Anthropogenic and biogenic carbon dispersion in urban environment: a case study in London

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Motivation

- Physical models for carbon cycle and climate (CMIP)
- Carbon emission in urban environment: (anthropogenic)
  - Urban area accounts for 67 – 71% energy-related CO2 emission in 2006 (IEA)

- Biogenic emission (source/sink):
  - Globally, burning of fossil fuel ~ 10.9 Pg C yr^{-1},
    v.s. removal by terrestrial ecosystems 3.4 Pg C yr^{-1} (1 Pg = 10^{15} g)
    (without considering emission by land-use change)
- Interplay of biogenic and anthropogenic carbon emissions in urban environment
  - Fine-scale modelling of urban flow, emission
  - Biogenic models
  - Might provide new insights on urban carbon management

CMIP: Coupled Model Intercomparison Project, see Anav et al. 2013, *Journal of Climate* ***26***(18): 6801-6843
IEA: International Energy Agency, see Dhakal 2010, *Current Opinion in Environmental Sustainability* ***2***: 277–283
Global carbon budget: fossil fuel burning and terrestrial ecosystem update, see Byrne et al. 2023, *Earth Syst. Sci. Data* ***15***: 963–1004,

Methodology

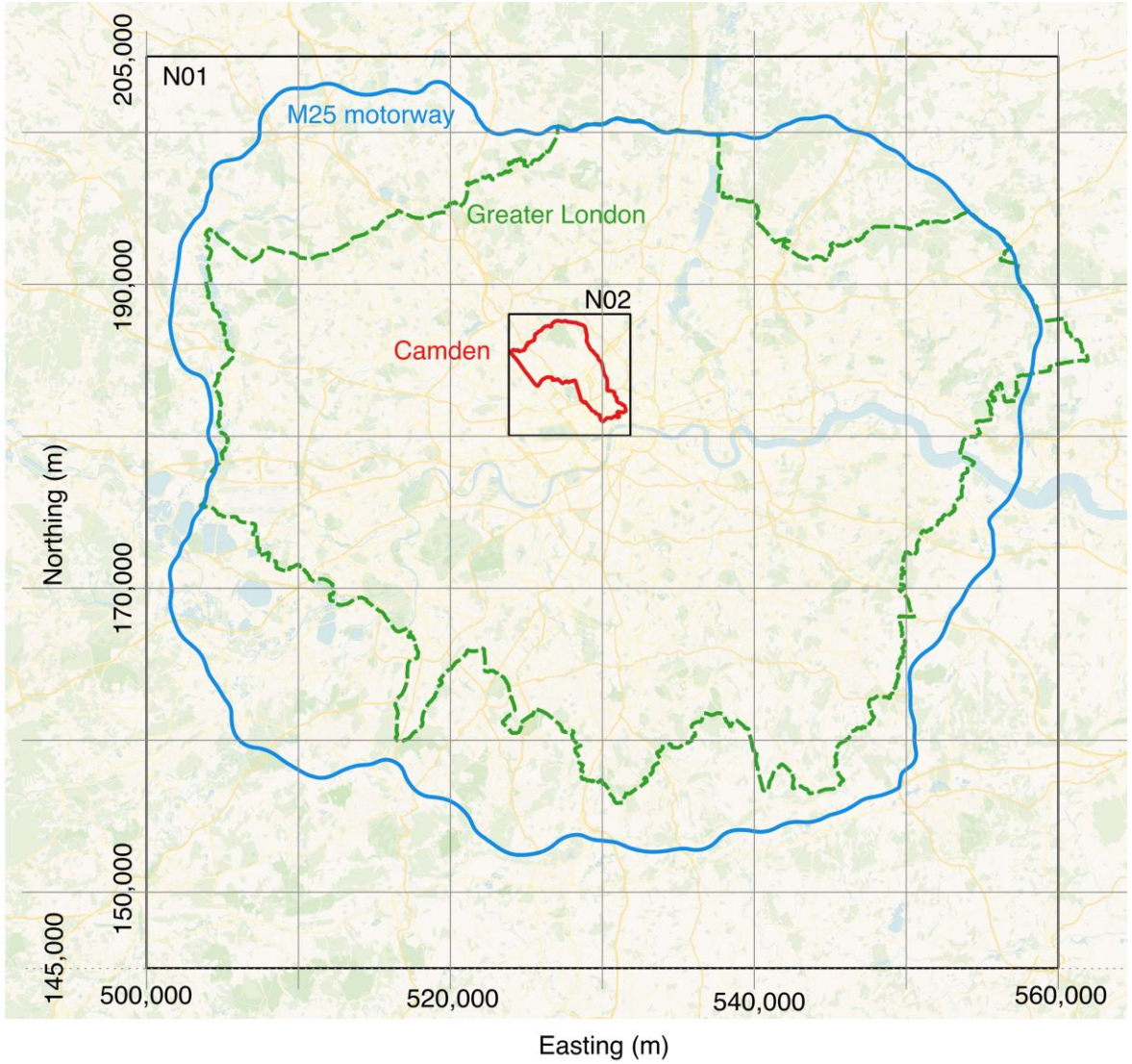
- Study area
- Input data
- Biogenic flux module

Study area

- London borough of Camden
- M25 motorway (Greater London)

Computational domain

- Two nested domain
  - Parent domain N01 (Greater London):
    - 60km x 60km
    - 3km in z-direction
  - Child domain N02 (Camden):
    - 8km x 8km
    - 1km in z-direction



Case settings

- Spatial discretisation:

	Grid size	# of grid
Parent domain	100m x 100m x 50m	600 x 600 x 60
Child domain	10m x 10m x 10m	800 x 800 x 100

- Run on archer2 (UK Tier 1 HPC)
  - 10 nodes (1280 cores)
  - Depending on wind speed, 7 ~ 15 hr CPU time for 1 day simulation
- Activated physics model
  - Urban surface (only in child domain)
  - Radiation (clear sky)
  - Land surface
  - Biogenic and anthropogenic CO_2 dispersion

Static/dynamic driver

- Static driver

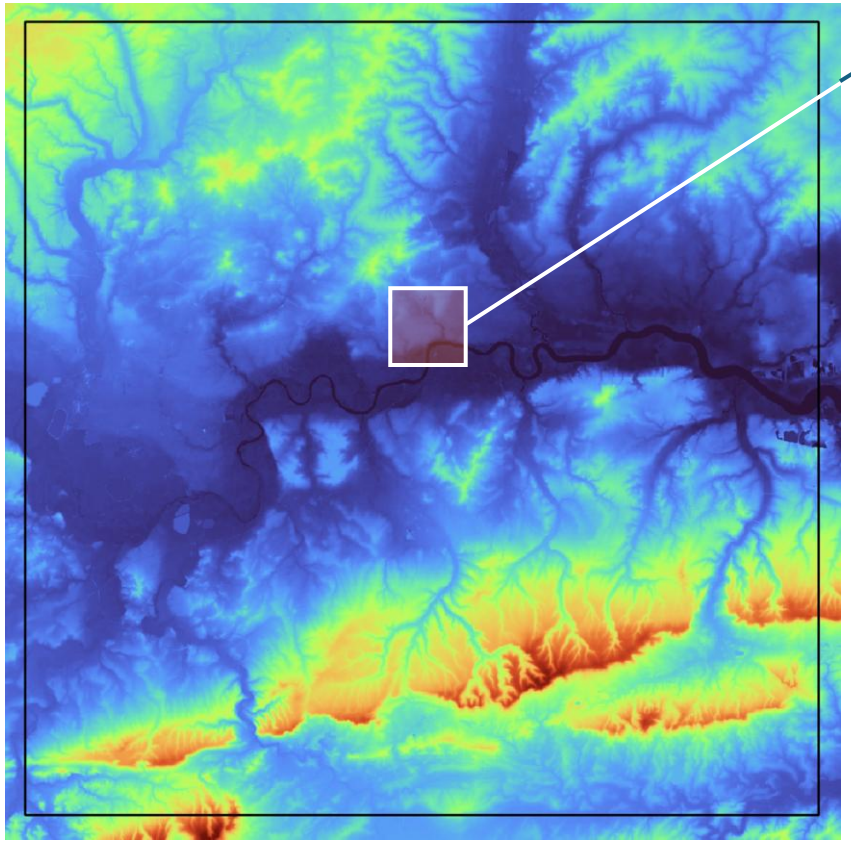
Type	***Data source***
Terrain height	Ordnance Survey @ 50m, National Lidar @ 1m
Buildings (shape and height)	Ordnance Survey topography map, OS Building height attribute
Landuse and vegetation type	ESA WorldCover @ 10m
EVI, LSWI	Sentinel-2 multispectral image @ 10m

- Dynamic driver

Type	***Data source***
Wind / pressure / humidity / temperature at pressure levels	ERA5 hourly data on pressure levels (reanalysis) @ 0.25 deg
Wind / pressure / humidity / temperature at ground level	ERA5-Land hourly data @ 0.1 deg
CO2 mixing ratio at pressure levels	CAMS global greenhouse gas reanalysis (EGG4) @ 0.75 deg 3-hourly

Static/dynamic driver

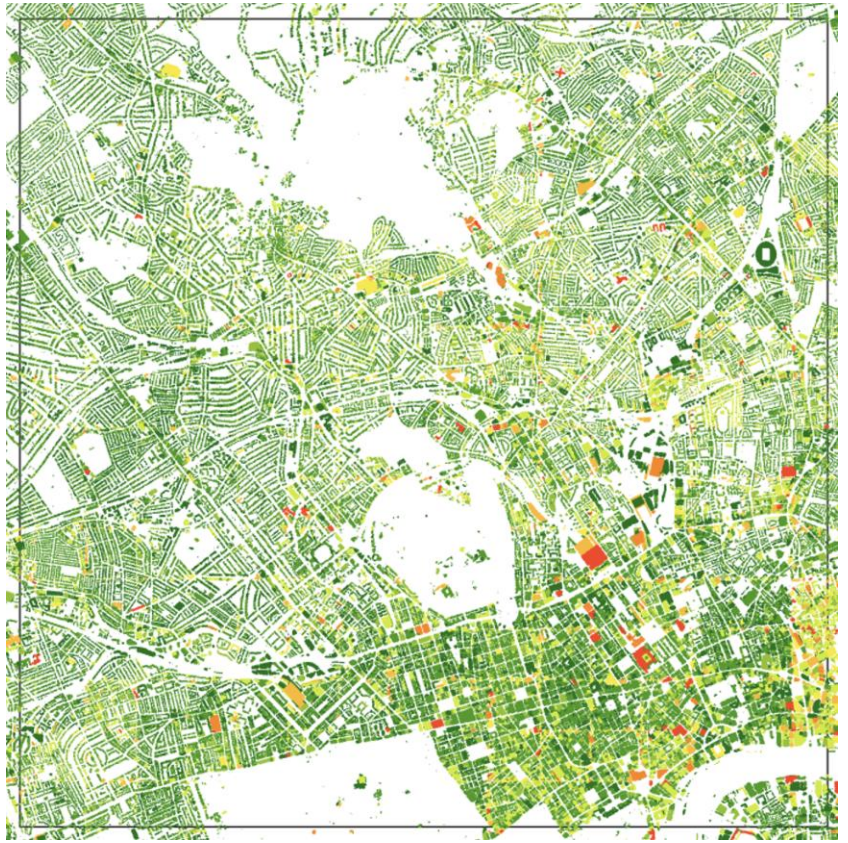
N01 Greater London



-2.3 273.4

Terrain height (m)

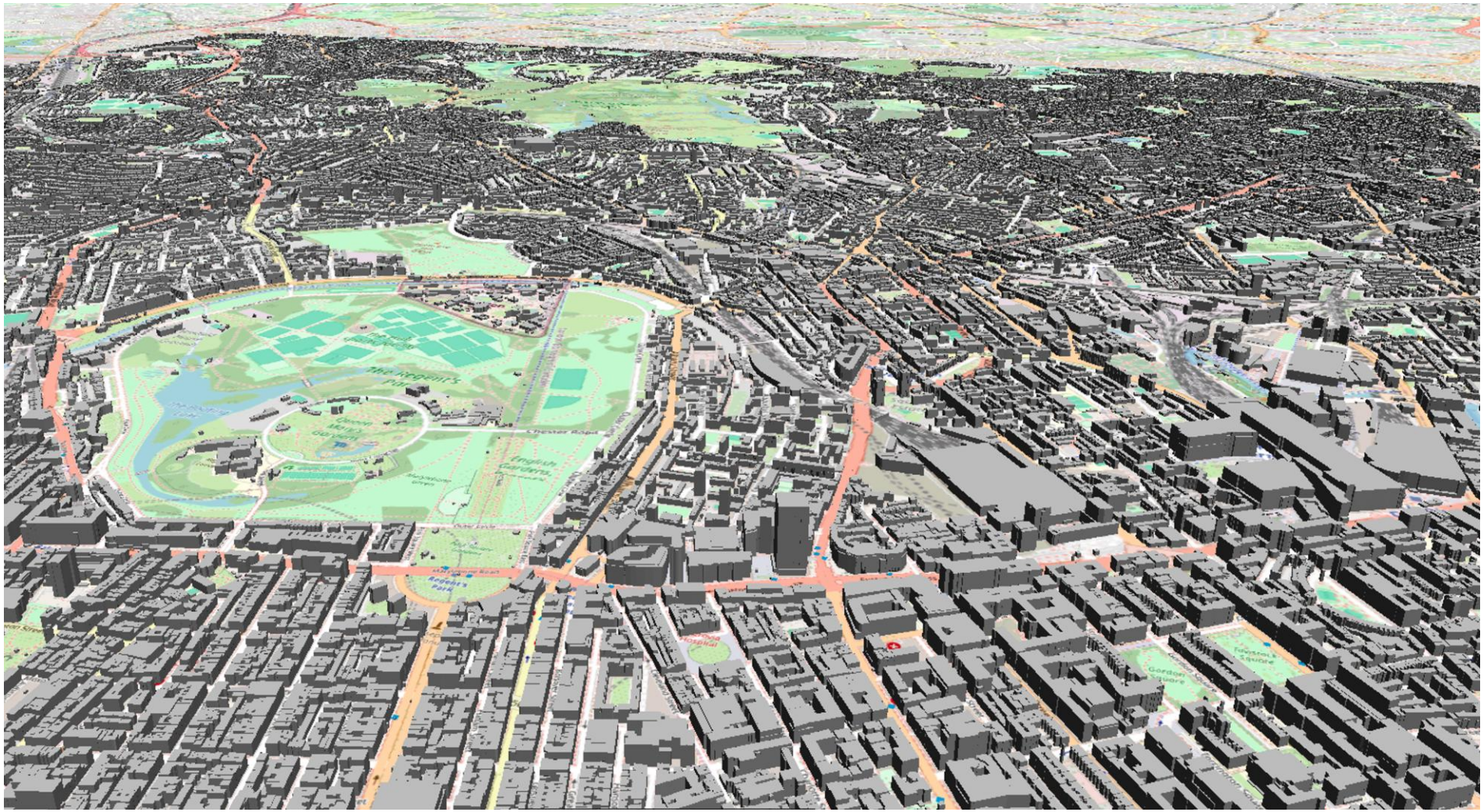
N02 Camden



0 2.5 4 5.5 7 8.5 10 11.5 13

Building height (m)

Static/dynamic driver

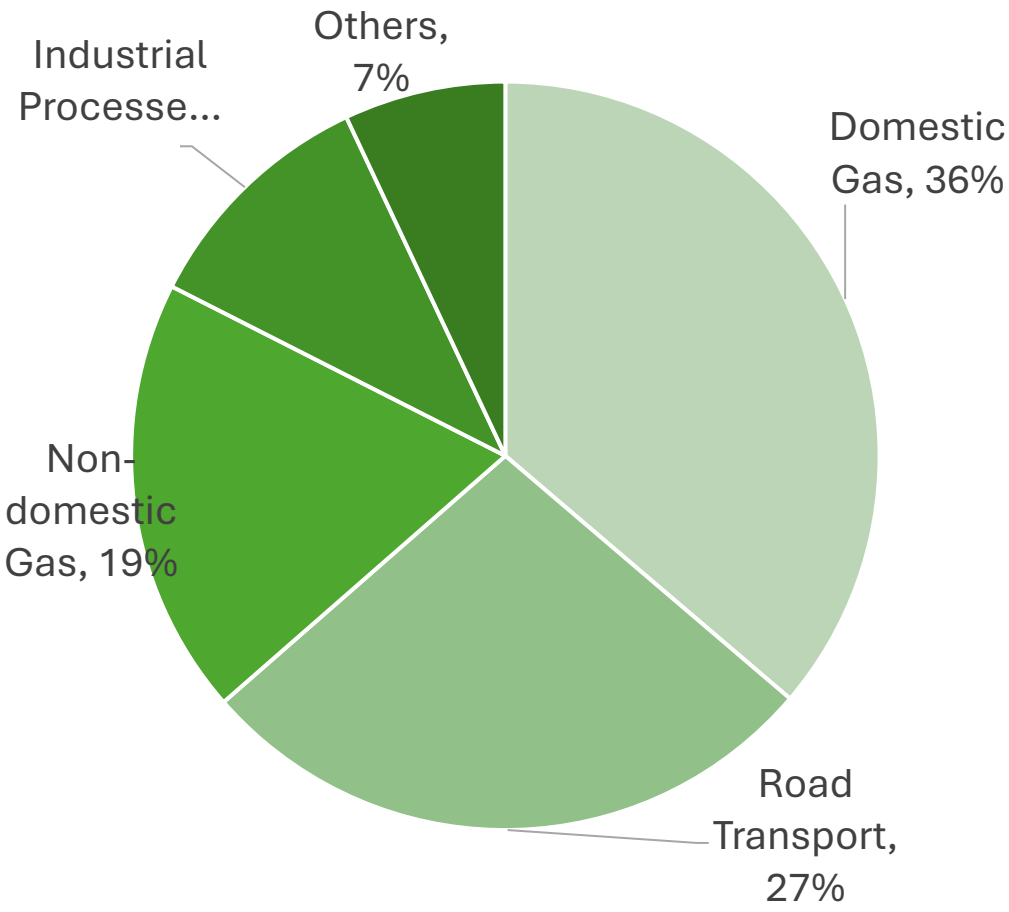


3D Bird’s-eye view of the child domain with buildings

Anthropogenic emission

- Based on LAEI[1] inventory (1km by 1km), further disaggregate activity data at **high resolution** 10m by 10m.
- Domestic gas emission: distribute using EPC records
- Non-domestic gas emission: using non-domestic EPC and DEC records
- Road transport: LAEI provides line shapefile and road section emission
- Other sectors: disaggregate evenly

- Temporal disaggregation: from annual total to hourly, using CAMS-TEMPORAL profile[2]

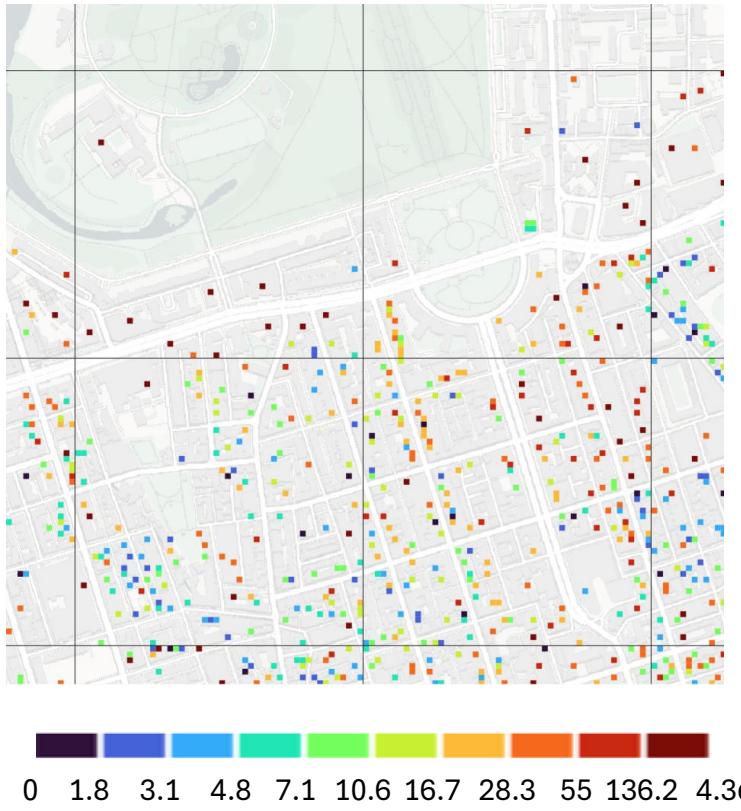


Major emission sectors in Greater London [1]

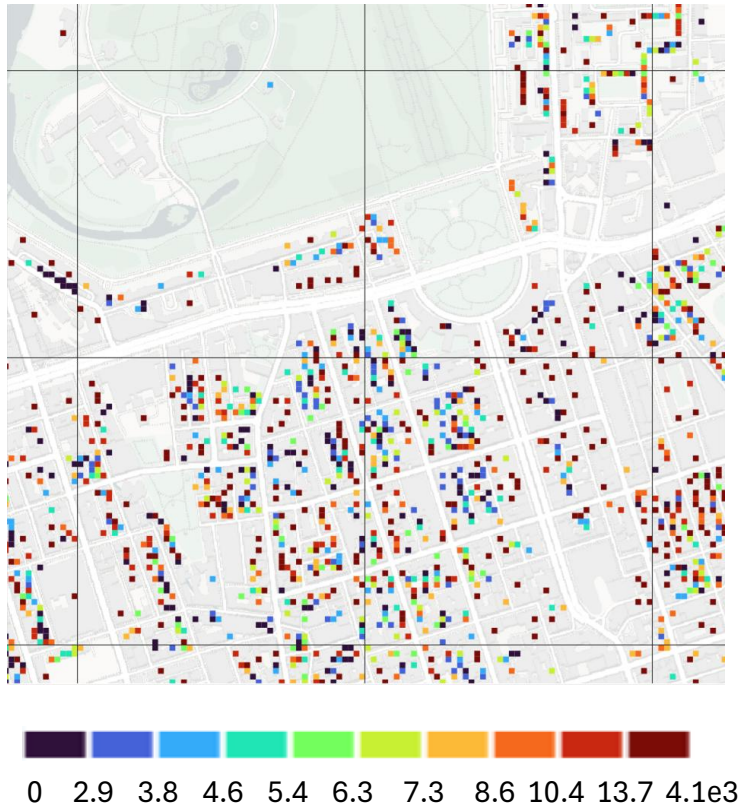
[1] London Atmospheric Emissions Inventory (LAEI) 2019, Greater London Authority
[2] Guevara, M., et al. (2021). Earth Syst. Sci. Data 13(2): 367-404.

Anthropogenic emission

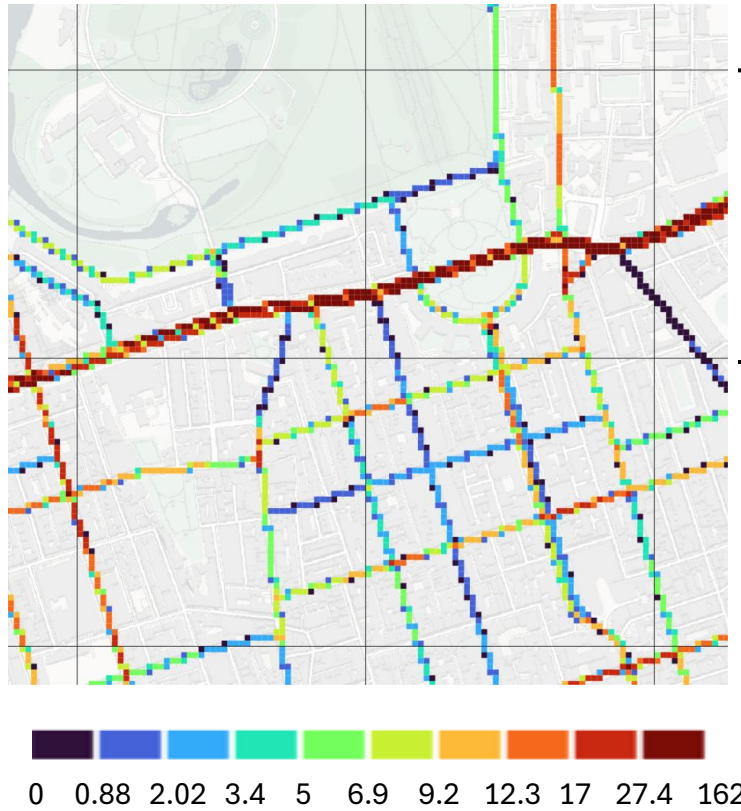
High spatial resolution (10m by 10m) CO_2 emission grid map for London



Non-domestic gas consumption emission (tonCO_2/yr)



Domestic gas consumption emission (tonCO_2/yr)



Major road traffic emission (tonCO_2/yr)

Biogenic emission

- Biogenic CO2 model based on WRF

Gross ecosystem exchange (photosynthesis)

$$\mathrm{GEE} = \lambda \times T_{\mathrm{scale}} \times P_{\mathrm{scale}} \times W_{\mathrm{scale}} \times \mathrm{EVI} \times \frac{1}{1 + \mathrm{PAR}/\mathrm{PAR}_0} \times \mathrm{PAR}$$

Temperature coeff.

Leafy degree coeff. (computed from EVI)

Water coeff. (computed from LSWI)

Radiation (computed from shortwave radiation)

Respiration rate

$$\mathrm{RESP} = \alpha T_{\mathrm{air}} + \beta$$

Net ecosystem exchange

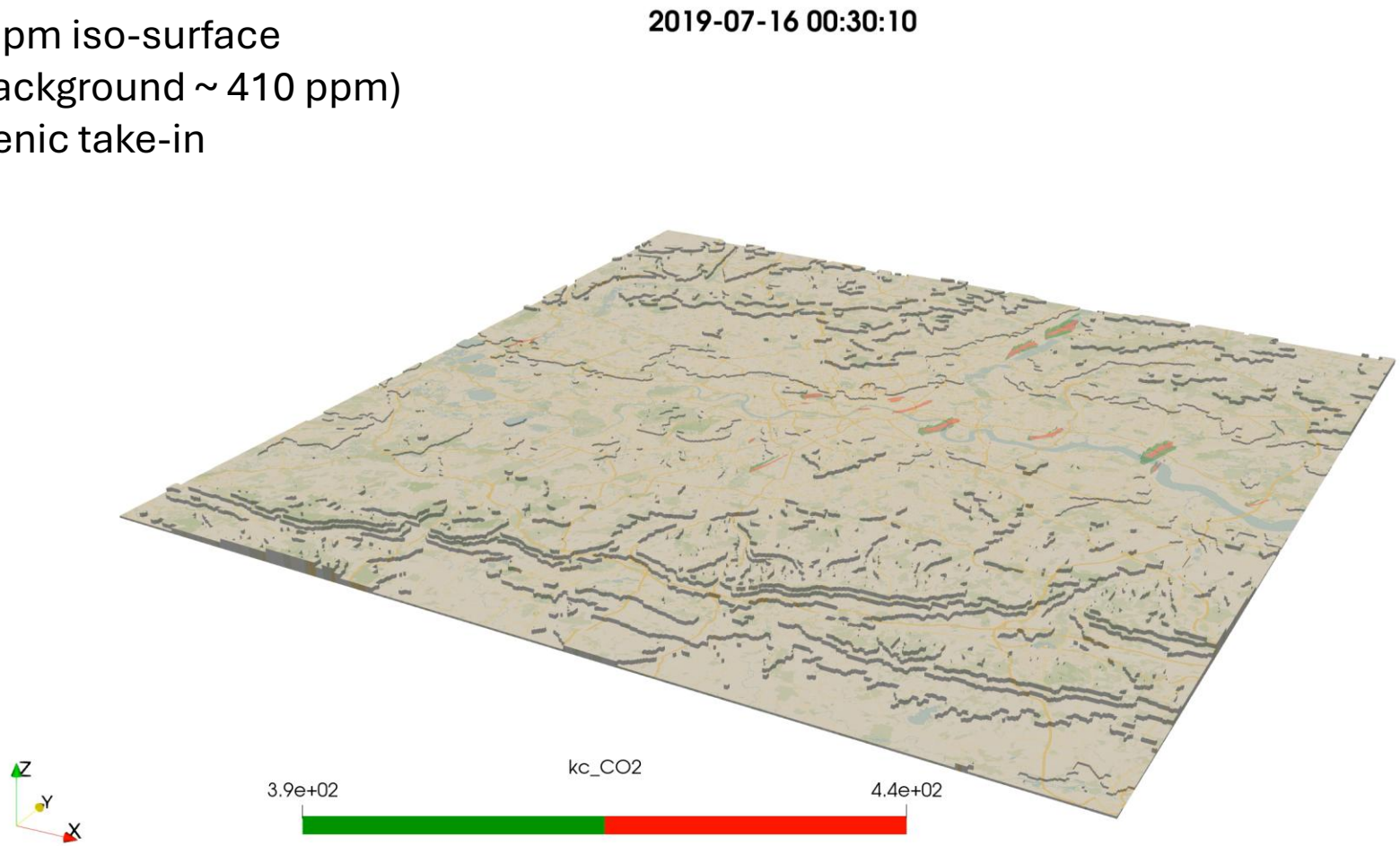
$$\mathrm{NEE} = -\mathrm{GEE} + \mathrm{RESP}$$

Results

Overview (Greater London in Summer)

Green – 390 ppm iso-surface
(lower than background ~ 410 ppm)
showing biogenic take-in

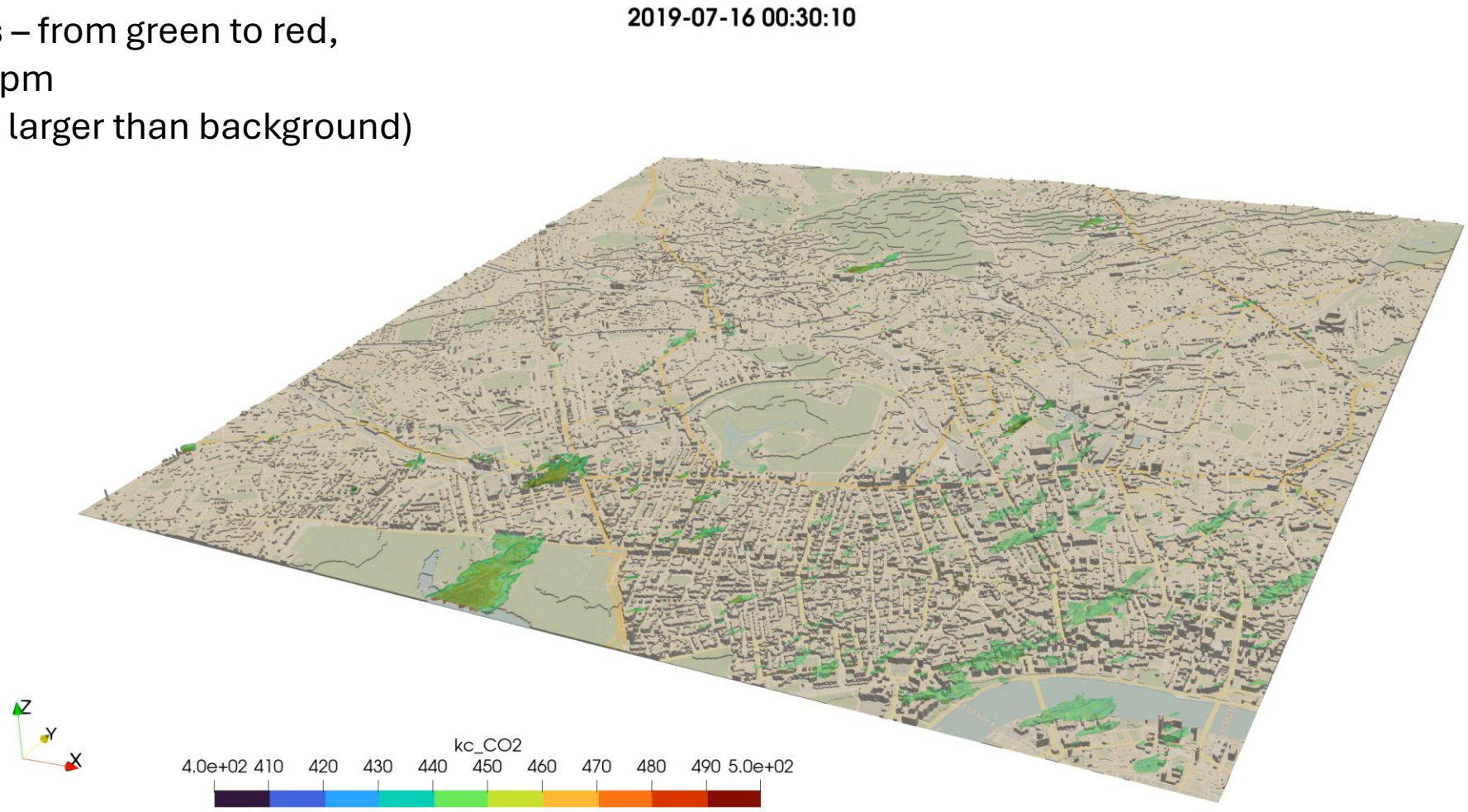
Red – 440 iso-surface
(higher than background)
showing anthropogenic
emission



z direction scaled up x5

Overview (Camden in Summer)

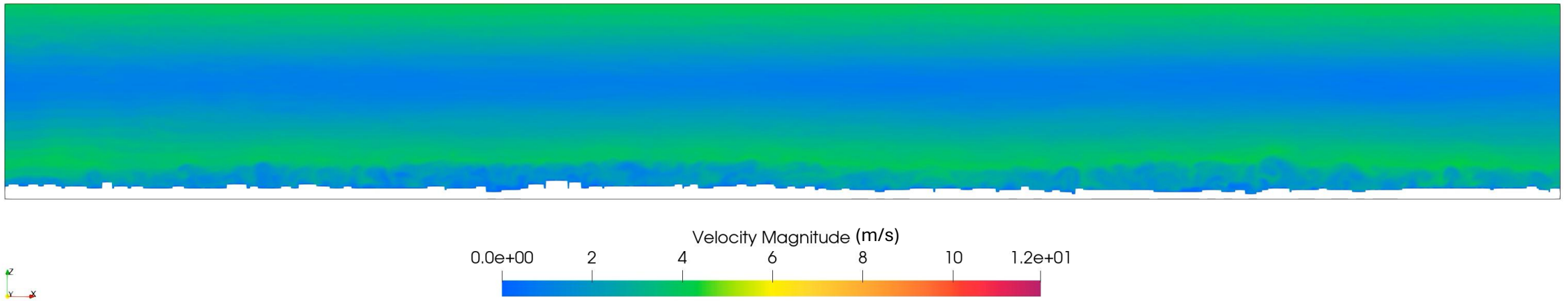
Iso-surfaces – from green to red,
440 to 500 ppm
(all surfaces larger than background)

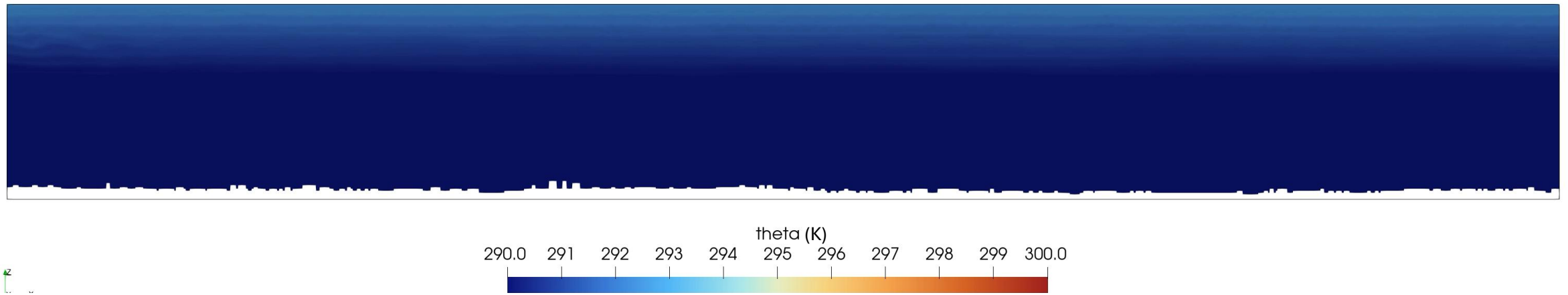


Urban boundary flow

y = 4000 m

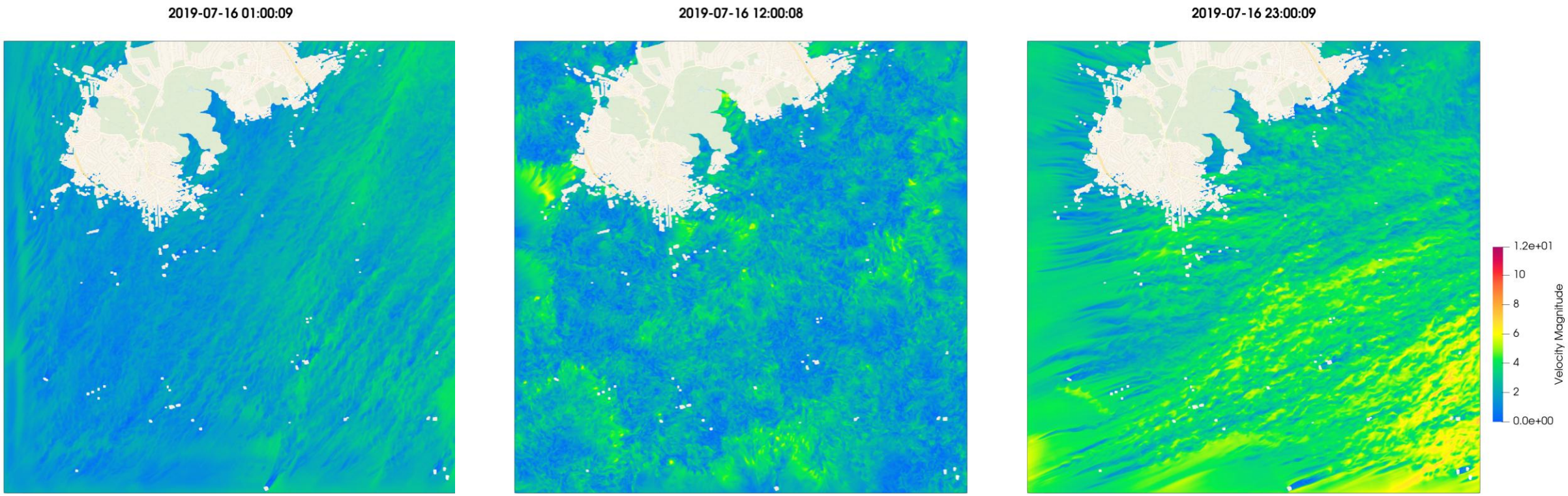
2019-07-16 00:30:10





Urban boundary flow

Velocity magnitude contour on z = 100 m at 1:00, 12:00 and 23:00



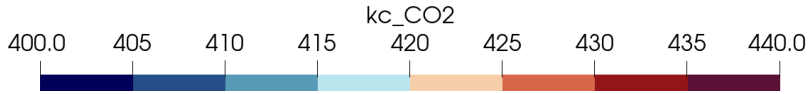
At the same height,

Night lower boundary layer, forced circulation

Day higher boundary layer, thermal-driven

CO2 mixing ratio diurnal variation

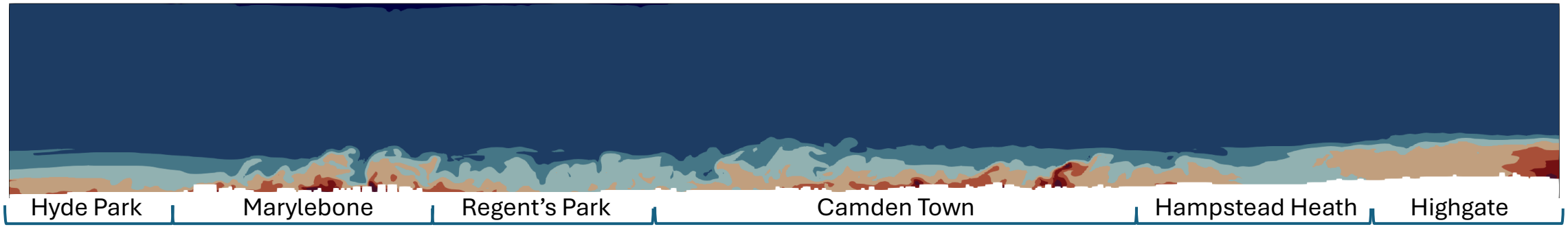
x = 4000 m cross-section CO2 mixing ratio in summer



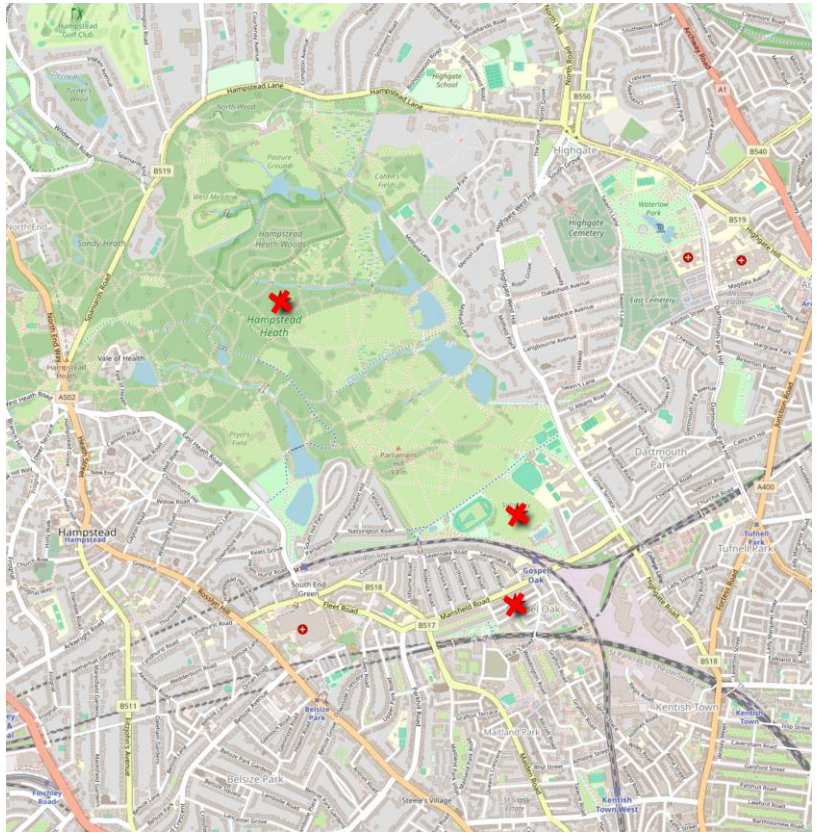
2019-07-16 03:00

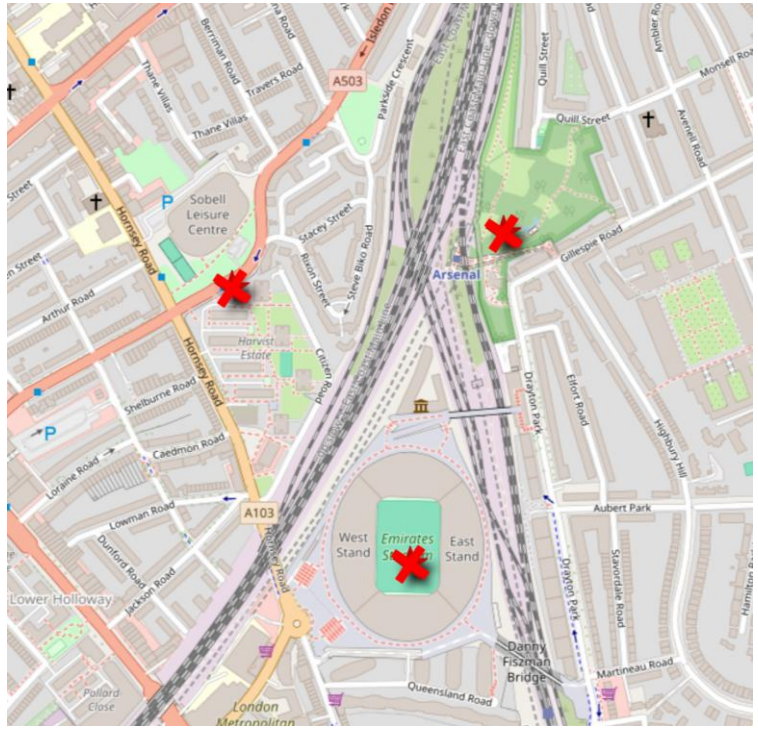
2019-07-16 12:00

2019-07-16 23:00



CO2 mixing ratio diurnal variation

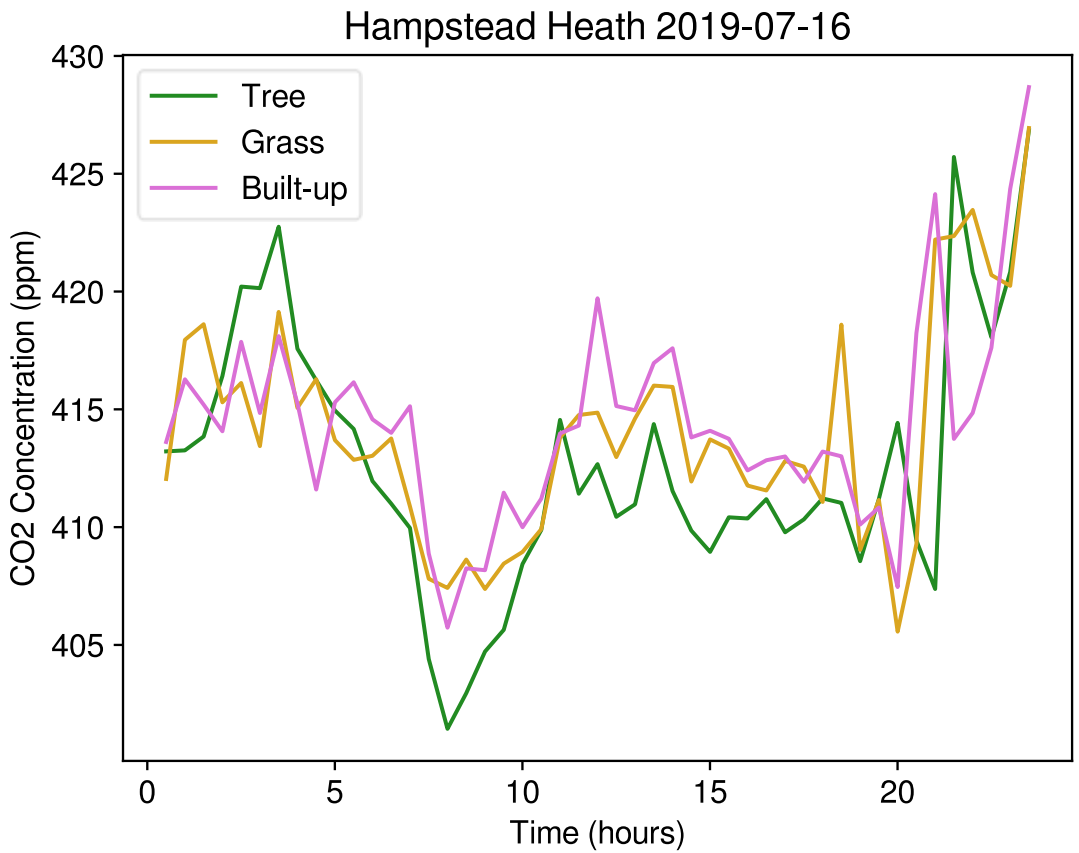


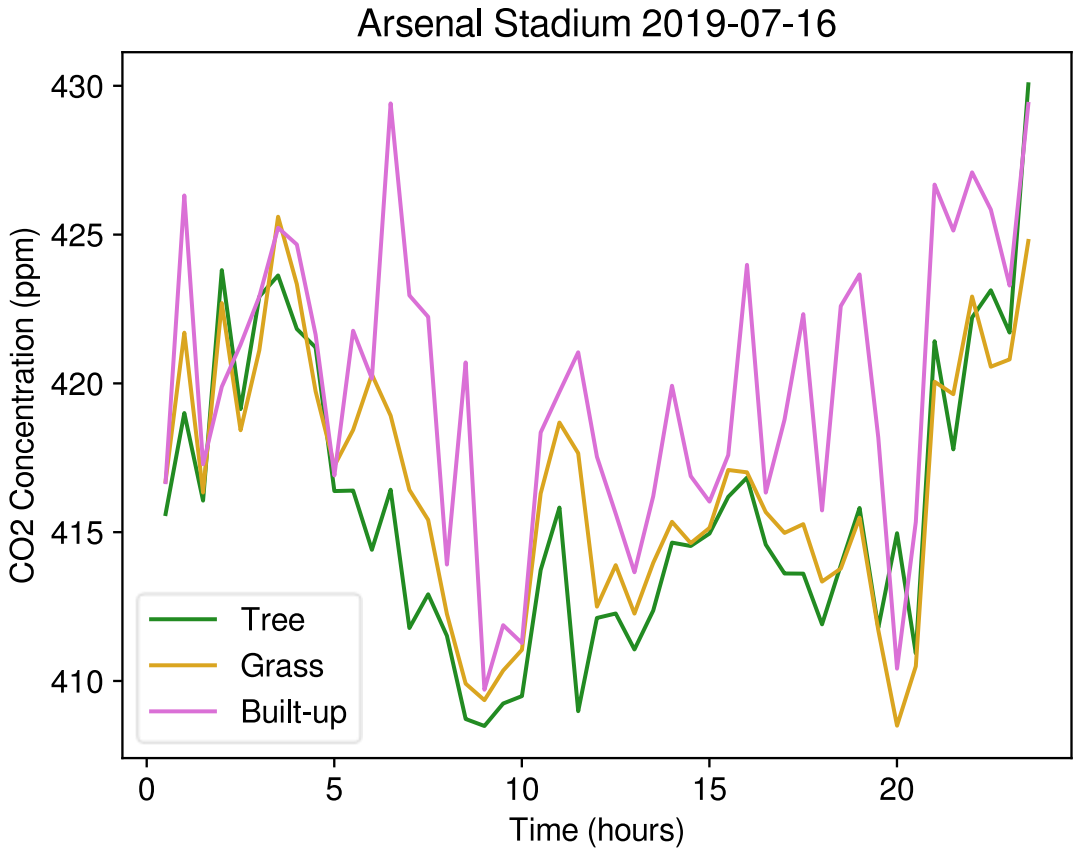


3 points in Hampstead Heath
- Large natural park
- Nearby residential areas

3 points in/around Arsenal Stadium
- Artificial land cover
- Grassland in stadium

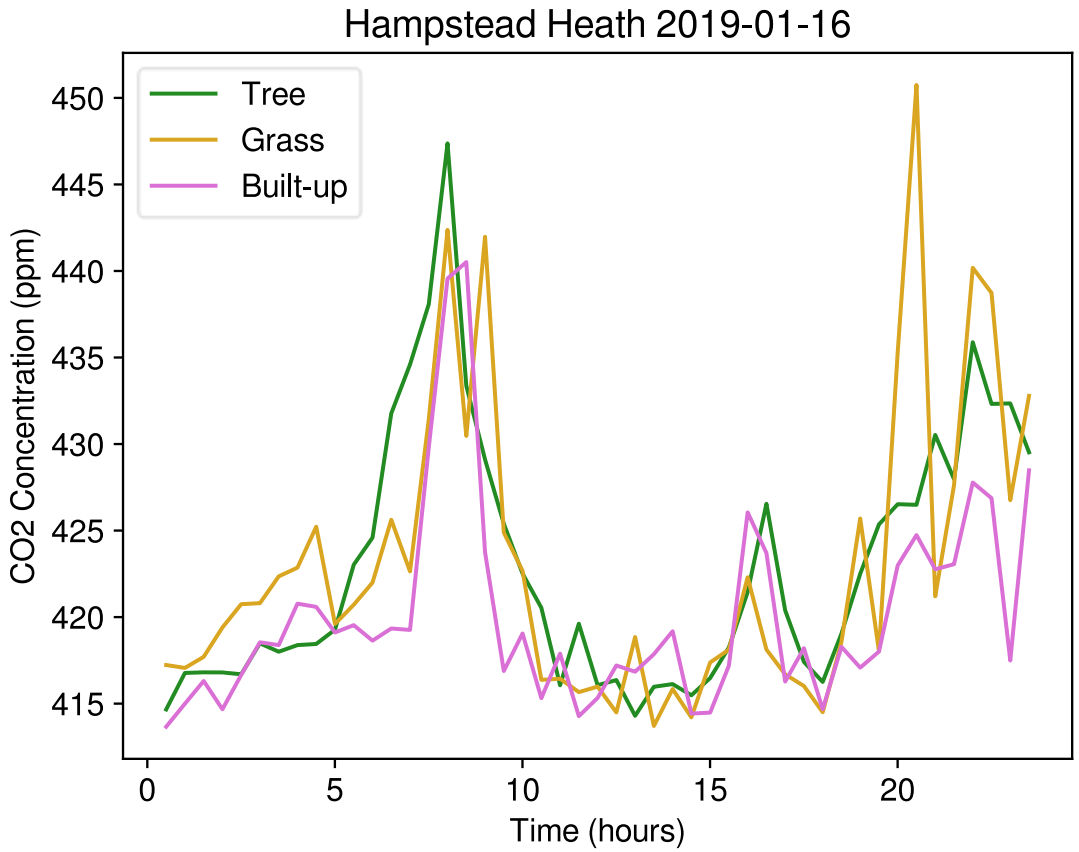
CO2 mixing ratio diurnal variation (summer)

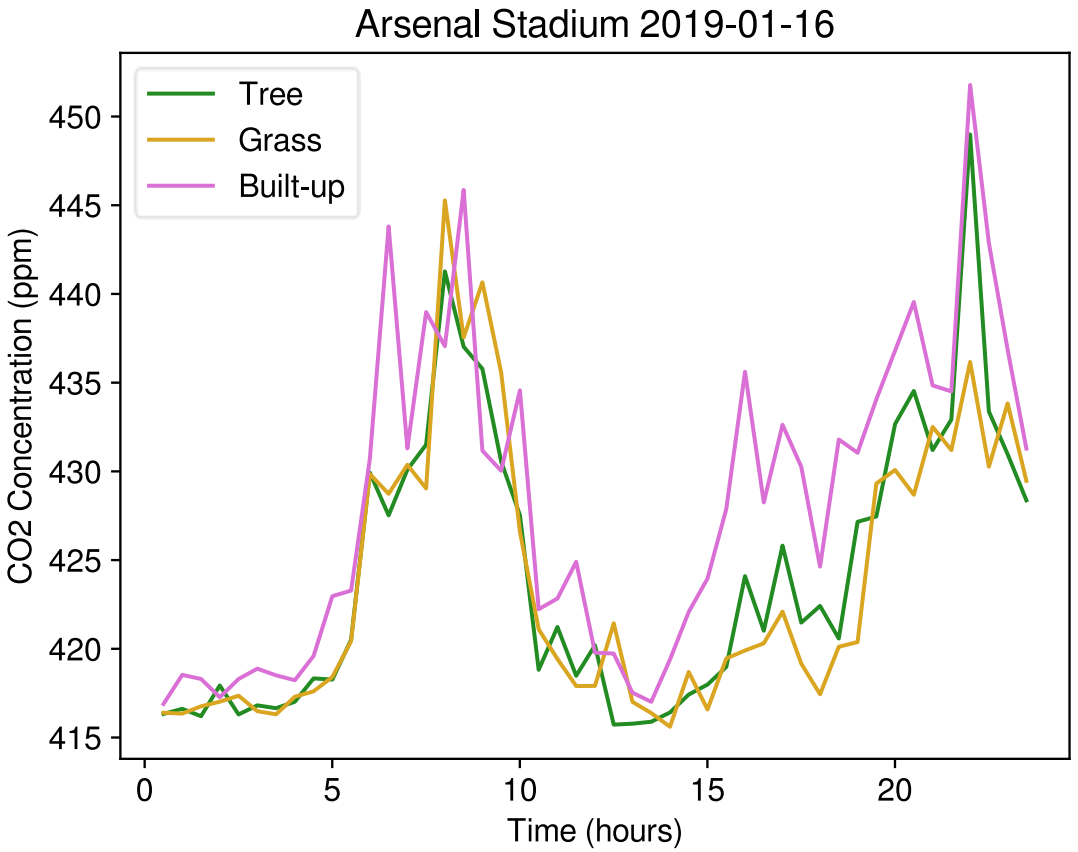




General trend: *high in night, low during the day*
Land-type relevance: *tree covered area has lower ppm, but not significant*
Urban boundary layer also has significant effects (high BL during day)

CO2 mixing ratio diurnal variation (winter)



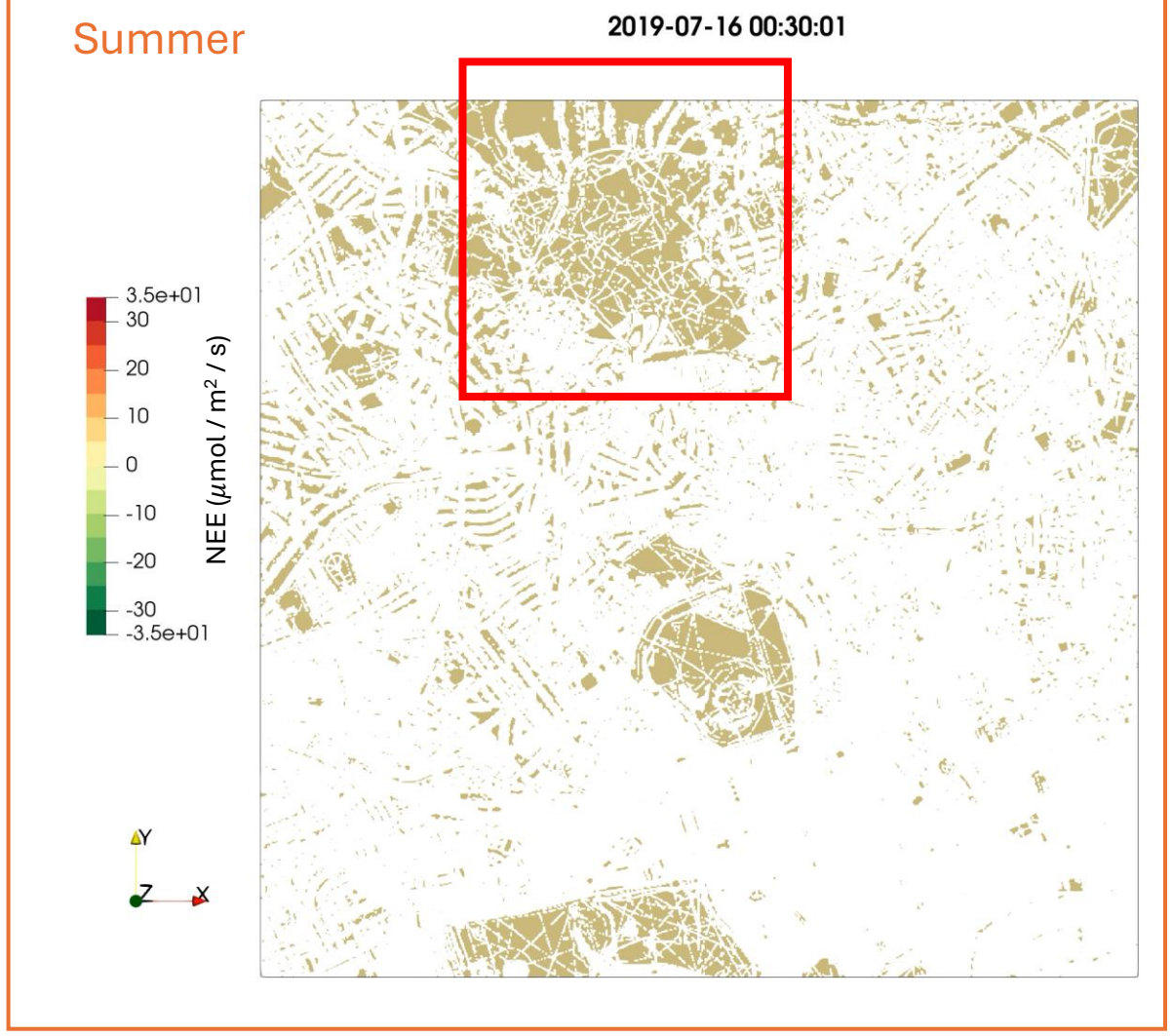


General trend:

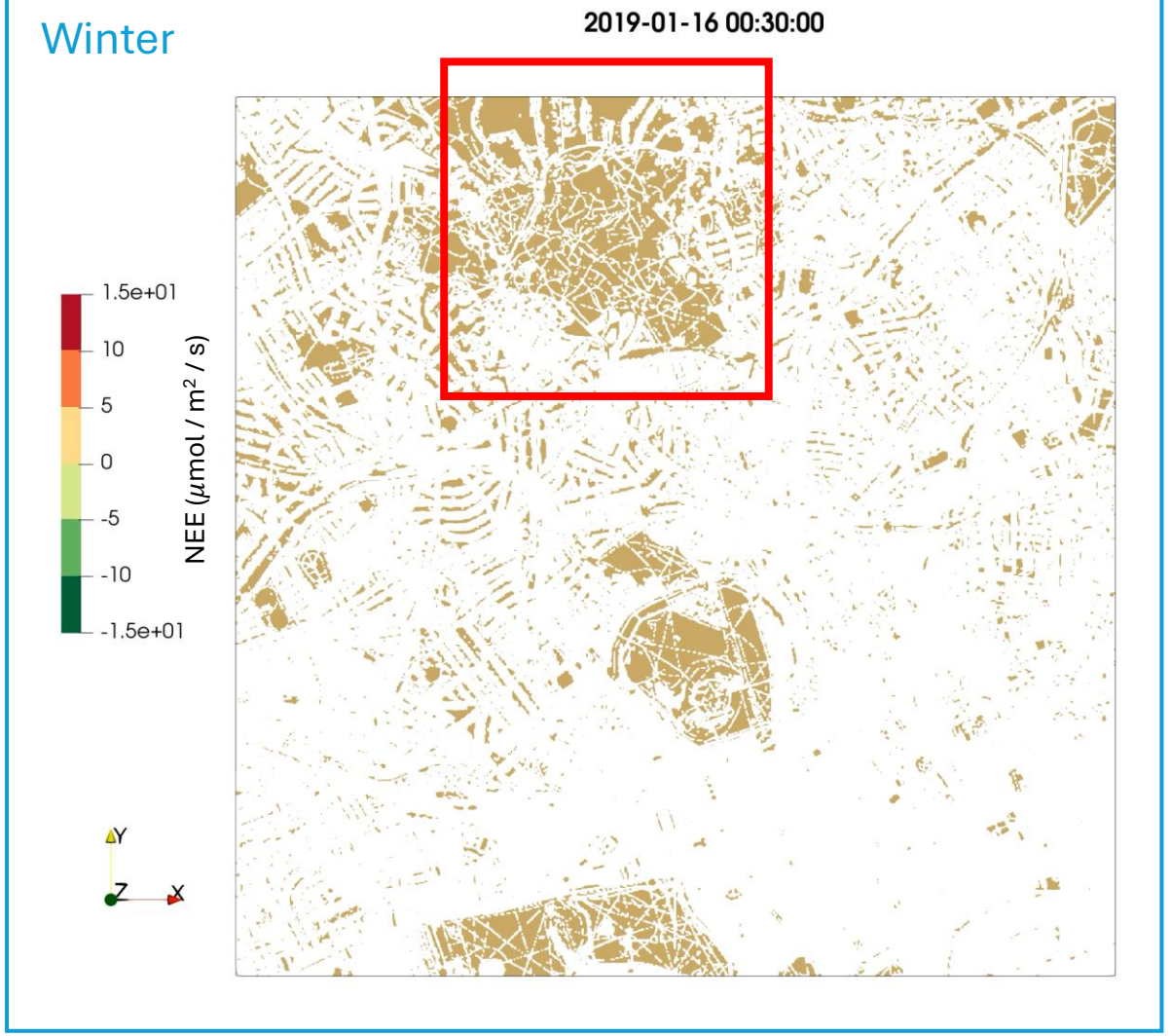
- winter sees larger diurnal change
- vegetation take-in weaker

Biogenic fluxes

Summer



Winter



(Note the difference in colour bar range)

Biogenic fluxes at Hampstead Heath

Summer

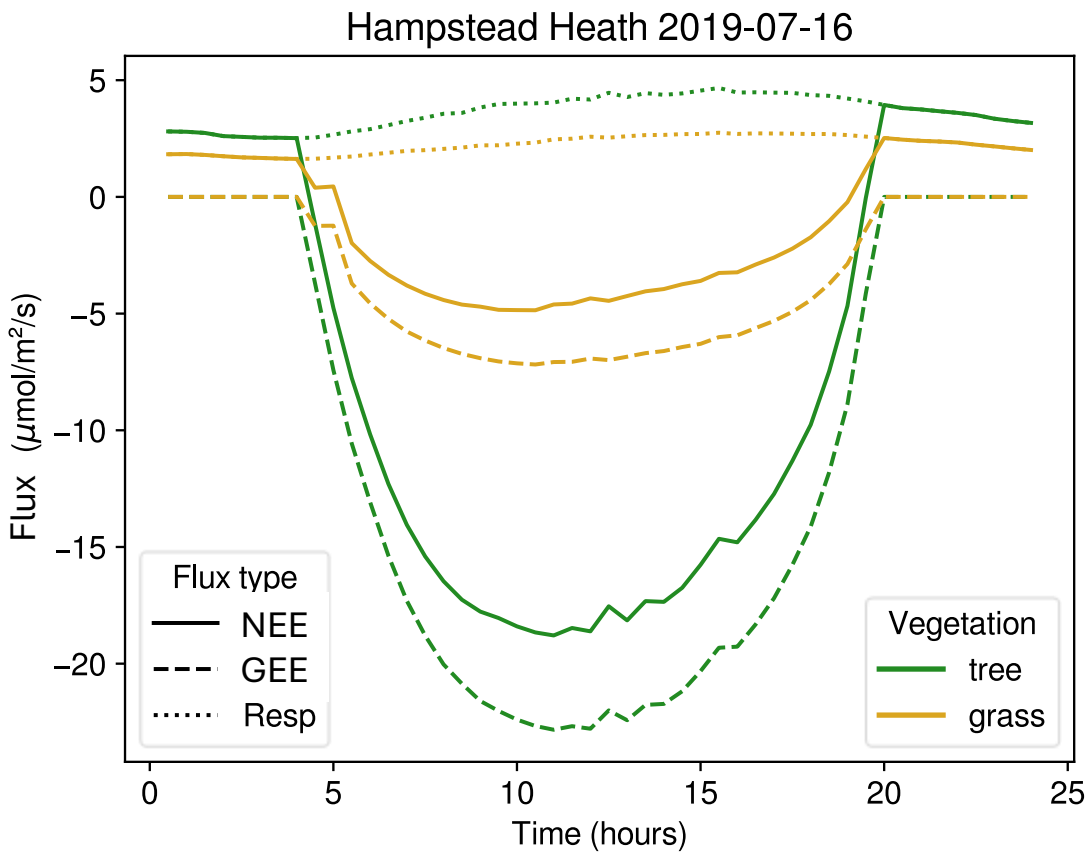
2019-07-16 00:30:01

Winter

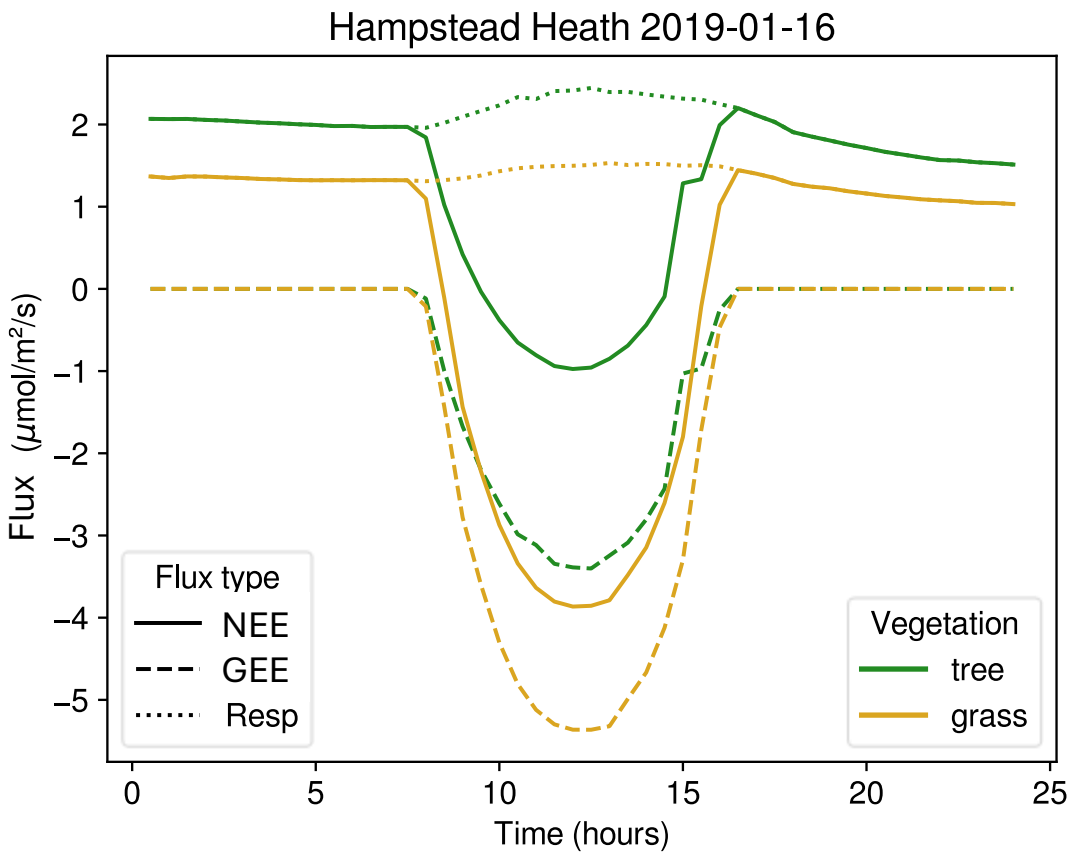
2019-01-16 00:30:00

Biogenic fluxes

Summer



Winter



Seasonal difference in biogenic fluxes (Note the difference in y-axis scale!)

- Summer: vegetation take-in
- Winter: shorter sunlit hours; trees GEE smaller

Conclusion

- A biogenic carbon module is developed in an urban LES model, PALM
- A case study of London borough of Camden is presented
- Seasonal difference and diurnal cycle is analysed

Next step…

- Case study of annual cycle
- Other cities/countries
- Varying vegetation inputs in the model to see impact of green infrastructure
- Data-driven models

Thanks for your attention!

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