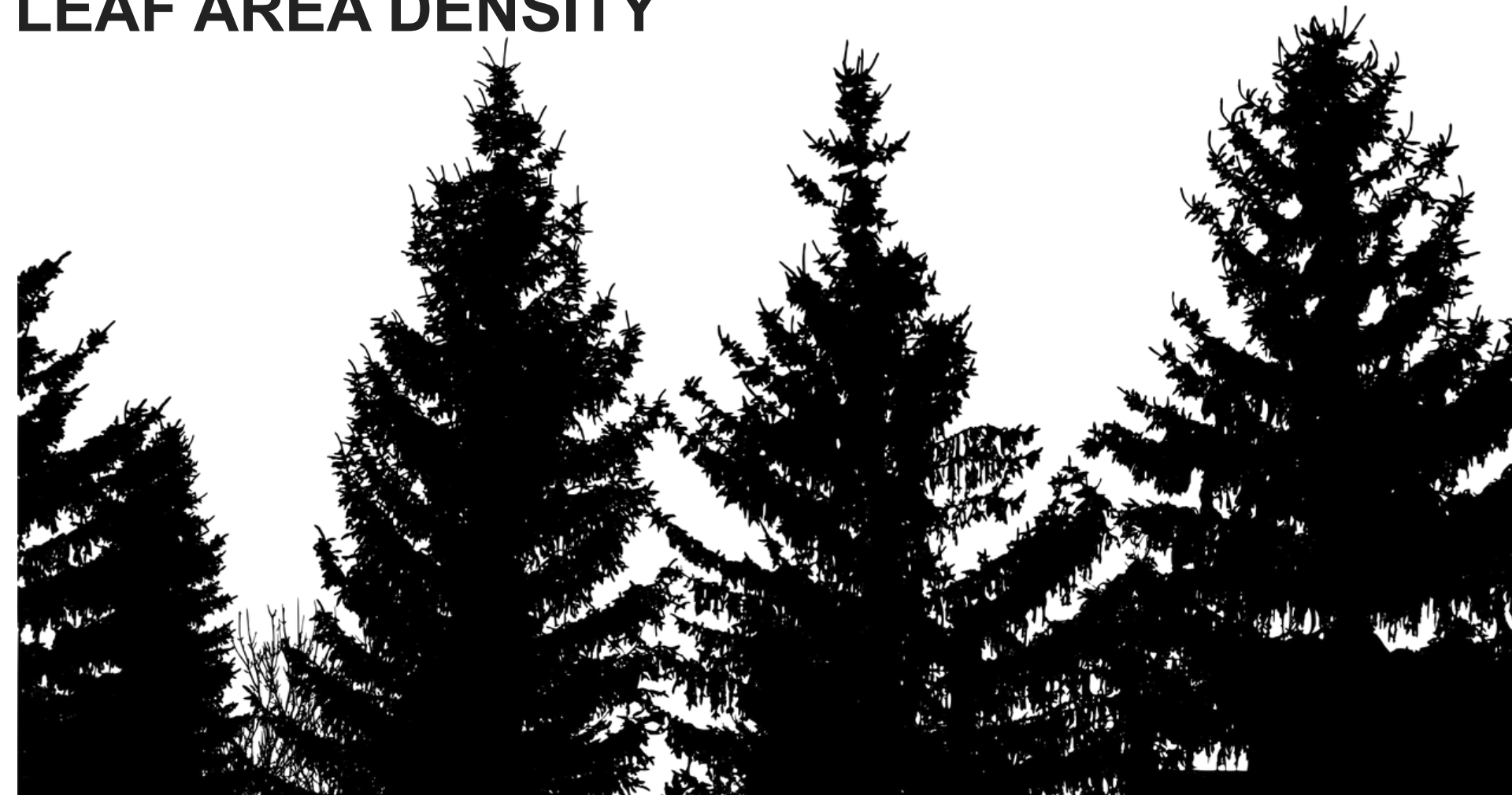


LAD Analysis

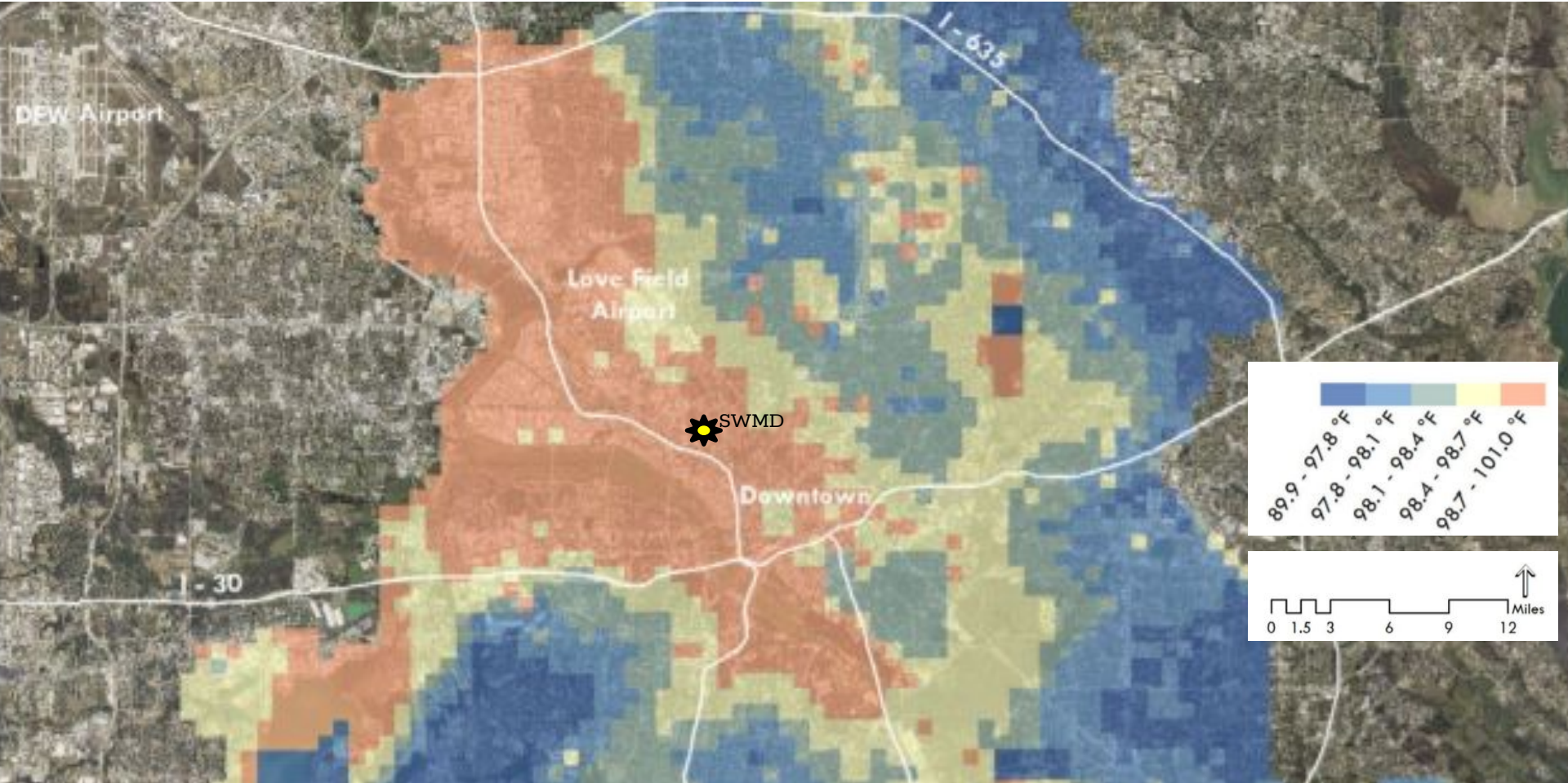
LEAF AREA DENSITY



LEAF AREA DENSITY

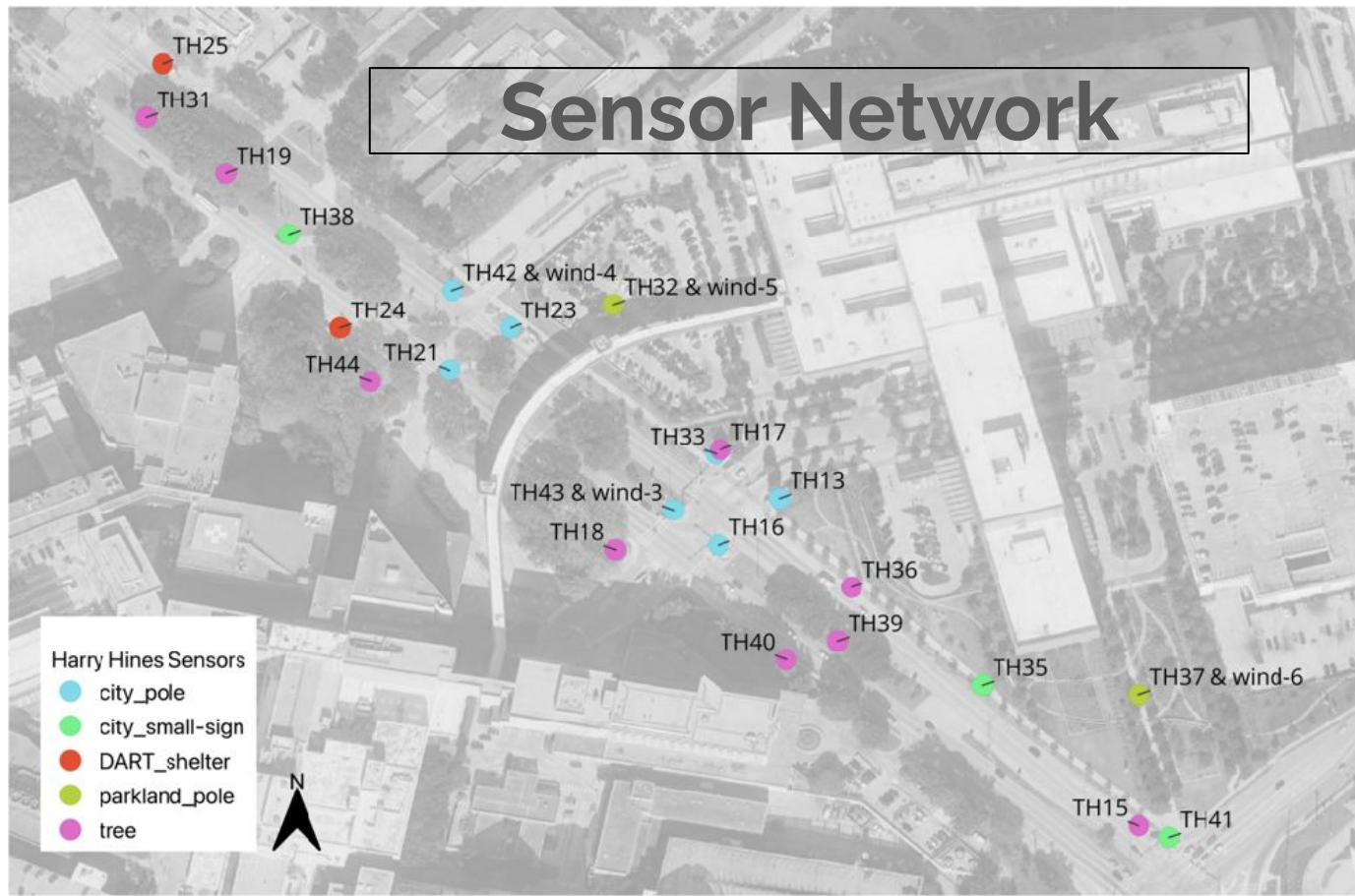
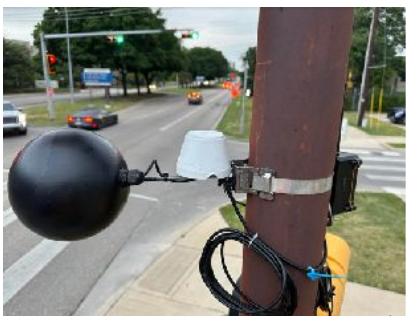


Defining SWMD environmental conditions

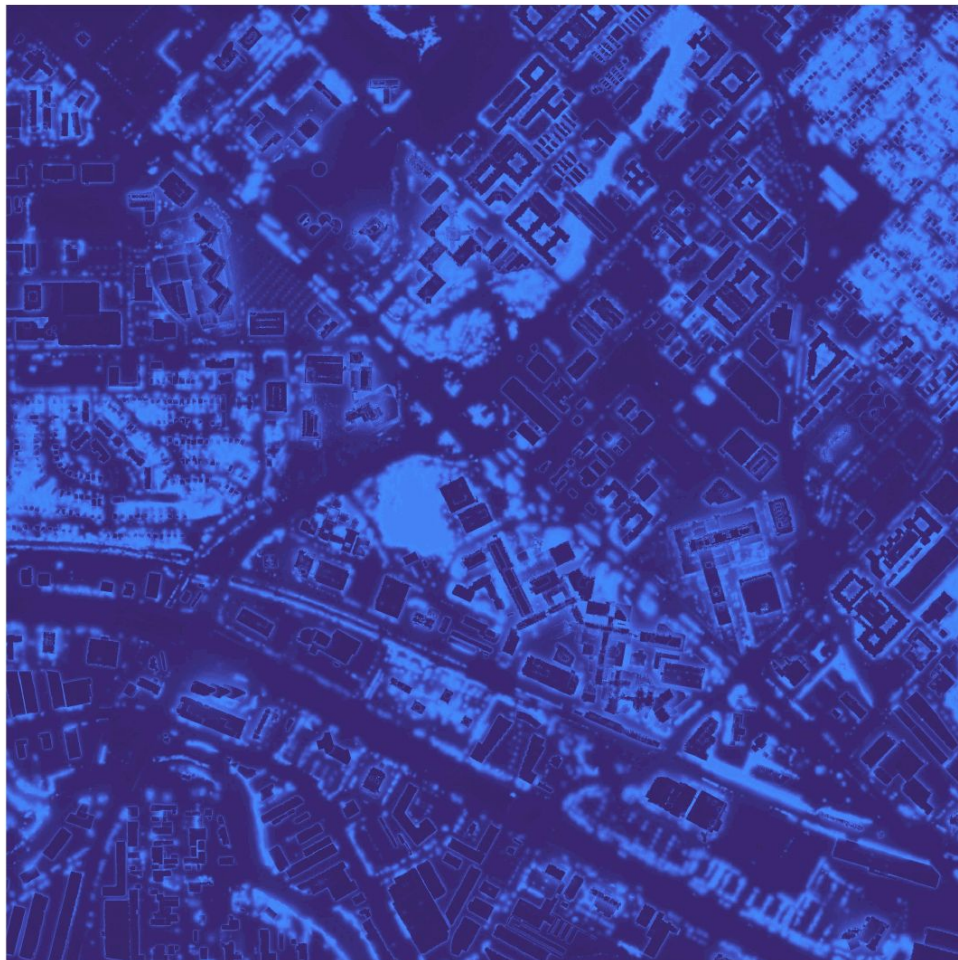


Satellite imagery can see trends over large areas and over time

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



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



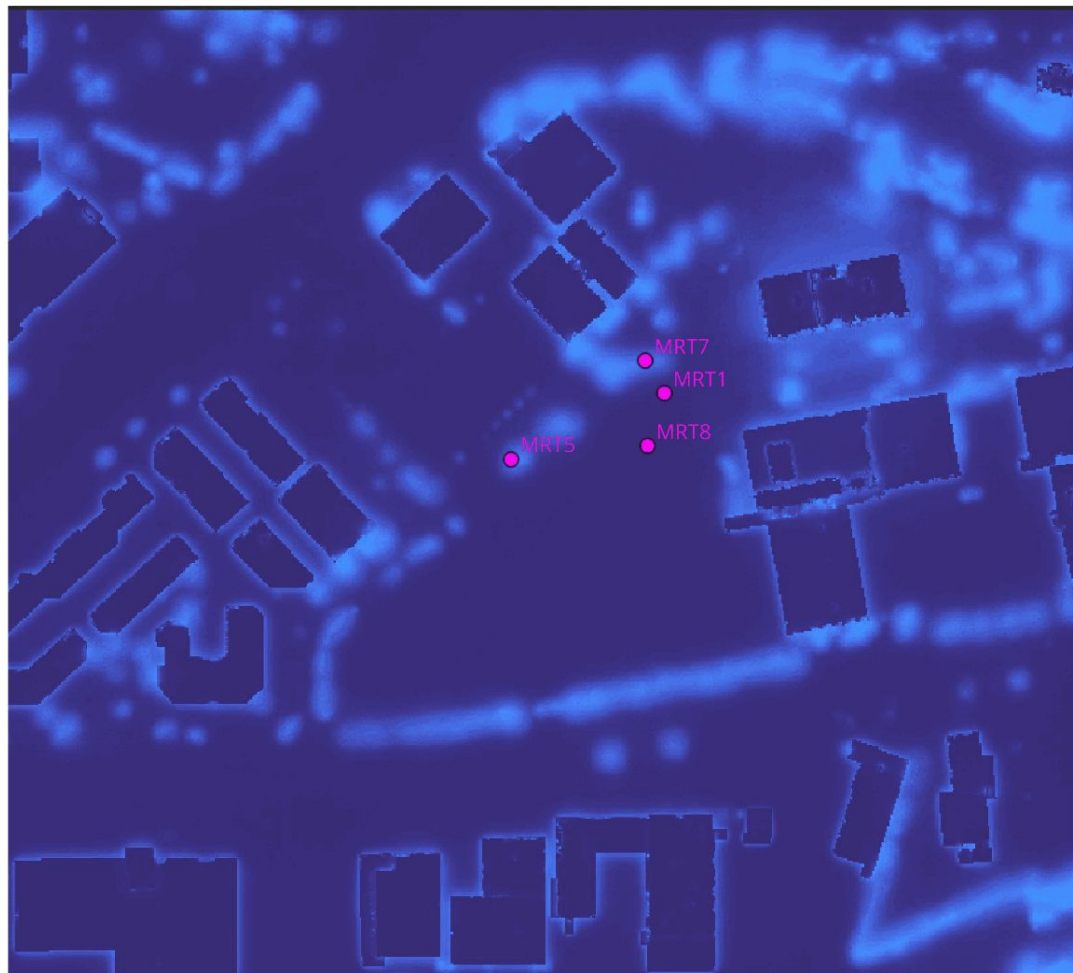
SOLWEIG tMRT 0:53

71C

Harry Hines SWMD
July 12th 2023



21C

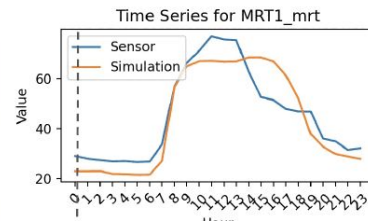


Sensors vs simulation: mean radiant temperature

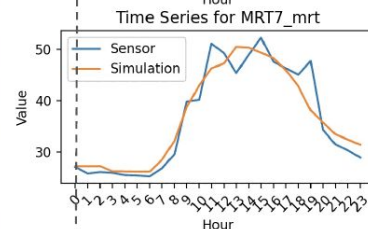
SOLWEIG tMRT 0:53

Pegasus Park
July 12th 2023

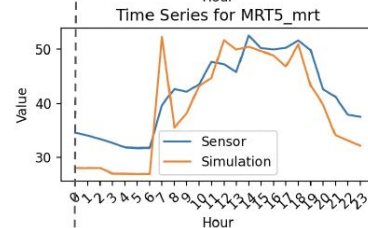
70C



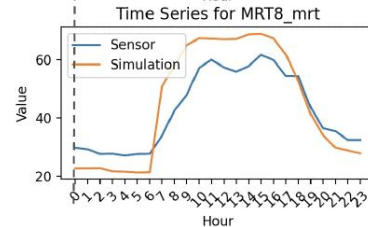
$r^2 = 0.82$ maybe off
due to geopositioning
and old lidar data
(2018)



$r^2 = 0.91$ pretty close



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

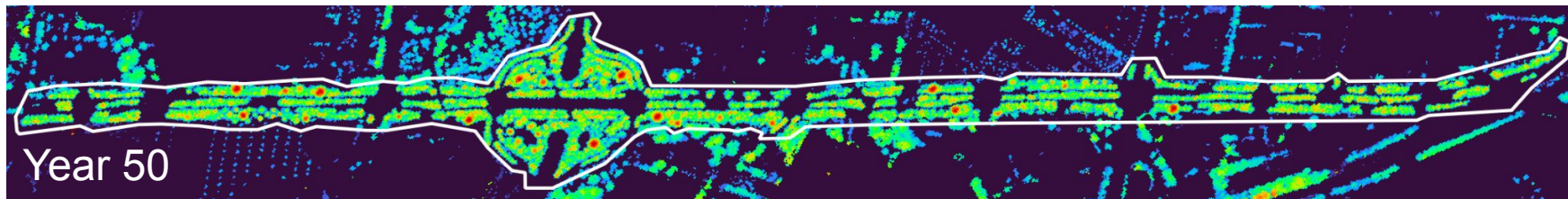
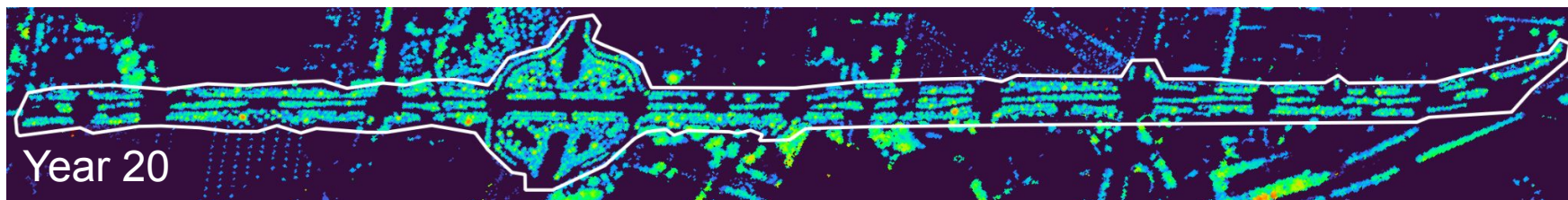
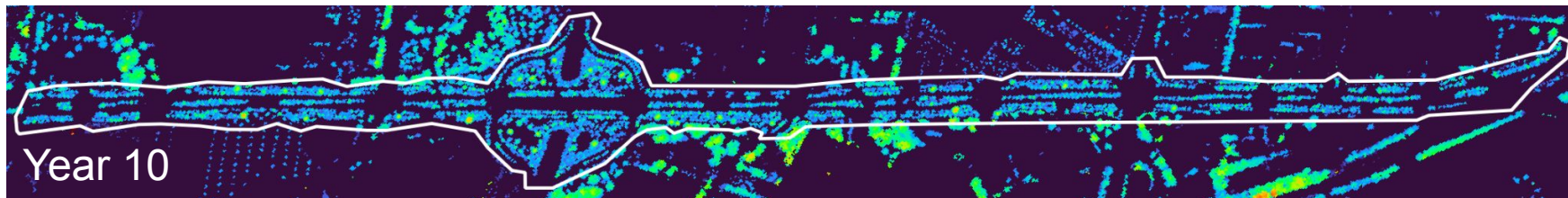
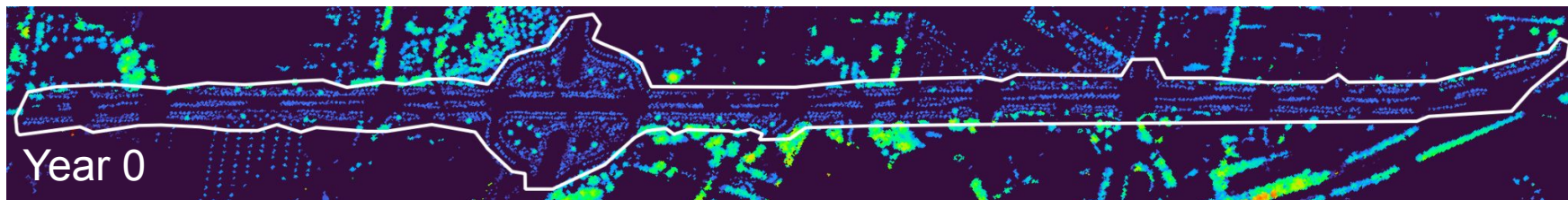


$r^2 = 0.54$ old lidar
data: this small tree
didn't exist in the
simulation

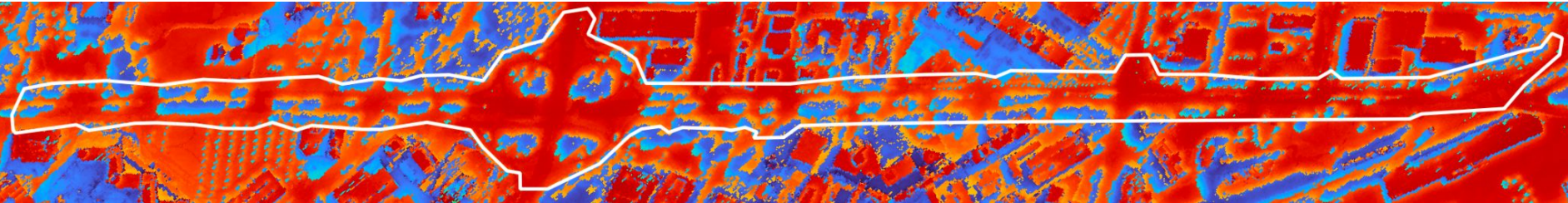
21C

Canopy Growth Model of FO-30% design

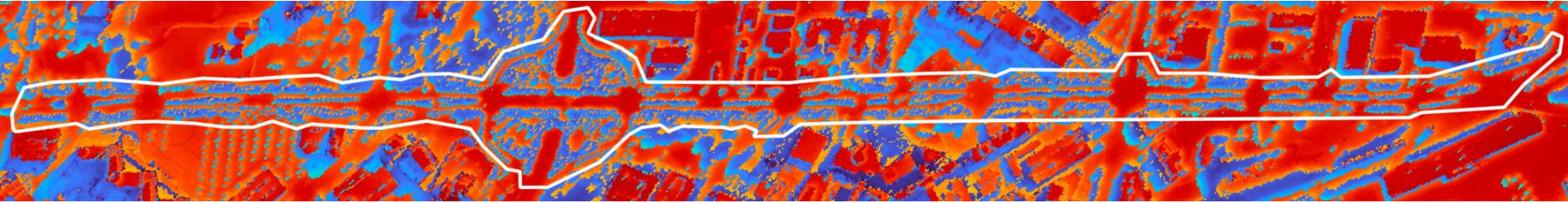
0m  30m



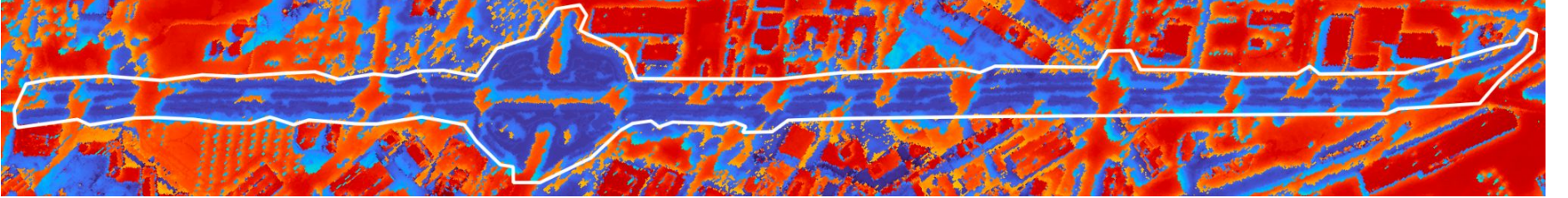
Existing Conditions vs FO 30% Summer Afternoon Mean Radiant Temperature, years 0 and 50



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

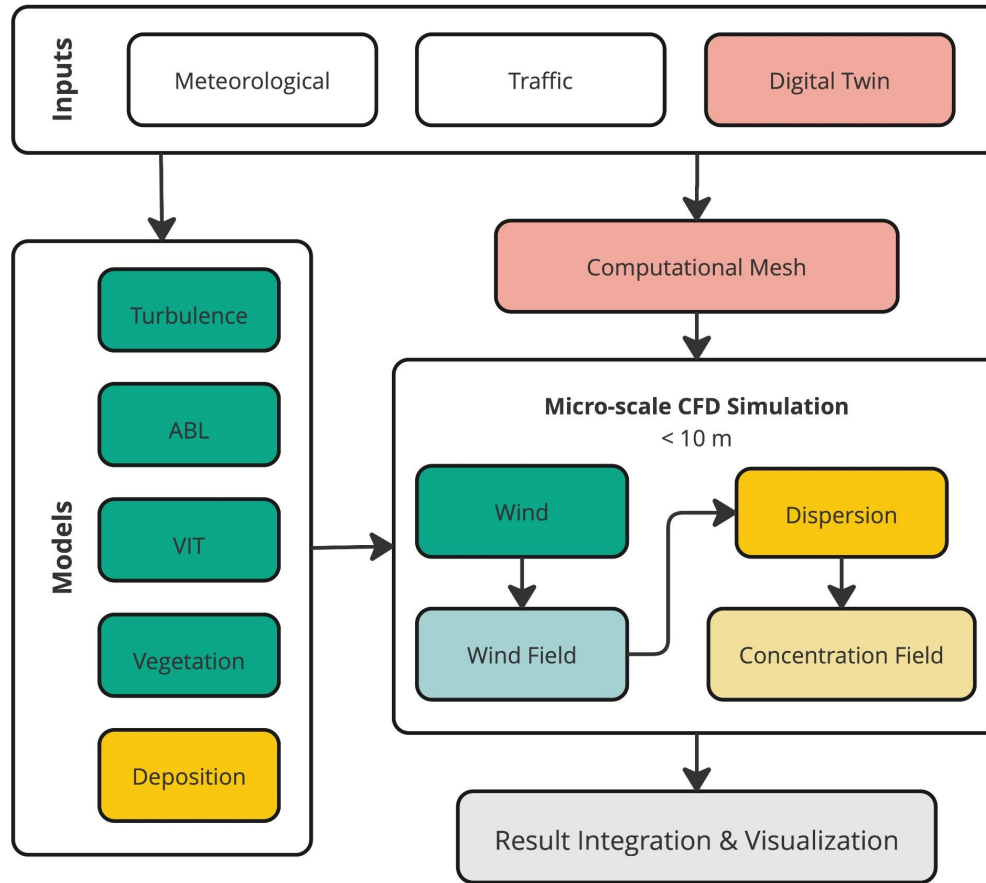
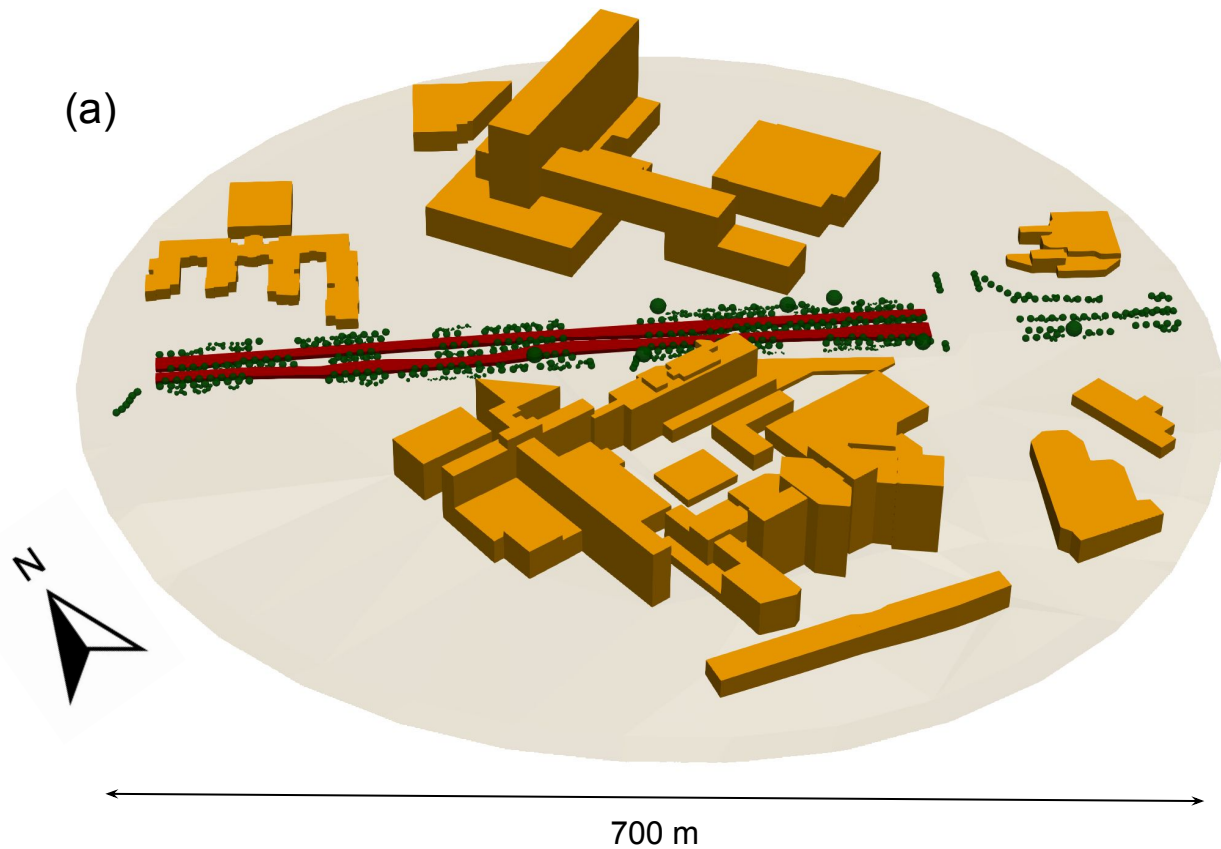
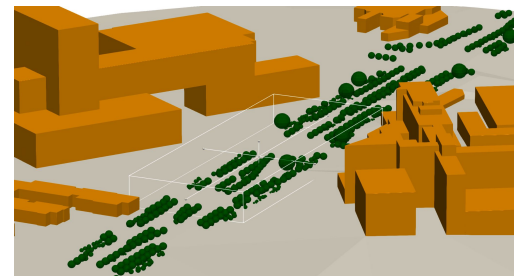


Figure. Schematic of proposed framework and models for urban CFD simulations.

(a)



(b)



Terrain
Buildings
Vegetation
Traffic zones



Windrose Plot for [DAL] DALLAS/LOVE FIELD
Obs Between: 01 Jan 2004 07:53 AM - 31 Dec 2023 07:53 PM America/Chicago
↳ constraints: 7 AM-7 PM

(a)

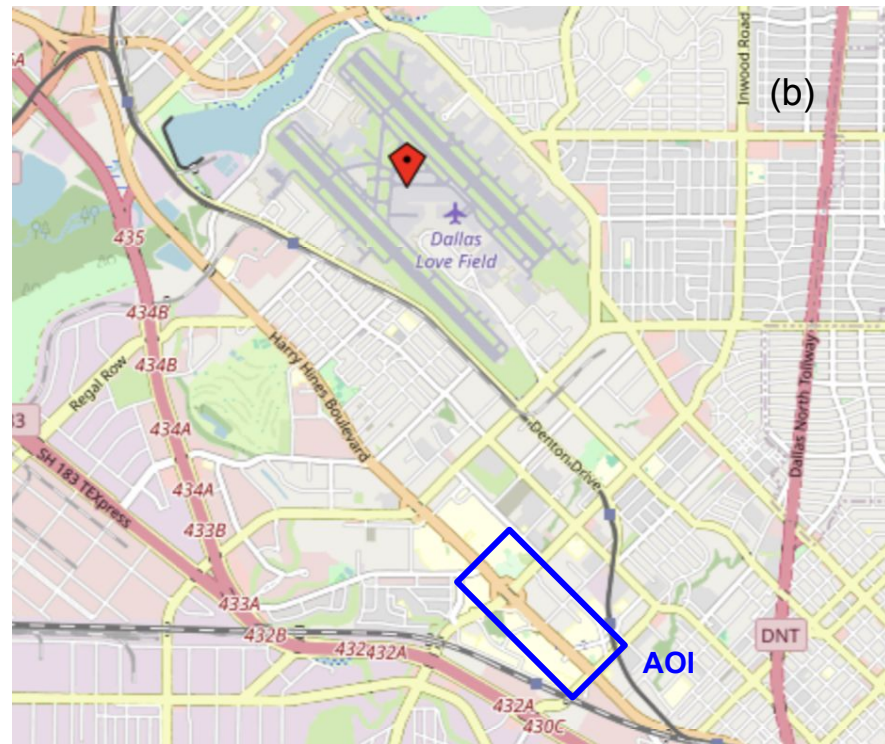
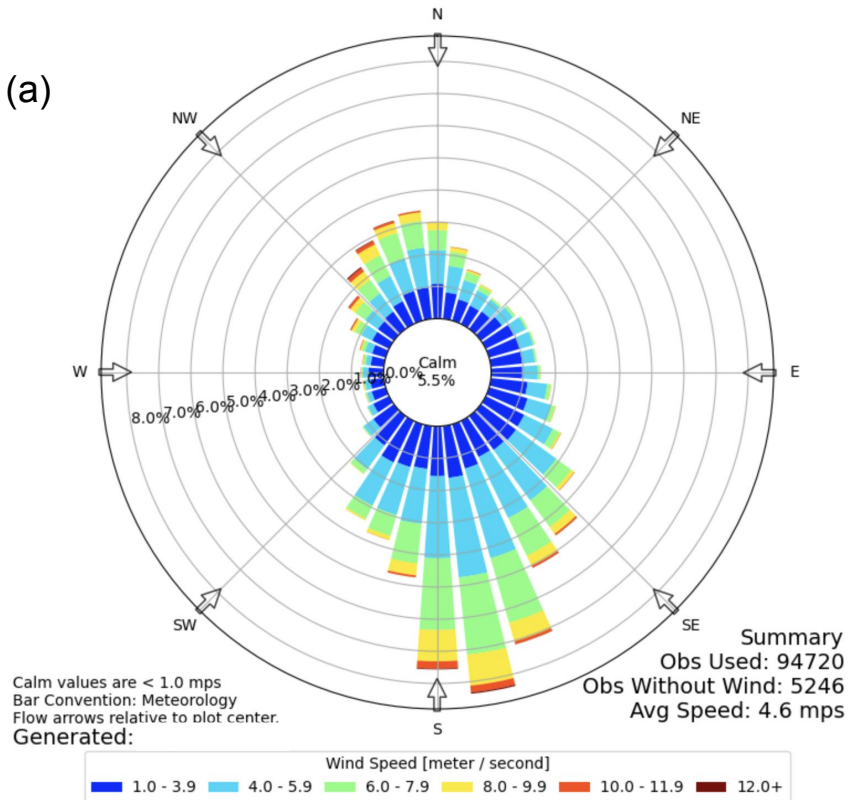


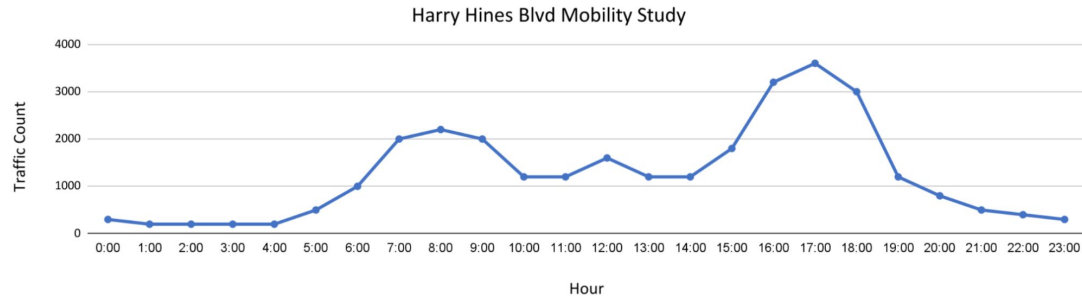
Figure. Windrose plot for Dallas Love Field in Dallas, TX (32.8 N, 96.8 S). (a) Windrose plot from January 2004 to December 2023. The data considered all months and was limited to a time range from 7 am to 8 pm. (b) Weather station site (Dallas Love Field) in Dallas, TX (32.8 N, 96.8 S). Area of interest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

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).

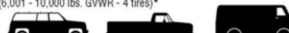
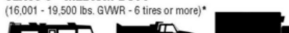
$$\frac{\partial k}{\partial t} + \langle u_j \rangle \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \varepsilon + S_{VIT}$$

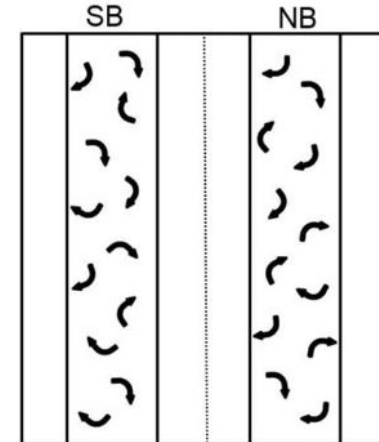


Vehicle Induced Turbulence (VIT)

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.

LAW ENFORCEMENT VEHICLE IDENTIFICATION GUIDE	
CLASS 1 - LIGHT-DUTY (6,000 lbs. or less GVWR - 4 tires)* 	CLASS 3 - MEDIUM-DUTY (10,001 - 14,000 lbs. GVWR - 6 tires or more)* 
CLASS 2 - LIGHT-DUTY (6,001 - 10,000 lbs. GVWR - 4 tires)* 	CLASS 4 - MEDIUM-DUTY (14,001 - 16,000 lbs. GVWR - 6 tires or more)* 
Class 1 through 2 exclude passenger cars, light trucks and mini vans, full size pickups, sport utility vehicles, full size vans.	CLASS 5 - MEDIUM-DUTY (16,001 - 19,500 lbs. GVWR - 6 tires or more)* 
CLASS 1 AND 2 - LIGHT-DUTY TOW (Gross Vehicle Weight Rating (6,000 to 10,000 lbs.) Passenger cars, small SUVs and pickup trucks ☐ Year, make and model? ☐ 4x4 or AWD? ☐ Number of occupants? ☐ Keys? ☐ Full-size pickup or van? ☐ Trailer? ☐ Is it loaded? ☐ What is the load?	CLASS 6 - MEDIUM-DUTY (19,501 - 26,000 lbs. GVWR - 6 tires or more)* 
VEHICLES IN THESE CLASSES USUALLY HAVE FOUR TIRES.	Class 3 through 6 include a range of mid-sized to larger vehicles including delivery trucks, utility vehicles, motor homes, package parcel trucks, ambulances, small dump trucks, landscape vehicles, small ballbed and stake-type trucks, refrigerated and box trucks.
	CLASS 7 - HEAVY-DUTY (26,001 - 33,000 lbs. GVWR - 6 tires or more)* 
	CLASS 8 - HEAVY-DUTY (33,001 lbs. and over GVWR - 10 tires or more)* 
	Class 7 and 8 includes a range of heavier vehicles including large delivery trucks, motor coaches, all tractor-trailer combinations, refuse trucks, construction vehicles, etc.
	CLASS 7 AND 8 - HEAVY-DUTY TOW (Gross Vehicle Weight Rating (Class 7 - 26,001 to 33,000 lbs.) (Class 8 - 33,001 and up to state limit) ☐ Year, make and model? ☐ Two or three axle truck or tractor-trailer? ☐ Bus or motor home? ☐ What is the load and is it damaged? ☐ Number of occupants? ☐ Keys?
	STRAIGHT TRUCKS, BUSES OR MOTOR HOMES IN THESE CLASSES WILL USUALLY HAVE SIX TO TEN TIRES. TRACTOR AND TRAILER COMBINATIONS WILL HAVE FOURTEEN OR MORE TIRES.



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

TKE method
Isotropic
No direction



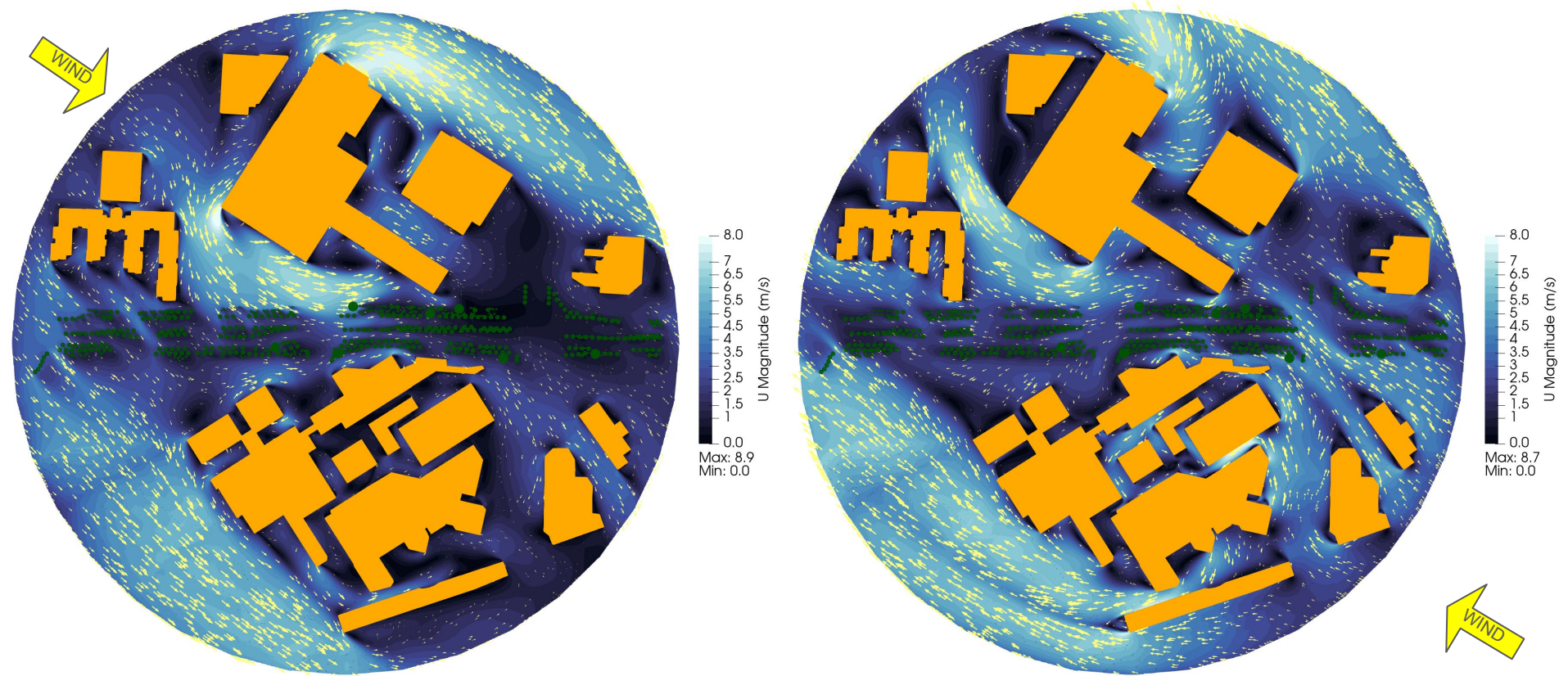
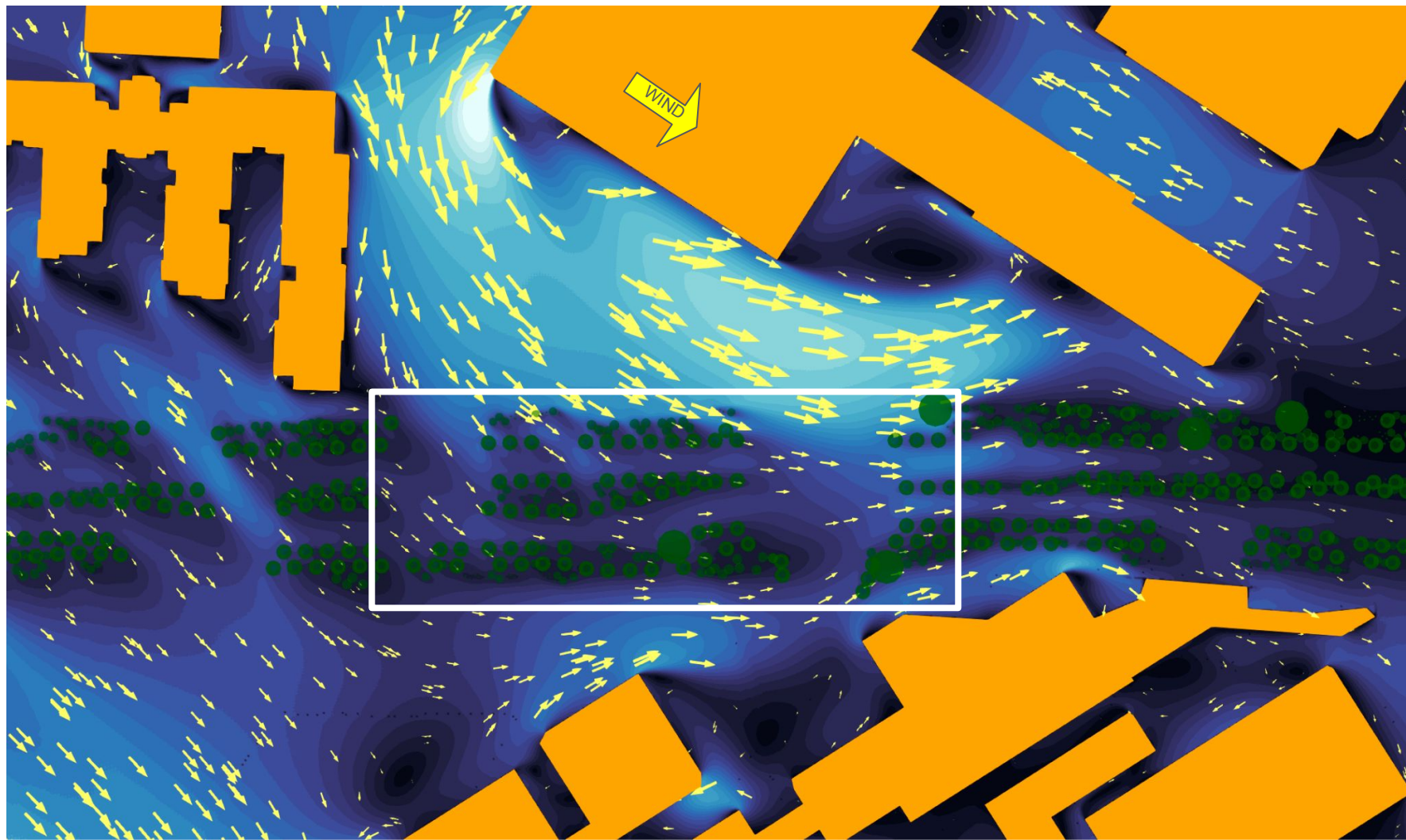


Figure. Wind speed on a terrain-following surface 1.5 m above ground at the Harry Hines corridor. Wind speed at pedestrian level for the selected wind directions. The color bar indicates the wind speed (m/s), and the yellow vectors indicate the direction of the wind. Note that the region shown extends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



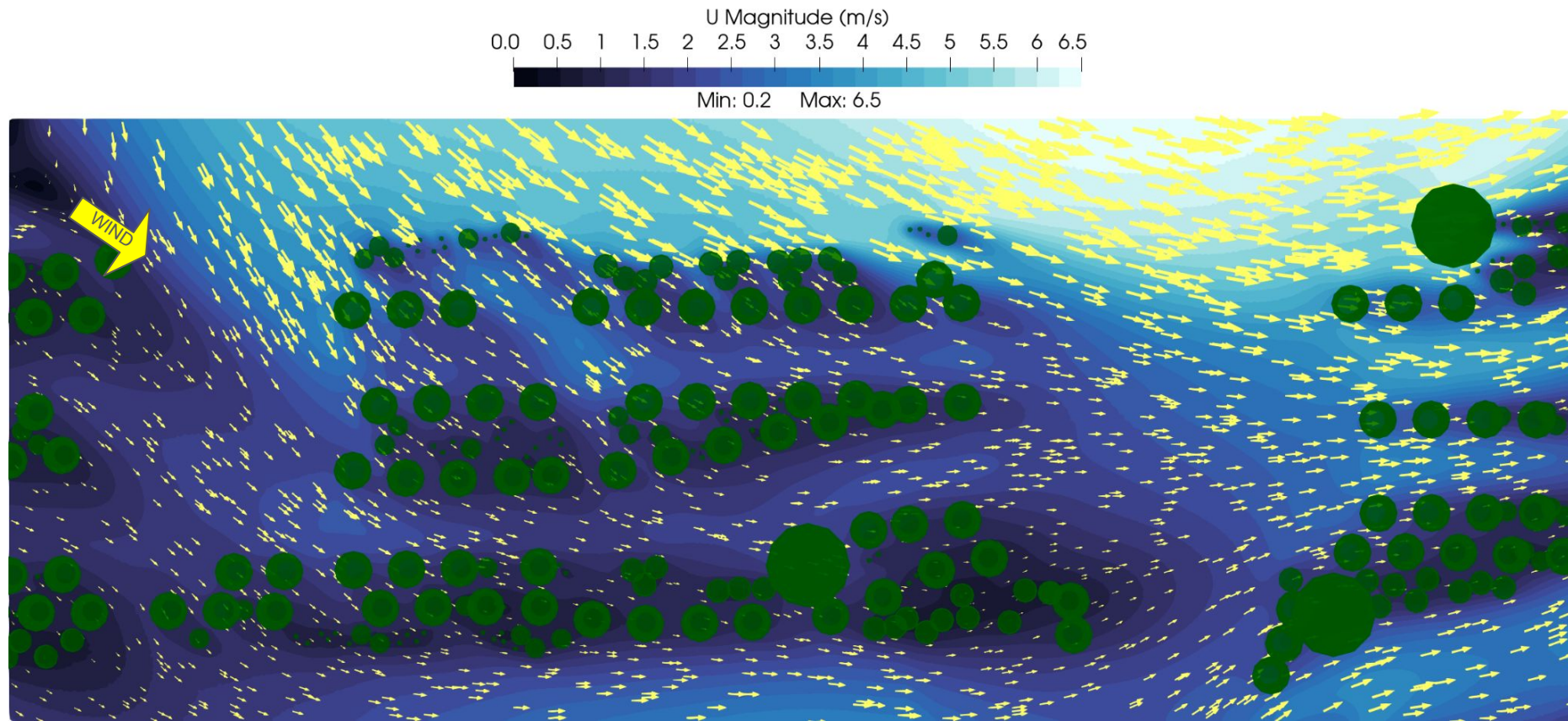
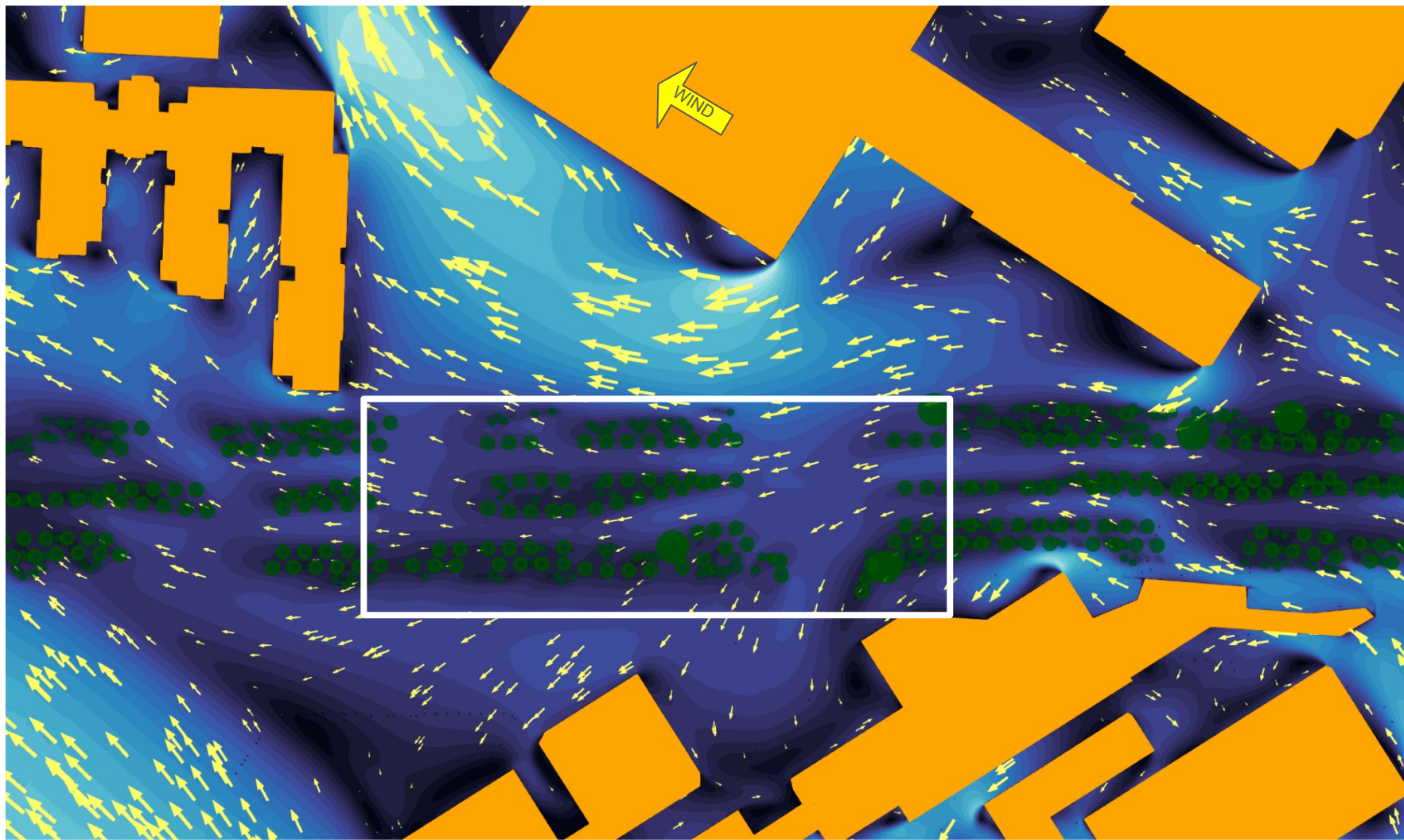


Figure. Wind speed on a terrain-following surface 1.5 m above ground at the Harry Hines corridor. Wind speed at pedestrian level (1.5 m above ground) for the selected wind directions. The color bar indicates the wind speed (m/s), and the yellow vectors indicate the direction of the wind flow. Note that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





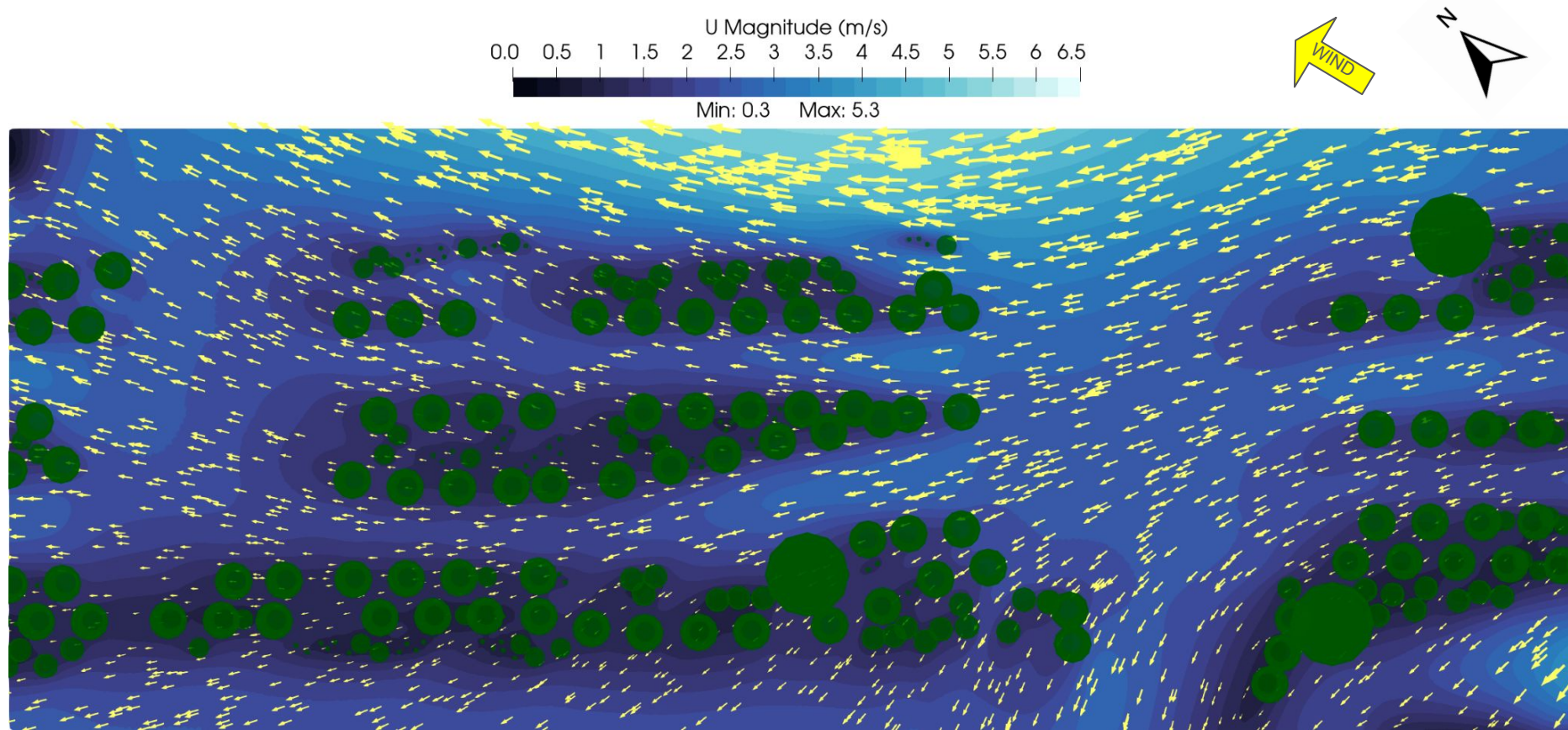


Figure. Wind speed on a terrain-following surface 1.5 m above ground at the Harry Hines corridor. Wind speed at pedestrian level (1.5 m above ground) for the selected wind directions. The color bar indicates the wind speed (m/s), and the yellow vectors indicate the direction of the wind flow. Note that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

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

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



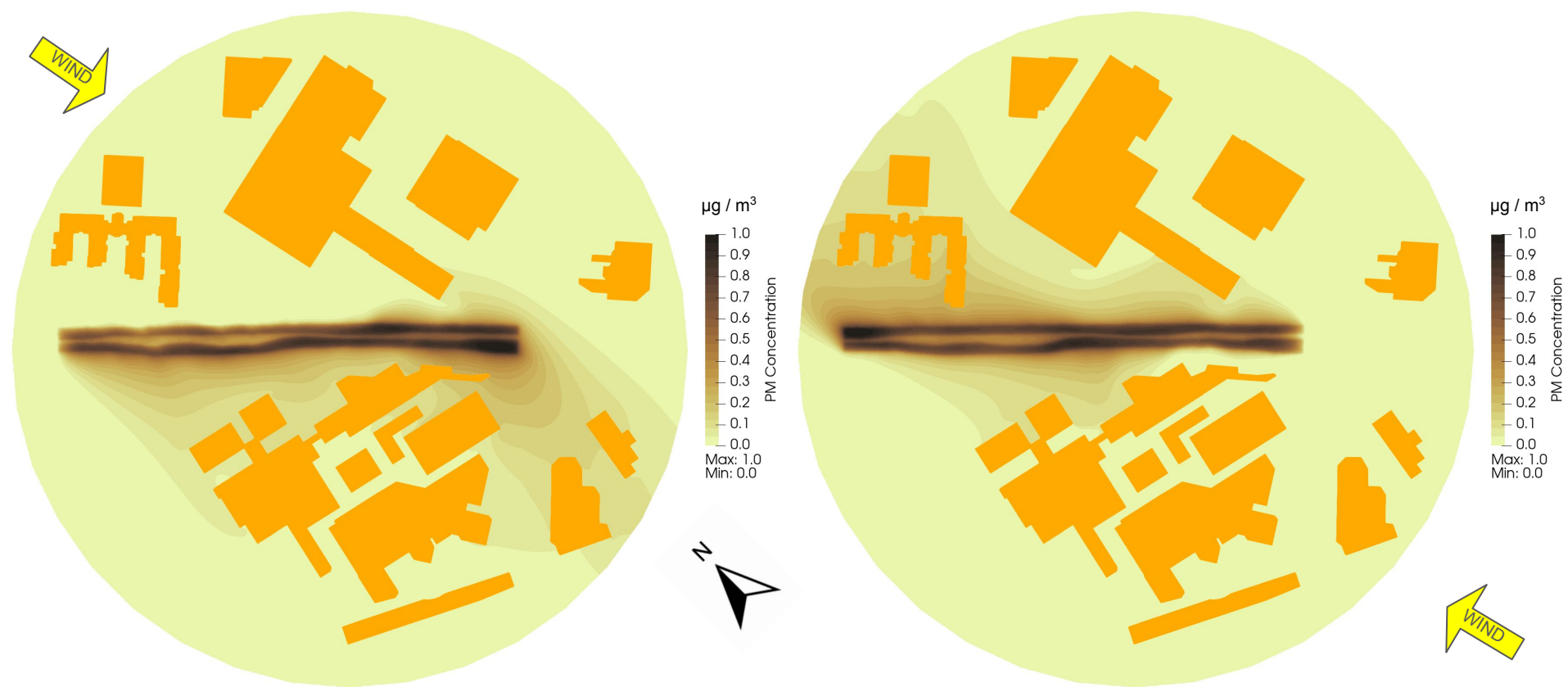
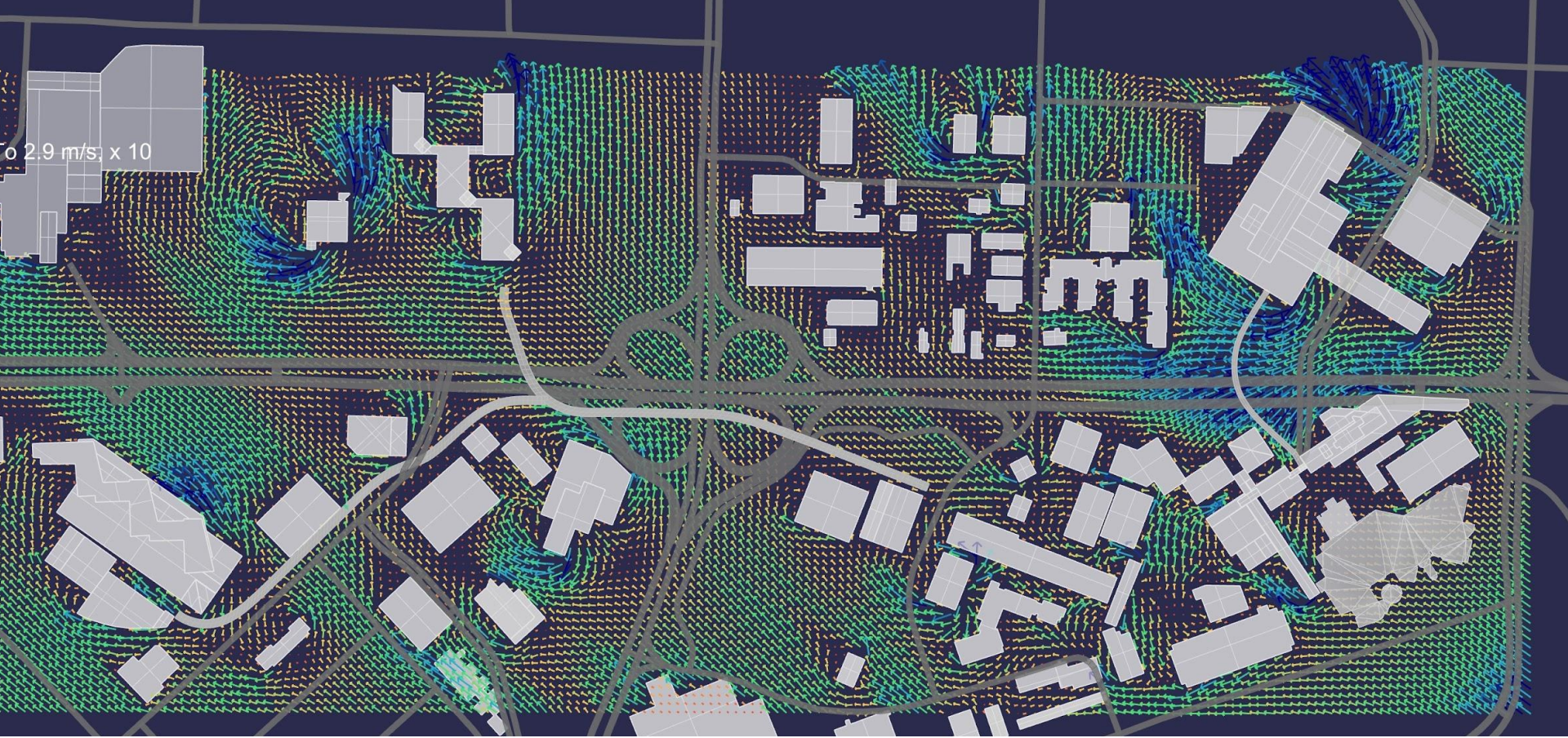


Figure. PM concentration on a terrain-following surface 1.5 m above ground at the Harry Hines corridor. PM_{2.5} concentration at pedestrian level for the selected wind directions. Note that the region shown extends 350 m from the center location.



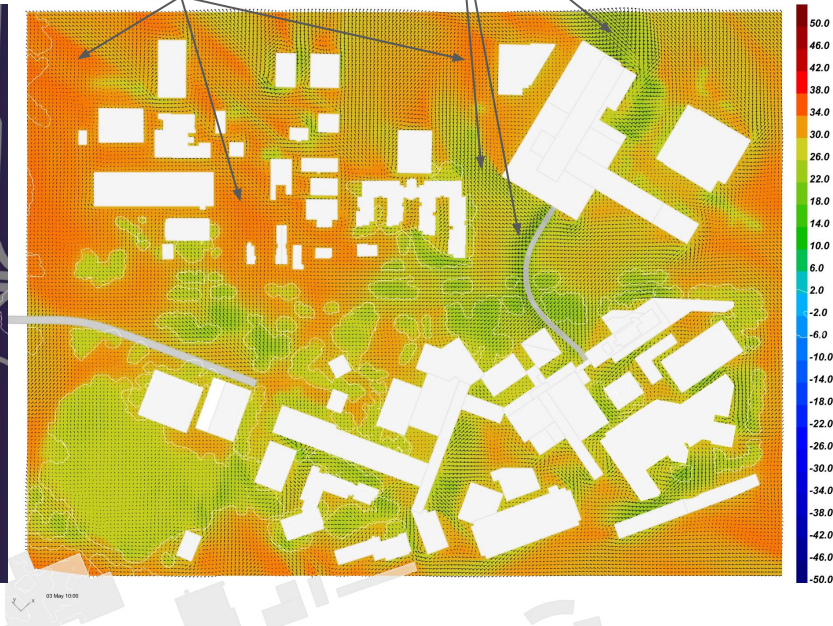
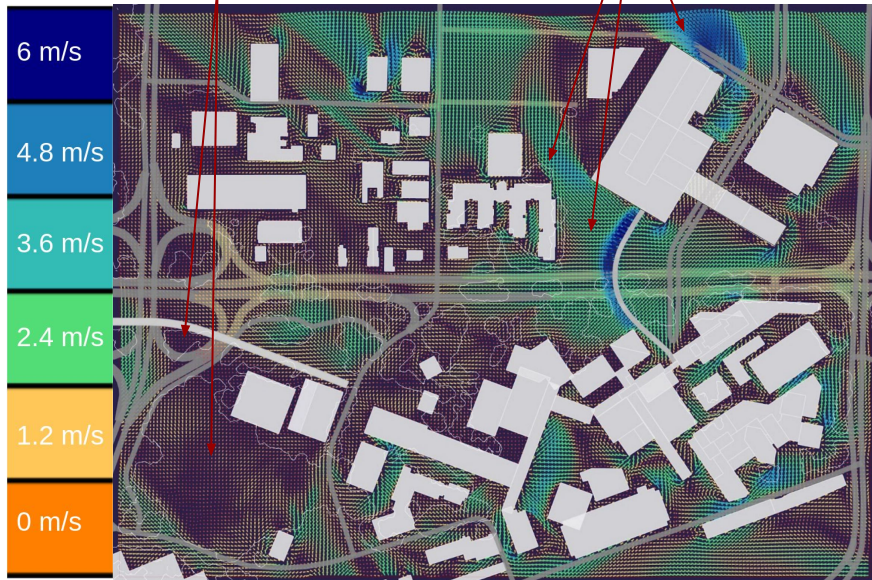
Microclimate Wind Study

Where structures increase wind-speed

Areas where adding new shade trees might not help

Where trees reduce wind-speed

Where new shade trees would help a lot

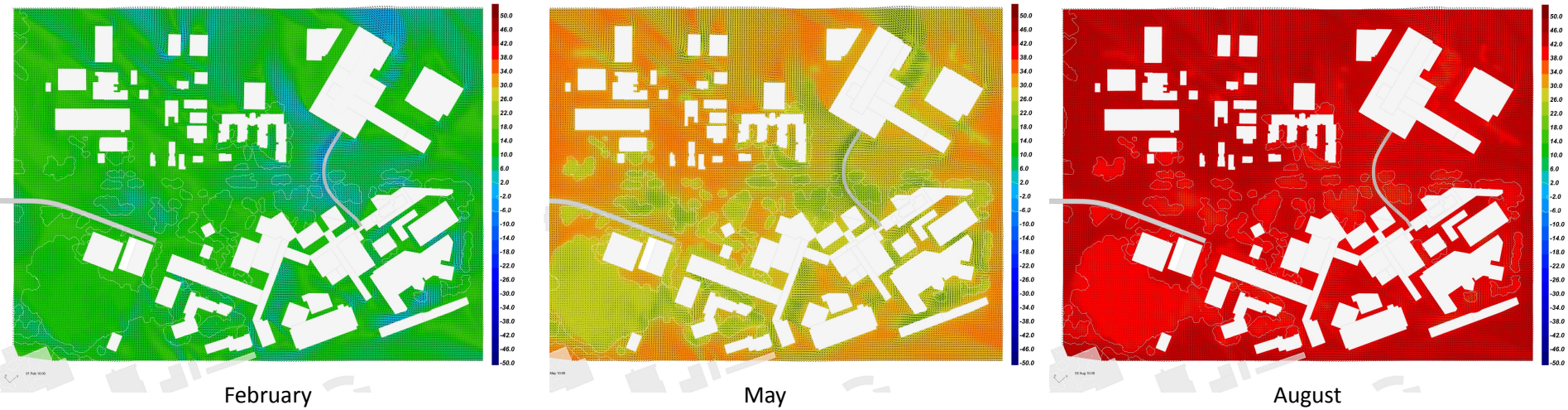


Wind Flow Simulation

Thermal Comfort Simulation

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





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, ...)



