Modeling urban traffic heat flux in the Community Earth System Model

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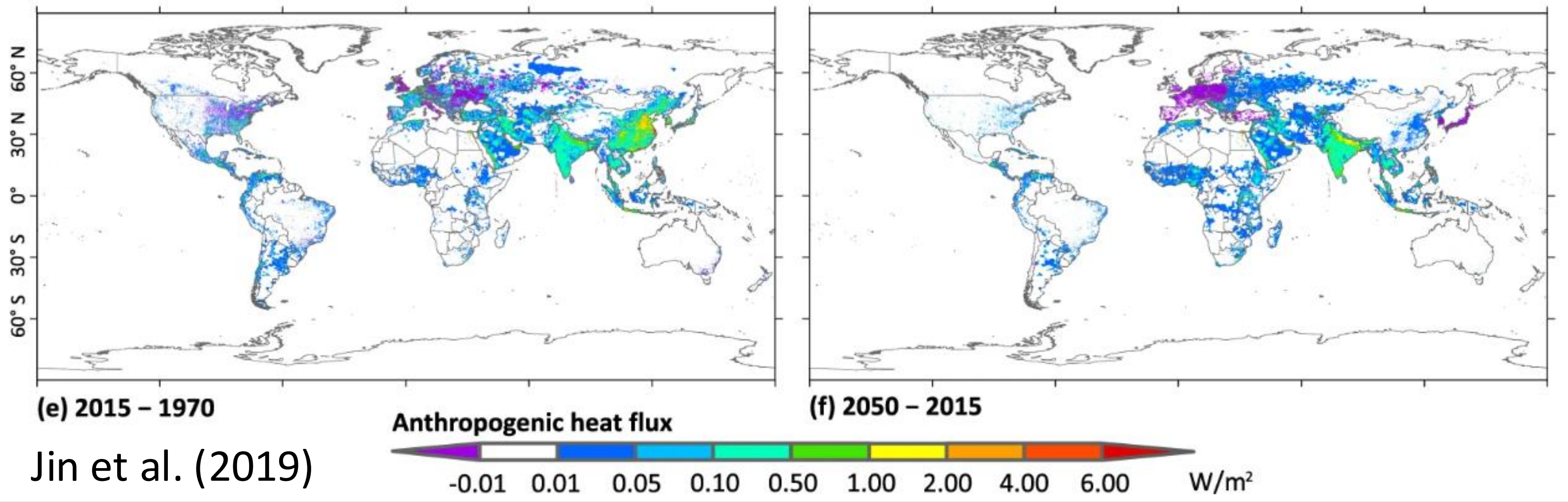
Prof. David Topping and Dr. Thomas Bannan for providing sensor data. Transport for Greater Manchester (TfGM) for providing traffic data. Dr. Xiaodan Xu for giving comments.

Introduction: Anthropogenic Heat Flux (AHF)



Jin et al. (2019)

Global average AHF is **~1%** of greenhouse gas forcing (Flanner, 2019).

Three sources of AHF in urban areas：

Building heating & air conditioning (~15-50%)

Traffic (~15-50%)

Human metabolism (~5-8%)

Gaps and Needs

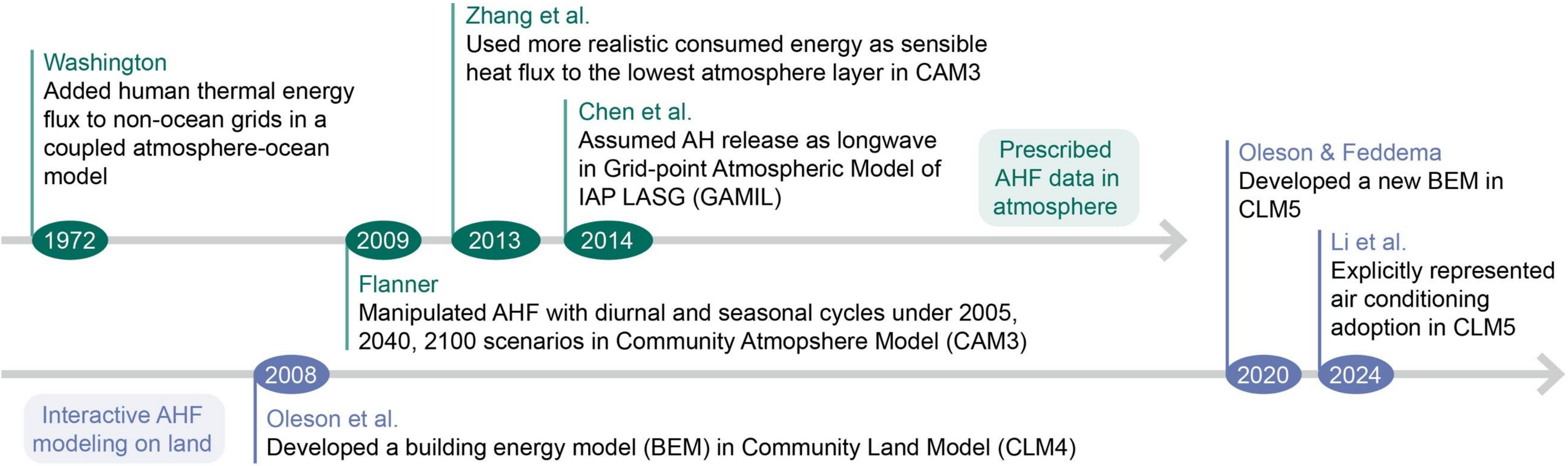
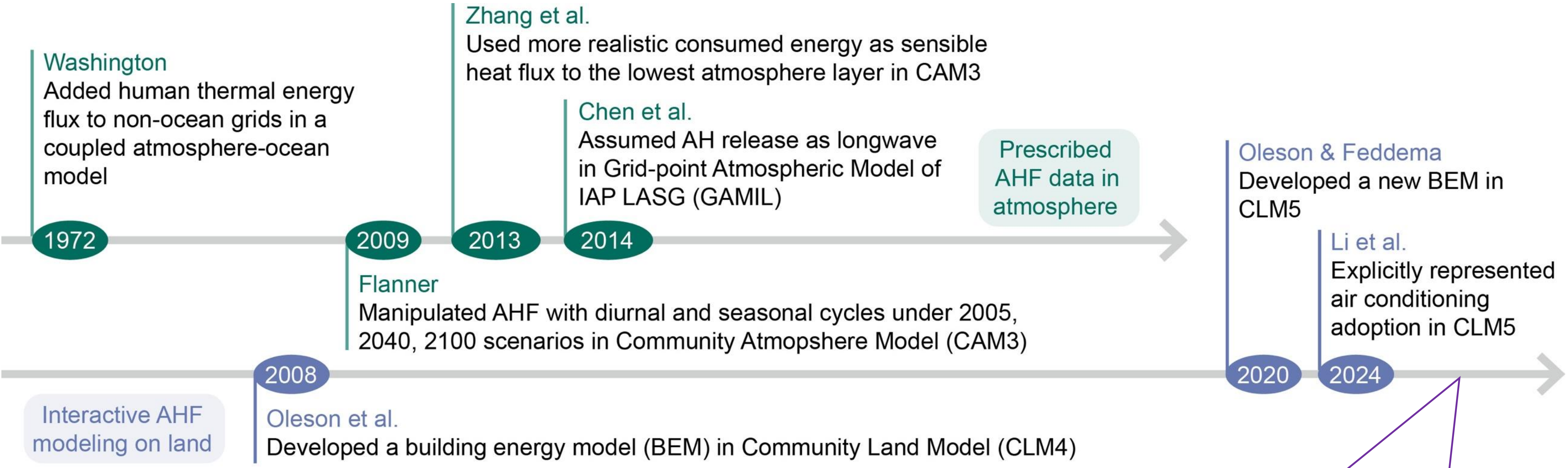


Fig. Timeline of incorporating anthropogenic heat in global climate simulation.

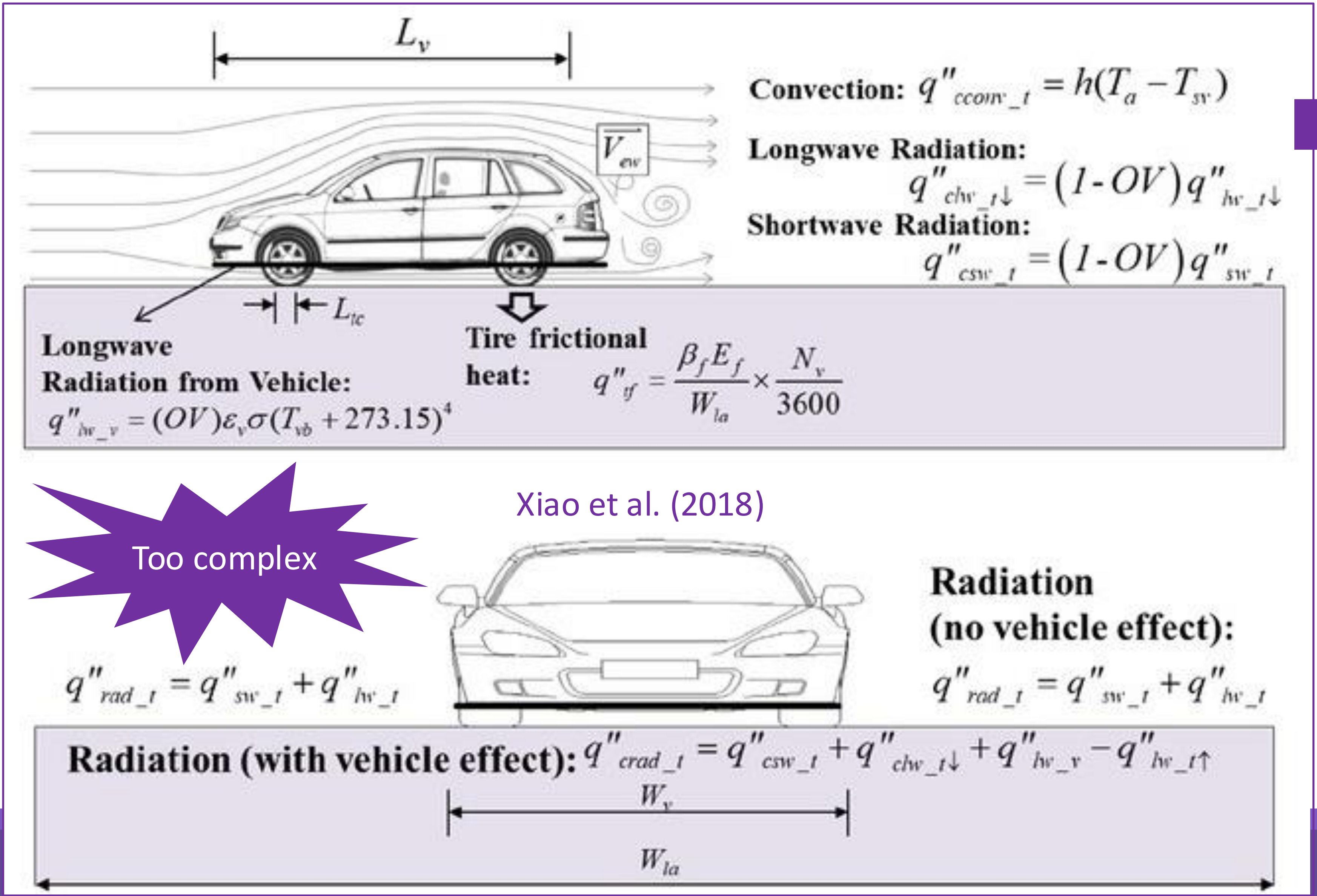
Gaps and Needs



This study incorperated traffic-related AHF in CTSM and modeled traffic heat in CLMU.

Fig. Timeline of incorporating anthropogenic heat in global climate simulation.

Representation and Parameterization of traffic-related processes



Biogeophysical processes

- Radiative heat
- Tire frictional heat
- Sensible heat from engine
- Convection heat

Simplified

Q

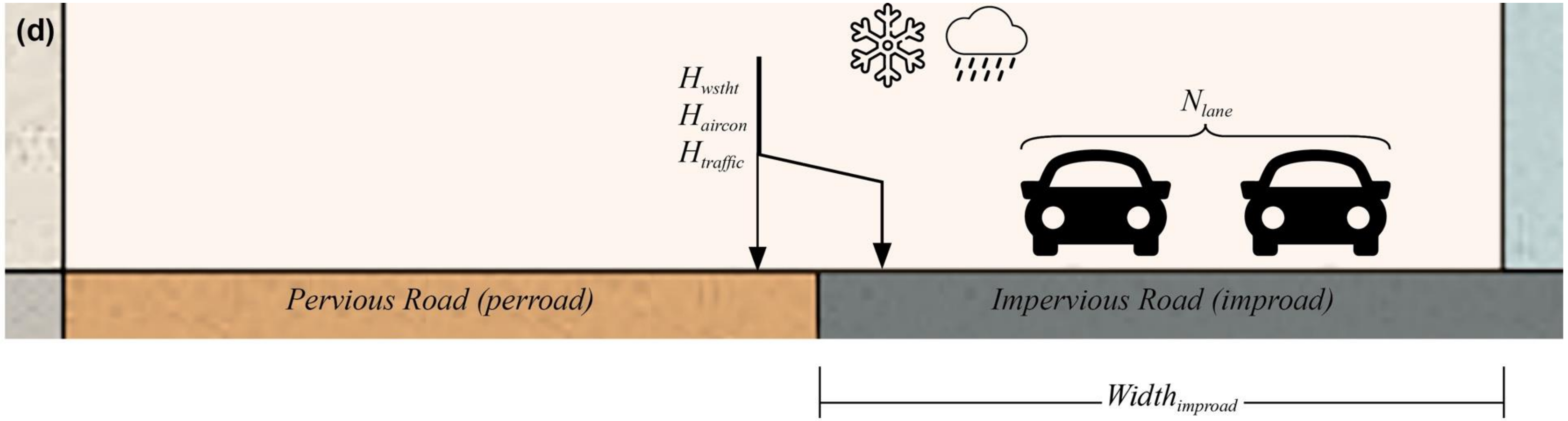
$Q_{traffic}$

In the real world, traffic heat influences the ground and air instantaneously.

In the model, we simplified them as one variable $Q_{traffic}$, and added it to the ground first.

Xiao et al. (2018). https://doi.org/10.1175/JAMC-D-17-0315.1

Representation and Parameterization of traffic-related processes



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- Radiative heat
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Simplified

Q

$Q_{traffic}$ is traffic-induced sensible heat flux, added to the surface energy balance as a separate component from the overall Q_h (Equation 2):

$$\begin{aligned} R_n &= SW_{down} - SW_{up} + LW_{down} - LW_{up} \\ &= Q_h + Q_{le} + (Q_g - Q_{ac} + Q_{heat} - Q_v) - Q_{heat} - Q_w - \boxed{Q_{traffic}} \\ &= Q_h + Q_{le} + Q_g - Q_{ac} - Q_v - Q_w - \boxed{Q_{traffic}.} \end{aligned} \tag{2}$$

The model assumes the AHF coming into the climate system is from building energy consumption and urban traffic (Equation 3):

$$\mathrm{AHF} = Q_{heat} + Q_w + \boxed{Q_{traffic}.} \tag{3}$$

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In the model, we simplified them as one variable $Q_{traffic}$, and added it to the ground first.

Traffic Heat ($Q_{traffic}$) Estimation: A Bottom-Up Approach

$$Q_{traffic} = \frac{E_{total}}{A_{improad}} = \frac{E_{vehicle} \cdot N_{lane} \cdot Flow_{vehicle}}{Speed_{vehicle} \cdot Width_{improad} \cdot 3600},$$

- $Q_{traffic}$: Traffic sensible heat flux (W/m^2)
- E_{total}: Total traffic heat release rate (W)
- $A_{improad}$: Area of impervious road (m^2)
- $E_{vehicle}$: Heat release rate per vehicle (W)
- N_{lane}: Number of vehicle lanes
- $Flow_{vehicle}$: Number of vehicles per hour per lane (vehicles/hour-lane)
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We estimated traffic heat in a bottom-up approach rather than a top-down approach using energy inventories.

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Constant

$$N_{lane} = \begin{cases} 0, & \frac{Width_{improad}}{Width_{lane}} < 0.5 \\ 1, & 0.5 \leq \frac{Width_{improad}}{Width_{lane}} < 1 \\ \left\lfloor \frac{Width_{improad}}{Width_{lane}} \right\rfloor, & \end{cases}$$

N_{lane} = 0, 1, 2, 4, 6. $Width_{improad}$: Width of impervious road. $Width_{lane}$: Lane width (3.5 m).

Constant

$$Width_{improad} = \left(\frac{H_{roof}}{HWRatio}\right) \cdot (1 - F_{perroad}),$$

H_{roof}: Roof height. $HWRatio$: Canyon height-to-width ratio. $F_{perroad}$: Fraction of pervious road.

① N_{lane} and $Width_{improad}$ are two morphological parameters, calculated based on CTSM's default surface input data (i.e., H_{roof}, $HWRatio$, $F_{perroad}$).

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Annual

Heat release rate per vehicle varies by four vehicle types (i.e., gasoline, diesel, hybrid, electric).

$$E_{vehicle}(y) = \frac{\sum p_{v,y} \cdot E_v \cdot R_v}{\sum p_{v,y}},$$

p: Fraction of a vehicle type.

E · *R*: Heat release per vehicle.

Vehicle type	Vehicle heat release unit: KW)
Gasoline	18.9
Diesel	19.34
Hybrid	5.24
Electric	0.67·SFT

Annual & hourly

$$Flow_{vehicle}(l,t) = \mathrm{AADT}_{l,t} \cdot \mathrm{SF}_t,$$

AADT: Annual average daily traffic volume. SF: Scale factor at the hour of the day.

② $E_{vehicle}$ and $Flow_{vehicle}$ are time-varying, considering technology development and future energy transition.

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Model time step

$$Speed_{vehicle}(t) = Speed \cdot \mathrm{SFRain}_t \cdot \mathrm{SFSnow}_t,$$

Speed: Constant vehicle speed (40 km/h). SFRain: Scale factor of rain. SFSnow: Scale factor of snow.

Rakha et al. (2012)

$$\mathrm{SFSnow(t)} = \begin{cases} 0.96, & 0 < Snow_t \leq 0.000353 \\ 0.92, & 0.000353 < Snow_t \leq 0.000706 \\ 0.91, & 0.000706 < Snow_t \leq 0.00353 \\ 0.87, & Snow_t > 0.00353 \\ 1.0, & Snow_t = 0 \end{cases}$$

Liu et al. (2017)

$$\mathrm{SFRain(t)} = \begin{cases} 1.0 - 60 \cdot Rain_t, & 0 < Rain_t \leq 0.00083 \\ 1.0 - (90 \cdot Rain_t + 0.0425), & Rain_t > 0.00083 \\ 1.0, & Rain_t = 0 \end{cases}$$

③ $Speed_{vehicle}$ accounts for the secondary impacts of weather conditions.

We estimated traffic heat in a bottom-up approach rather than a top-down approach using energy inventories.

Model Modification

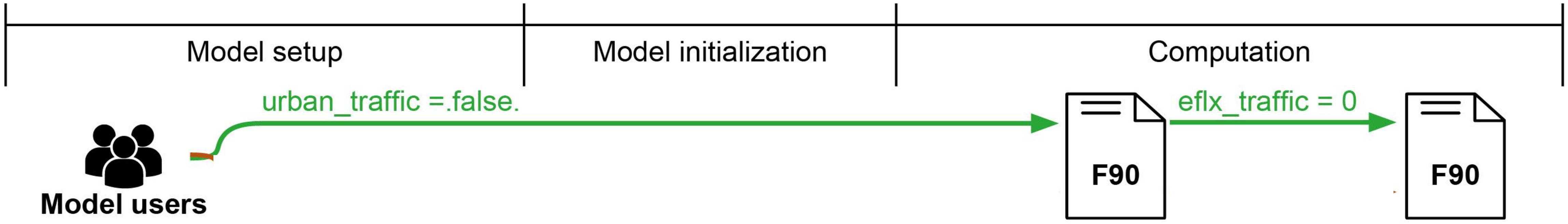


Fig. Workflow of incorporating urban traffic modeling in the Community Terrestrial Systems Model (CTSM).

Model Modification

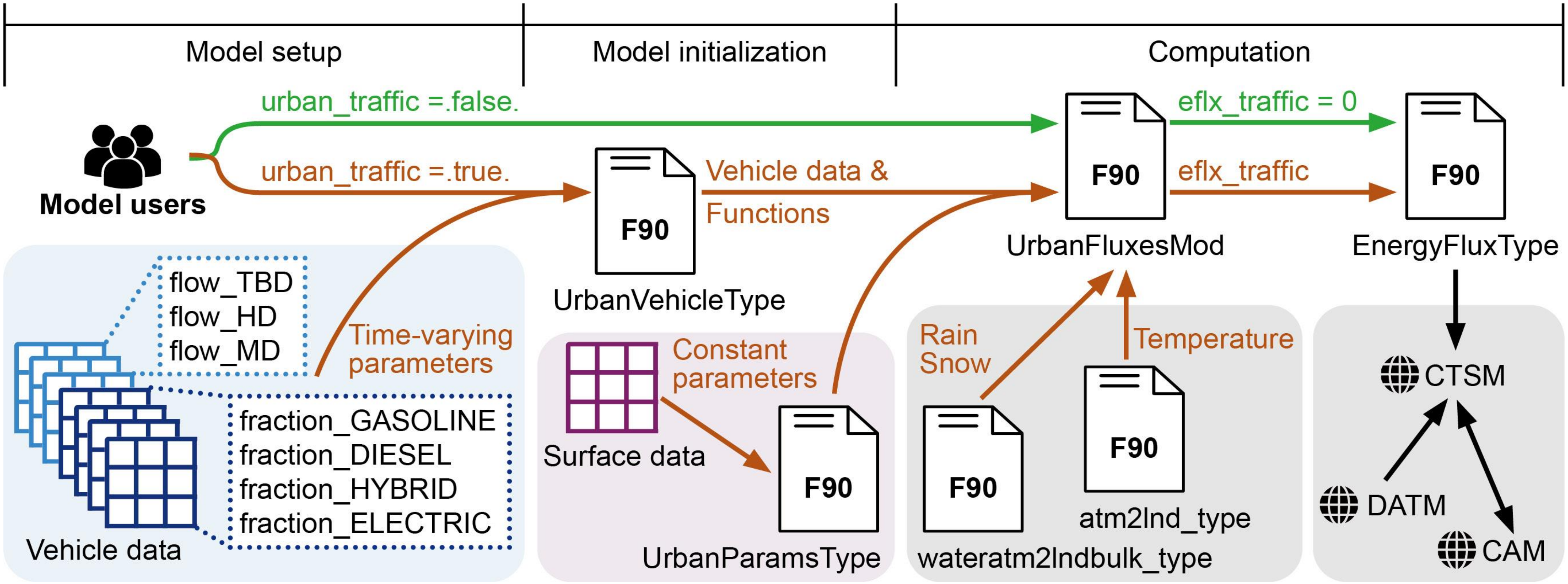
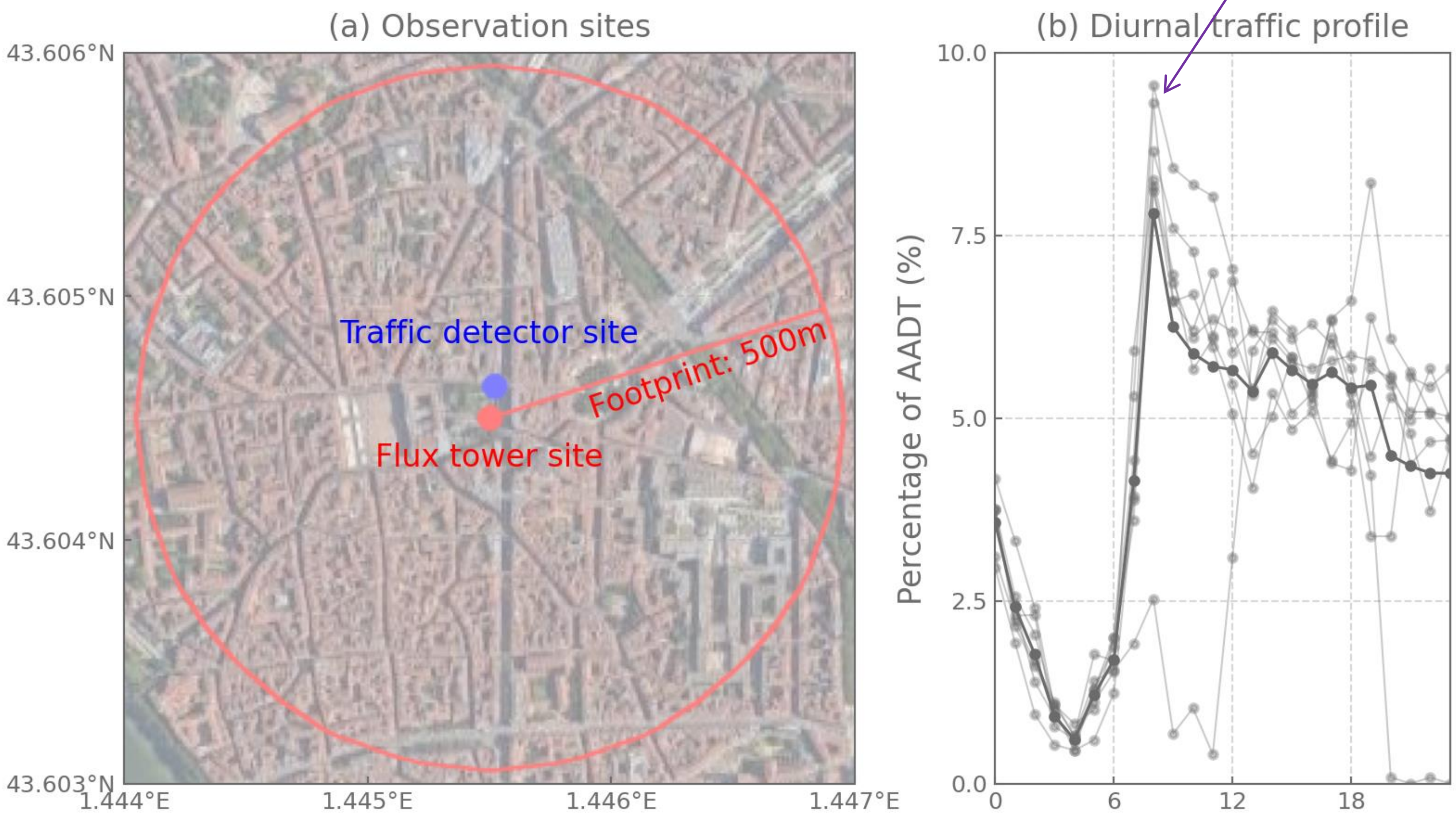


Fig. Workflow of incorporating urban traffic modeling in the Community Terrestrial Systems Model (CTSM).

Case Study 1: Capitole of Toulouse, France (FR-Capitole), 2004

Traffic rush in the **morning**



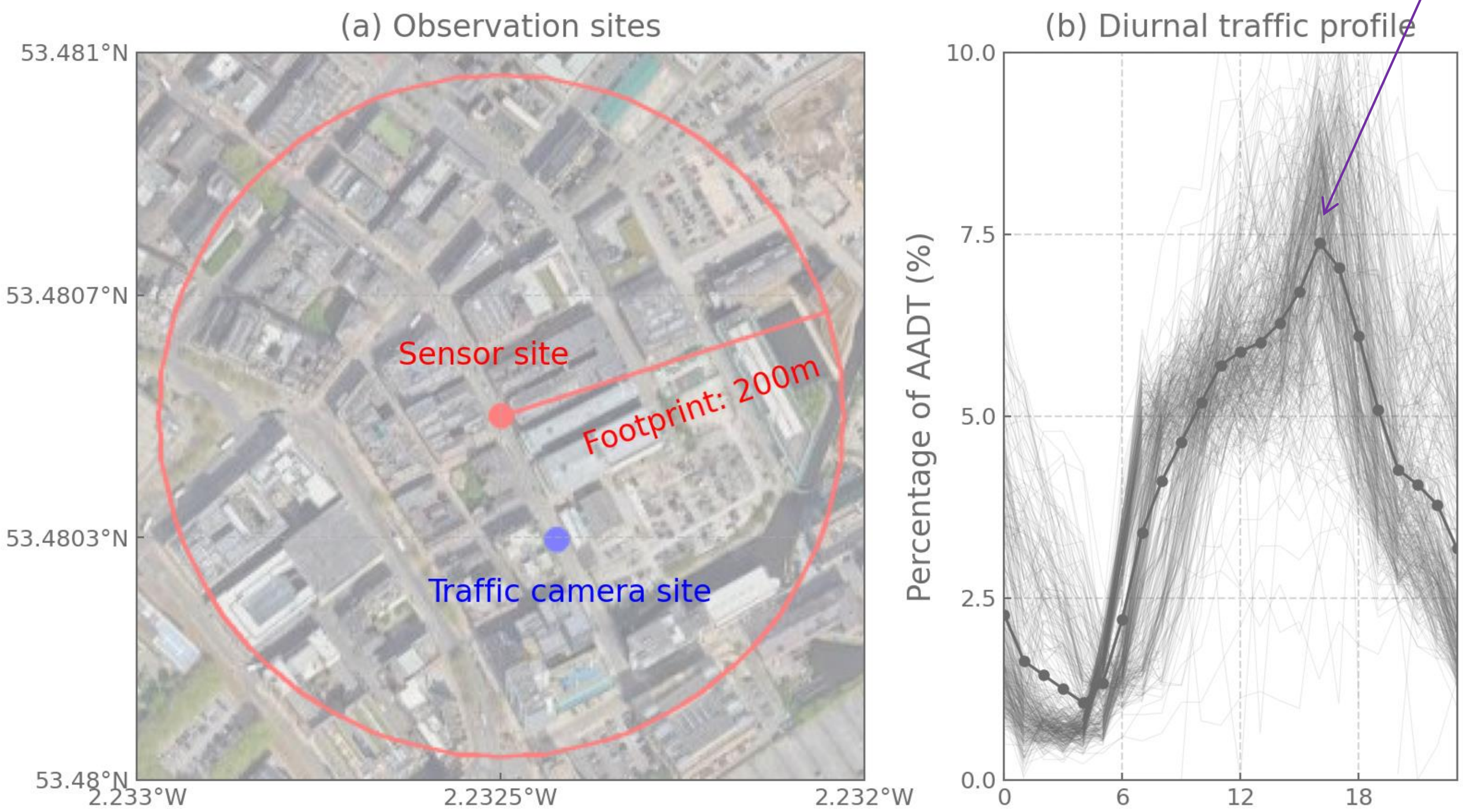
- Atmospheric data came from the **Urban-FLUMBER** flux tower site.
- Traffic volume came from the **UTD19** dataset.

AADT (vehicles/ day-lane)	**4404**
Gasoline	40.6%
Diesel	59.4%
Hybrid	0%
Electric	0%

Annual mean $Q_{traffic}$: 22.23 W/m^2

Understanding traffic capacity of urban networks. (2019). https://doi.org/10.1038/s41598-019-51539-5
European Automotive Manufacturers Association. (2021). Vehicles in use, Europe 2021.

Case Study 2: Manchester, UK (UK-Manchester), 2022



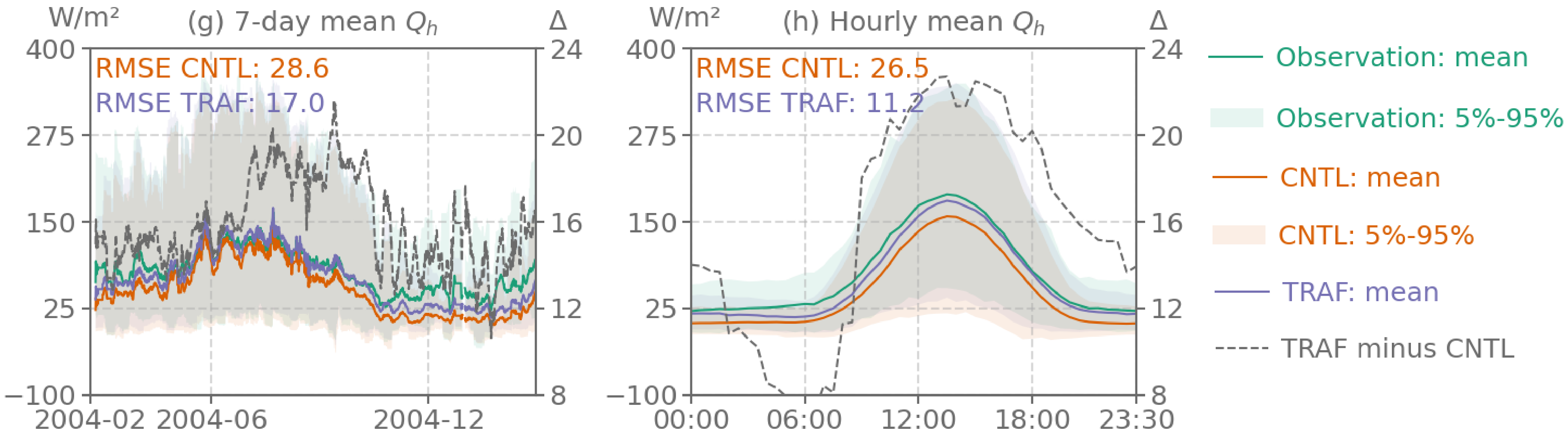
- Atmospheric data came from the low-cost **sensor**.
- Traffic volume came from a **VivaCity** camera.

AADT (vehicles/ day-lane)	**4697**
Gasoline	59.4%
Diesel	34.7%
Hybrid	4.9%
Electric	1%

Annual mean $Q_{traffic}$: 16.27 W/m^2

European Automotive Manufacturers Association. (2024). Vehicles on European Roads 2024.

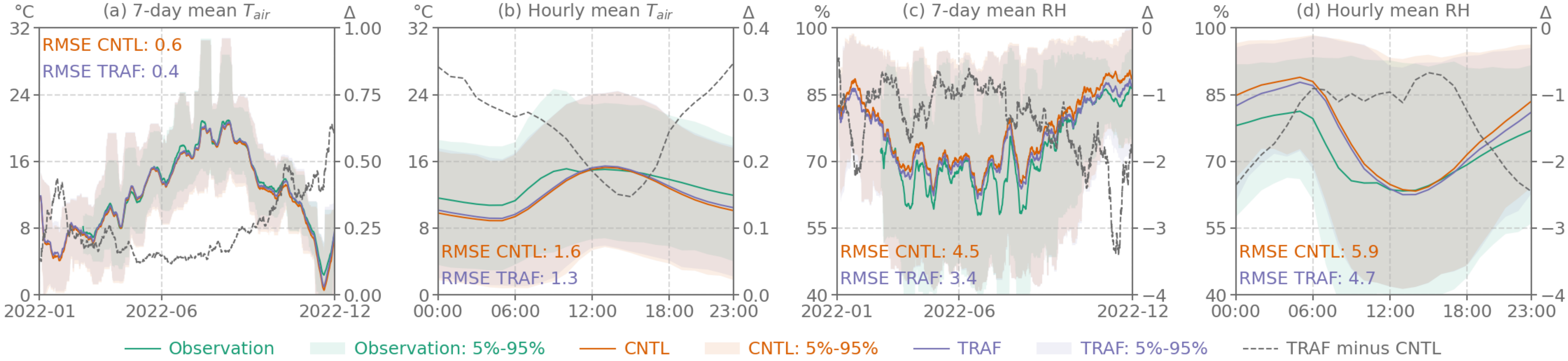
Improved Turbulent Heat Flux at FR-Capitole



- $Q_{traffic}$ narrowed the underestimation of sensible heat flux, particularly in summer and during the day.
- $Q_{traffic}$ is partitioned for sensible heat and latent heat. So both energy and moisture are influenced.

Fig. Sensible heat flux (Q_h) at FR-Capitole. Δ denotes TRAF minus CNTL.

Improved 2 m Air Temperature and Relative Humidity at UK-Manchester



- Higher ΔT_{air} in winter than in summer
- Higher ΔT_{air} at night than during the day

- More RH reduction in winter than in summer
- More RH reduction at night than during the day

Fig. 2 m air temperature (T_{air}) and relative humidity (RH) at UK-Manchester. Δ denotes TRAF minus CNTL.

Better AHF? Hard to say.

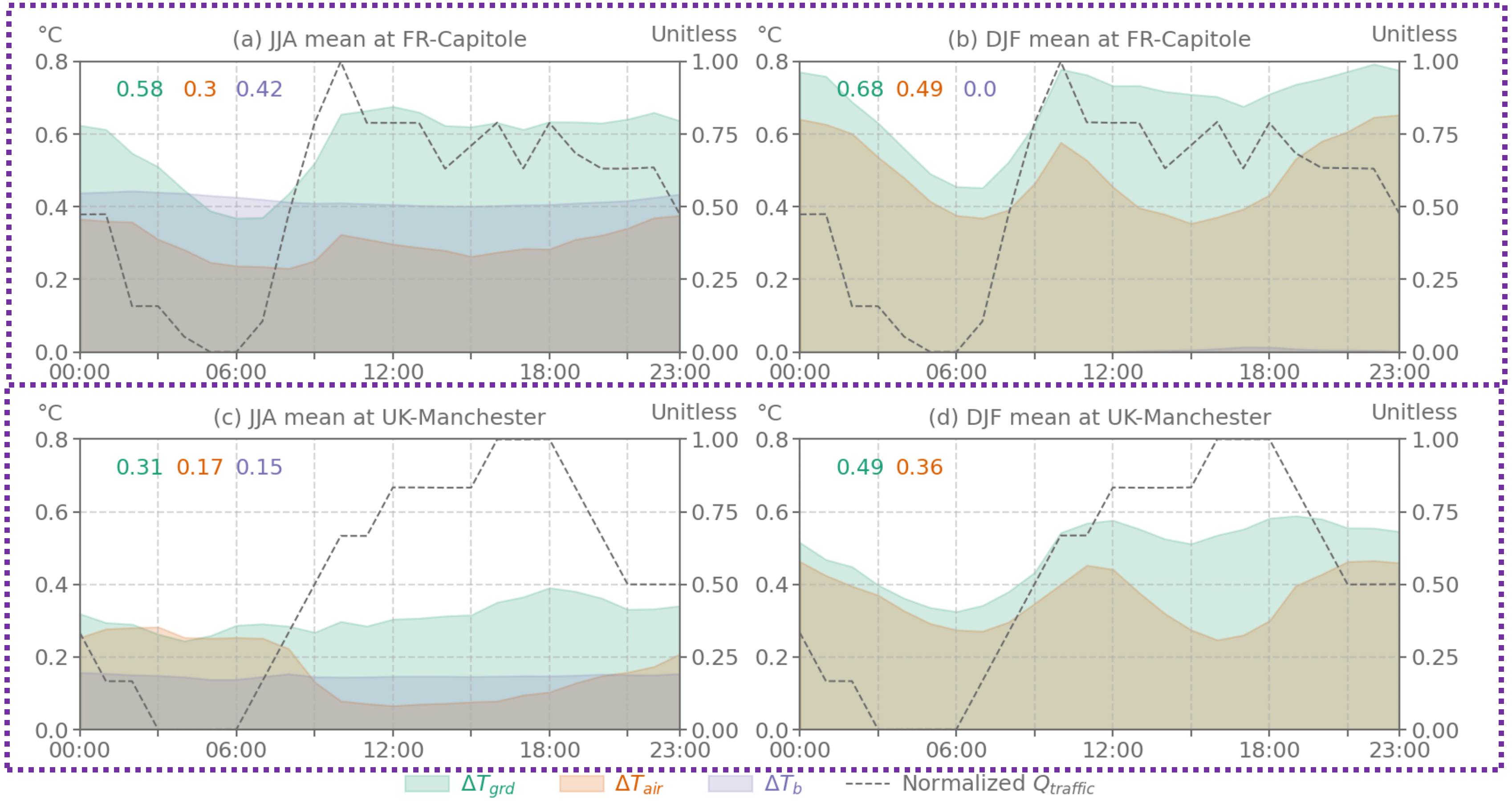
Data source	Method	Sectors	FR-Capitole	UK-Manchester
CNTL simulation	Bottom-up		6.45 for 2004	9.99 for 2022
TRAF simulation	Bottom-up		27.91 for 2004	25.68 for 2022
AH4GUC for the 2010s	Top-down		41.78	21.4
Jin et al. (2019) for 2015	Top-down		19.6	29.9
AH-DMSP for 2010	Nighttime light data		0.1	0.6

- AH4GUC: Varquez et al. (2021). Global 1-km present and future hourly anthropogenic heat flux.
- Jin et al. (2019). A new global gridded anthropogenic heat flux dataset with high spatial resolution and long-term time series.
- AH-DMSP: Yang et al. (2017). A new global anthropogenic heat estimation based on high-resolution nighttime light data.

Table. List of Annual Mean Anthropogenic Heat Flux (AHF, unit: W/m^2).

Temperature Responses to Traffic Heat

Densely built-up areas were more likely to experience greater traffic-induced temperature increases than sparsely built-up areas.



FR-Capitole
- Narrow canyon
- Less pervious road
- More buildings

>

UK-Manchester
- Wide canyon
- More pervious road
- Less buildings

Fig. Diurnal variations of Δ ground, canopy air, and indoor temperatures (TRAF minus CNTL).

Traffic-Induced Urban Warming Effects

Similar traffic volume, different temperature increases.

Vehicle-related factors on $Q_{traffic}$:
- Traffic volume
- Vehicle types (i.e., gasoline, diesel, hybrid, electric)
- Traffic diurnal cycle

Urban surface factors on $Q_{traffic}$ absorption:
- Densely or sparsely built-up
- Narrow or wide canyon
- Pervious road (evaporation)

Sensitivity to $Q_{traffic}$:
- Background climate (i.e., temperate, tropical, polar, arid)

Site name	FR-Capitole	UK-Manchester
Annual mean $Q_{traffic}$ (W/m^2)	22.23	16.27
Ground temperature increase (℃)	0.64	0.38
2 m air temperature increase (℃)	0.4	0.25
Indoor temperature increase (℃)	0.27	0.05
AADT (vehicles/day-lane)	4404	4697
Vehicle type	40.6% gasoline and 59.6% diesel	59.4% gasoline, 34.7% diesel, 4.9% hybrid, and 1% electric
Traffic rush hour	08:00	16:00
Canyon height-to-width ratio	1.32	0.75
Fraction of roof	0.62	0.35
Fraction of pervious road out of total canyon floor	0.26	0.69
T_BUILDING_MIN (℃)	11.95	16.95
Background climate	Temperate	Temperate

Future Direction

Global traffic input

- Time-varying traffic volume
- Time-varying vehicle type

Global simulations

- (Coupled simulation) Atmospheric response to traffic-related AHF
- Urban heat mitigation under energy transition scenarios (moving from ICEVs to EVs)
- Intercomparsion with existing inventory-based global AHF dataset

Single-point simulations

- Model validation at more urban sites such as the Urban-PLUMBER, with different traffic and climate conditions

Thanks! Any questions or comments?

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