King's College London
Simon Fraser University
The University of Hong Kong
The University of British Columbia

The HKD3D Study

A dynamic three-dimensional exposure model for Hong Kong

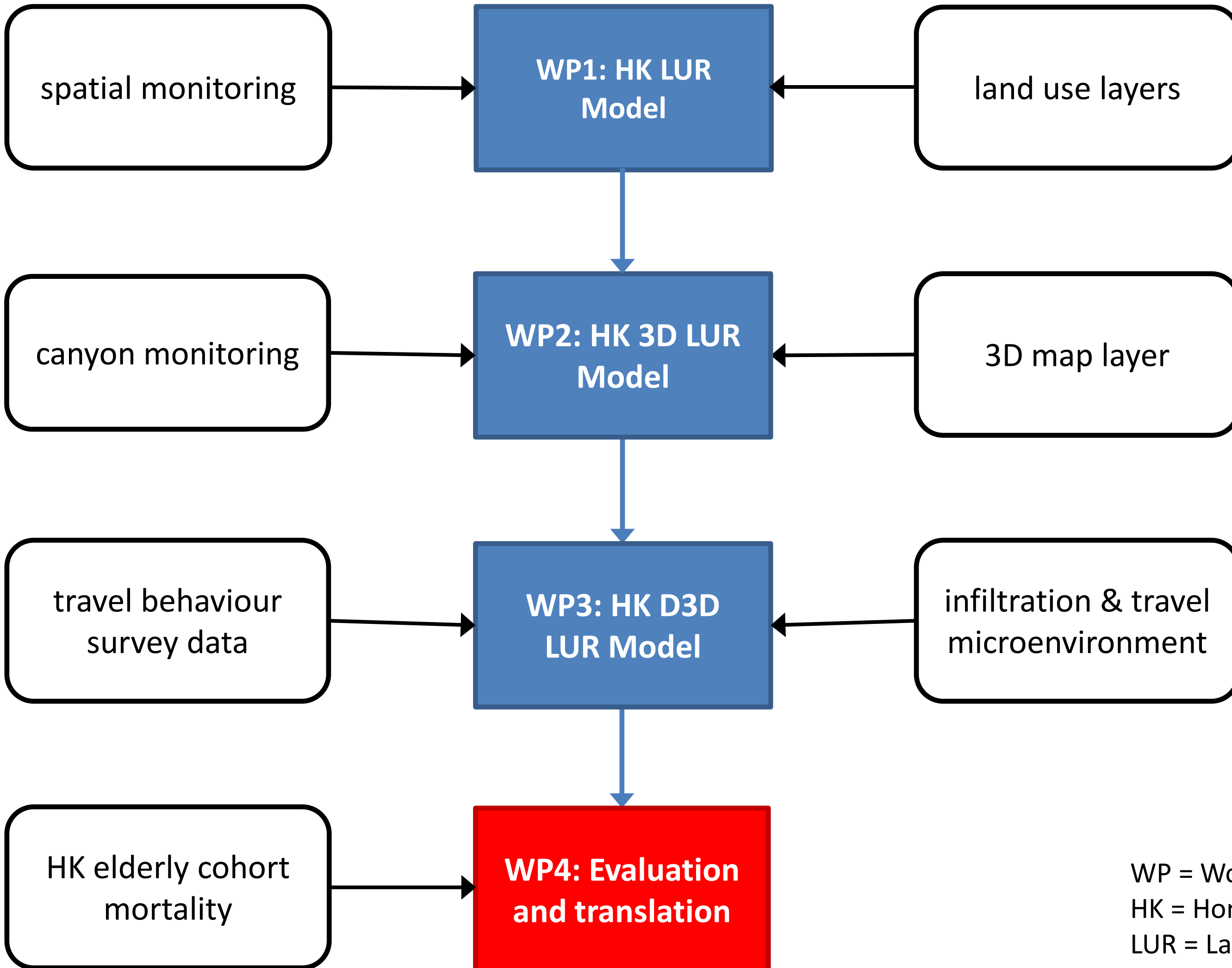
Ben Barratt, HEI Annual Conference, 1 May 2017

Populations across the world are increasingly exposed like this:

The HKD3D Study

- Request for Applications (RFA) Aim:
  - To develop and demonstrate improved methods for exposure assessment of traffic-related air pollution.
- Objectives:
  - To investigate the behavior and distribution of air quality in a 3D urban landscape using air quality sensor networks and population mobility datasets;
  - to develop, evaluate and demonstrate a dynamic 3D air pollution exposure model for Hong Kong (HK); and
  - to create an incremental methodology that can be applied in megacities across Asia and the developing world.

HKD3D Study Design

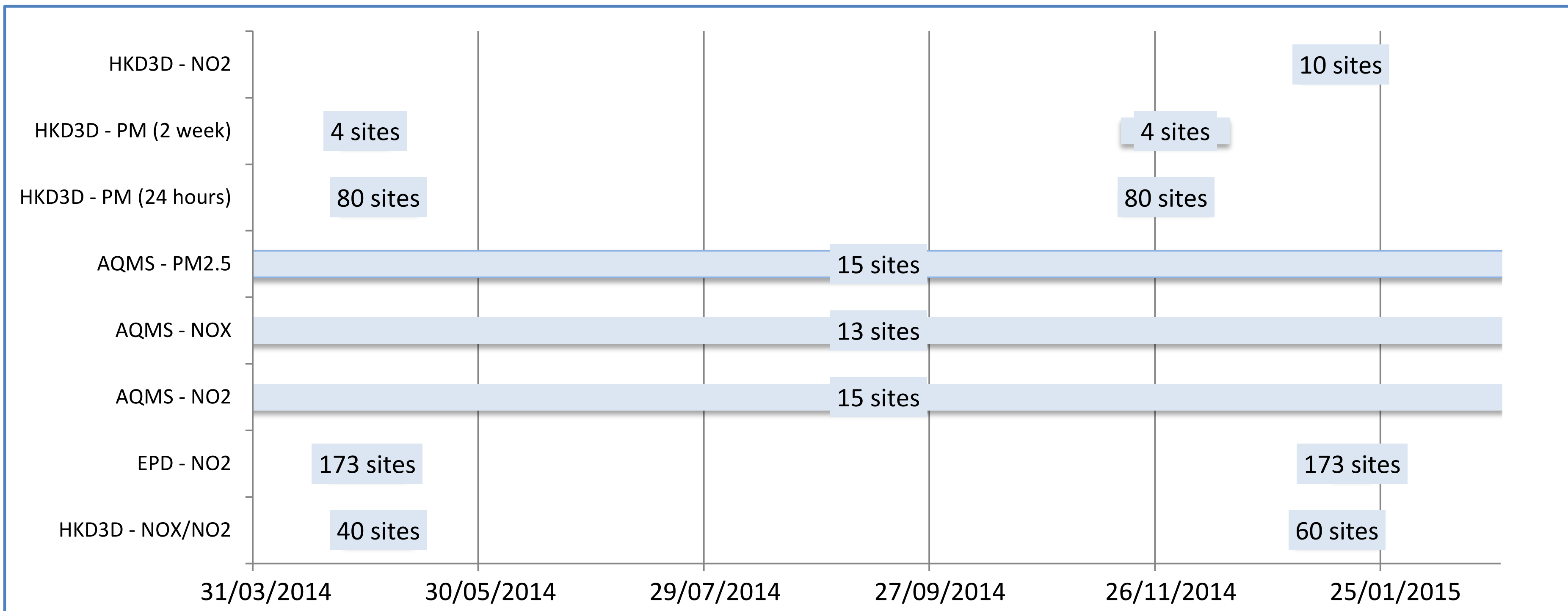


WP = Work Package
HK = Hong Kong
LUR = Land Use Regression
3D = 3-dimensional

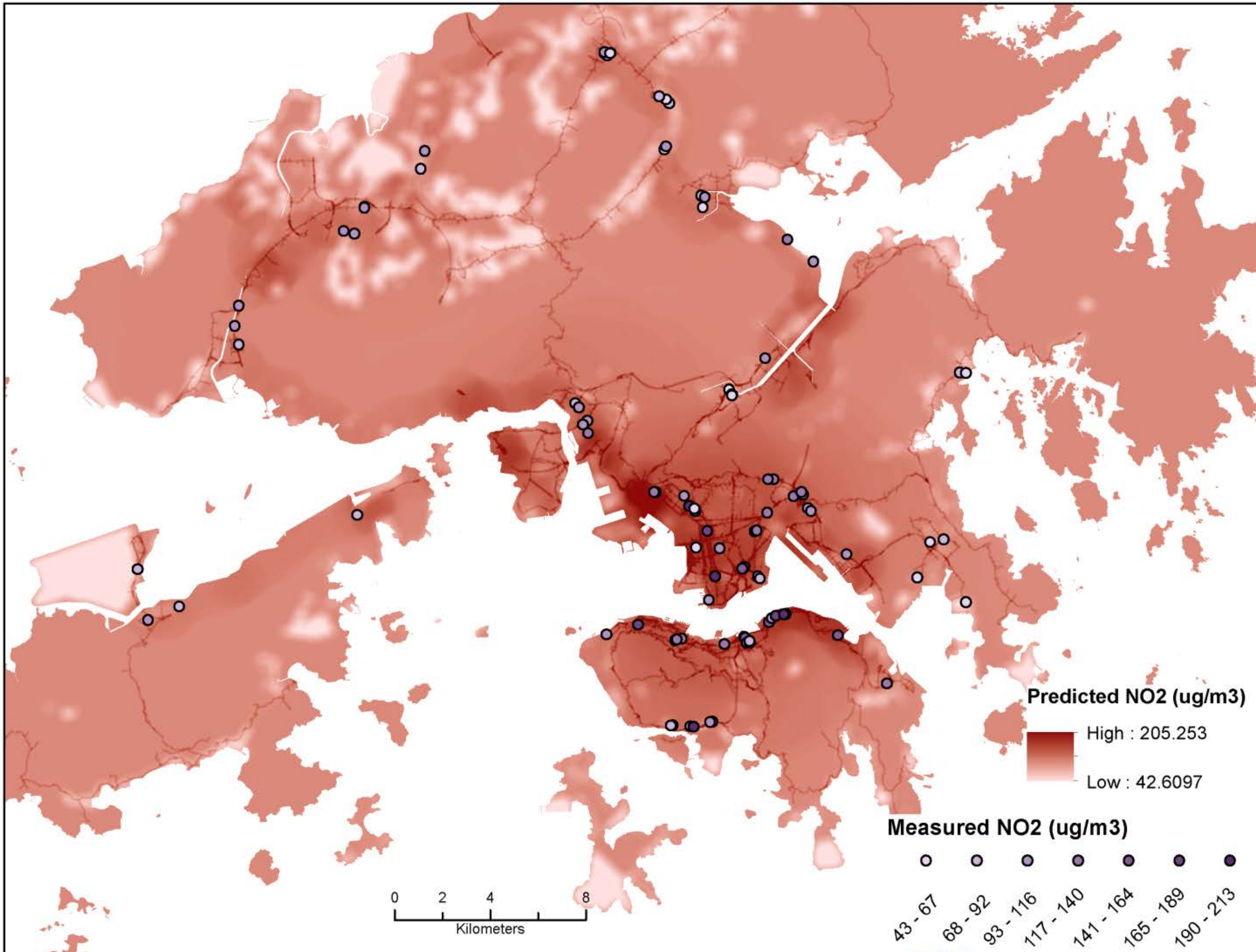
Work Package 1:
2-dimensional Land Use Regression (LUR)

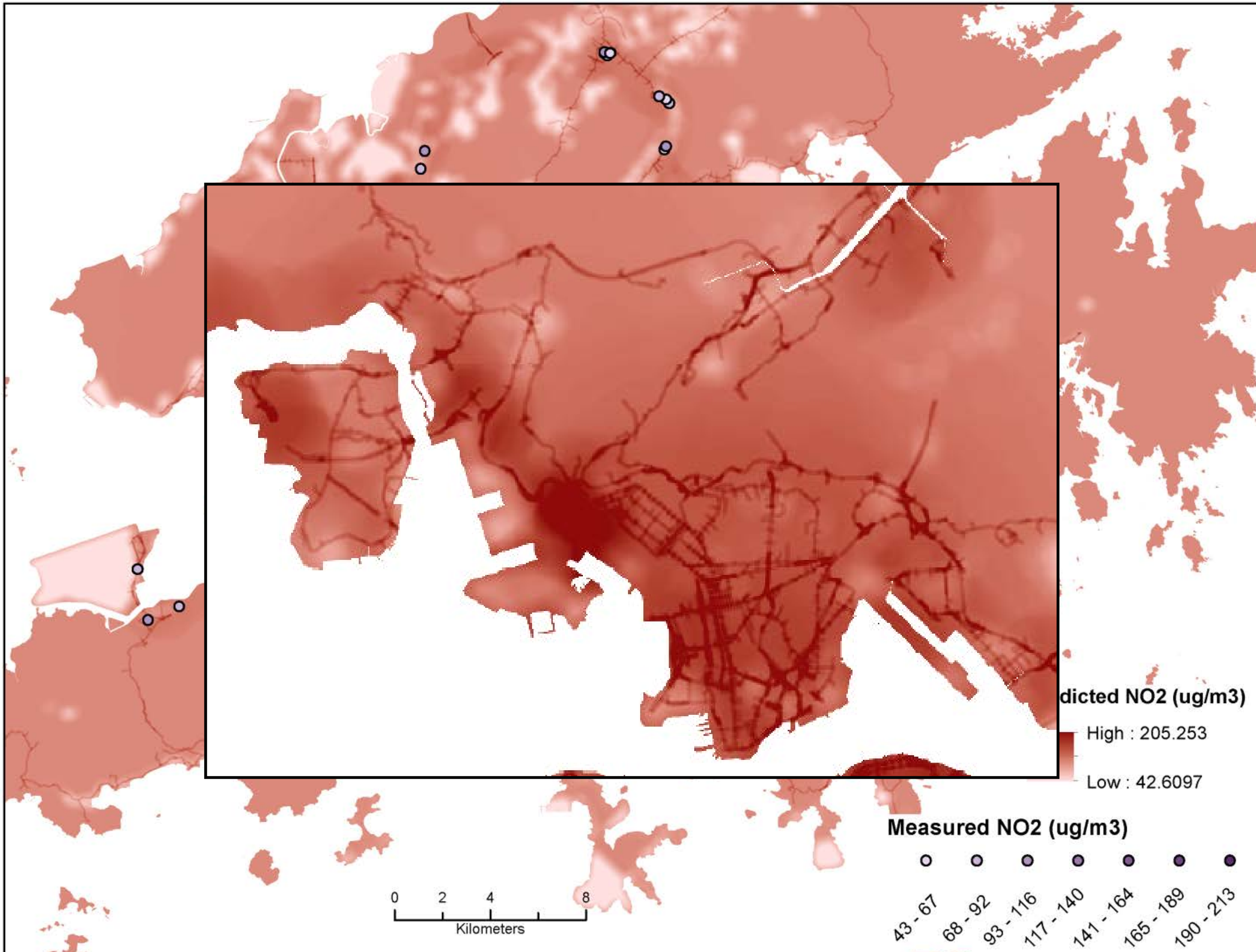
Summer and winter spatial campaigns

- NO_2 and NO at 40 sites by Ogawa badges
- NO_2 at 173 sites by diffusion tube by Hong Kong Environmental Protection Department (HK EPD)
- $PM_{2.5}$ and Black Carbon (BC) at 80 sites for 24 hours
- $PM_{2.5}$ and BC at 4 sites for 2 weeks
- NO_2, NO_X and $PM_{2.5}$ continuous at 15 reference sites (HK EPD)



AQMS = Air Quality Monitoring Station


Predicted NO2 (ug/m3)
High : 205.253
Low : 42.6097
Measured NO2 (ug/m3)
43 - 67
68 - 92
93 - 116
117 - 140
141 - 164
165 - 189
190 - 213
0
2
4
8
Kilometers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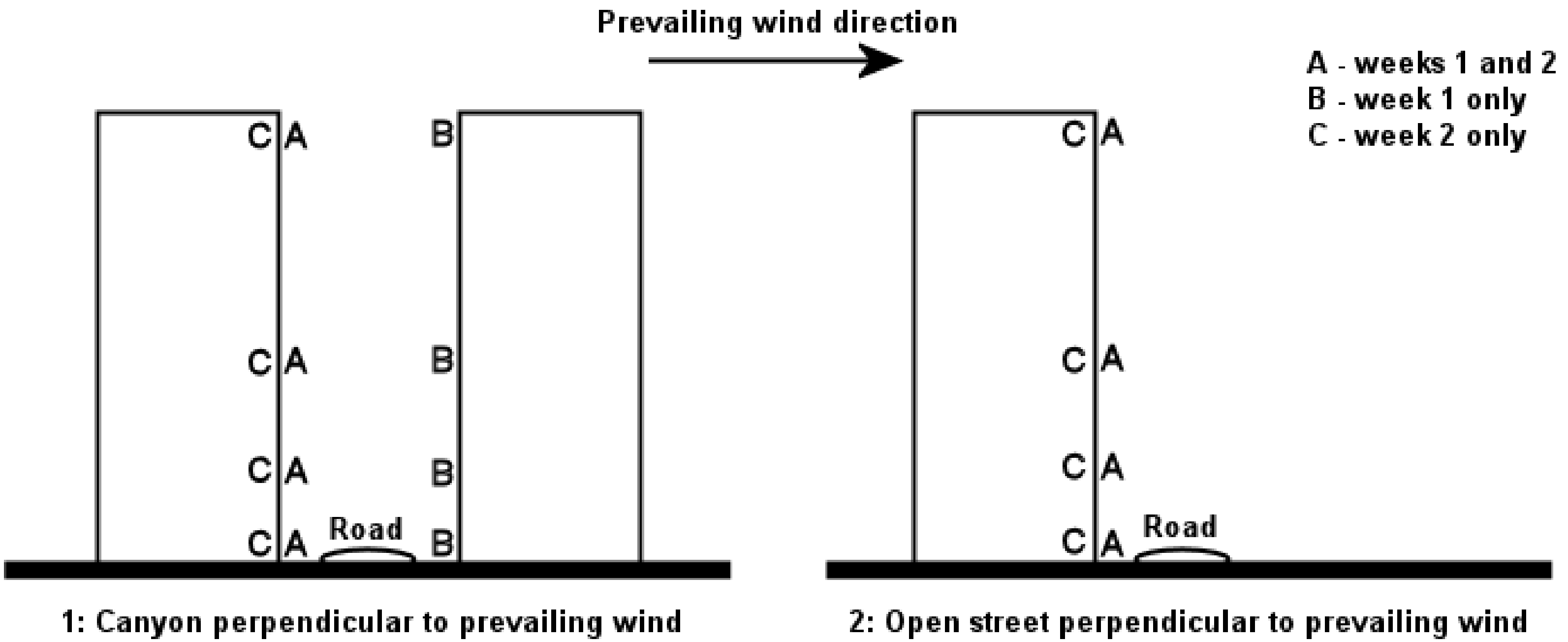
2D LUR explanatory variables

	NO_2	NO	$PM_{2.5}$	Black Carbon
R^2	0.46	0.50	0.59	0.50
Adjusted R^2	0.43	0.48	0.54	0.44
Root-mean-square error (RMSE)	28 μg/m^3	62 μg/m^3	4.0 μg/m^3	3.7 μg/m^3
Variables	Expressway road length (1000m) Main road length (50m) Elevated road length (5000m) Open Area (300m)	Elevated road length (500m) Build Volume (25m) Industrial (25m) Population density (100m)	Expressway road length (25m) Distance from Shenzhen Car Park Density (1000m) Car Park Density (25m) Government (100m) Industrial (25m)	Expressway road length (3000m) Expressway road length (50m) Longitude Car Park Density (50m) Commercial (500m) Residual (50m) Mixed Land Use (500m) Undeveloped Land (500m)

- R^2 similar to comparable models in the region, but lower than most western LURs

Work package 2:
Vertical monitoring campaigns

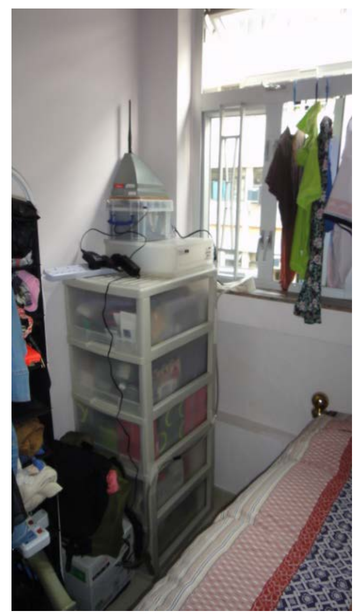
Canyon monitoring campaigns



- Warm and cool seasons
- 2 open sites, 4 canyon sites (+ 4 street/rooftop canyon sites)
- BC (microaethalometer), $PM_{2.5}$ (TSI Sidepak), $CO+NO+NO_2$ (AQMesh electrochemical sensors)


四點金


永利興食品有限公司

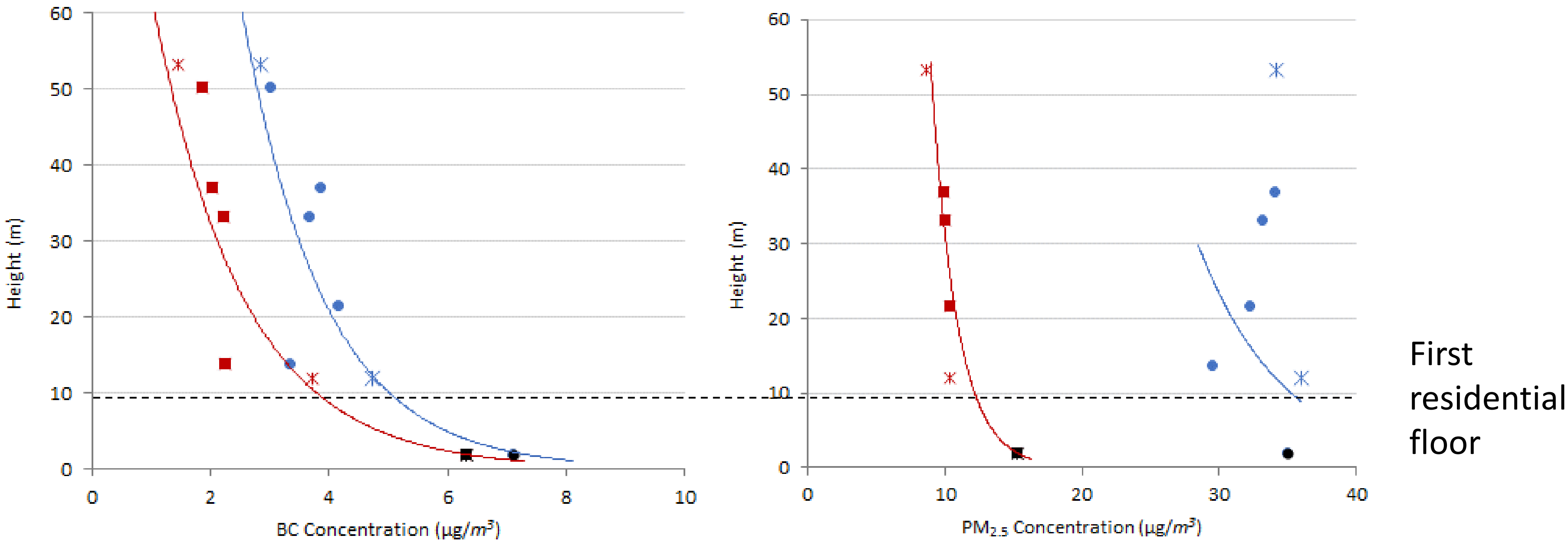


Canyon identification and recruitment

District	Height/ Width Ratio	Annual Average Daily Traffic (AADT)	Population Density	Description	Floors (A)	Floors (B)	Response Rate
Canyon Sites							
Jordan	7.4	Low	High	Old residential slab	1, 3, 9, 15	3, 13	7% (24/360)
Mong Kok	3	Med	High	Large residential towers	2, 5, 12, 20	11, 14, 20	5% (17/321)
Hung Hom	2.1	High	High	Large residential towers	2, 3, 5, 11, 14	2, 6, 13	2% (10/585)
North Point	3.6	High	High	Mixed age residential tower and slab	3, 5, 9, 10, 16	2, 17	2% (12/532)
Open sites							
Sai Wan	-	High	High	Residential slab	2, 4, 11, 15	none	3% (7/260)
Choi Hung	-	High	High	Residential slab	1, 4, 6, 19	none	2% (6/400)

(Plus street level and rooftop level paired monitoring at four AQMS sites)

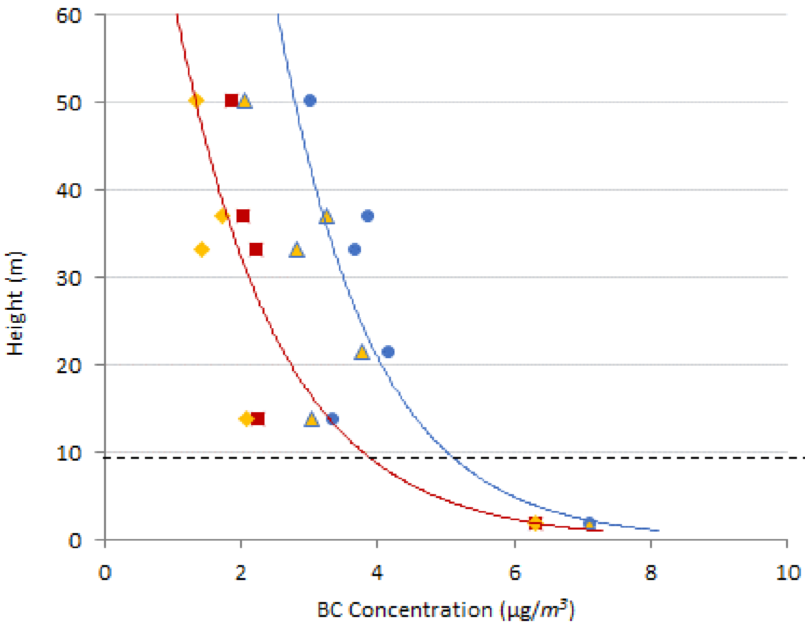
Vertical dispersion of traffic emissions

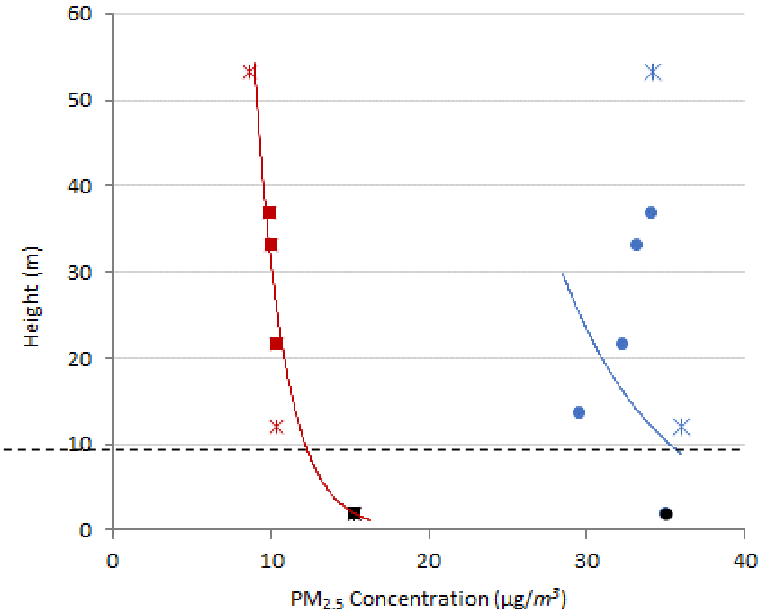


No evidence of stagnation within canyons

Vast majority of the population lives within the well mixed zone

Vertical dispersion of traffic emissions





First residential floor

- No evidence of stagnation within canyons
- Vast majority of the population lives within the well mixed zone
- Little protective effect inside homes

Pollution infiltration into homes

	$PM_{2.5}$ warm	$PM_{2.5}$ cool	BC warm	BC cool
Natural ventilation	81%	91%	88%	91%
Mechanical ventilation	40%		45%	
US homes (MESA-Air)	47%-62%		-	

- Implications for socioeconomic status (SES), energy use, building design, schools
  - All homes and schools have air conditioning, but it is rarely used to save money.

Implications for urban development

From this…

To this

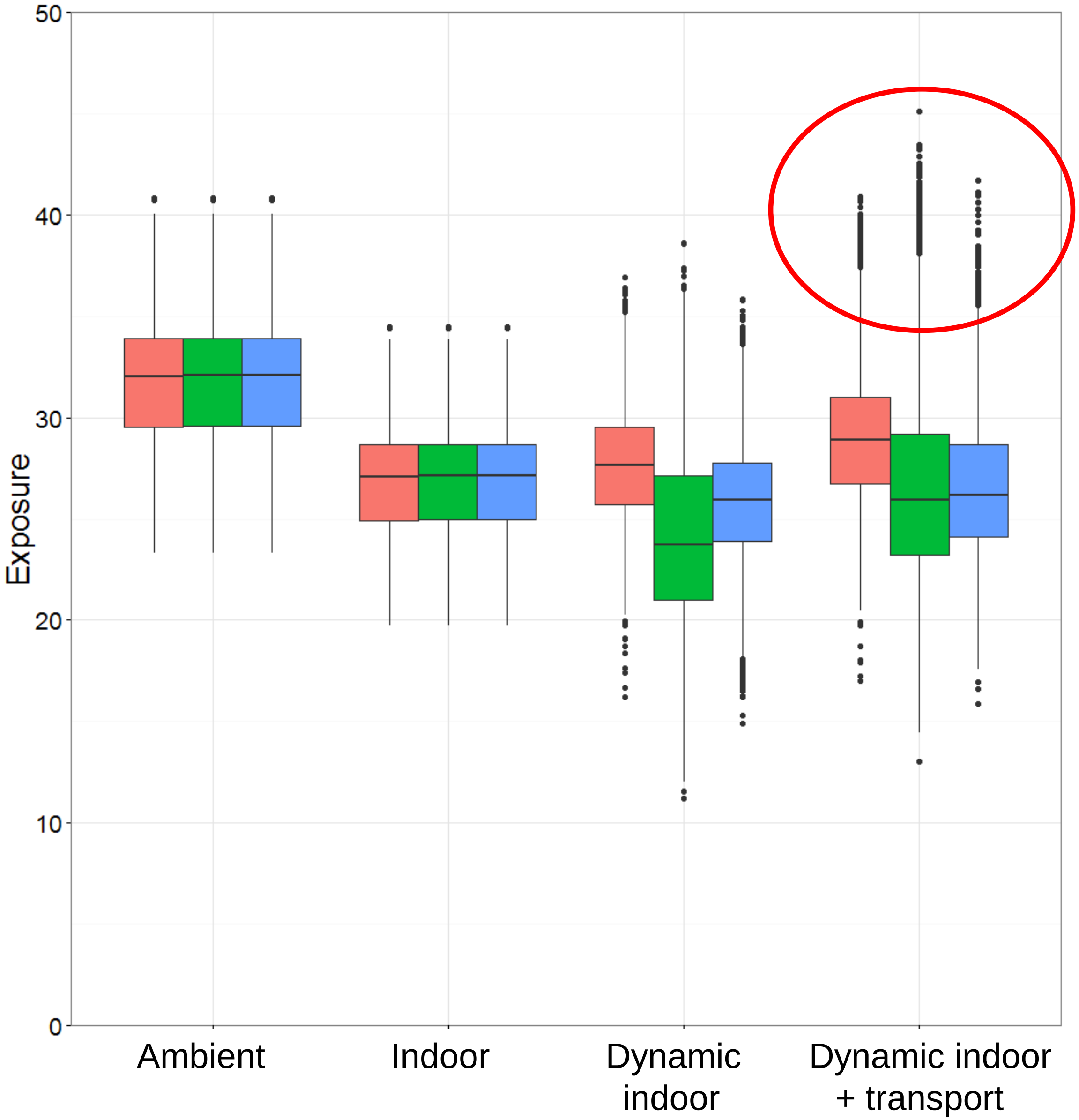
Work Package 3:
Dynamic 3D model

Model design

- Utilized LUR model exposure estimates, infiltration factors, transport microenvironment factors (from literature) and Travel Characteristic Survey (n=101,385) for population mobility.
- Staged model evaluation to identify exposure measurement error and possible bias in risk estimates

- ➢ Stage 1: Ambient exposure at residential address
- ➢ Stage 2: Indoor exposure at residential address
- ➢ Stage 3: Dynamic with indoor microenvironments
- ➢ Stage 4: Dynamic with indoor + transport microenvironments

Impact of mobility by age group ($PM_{2.5}$)



1 – <18 years
2 – 18-64 years
3 – 65=> years

Exposure estimates for populations aged <18 vs >65 years:

$PM_{2.5}$: +13%
NO_2: +14%
BC: +39%

Work Package 4: Evaluation

HK Elderly Health Service Cohort

- Epidemiologic effect estimates based on an existing cohort of 66,000 Hong Kong residents above the age of 65 (~9% of population of this age) where floor of residence is known.
- Risk estimates and confidence intervals calculated for a range of health outcomes using increasing exposure model complexity: 2-dimensional (2D), 3-dimensional (3D) and dynamic 3-dimensional (D3D).

2D vs D3D hazard ratios

Cause of Death	Fine particulates ($PM_{2.5}$)		Nitrogen Dioxide (NO_2)	
	2D	D3D	2D	D3D
All natural causes	**1.03 (1.01, 1.06)***	**1.07 (1.04, 1.09)***	1.00 (0.97, 1.03)	**1.06 (1.03, 1.08)***
Cardiovascular	**1.06 (1.02, 1.10)***	**1.10 (1.05, 1.14)***	1.00 (0.95, 1.05)	**1.09 (1.04, 1.14)***
Ischemic Heart Disease (IHD)	1.03 (0.97, 1.10)	**1.09 (1.03, 1.17)***	1.09 (1.00, 1.18)	**1.15 (1.06, 1.24)***
Cerebrovascular	1.06 (0.99, 1.13)	**1.08 (1.01, 1.16)***	1.00 (0.91, 1.09)	1.06 (0.98, 1.15)
Respiratory	1.02 (0.97, 1.06)	**1.06 (1.01, 1.11)***	0.99 (0.93, 1.06)	1.06 (1.00, 1.12)
Pneumonia	1.00 (0.94, 1.06)	1.05 (0.99, 1.12)	0.98 (0.90, 1.06)	1.06 (0.99, 1.14)
COPD	1.06 (0.97, 1.15)	1.09 (1.00, 1.19)	1.02 (0.90, 1.15)	1.06 (0.96, 1.18)
External causes	1.02 (0.90, 1.16)	1.04 (0.90, 1.19)	1.10 (0.92, 1.31)	1.08 (0.93, 1.27)

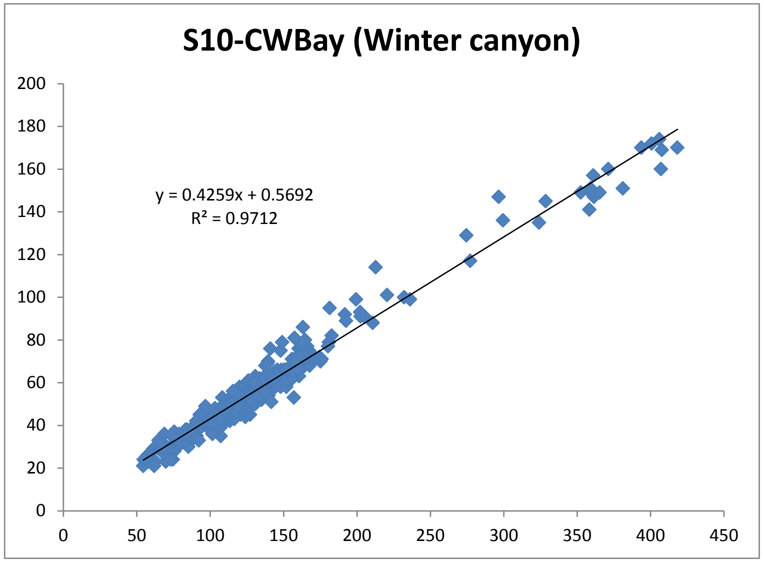
Hazard ratios (95% Confidence Interval) per interquartile range (IQR) increase of pollutants for baseline exposure. *p<0.05.

Dynamic component had little impact due to cohort's age-related homogeneity.

Some challenges

1. Field conditions (heat, monsoon, pollution, security, travel)
2. Canyon resident recruitment, especially at ground floor
3. Subtle vertical gradients, requiring high sensor precision
4. Derivation of a region-wide canyon decay rate

The importance of inter-unit precision

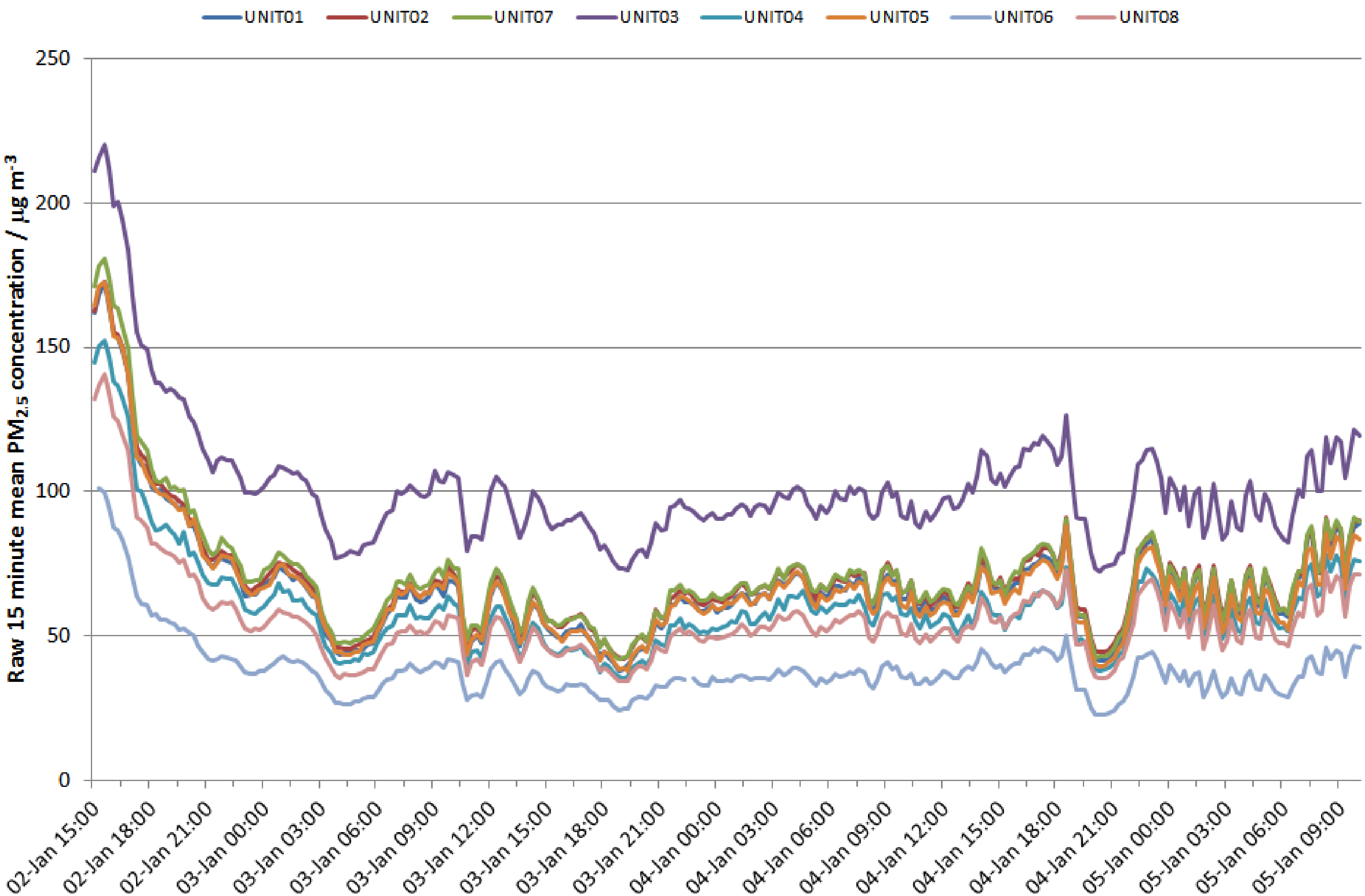


SidePak accuracy scaling

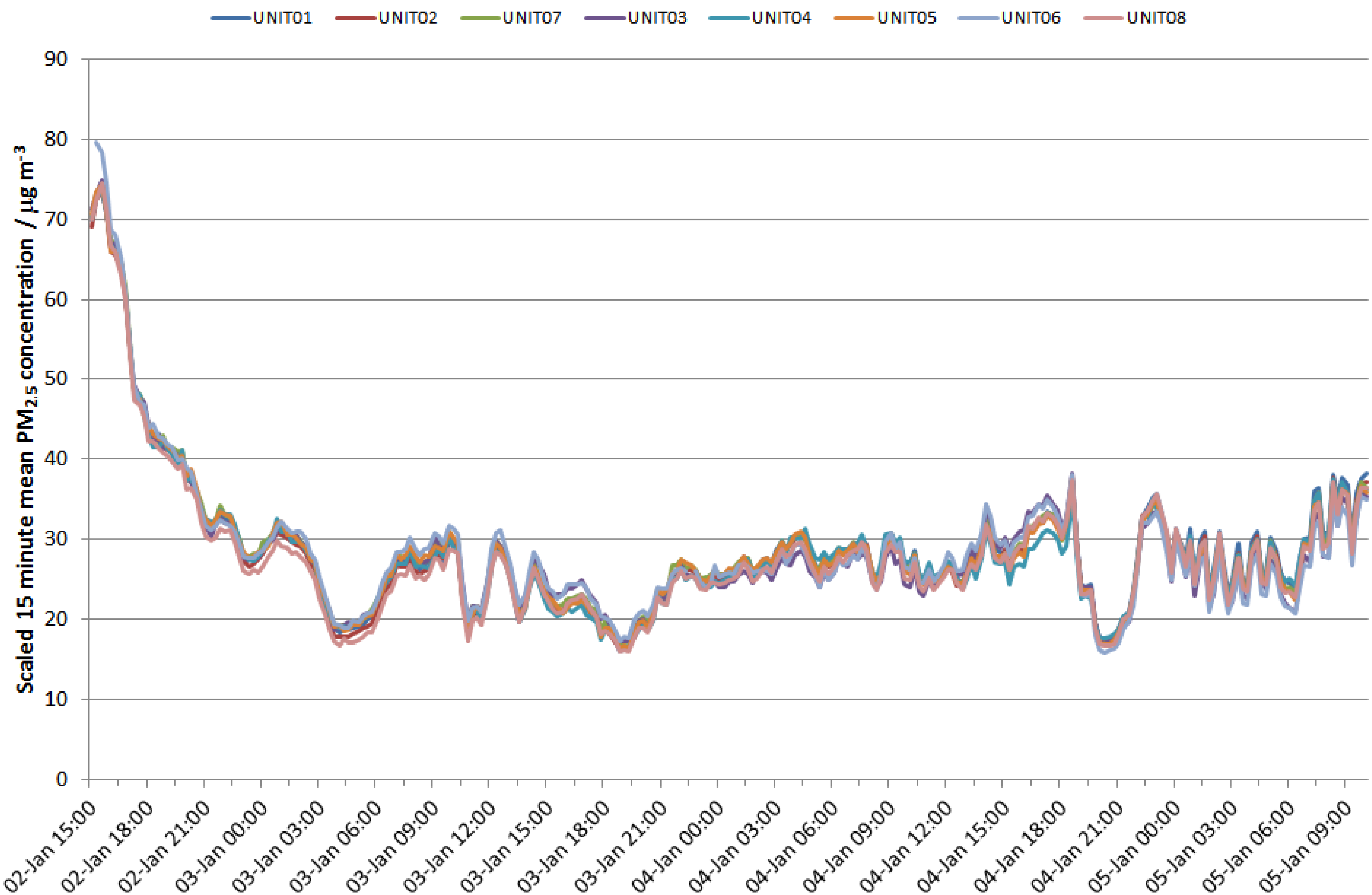
The figure and table compare multiple units of the same instrument type.

SidePak inter-unit precision scaling

Unit \ R^2	S01	S02	S03	S04	S07	S09	S10	S11	S12	CAN06
S01		1.00	0.21	0.97	0.98	0.99	1.00	0.96	1.00	1.00
S02	1.00		0.21	0.97	0.98	0.99	1.00	0.97	1.00	1.00
S03	0.21	0.21		0.12	0.27	0.24	0.25	0.28	0.25	0.19
S04	0.97	0.97	0.12		0.94	0.96	0.95	0.92	0.96	0.98
S07	0.98	0.98	0.27	0.94		0.96	0.98	0.99	0.99	0.98
S09	0.99	0.99	0.24	0.96	0.96		0.99	0.96	0.99	0.99
S10	1.00	1.00	0.25	0.95	0.98	0.99		0.98	1.00	0.99
S11	0.96	0.97	0.28	0.92	0.99	0.96	0.98		0.98	0.97
S12	1.00	1.00	0.25	0.96	0.99	0.99	1.00	0.98		0.99
S13	1.00	1.00	0.19	0.98	0.98	0.99	0.99	0.97	0.99	
Offset	1	5		41	29	2		3	1	5
Gradient	1.01	1.02	-	0.95	0.91	1.14		1.89	0.96	1.28



- Co-location precision and reference testing pre and post campaign ($PM_{2.5}$)



- Co-location precision and reference testing pre and post campaign ($PM_{2.5}$)

Electrochemical stability issues

- Inter-unit precision scaling of electrochemical sensors was not maintained during campaigns
- Issues with stabilisation, temperature, humidity, drift
- High humidity caused frequent sensor failures

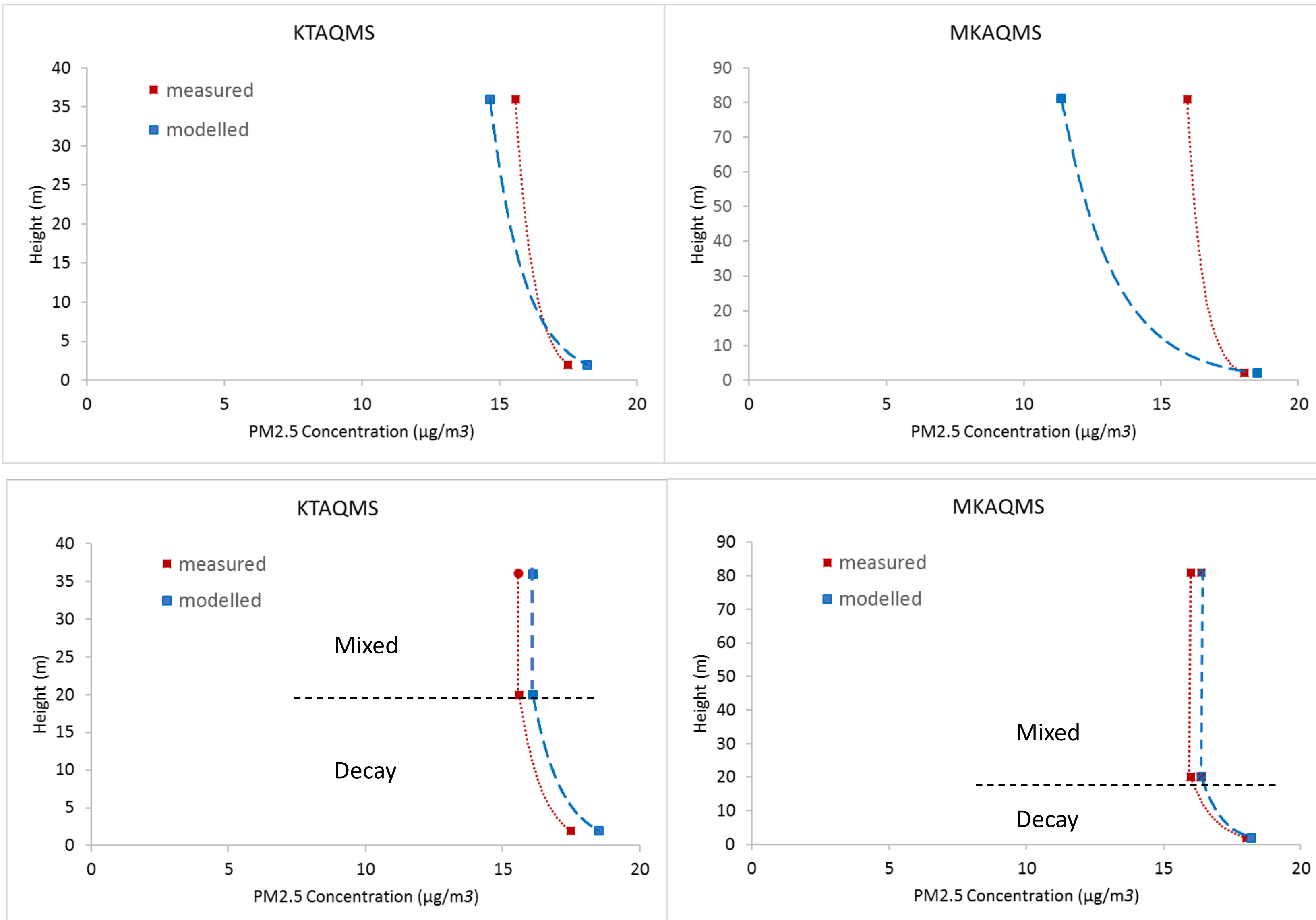
NO	R^2			Gradient			Offset (ppb)		
Test period:	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
UNIT01 (ref)	1.00	1.00	1.00	1.00	1.00	1.00	0	0	0
UNIT02	0.69	0.11	0.71	1.03		0.44	2		-25
UNIT03	0.98	0.99	0.98	1.17	1.28	1.69	-33	-4	-2
UNIT04	0.99	0.99	0.87	1.25	1.48	1.16	-16	7	-62
UNIT05	0.96	0.97	0.94	1.5	1.27	1.06	8	19	-12

Inter-unit precision test results during summer canyon campaign

Assigning a decay typography

- Hypothesis was that different canyon types would produce consistently different decays, necessitating a typography
- More rapid mixing than expected meant that a more general approach was needed, assuming a common decay factor
- Exponential decay shape assumed based on published literature

Continuous decay or well mixed?



Study conclusions

- Improved urban building design appears to be stimulating the dispersion of local traffic-related air pollutant emissions in street canyons, with no evidence of widespread stagnation found.
- Rapid vertical dispersion means that high resolution 2D models will overestimate roadside residential exposure above ground floor.
- Typical Hong Kong residences provide very little protection from outdoor air pollution, unless you can afford mechanical ventilation and/or work in a modern office.
- Dynamic models can identify differential exposures between population subtypes; on average, young males are in the highest exposure group in Hong Kong.
- A more personalised exposure methodology led to stronger evidence for the health impact of air pollution on respiratory and cardiovascular health in Hong Kong than previously published.

Acknowledgements

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Co-Investigators and research staff:
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