Cooling Singapore
Digital Urban Climate Twin (DUCT)

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COOLING SINGAPORE

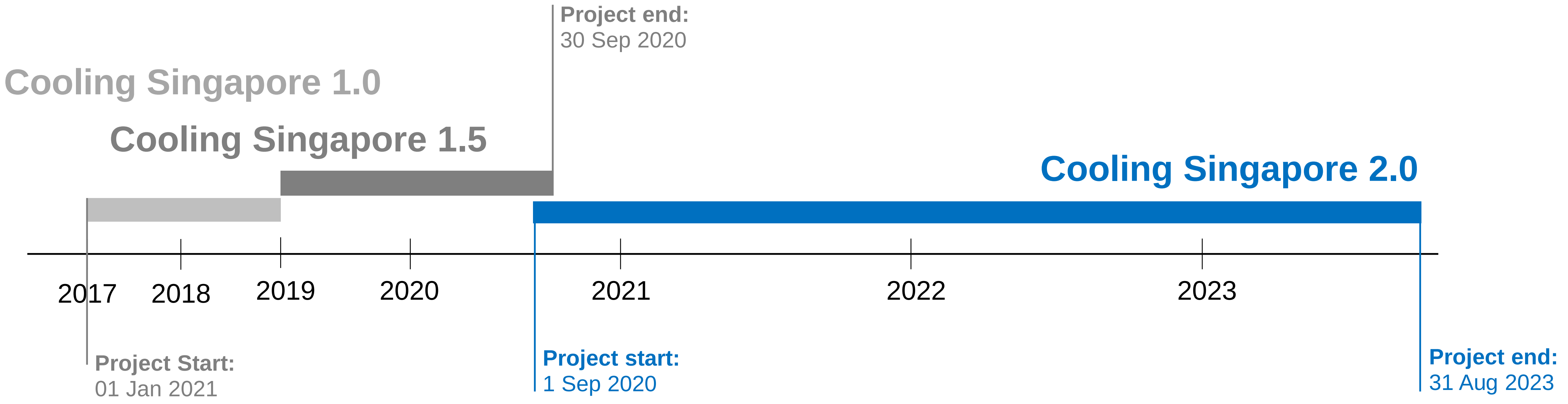
Agenda

- Introduction to Cooling Singapore
- Urban heat mapping (mitigation strategies)
- Urban heat assessment
- Technology use for climate informed decisions (DUCT)

Cooling Singapore

“The city is warmer than its surrounding – by up to 7˚C – due to the Urban Heat Island effect”

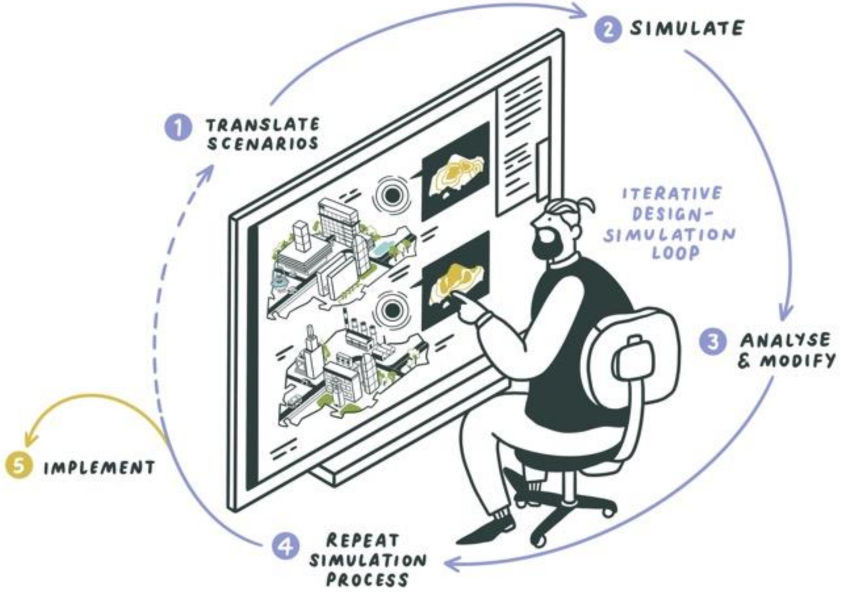
Cooling Singapore Timeline



The Cooling Singapore Initiative

Cooling Singapore 1.0	Cooling Singapore 1.5	Cooling Singapore 2.0
Jan 2017 – Dec 2018 (24 months)	Apr 2019 – Sep 2020 (18 months)	Sep 2020 – Aug 2023 (36 months)
NRF – CREATE Program	NRF – Virtual Singapore Program	NRF – Urban Solutions and Sustainability Program
4 research partner institutions	5 research partner institutions	6 research partner institutions
26 team members (incl. PIs)	29 team members (incl. PIs)	29 team members (incl. PIs)

Cooling Singapore is a research project dedicated to developing solutions to address the urban heat challenge in Singapore.



Source (image): H. Aydt (2020). Cooling Singapore – Towards Urban Climate Design and Management in Indicia 03, editors: S. Cairns and D. Tunas (forthcoming)

Urban heat mapping
(mitigation strategies)

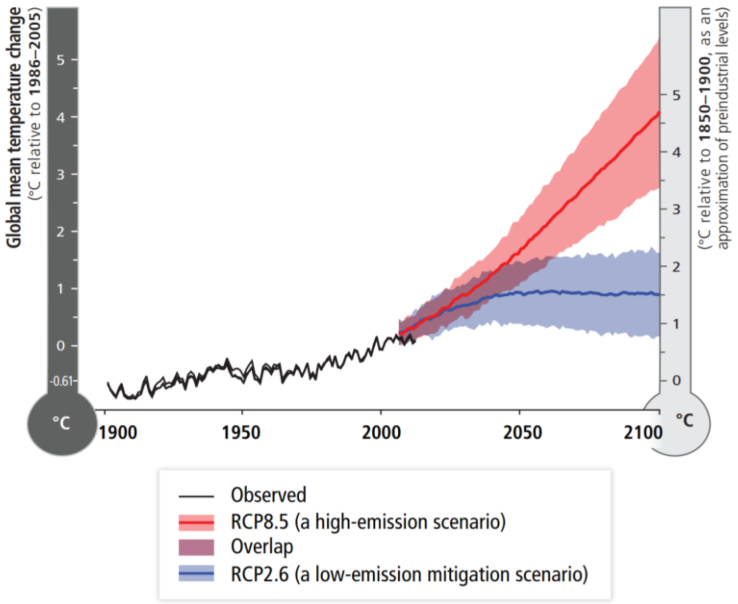
Urban Heat Challenge

Climate Change

23.9 – 32.3˚C Current daily mean temperature range[1]

1.4 – 4.6˚C Expected increase due to climate change (by 2100)[2]

25.3 – 36.9˚C Expected daily mean temperature range (by 2100)

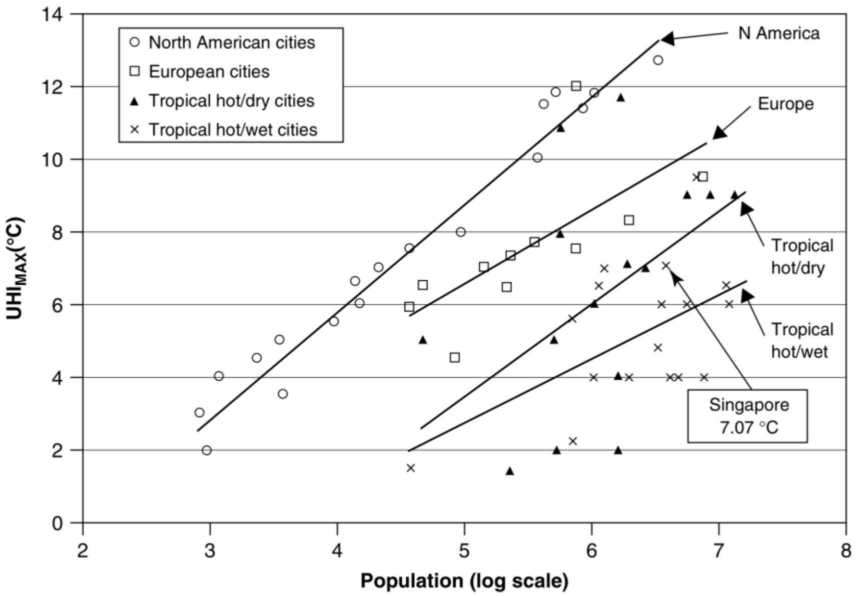


Urban Heat Island

7˚C Maximum UHI intensity measured on 17 May 2003, 22:00 at Orchard Road[3]

5.4˚C Current maximum mean UHI intensity[4]

UHI depends on various factors (e.g., population size, urban design, energy consumption, etc)

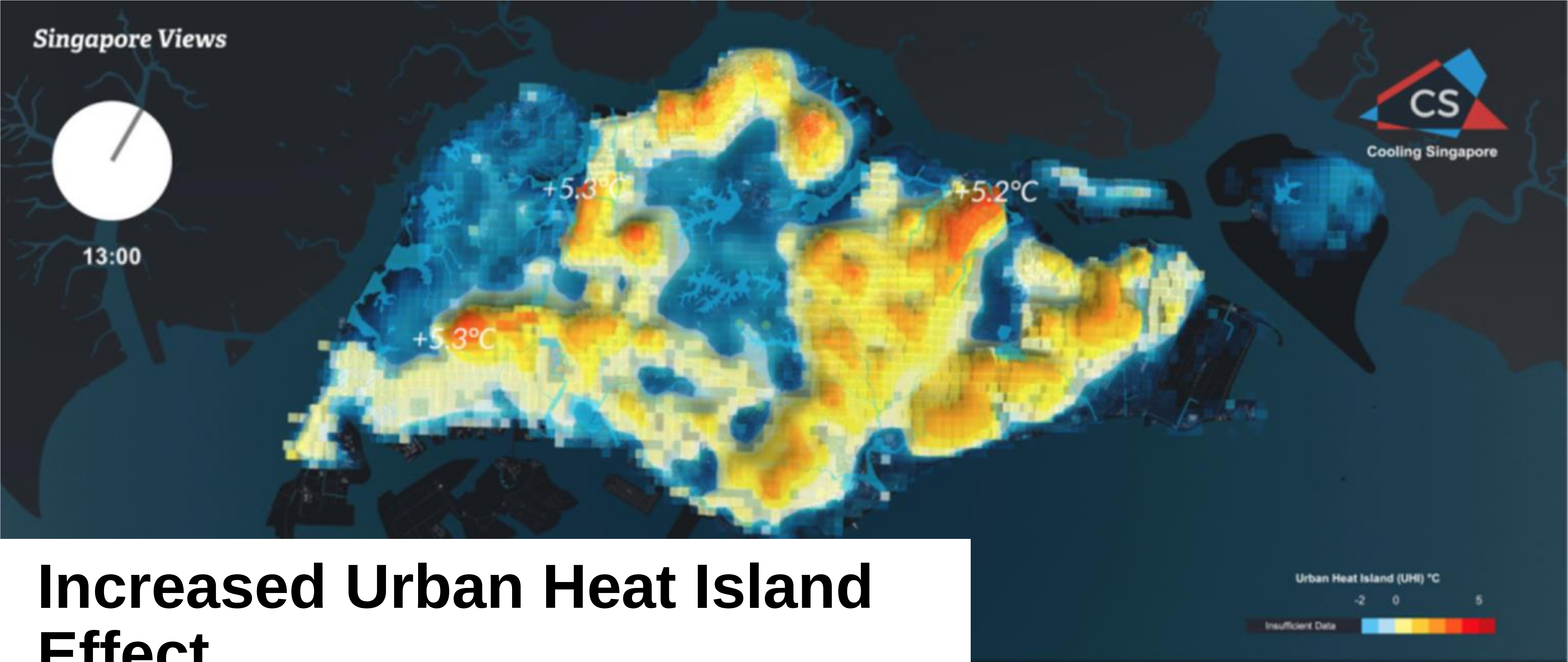


1: Minimum and maximum daily temperatures, source: http://www.weather.gov.sg/climate-climate-of-singapore/
2: Second National Climate Change Study, 2015
Figure: IPPC WG2 AR5 (March 2014) Report: Summary for Policymakers

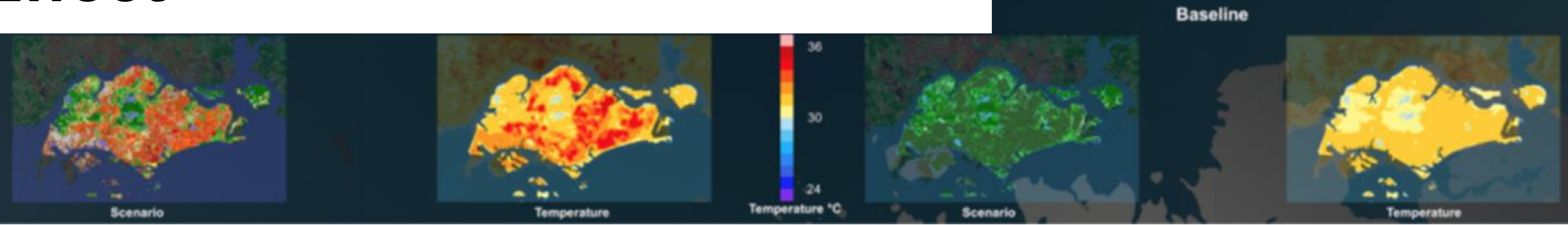
3 and Figure: Chow, W.T. and Roth, M., 2006. Temporal dynamics of the urban heat island of Singapore. International Journal of climatology, 26(15), pp.2243-2260.
4: Model-based estimation.

Population Growth, Urbanisation and Densification

Increased Energy Consumption



Increased Urban Heat Island Effect



Reduced Outdoor Thermal Comfort

Image: Straits Times (2016). Singapore

Reduced Daytime Outdoor Activities

Increased Public Health Risks and Heat Stress

Increased Economic Cost

Additional Environmental Challenges

- **The Urban Heat Island (UHI) effect in Singapore is up to 7°C**
- **UHI threatens liveability, health and economic performance**
- **Mitigation strategies can be effective with a roadmap for science, agencies, industry, and citizens**

The UHI effect has a negative impact on the Economy

Accumulated economic impact (in $) on the 1692 largest cities in the world under RCP 8.5 and RCP 4.5:

- ***UHI can have a <u>greater impact</u> on the economy than global climate change.***
- ***UHI <u>amplifies</u> global climate change.***

Table 1 | Accumulated economic impacts of global climate change (GCC) and urban heat island (UHI) separately and combined under different emission scenarios.

	RCP8.5 (Business-as-usual)	**RCP4.5** (Moderate climate change mitigation)
GCC	$\$3.21 \times 10^{13}$ [38.9%]	$\$1.49 \times 10^{13}$ [26.9%]
UHI	$\$1.54 \times 10^{13}$ [18.6%] (0.48)	$\$1.54 \times 10^{13}$ [27.9%] (1.03)
Total	$\$8.26 \times 10^{13}$ (2.57)	$\$5.53 \times 10^{13}$ (3.71)

Combined impact of UHI and GCC greater than the sum of both (i.e., UHI amplifies).

In some cases, the impact of UHI can be greater than that of GCC.

Figures in brackets represent the present value of losses due to GCC/UHI as a percentage of the present value of the total losses. Figures in parenthesis represent the present value of the losses due to UHI/Total as a fraction of the present value of the losses produced by GCC alone. The symbol $ denotes US dollars. A 3% discount rate was used. Figures are rounded to three significant digits.

Sources: Estrada, Francisco, WJ Wouter Botzen, and Richard SJ Tol. "A global economic assessment of city policies to reduce climate change impacts." Nature Climate Change (2017).

Cooling Singapore

Partners:
ETH + MIT + TUM + CARES + SMU + NUS

PRODUCTS AND OUTPUT

Reports and Guides
- UHI Position Paper
- OTC Position Paper
- Mitigation Strategies Catalogue
- Tools for Cooling Singapore Report
- Cooling Agents Report

Visualisation and Mapping of Heat and Energy
- UHI maps (city scale)
- Assessment of OTC strategies (local scale)
- Tempo-spatial energy flux – Transport
- Tempo-spatial energy flux – Buildings

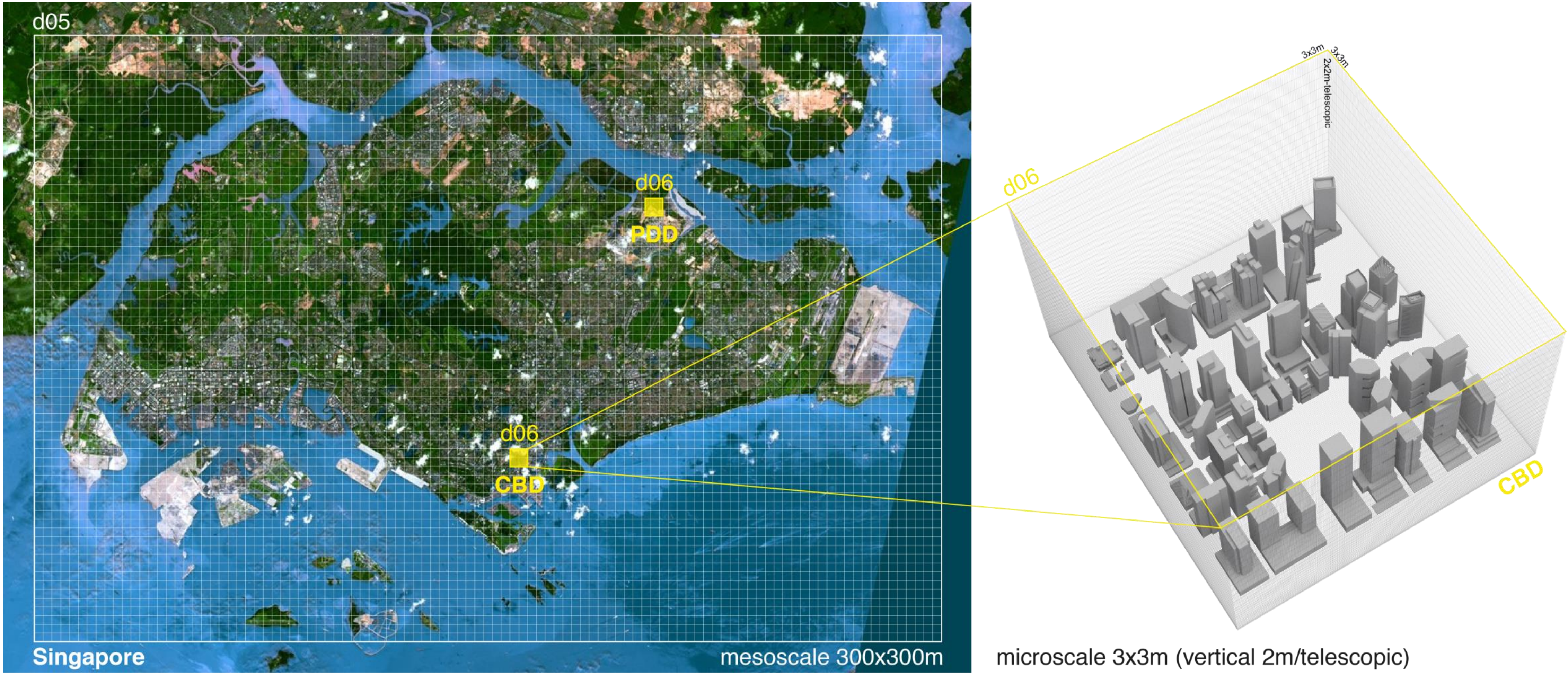
Campaigns
- Populations survey campaign
- Citizen engagement campaign
- Climate measurement study
- ESUM+ campaign

Applications
- Mitigation strategy app
- Digital Urban Climate Twin (DUCT)

Urban heat assessment

Mapping the UHI / Local Outdoor Thermal Comfort (OTC)

SPATIAL SCALES

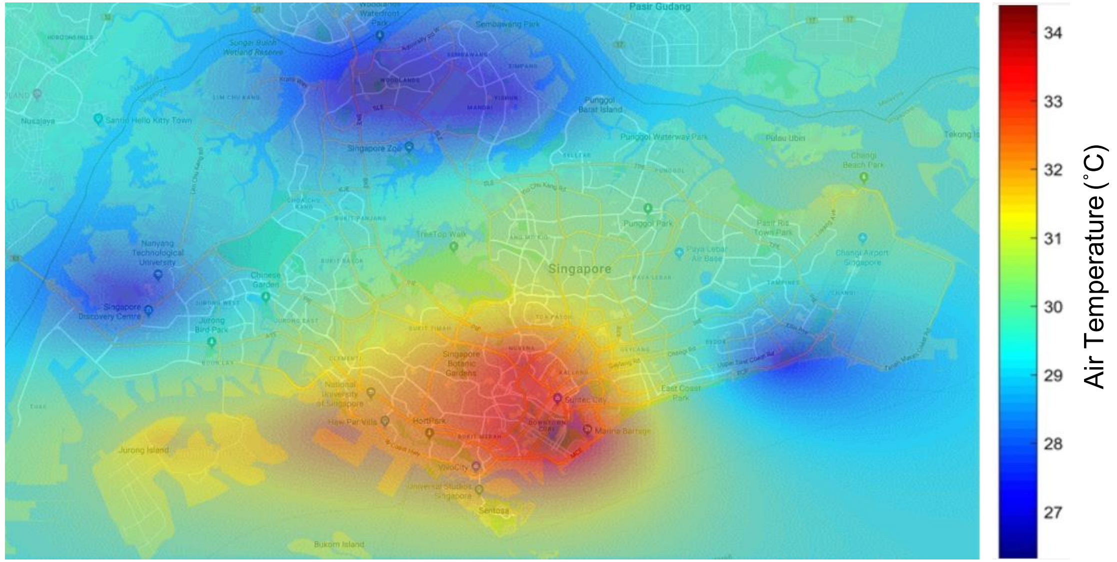


Mapping the UHI

Sensors

Local Sensor network / Crowdsourced

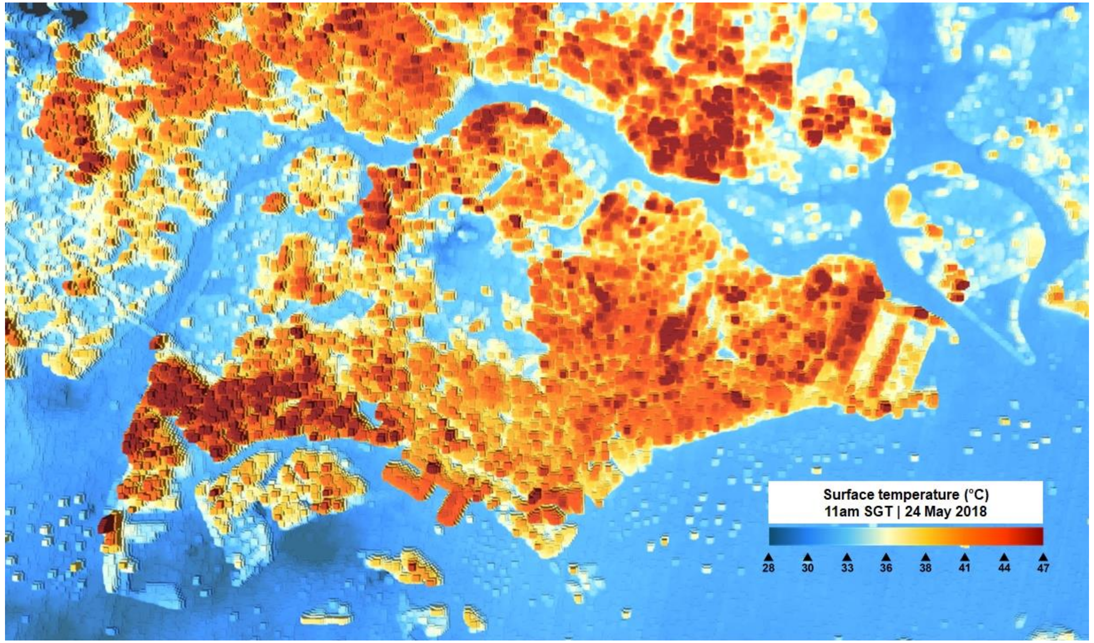
(based on portable sensors for 9pm local time)



- ✓ Measure climate variables
- ✓ Isolated information (discrete points)
- ✓ Need to do spatial interpolation

Remote Sensing

(based on Landsat-8 satellite image for 11am local time)



- ✓ Measure surface temperature (but **not** air temperature and convection)
- ✓ Covers the entire island
- ✓ Data quality (spatial/temporal resolution) depends on satellite characteristics

No sensor-based method sufficient to map the UHI in its entirety.

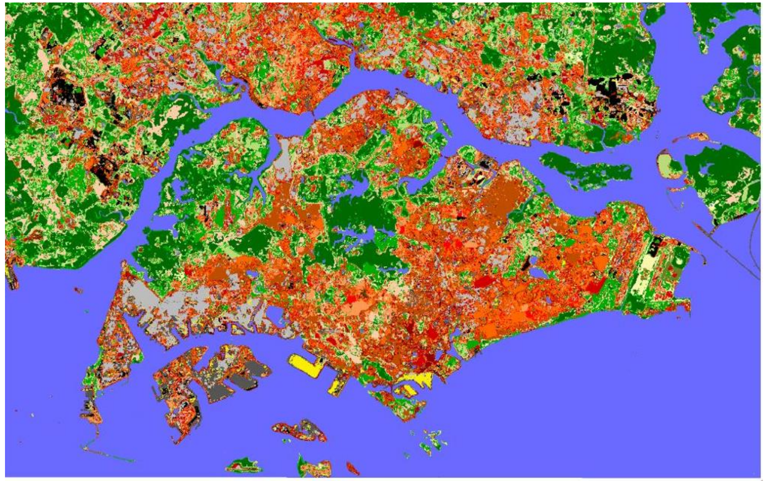
Mapping the UHI

Land Use

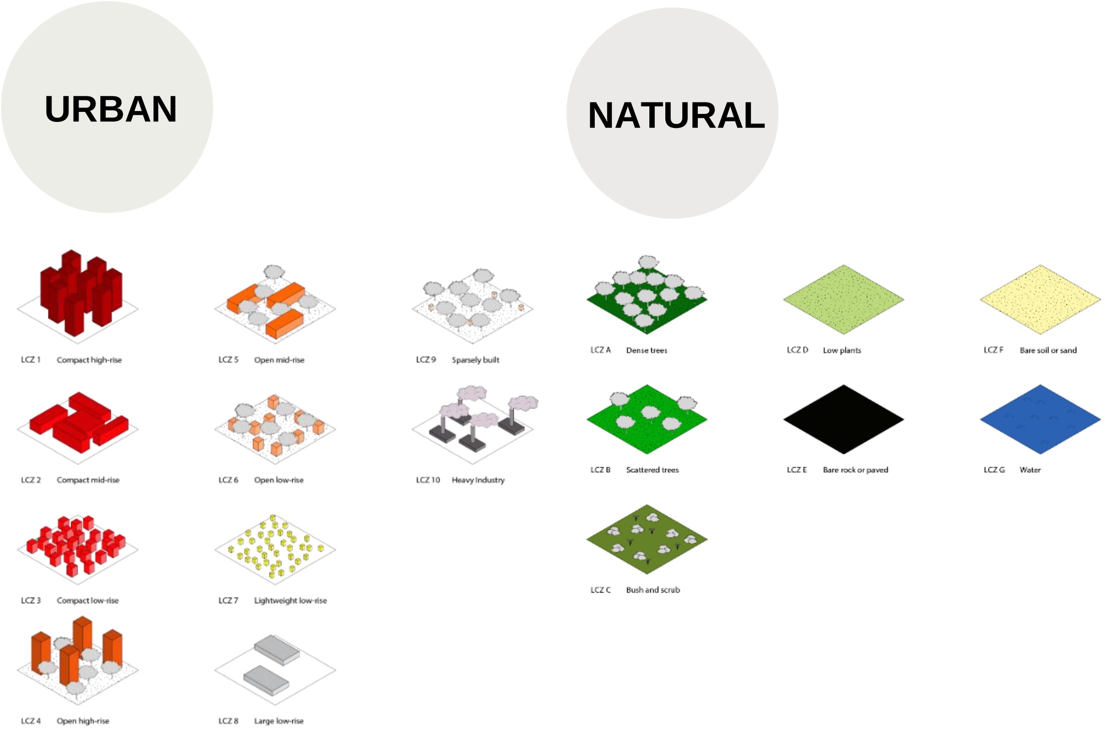
Is the <u>First step</u> to evaluate near surface air temperatures

Local Climate Zones (LCZs) is a classification scheme that comprises 17 zones based on:

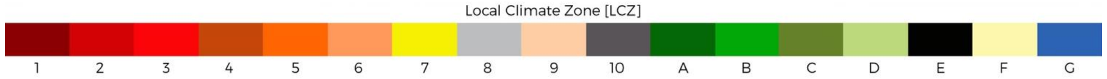
- ✓ properties of **surface structure** (building and tree height and density) and,
- ✓ properties of **surface cover** (pervious vs. impervious).



Current Land Use (LCZ) Scenario for Singapore



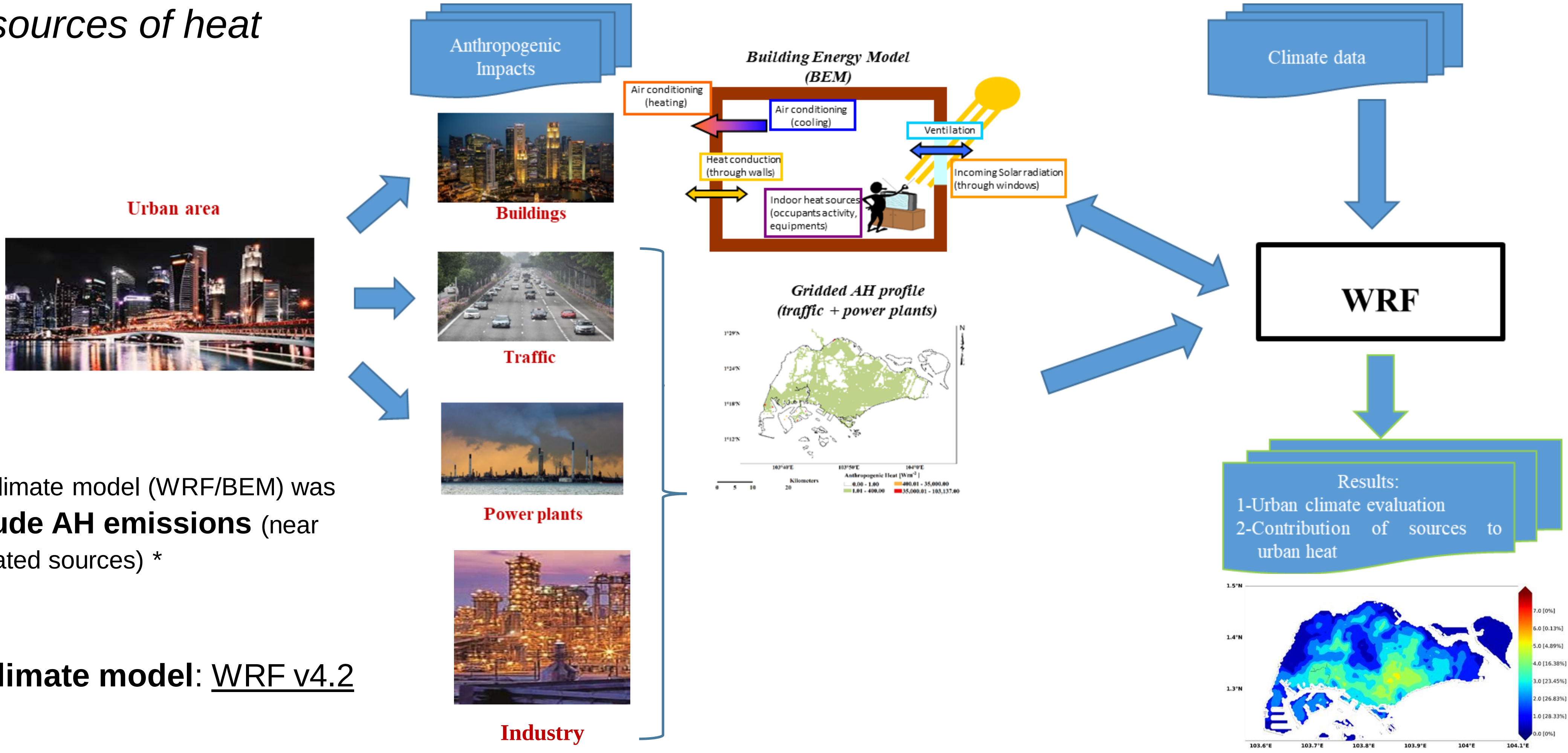
Urban and rural LCZs (Local Climate Zones)



Source: Adapted from Stewart, I.D., Oke, T.R. (2012). 'Local Climate Zones for urban temperature studies', Bulletin of the American Meteorological Society, 93: 1879-1900.

Mapping the UHI

Additional sources of heat



The mesoscale climate model (WRF/BEM) was modified to **include AH emissions** (near surface and elevated sources) *

Mesoscale climate model: WRF v4.2

* Publication: Singh et al. (2022). "**Numerical analysis of the impact of anthropogenic emissions on the urban environment of Singapore**" Science of the Total Environment 806, https://doi.org/10.1016/j.scitotenv.2021.150534

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Mapping the UHI

Scenario evaluation

Model (based on Local Climate Zones)

Output: Temperature Maps

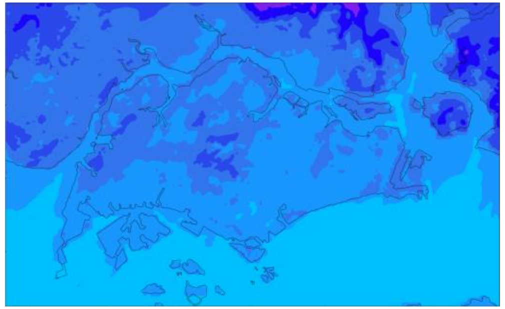
UHI Intensity Map =

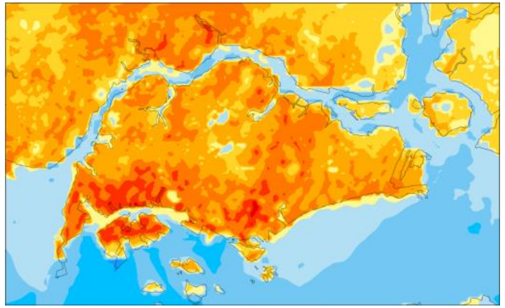
Urbanised – All_Green

Snapshot at 02:00

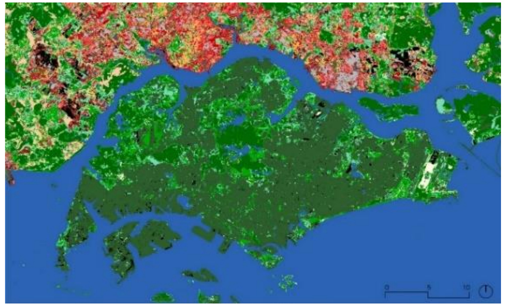
Snapshot at 14:00

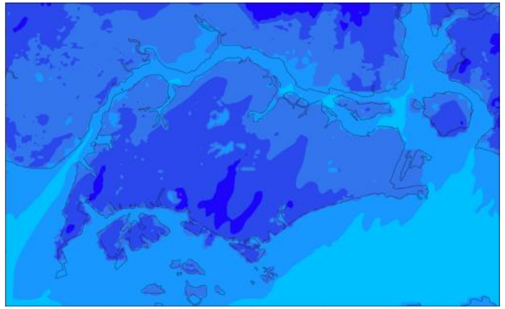
***Urbanised* Scenario**

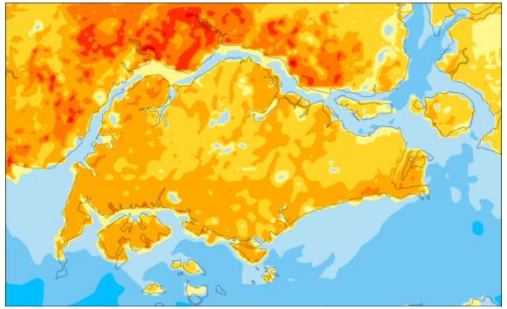




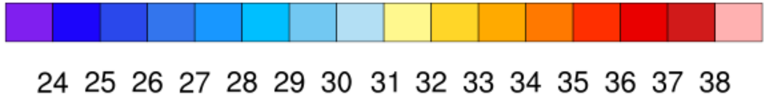
Hypothetical **'*All Green*' Scenario** (used as **baseline** for calculating the urban heat island in Singapore)







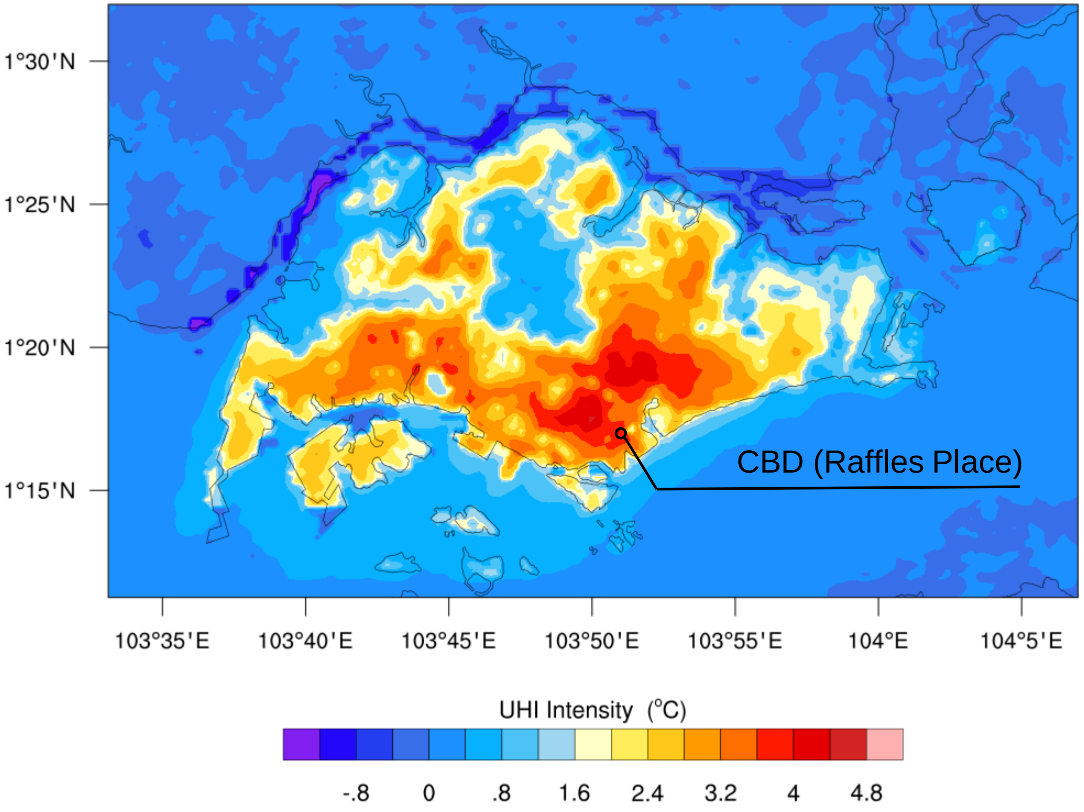
Air Temperature at 2m (in ˚C)



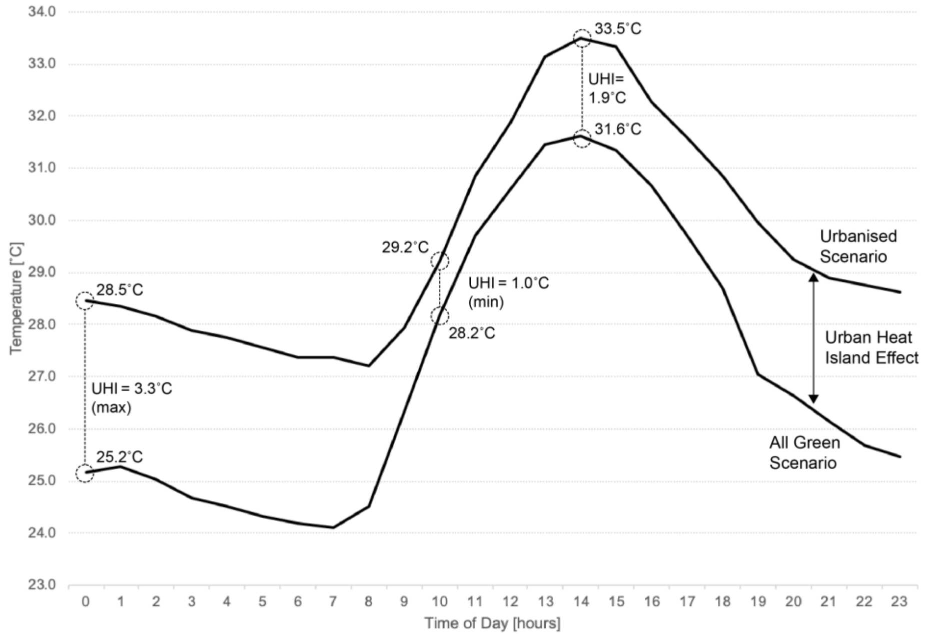
Mapping the UHI

WRF mesoscale model

UHI Intensity Map
(snapshot at 4am)



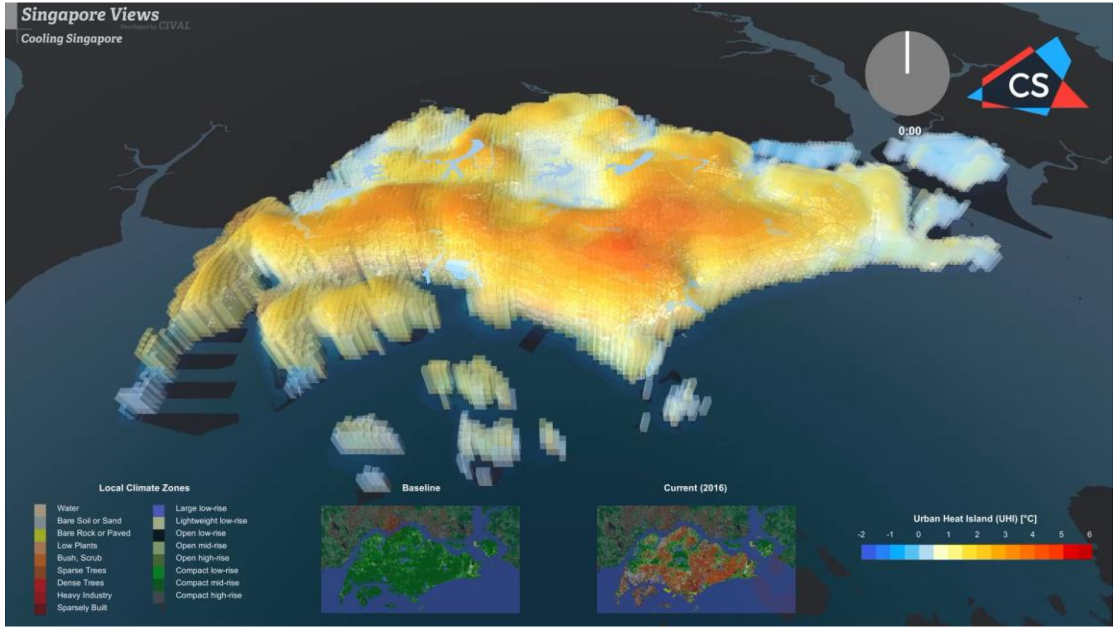
24h Timeseries of Average Air Temperature at CBD
(based on simulation results of both scenarios: urbanised and all-green)



Mapping the UHI

Some of the Goals

Estimate the **current level of UHI Intensity**



Estimate the **impact of A.H.** on the UHI effect and OTC

- A.H. from buildings
- A.H. from transportation
- A.H. from power plants
- A.H. from industry

Assess the **impact of selected UHI mitigation strategies**.

Mitigation strategies

The temperature of 34 degree is based on MSS data where 30.0˚C is indicated as the highest monthly mean temperature[1] plus additional up to 4.6 degree (°C) temperature increase through to climate change[2]

1: Highest Monthly Mean Temperature (°C) / 1929-1941 and since 1948, average over all MSS Climate Station http://www.weather.gov.sg/climate-historical-extremes-temperature/

2: https://www.nccs.gov.sg/climate-change-and-singapore/national-circumstances/impact-of-climate-change-on-singapore

Urban heat intensity

Evaluation of current UHI intensity in Singapore.

- Modification of WRF/BEM to **include AH emissions** (near surface and elevated sources).
- Maximum UHI intensity during April 2016 (including building, traffic and power plants current AH emission) is 5.0°C during the morning period (6:00 to 8:00). Over the whole Singapore mean spatial UHI intensity reaches 1.9 °C.
- During the early morning, 20.3% of the area has UHI intensity more than 3.0°C (center, south of the island).

	ΔT_{air} [°C]		
	Hour: Between 0600 to 0800 Hour		
	Max	*Min*	*Spatial Mean*
Whole Singapore region	5.0°C	0.1°C	1.9°C
Only urban area	5.0°C	0.3°C	2.7°C
Percentage of urban area	***1%***	***10%***	***25%***
	≥4.6°C	≥3.9°C	≥3.3°C

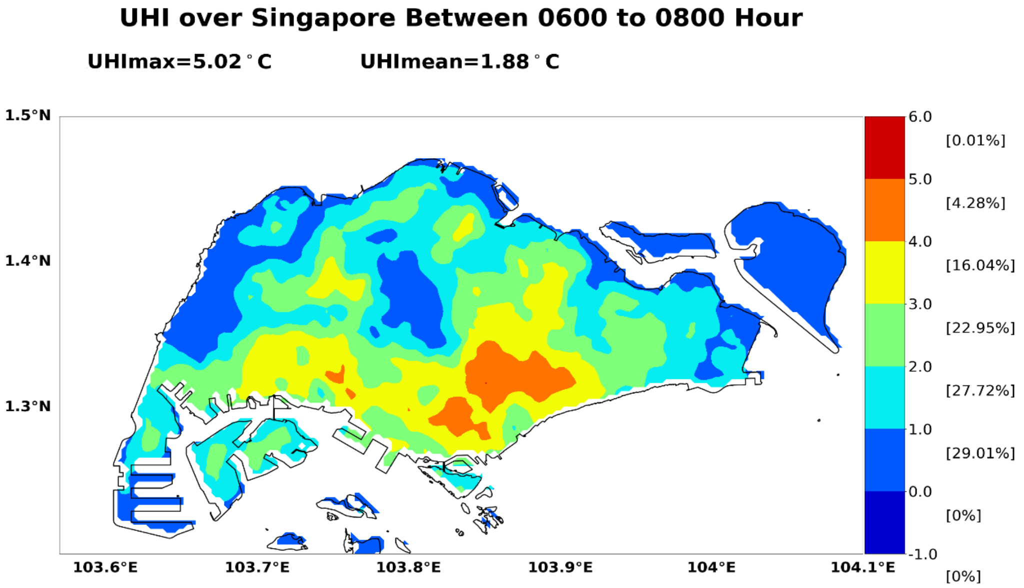


Image: Spatial distribution of average UHI intensity including buildings, road traffic and power plants over Singapore region between hour 6 to 8 (early morning), with percentage of area in each range | Cooling Singapore, 2020
Data: output of power-traffic simulation, and climate data received from the National Environmental Agency (NEA) of Singapore.

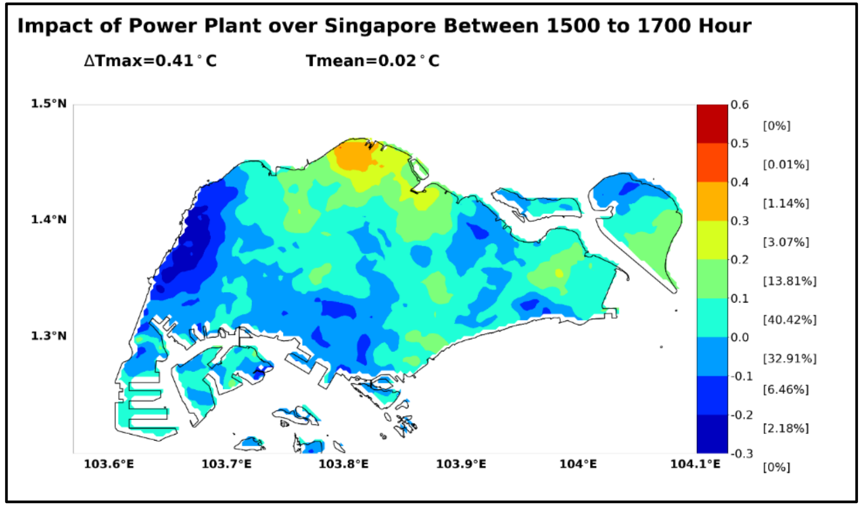
Urban heat intensity

Contribution of AH generated by power plants and road transport (current situation)

Based on local maximum ΔT

- **Current power plants AH emission** has a maximum contribution of 0.4 °C during the evening period (15:00 to 17:00). it is a very localized impact. Only in 1.2% of the area of Singapore, the impact of power plants is higher than 0.3 °C

- **Current traffic AH emission** has a maximum contribution of 0.9 °C during the morning period (9:00 to 11:00). In 4.6% of the area of Singapore, the impact of traffic is higher than 0.4 °C



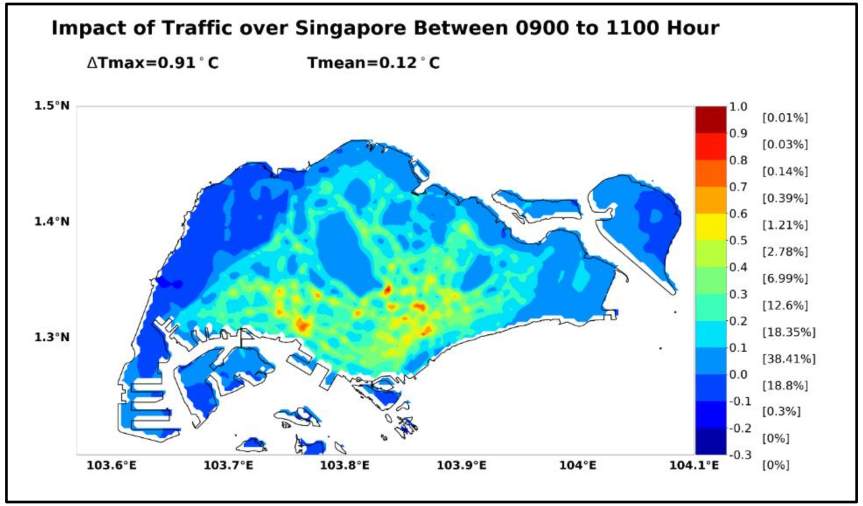


Image: Impact of power plant (between 1500 to 1700 Hours) and traffic (between 0900 to 1100 Hours) on air temperature (baseline scenario) | Cooling Singapore, 2020
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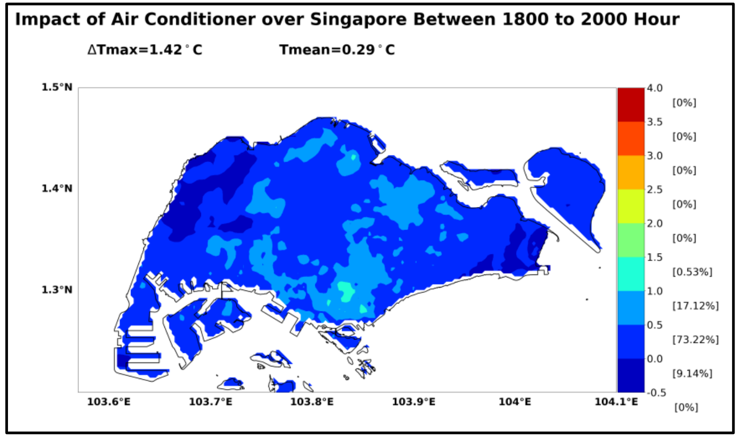
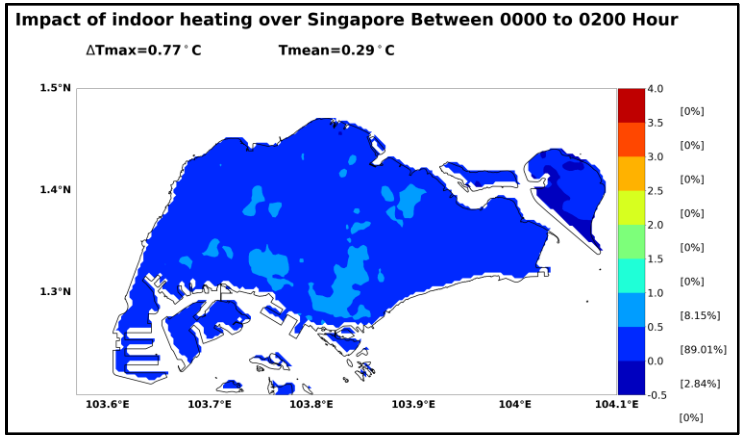
Urban heat intensity

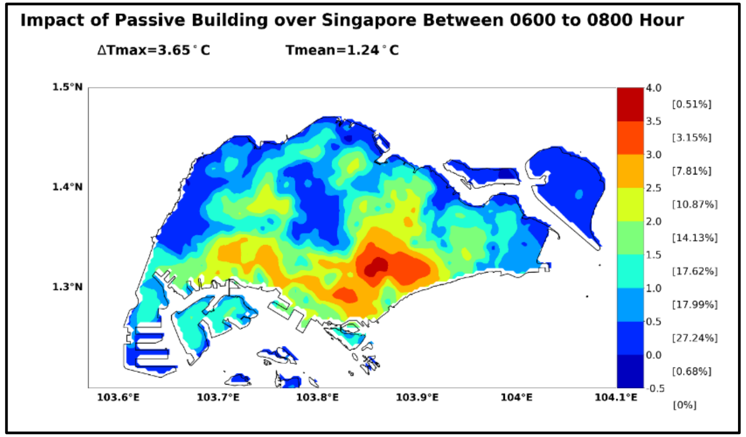
Contribution of different components of buildings

- **A/C impact** is maximum (1.4 °C) during the evening period. In 1% of total Singapore region, contribution is more than 1 °C
- **Building's impact** increase to 0.6 °C (6:00 to 8:00) from passive (no occupant with no equipment) to active (occupant with equipment).
- **Indoor heat impact** reaches 0.7 °C in 1 % of total Singapore region.

Maximum impact				
		A/C	**Indoor heat**	**Passive Building**
		Hour: 1800-2000*	Hour: 0000-0200*	Hour: 0600-0800*
Whole Singapore region	ΔT	1.4°C	0.8°C	3.7°C
	ΔTmean (spatial)	0.3°C	0.3°C	1.2°C
Only urban area	ΔT	1.4°C	0.8°C	3.7°C
	ΔTmean (spatial)	0.4°C	0.4°C	1.8°C
Percentage of urban area	1%	≥1.0°C	≥0.7°C	≥3.5°C
	10%	≥0.8°C	≥0.5°C	≥2.8°C
	25%	≥0.6°C	≥0.5°C	≥2.4°C







Data: output of building energy model simulations, and climate data received from the National Environmental Agency (NEA) of Singapore..

COOLING SINGAPORE

Urban heat intensity

Contributions to current UHI intensity in Singapore.

Maximum impact						
		Power Plant	**Traffic**	**A/C**	**Occupied Building**	**Passive Building**
		Hour: 1500-1700*	Hour: 0900-1100*	Hour: 1800-2000*	Hour: 0600-0800*	Hour: 0600-0800*
Whole Singapore region	ΔT	0.4°C	0.9°C	1.4°C	4.3°C	3.7°C
	ΔTmean (spatial)	0.0°C	0.1°C	0.3°C	1.5°C	1.2°C
Only urban area	ΔT	0.4°C	0.9°C	1.4°C	4.3°C	3.7°C
	ΔTmean (spatial)	0.0°C	0.2°C	0.4°C	2.2°C	1.8°C
Spatial analysis						
Percentage of urban area	1%	≥0.4°C	≥0.6°C	≥1.0°C	≥4.0°C	≥3.5°C
	10%	≥0.1°C	≥0.4°C	≥0.8°C	≥3.3°C	≥2.8°C
	25%	≥0.1°C	≥0.3°C	≥0.6°C	≥2.8°C	≥2.4°C

Urban heat intensity

Impact of urban heat on daily climate variables (Tmax, Tmin)

		ALL Green	Passive Building	Building+AC	Buildings+AC +Traffic	Buildings+AC +Traffic+PowerPlants
Mean value for whole urban area	**Tmax** (~afternoon)	31.5°C	+1.4°C	+1.7°C	+1.7°C	+1.8°C
	Tmin (~before sunrise)	24.8°C	+1.8°C	+2.4°C*	+2.5°C	+2.6°C

- ✓ Less impact on Tmax => good for outdoor thermal comfort
- ✓ Higher impact of building massing
- ✓ Negligible impact of traffic and power plants (mean urban values!)

- ✓ Further analysis by LCZ is being carried out

Impact of urban heat mitigation scenarios

Electric and autonomous vehicles

- Implementing 100% electric vehicles can produce a **max. reduction on Ta of 0.8°C**
- 24.2% of Singapore area would have a mean reduction higher than 0.2°C. Only a **small part of the island (1.0%) could register reductions higher than 0.5°C** during the morning.
- Although spatial mean impact of **electric and autonomous vehicles** can be similar, the **spatial pattern are different** since the routes taken by vehicles in each scenario changes

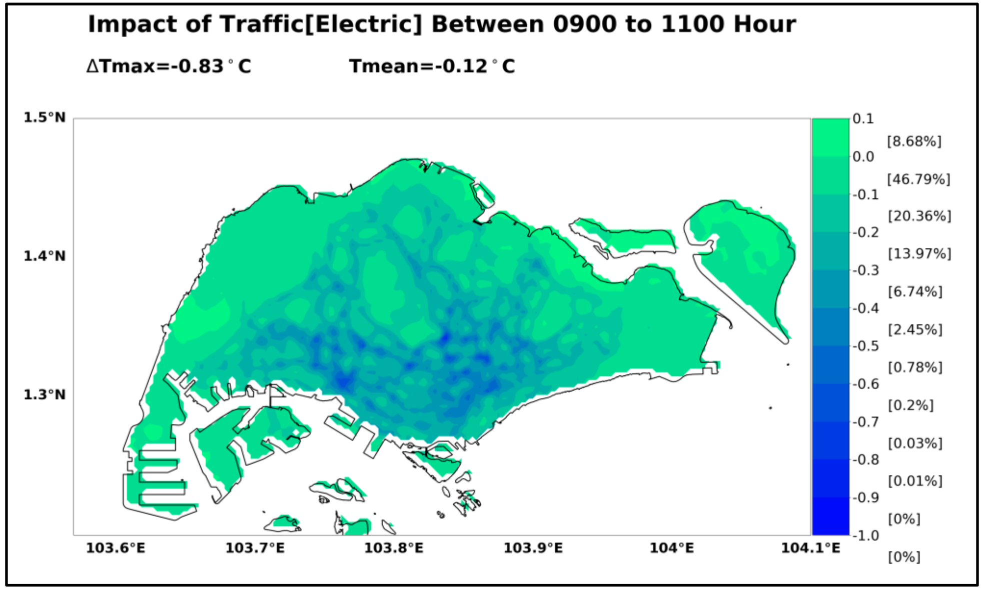


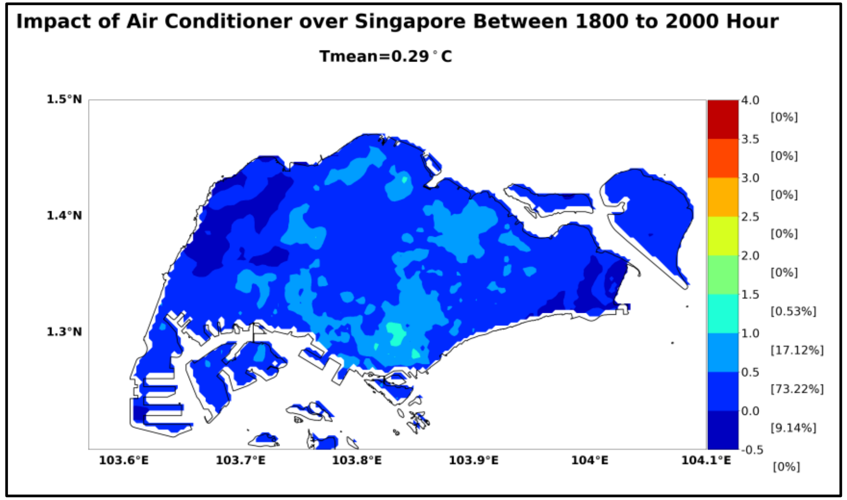
Image: Spatial distribution of hourly impact on air temperature due electric vehicles or autonomous between hour 0900 to 1100 | Cooling Singapore, 2020
Data: output of traffic simulations, and climate data received from the National Environmental Agency (NEA) of Singapore.

Impact of urban heat mitigation scenarios

Implementation of District Cooling

- Implementing 100% district cooling systems can **reduce the spatial mean UHII by ~0.2°C**. The maximum UHI concentrates close to the plants, where the AH is emitted.

Spatial analysis			
		A/C	**DC**
		Hour: 1800-2000*	Hour: 1800-2000*
Percentage of urban area	1%	≥1.0°C	≥1.8°C
	90%	<0.8°C	<0.5°C
	75%	<0.6°C	<0.2°C



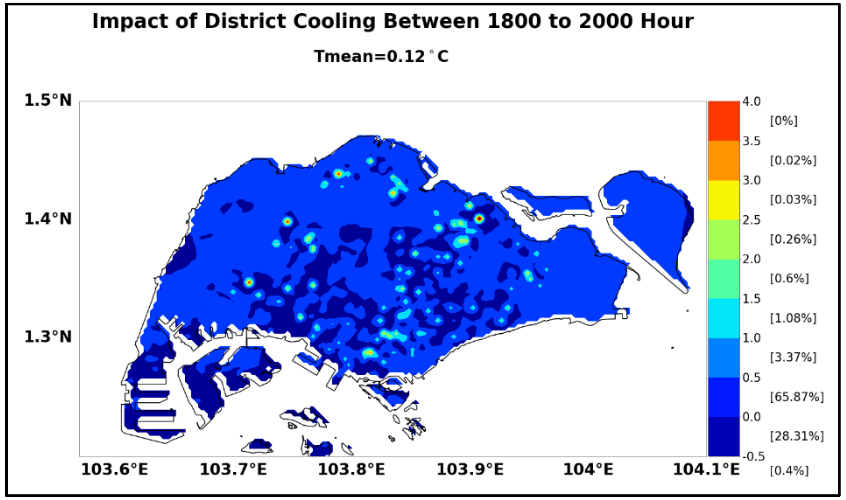


Image: Spatial distribution of impact of District Cooling Scenario plants over Singapore region for hour 1800 to 2000, with percentage of area in each range | Cooling Singapore, 2020
Data: output of traffic simulations, and climate data received from the National Environmental Agency (NEA) of Singapore.

Take away

- It is relevant to evaluate the contributors of the urban heat
- Close collaboration with governmental agencies is critical (access to accurate information)
- Multidisciplinary experienced team (energy, transport, climate) is highly required
- Dissemination of outcomes in a simple way (mapping) can increase understanding of the problem and definition of policy
- In the case of Singapore:
    - Mayor impact on Ta is due to buildings, followed by the A/C.
    - Passive building and A/C show a maximum impact of 3.7 °C (morning) and 1.4 °C (evening), respectively.
    - In 25% of the urban area, passive building and A/C have a maximum impact higher than 2.4 °C and 0.6 °C.
    - Maximum impact power plants (0.4 °C) and traffic emission (0.9 °C) is confined a small area of Singapore (specially Power Plants).
- Mitigation scenarios in Singapore:
    - EV can reduce more than 0.5 °C in 1% of the area of Singapore.
    - DC System can reduce spatial mean UHII by ~0.20°C (island wide).

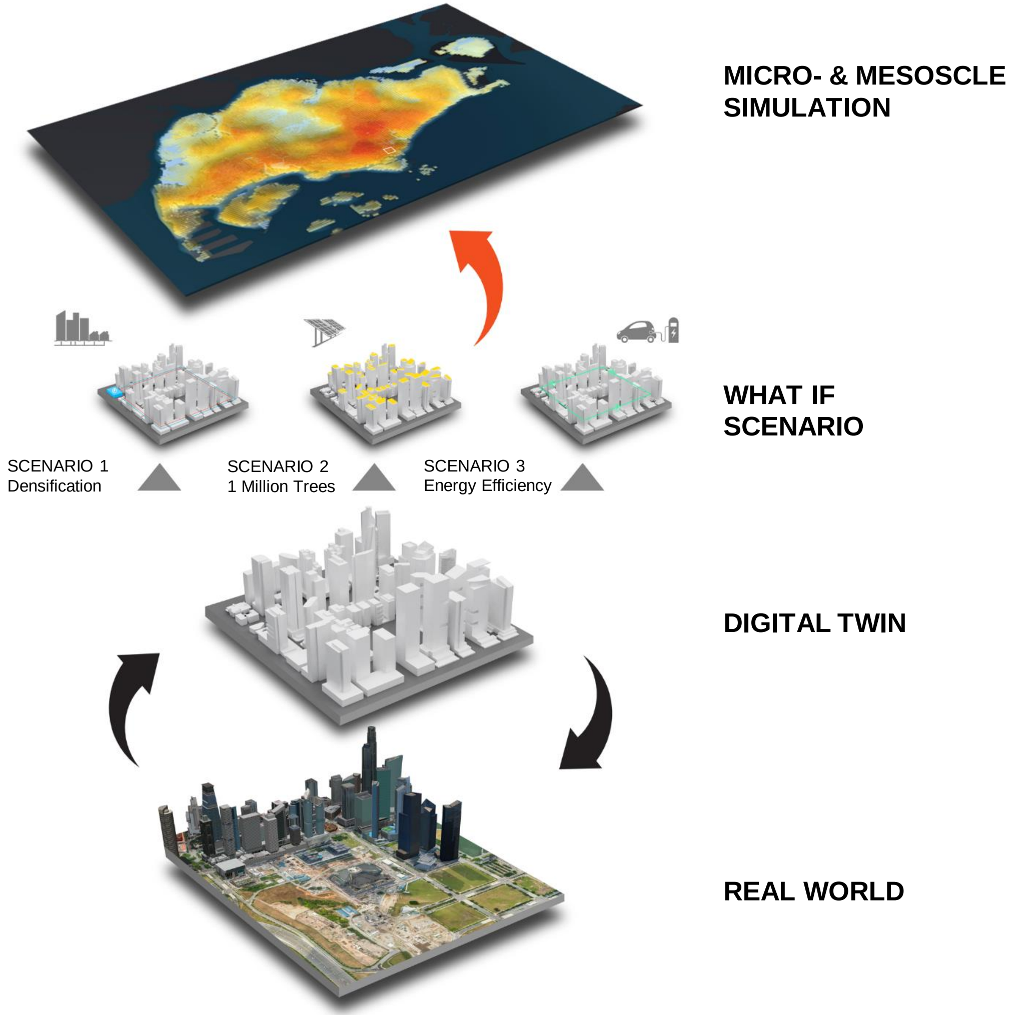
Technology use for climate-informed decisions (DUCT)

Cooling Singapore 2. 0 - Project objectives

- Build a **Digital Urban Climate Twin** (DUCT) for Singapore, which includes various computational models.

- Use the DUCT to evaluate quantitatively **what-if scenarios for future Urban Heat Islands (UHI) , Outer Thermal Comfort (OTC) and Energy Efficiency (EE) analysis**.

- Develop **climate-responsive design guidelines** for application at district- and island-scale.



Images: Lea Ruefenacht | Cooling Singapore, 2020

What is a Digital Urban Twin?

Image: Fahrul Azmi


Geometries?
Cross St
DT18
Boon Tat St
60
SGX Centre
3
Cross St
Raffles Quay
One Raffles Quay
One Raffles Quay
Central Blvd
Central Blvd
Commerce St
2D
Google
100%
Imagery date: 3/5/16
Google Maxar Technologies Urban Redevelopment Authority
90 m
Camera: 712 m 1°16'50"N 103°51'03"E
4 m

Systems and System Behavior?

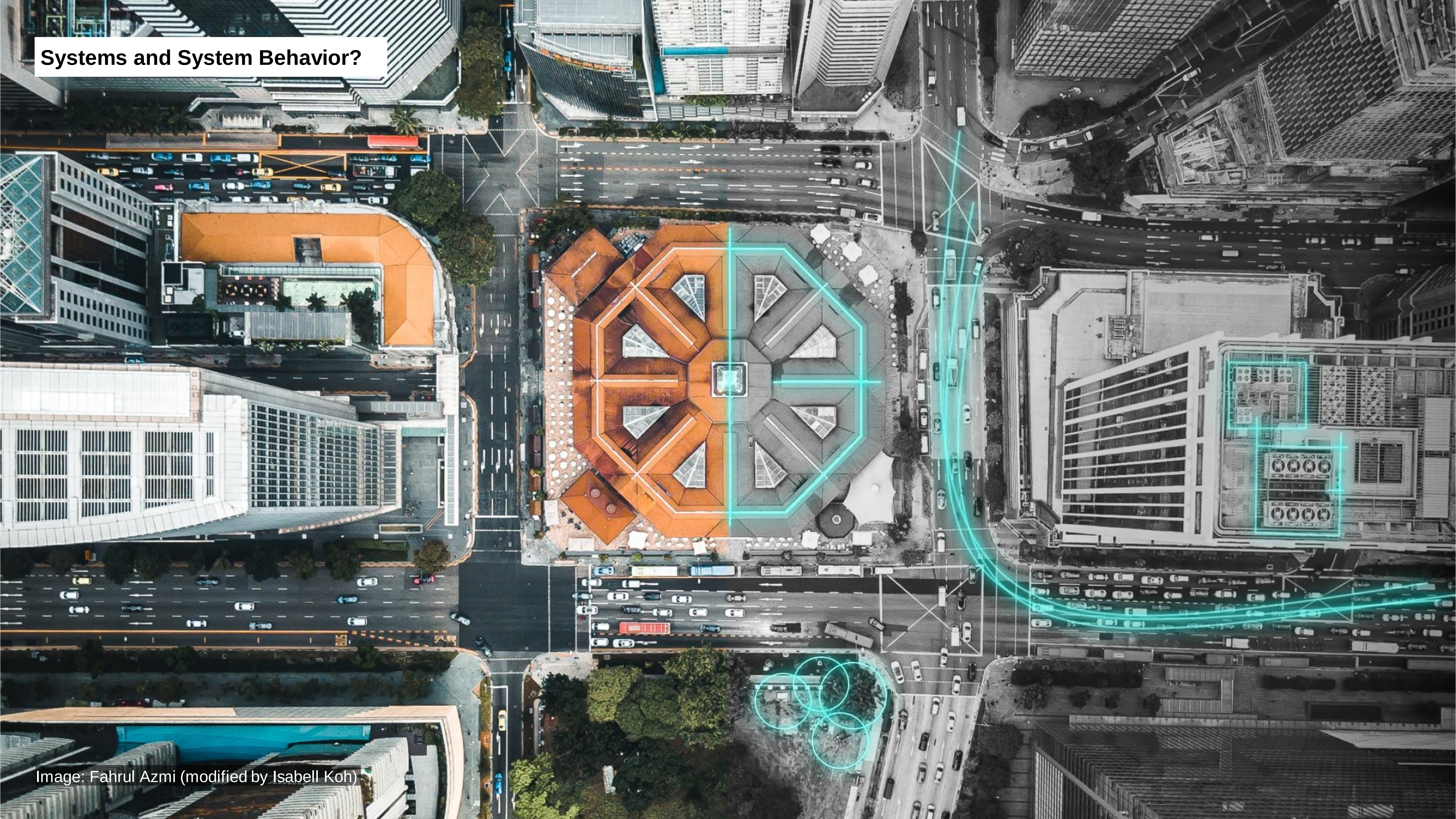


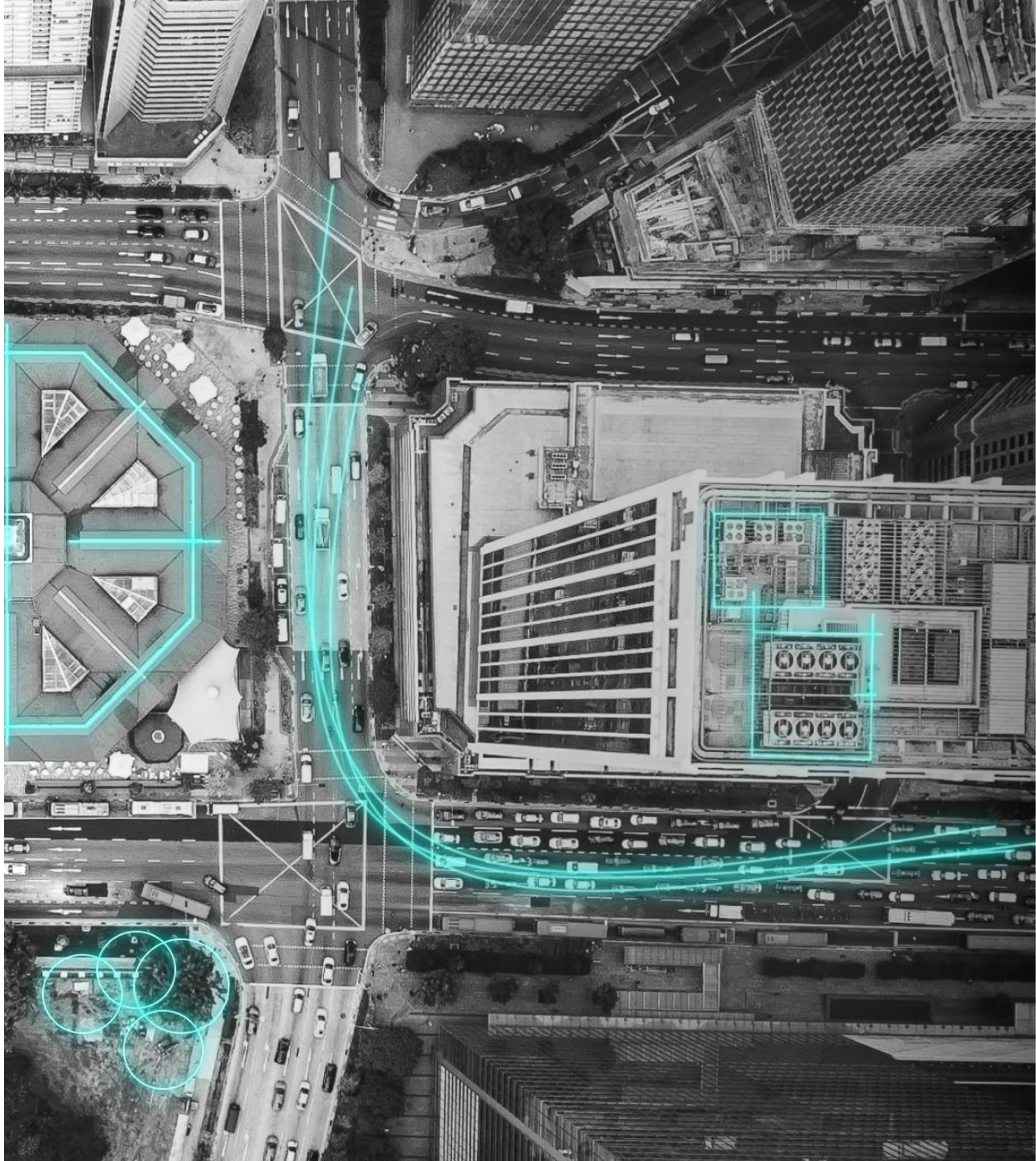
Image: Fahrul Azmi (modified by Isabell Koh)

What is a Digital Urban Twin?

Not only geometry and textures for the purpose of visualisation –

but also **dynamic behaviour of urban elements for the purpose of simulating cause and effect** (e.g., traffic, air conditioning, microclimate).

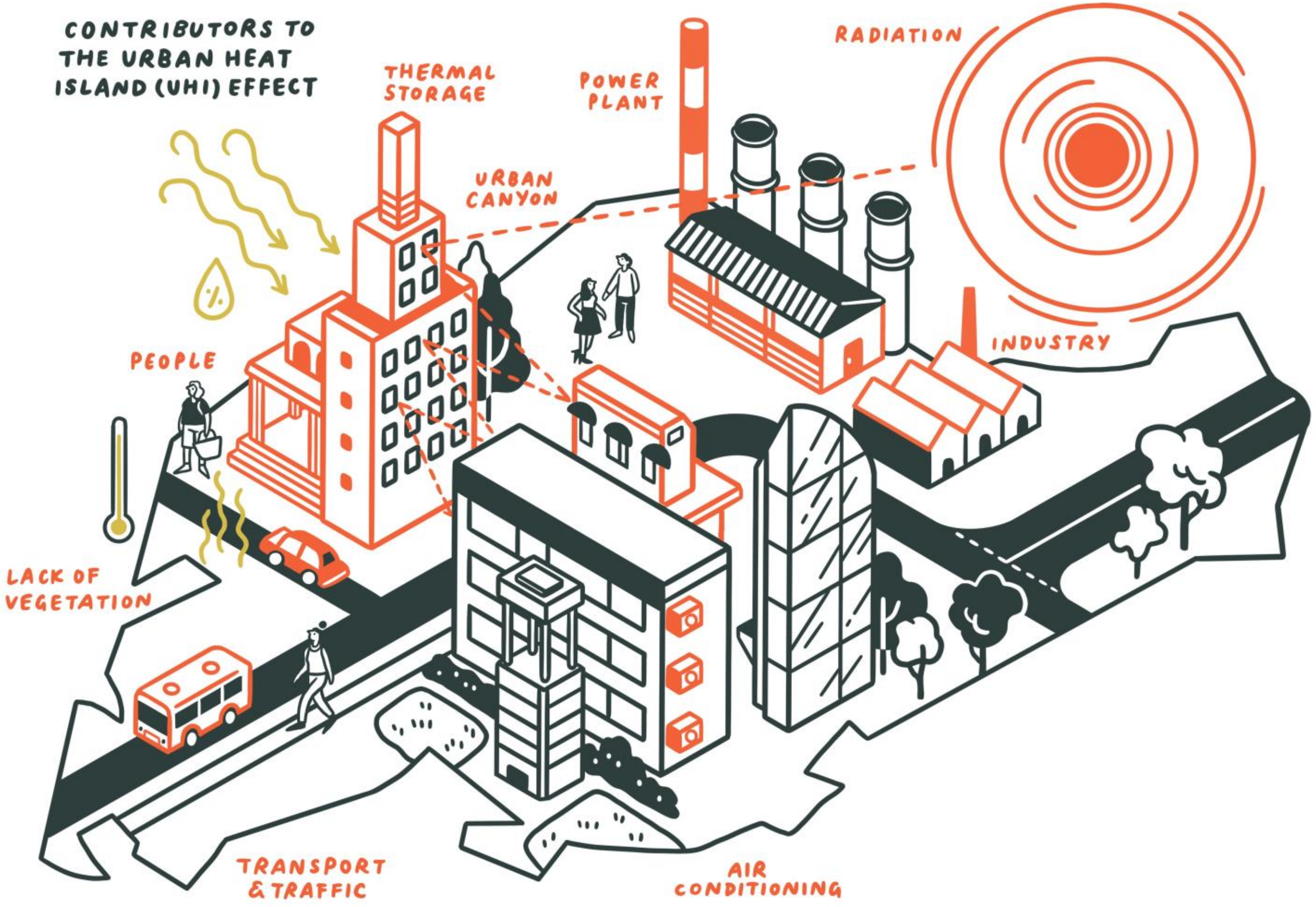
A digital twin of a city can be used to **conduct what-if analyses and perform experiments with a city *in-silico*** that would otherwise not be possible in the real world.



What is a Digital Urban Climate Twin?

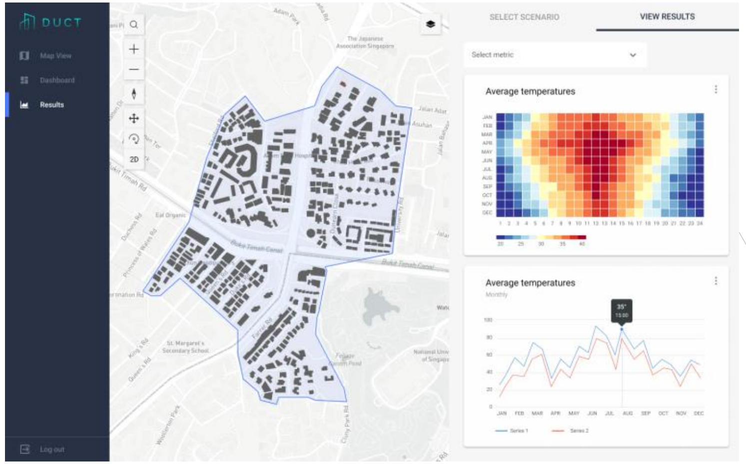
A Digital Urban Climate Twin (DUCT) is a digital urban twin specialised for urban climate.

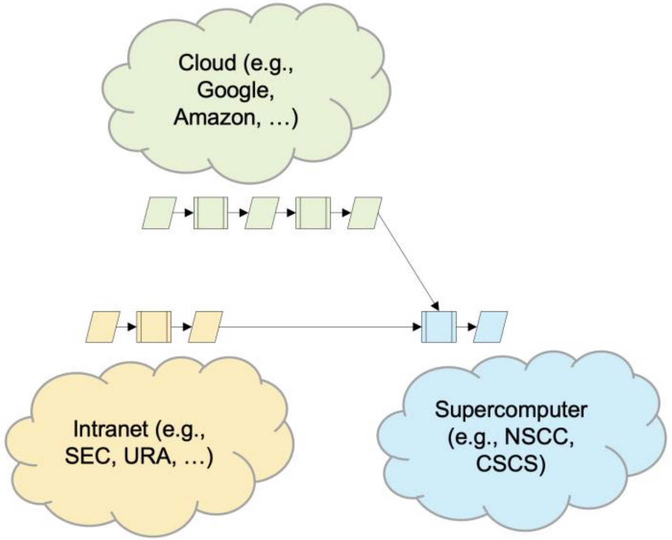
Cooling Singapore is building a DUCT for Singapore.



Source: H. Aydt (2020). Cooling Singapore – Towards Urban Climate Design and Management in Indicia 03, editors: S. Cairns and D. Tunas
Image: Idea Ink (2020)

Bridging the gap – from supercomputing to policy





POLICY

Masterplans/Roadmaps

EXPLORATION

What-if Scenarios

APPLICATION

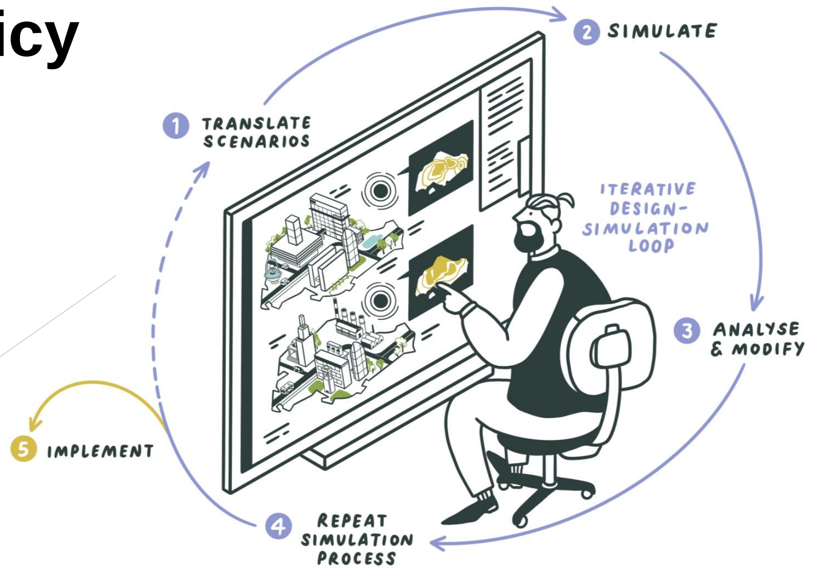
DUCT Applications

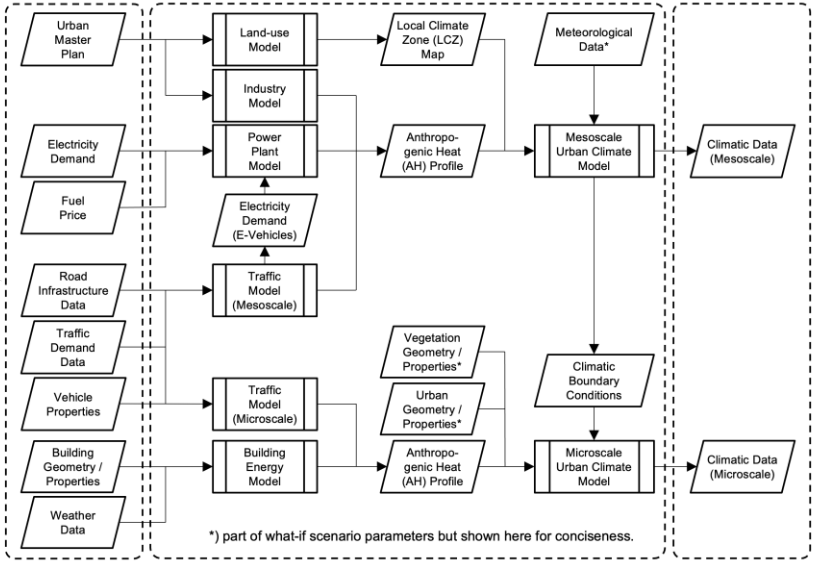
COMPUTATION

DUCT Federation of Models

INFRASTRUCTURE

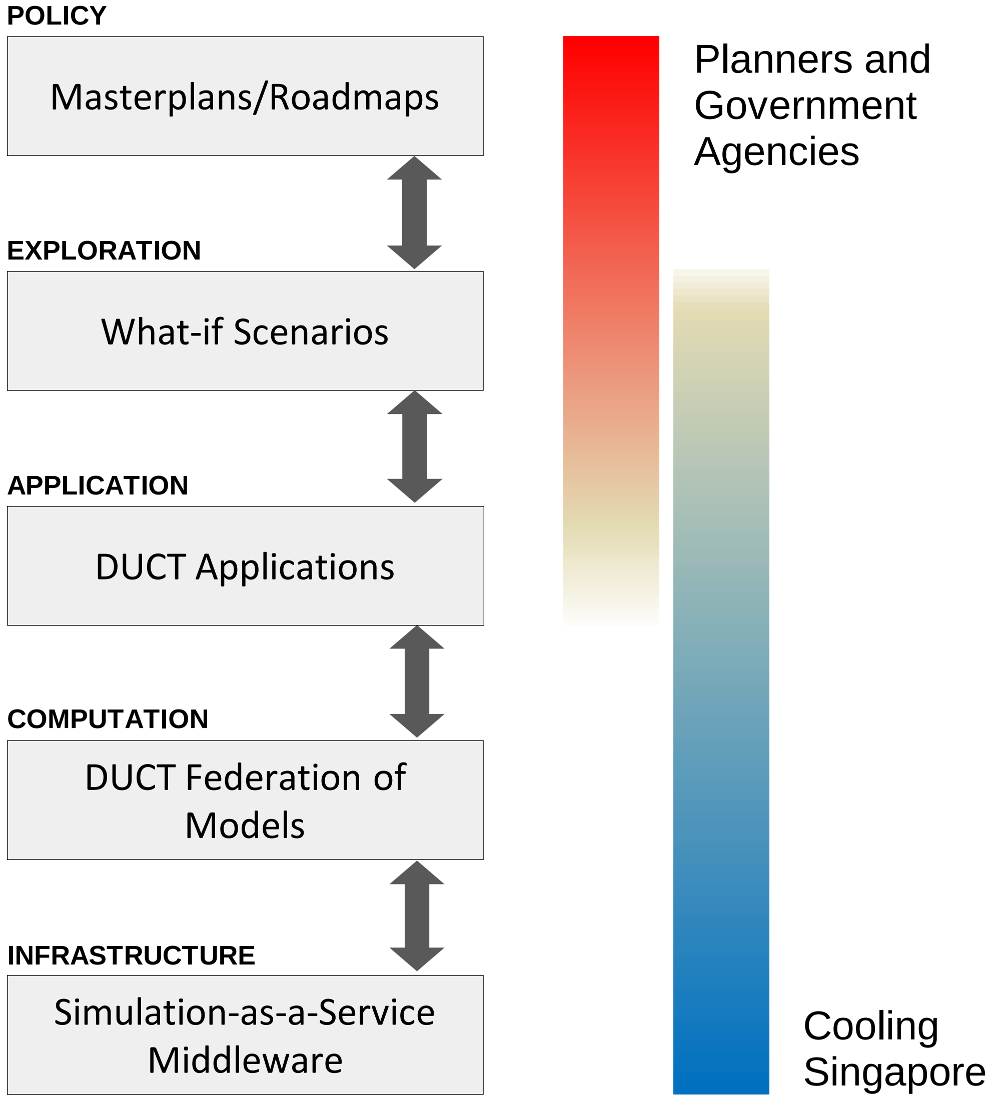
Simulation-as-a-Service Middleware





COOLING SINGAPORE

Bridging the gap – from supercomputing to policy

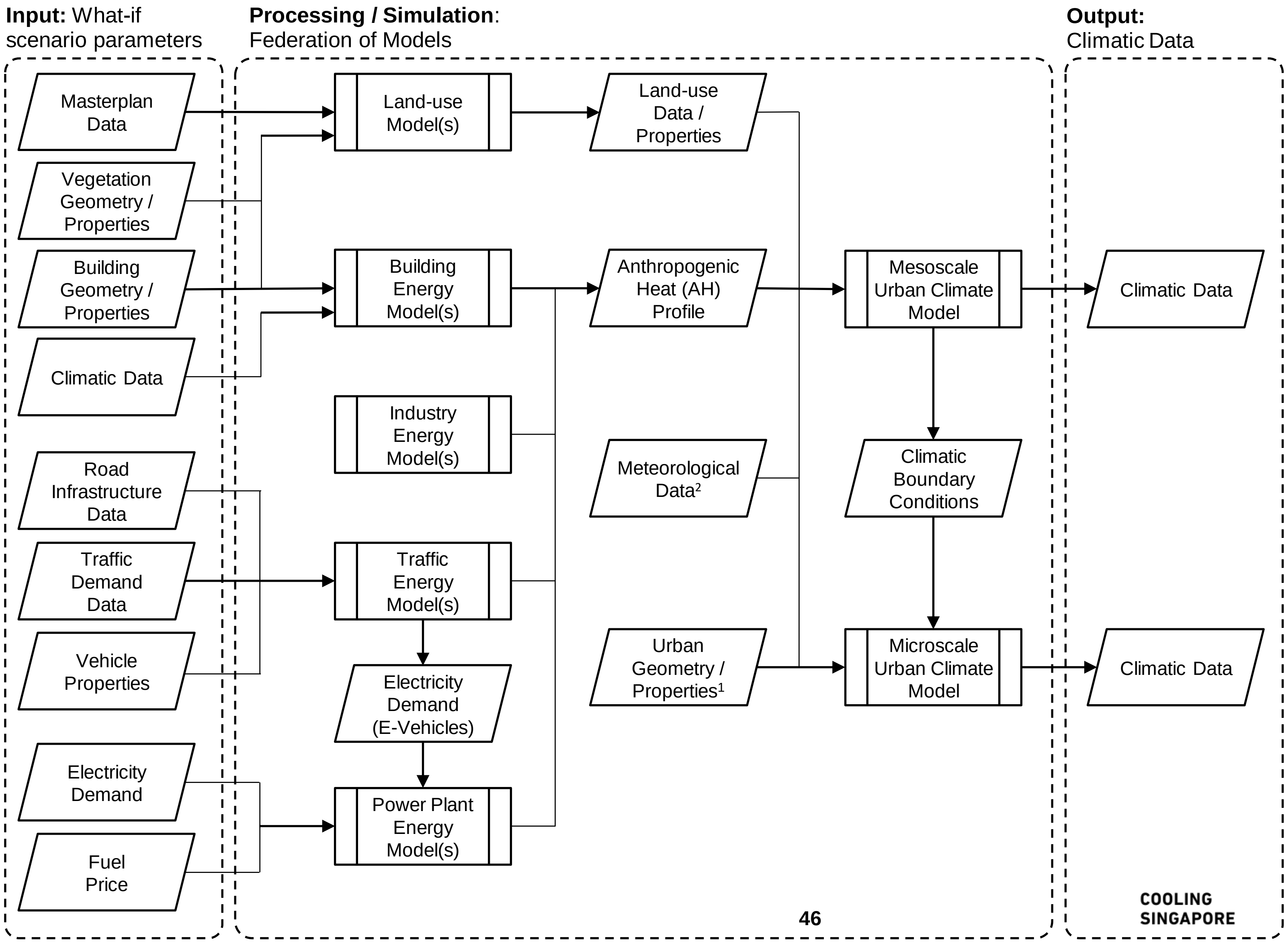


How does a DUCT work?

A DUCT is based on a federation of models – parts of which require supercomputing resources.

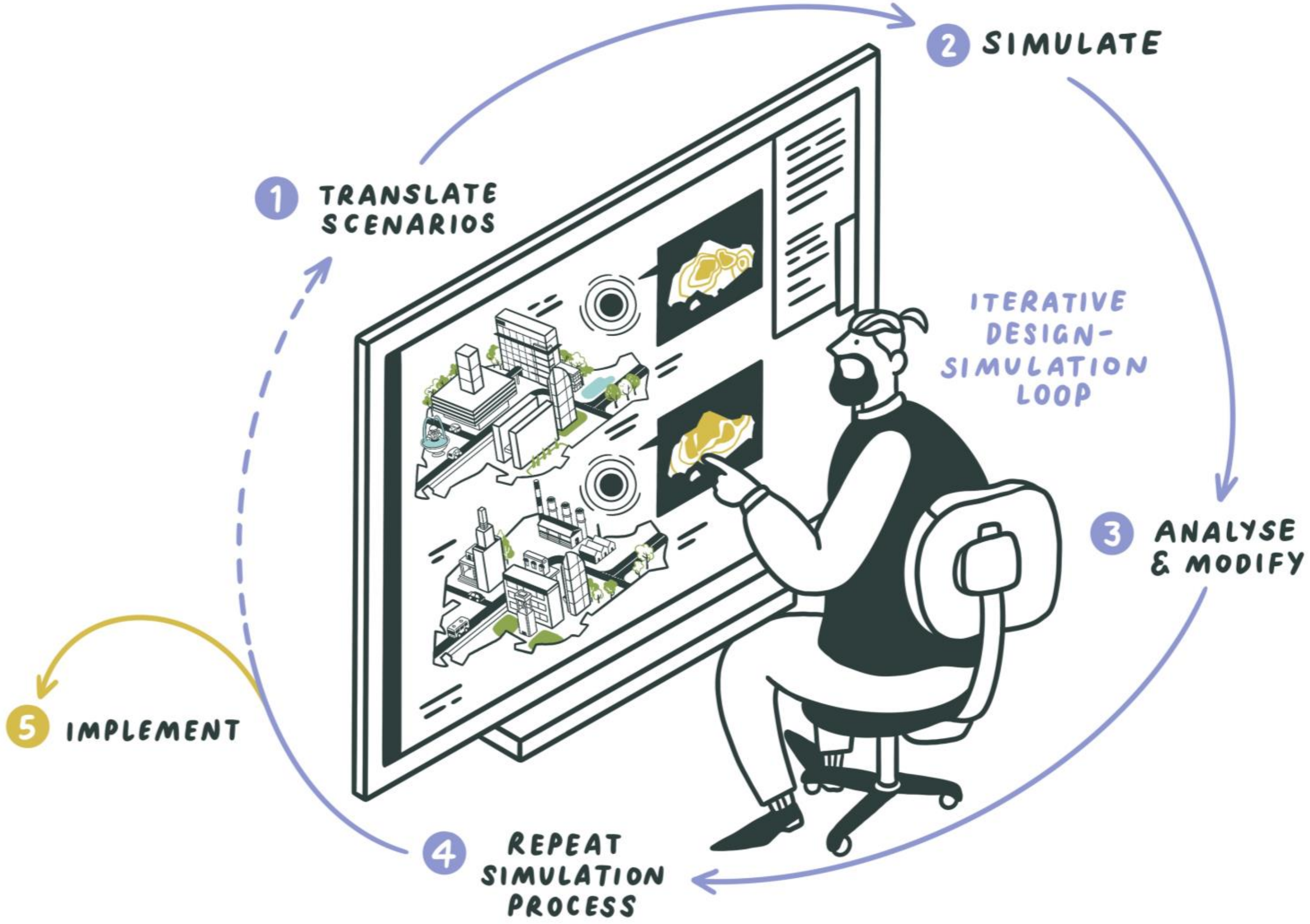
Models are built by scientists and domain experts with in-depth understanding of a given domain.

How can planners and decision makers use it?



How to use a DUCT for planning and policy?

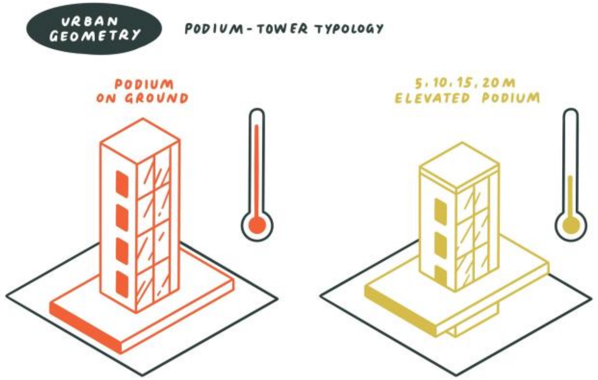
Ask what-if questions and explore how new master plans and policies perform in the simulation before implementing them.



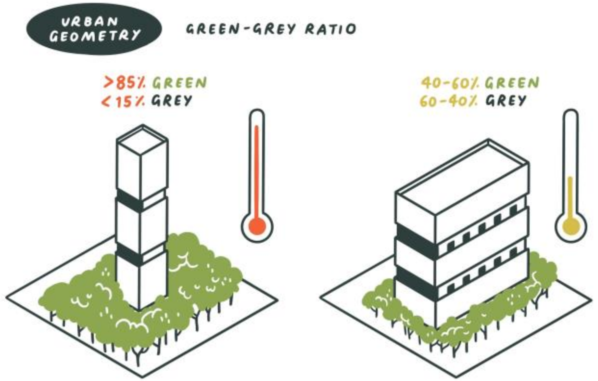
Source: H. Aydt (2020). Cooling Singapore – Towards Urban Climate Design and Management in Indicia 03, editors: S. Cairns and D. Tunas
Image: Idea Ink (2020)

What-if scenarios

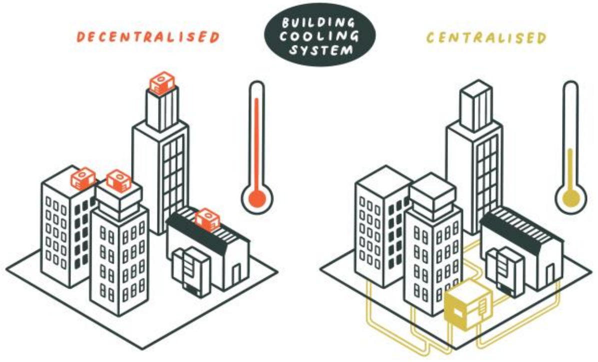
What is the urban geometry impact on Outer Thermal Comfort (OTC)?



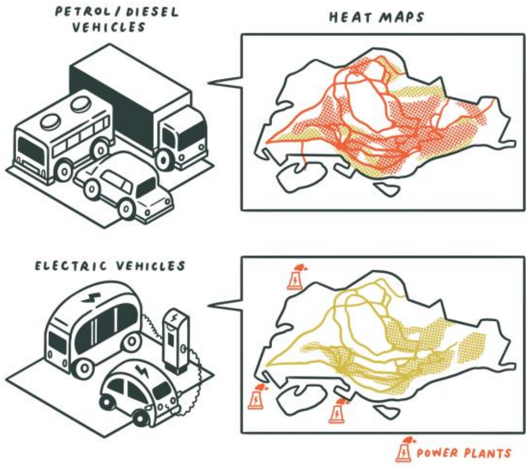
What is the impact of greenery on Urban Heat Island (UHI)?



What is the impact of District Cooling implementation on Energy Efficiency (EE)?



What is the impact of electric vehicle adoption on Anthropogenic Heat (AH) emissions?



Source: H. Aydt (2020). Cooling Singapore – Towards Urban Climate Design and Management in Indicia 03, editors: S. Cairns and D. Tunas
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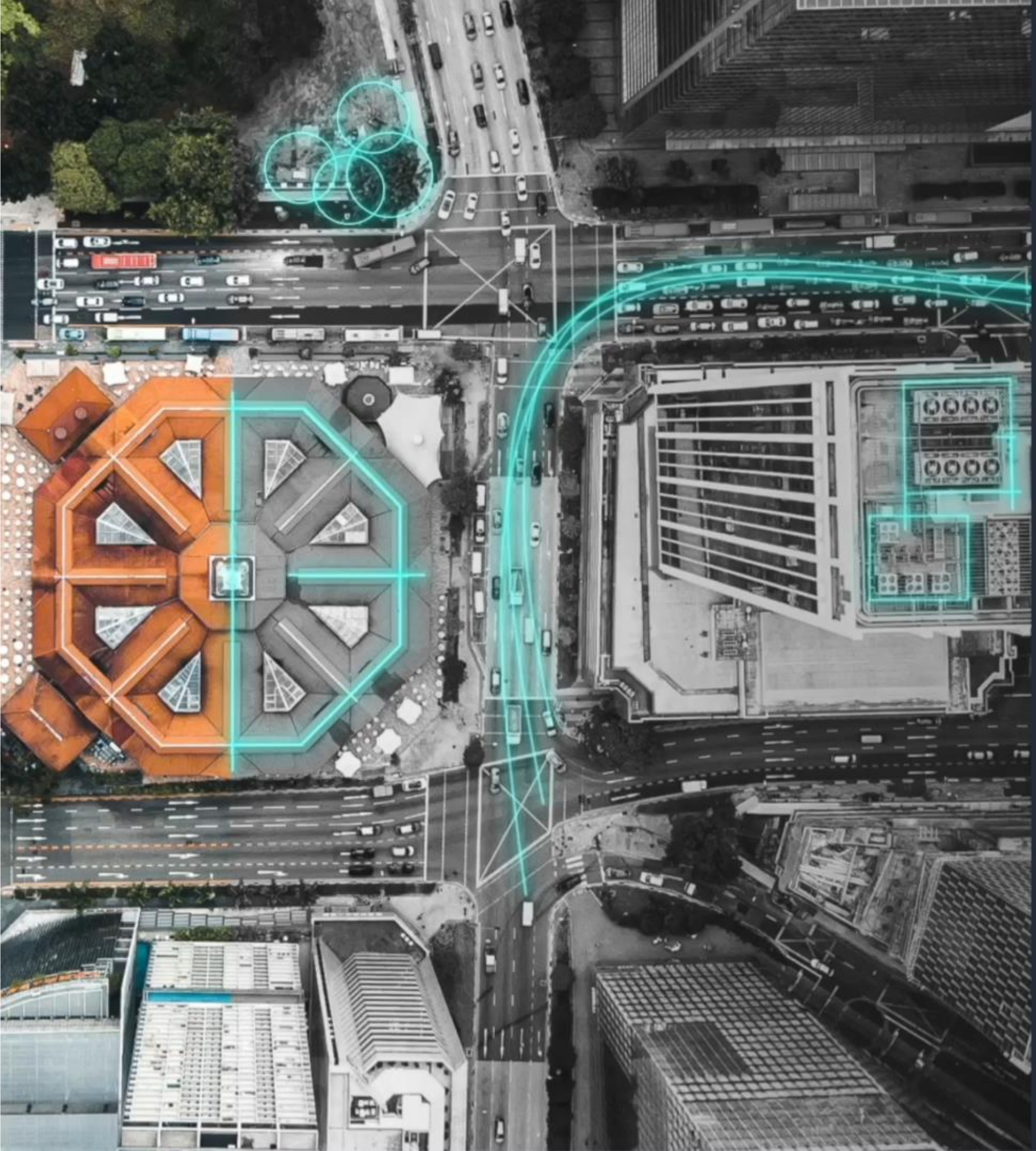
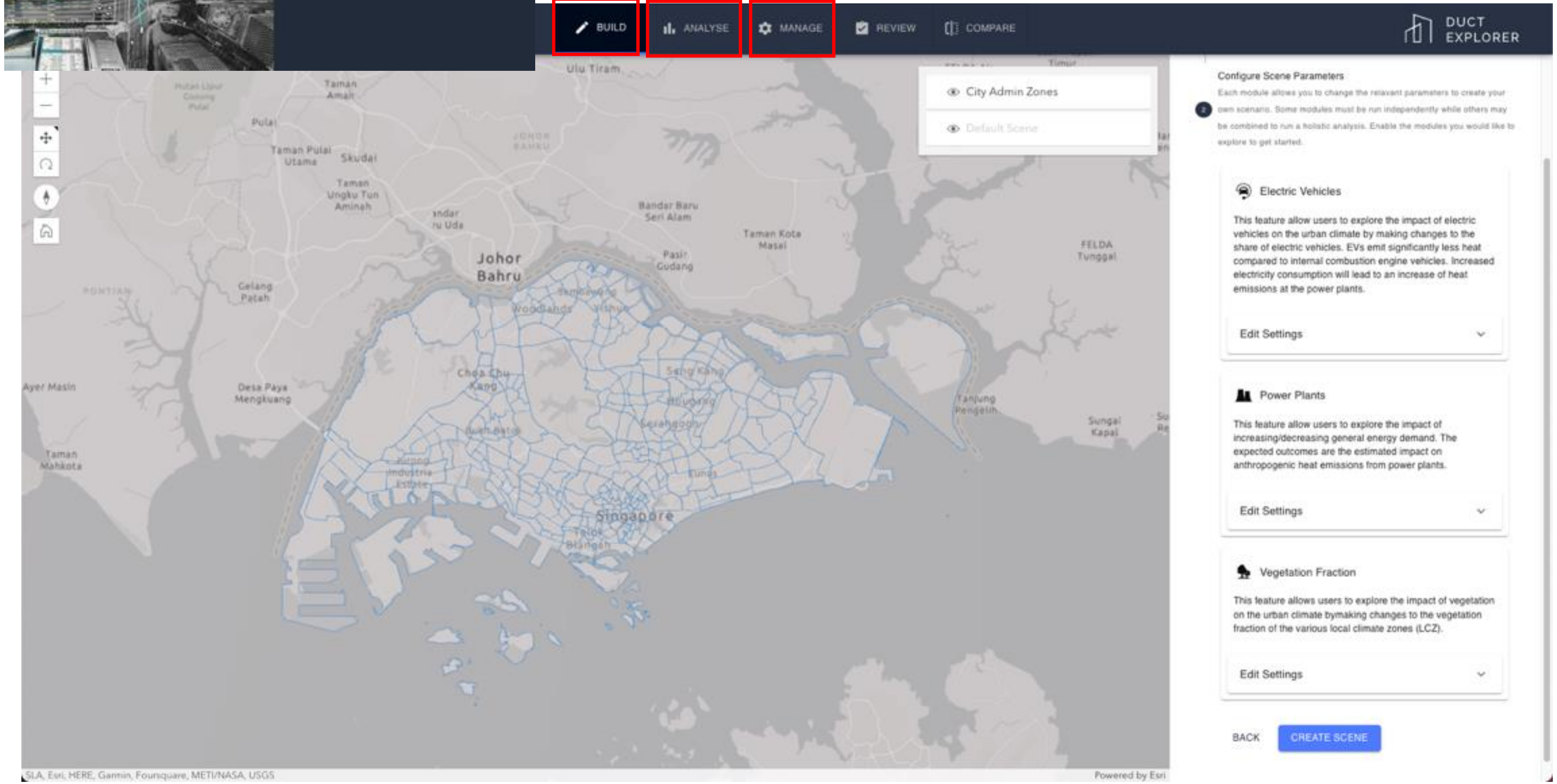


DUCT Explorer introduction

BUILD: Create new urban designs and customize urban parameters

ANALYSE: Run island-wide and district-scale analysis

MANAGE: Track all your analysis and view their progress



COOLING
SINGAPORE

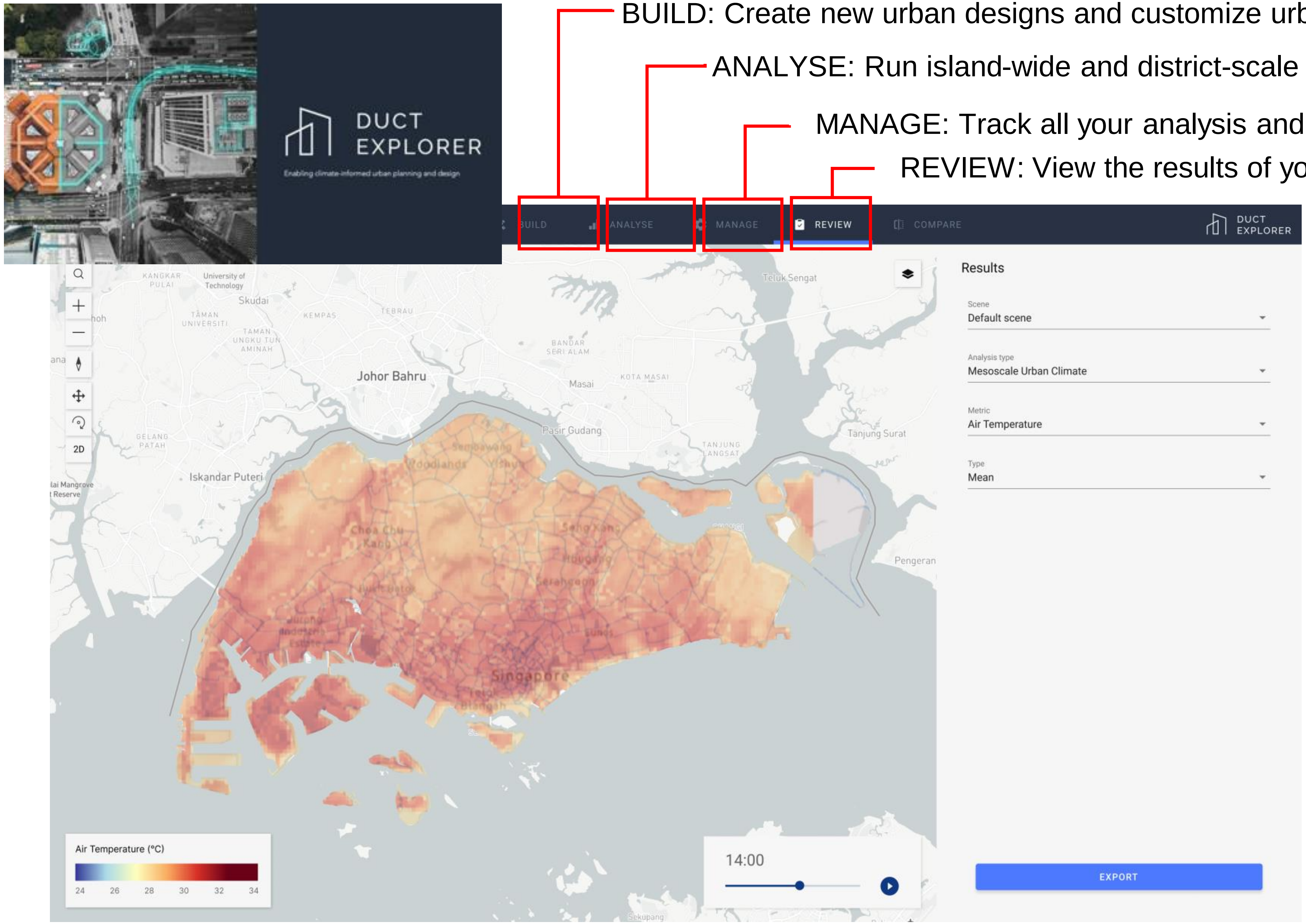
DUCT Explorer introduction

BUILD: Create new urban designs and customize urban parameters

ANALYSE: Run island-wide and district-scale analysis

MANAGE: Track all your analysis and view their progress

REVIEW: View the results of your analysis



DUCT Output:

- Urban Heat Island (UHI)
- Outer Thermal Comfort (OTP)
- Air Temperature
- Humidity
- Wind speed and direction
- Energy Efficiency
- ….

DUCT Explorer introduction

BUILD: Create new urban designs and customize urban parameters

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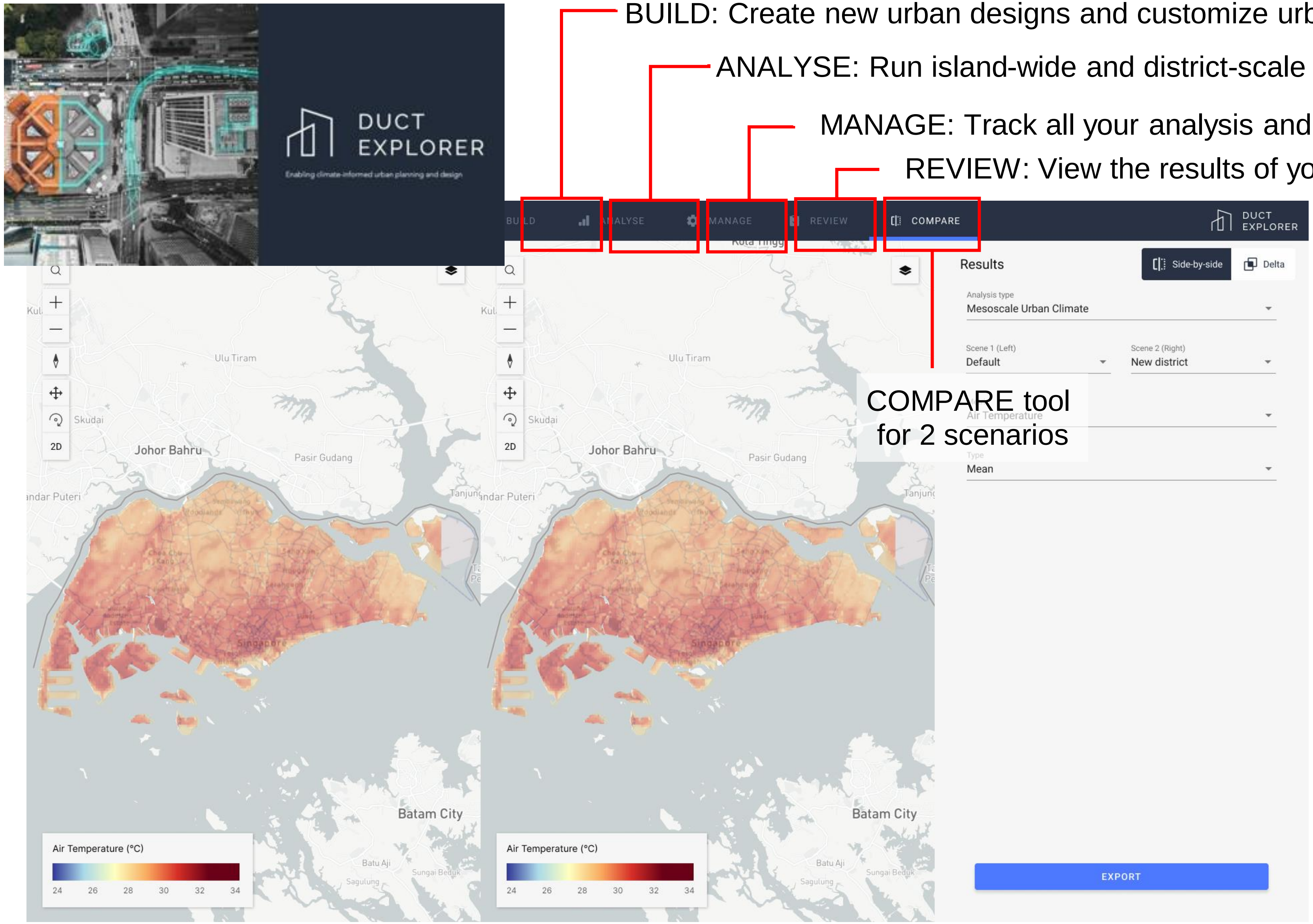

COMPARE tool for 2 scenarios

COOLING SINGAPORE

Is your city ready for the DUCT ?

Cooling Singapore 2.0

For more information please visit
https://sec.ethz.ch/research/cs.html