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# Modeling urban traffic heat flux in the Community Earth System Model: Formulation and validation for two test sites

Yuan Sun[1], Keith W. Oleson[2], Zhonghua Zheng[1]

[1] The University of Manchester
[2] NSF National Center for Atmospheric Research

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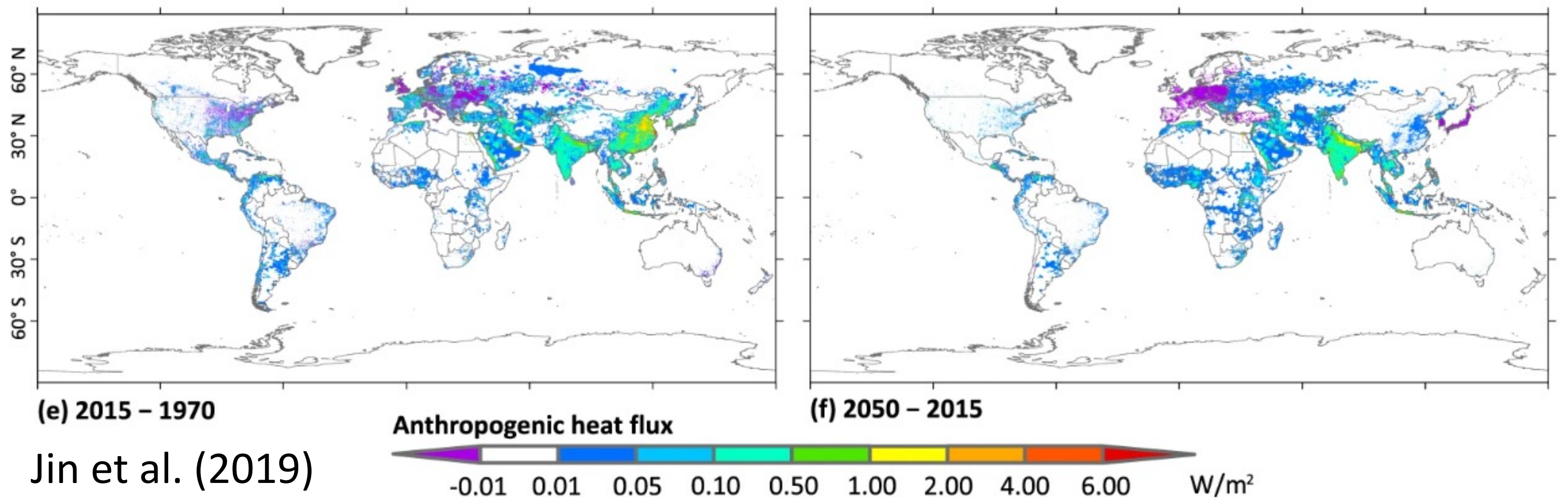
# Why? How? So What?

# Traffic contributes to anthropogenic heat flux (AHF) in global urban areas



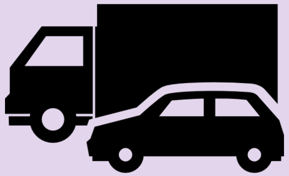

Jin et al. (2019)

Minimal at the global scale but significant at the local scale

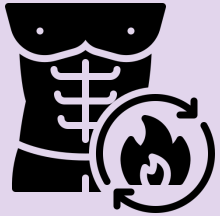
**Urban climate**

Three sources of AHF in urban areas：

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



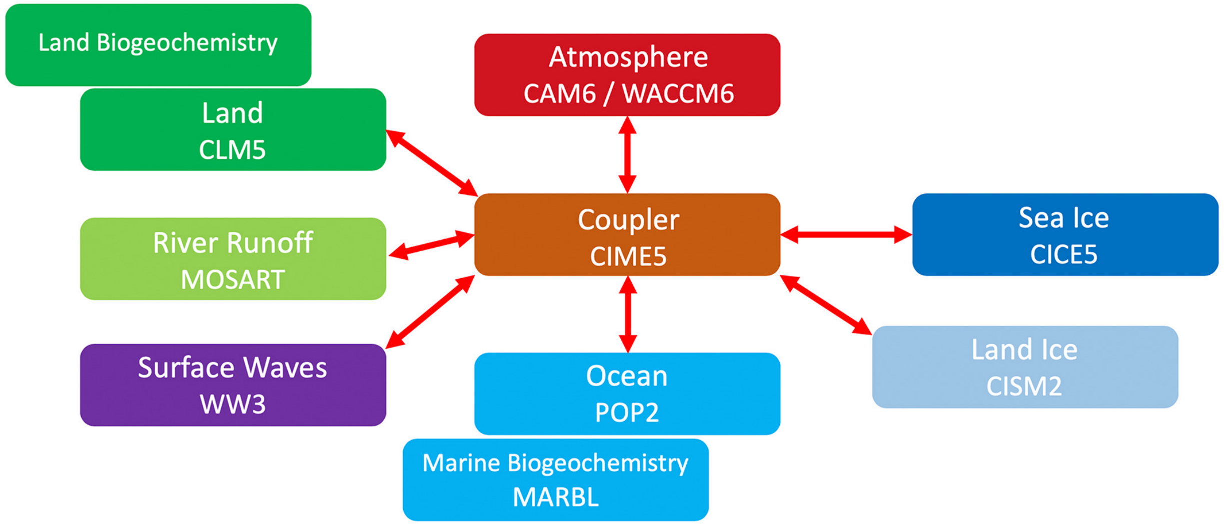
Traffic (~15-50%)

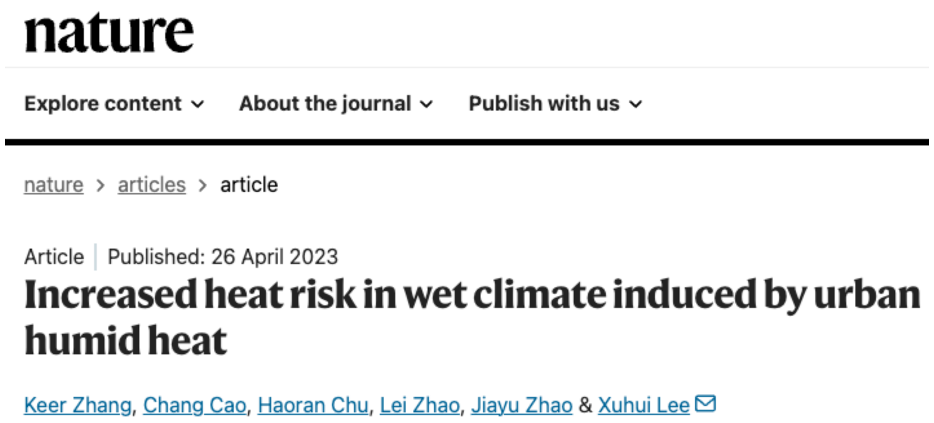


Human metabolism (~5-8%)

Jin et al. (2019). https://doi.org/ 10.1038/s41597-019-0143-1

# Earth system models as an emerging tool for urban climate simulations

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**Increased heat risk in wet climate induced by urban humid heat**

Keer Zhang, Chang Cao, Haoran Chu, Lei Zhao, Jiayu Zhao & Xuhui Lee


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**Elevated urban energy risks due to climate-driven biophysical feedbacks**

Xinchang 'Cathy' Li, Lei Zhao, Yue Qin, Keith Oleson & Yiwen Zhang

Advantages of Earth system models for large-scale urban climate simulation

- Uniformed model configuration and set-up
- Model capability of long-term climate projection

Fig. Schematic of the CESM2 component models. https://doi.org/10.1029/2019MS001916

# Earth system models have not incorporated urban traffic heat modeling yet

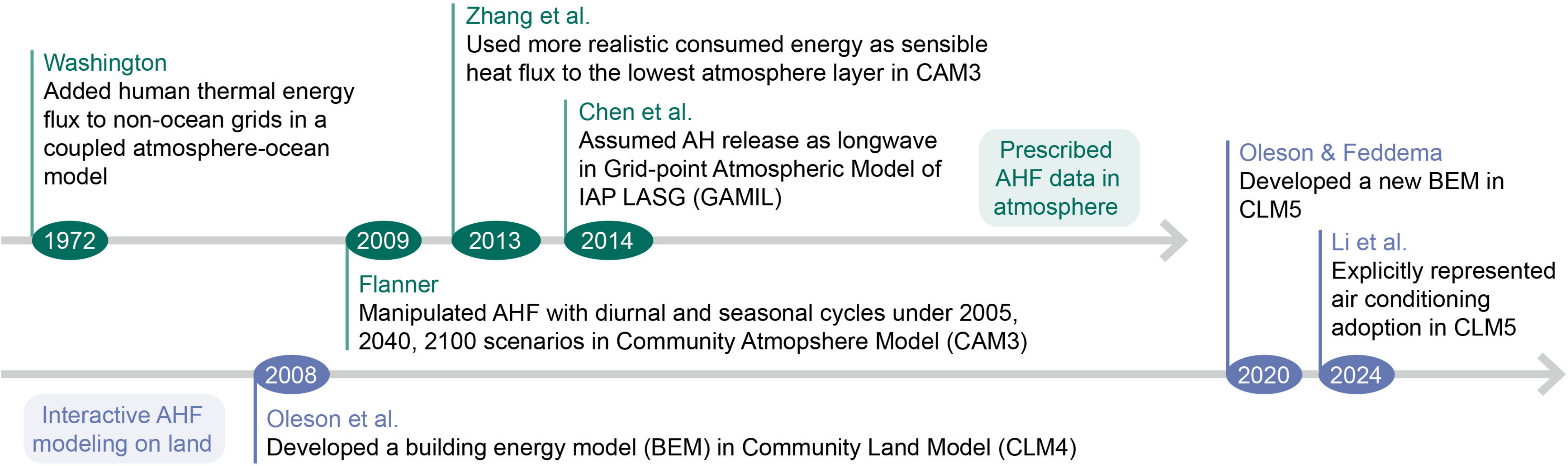



Fig. Timeline of incorporating anthropogenic heat in global climate simulation.

# Earth system models have not incorporated urban traffic heat modeling yet

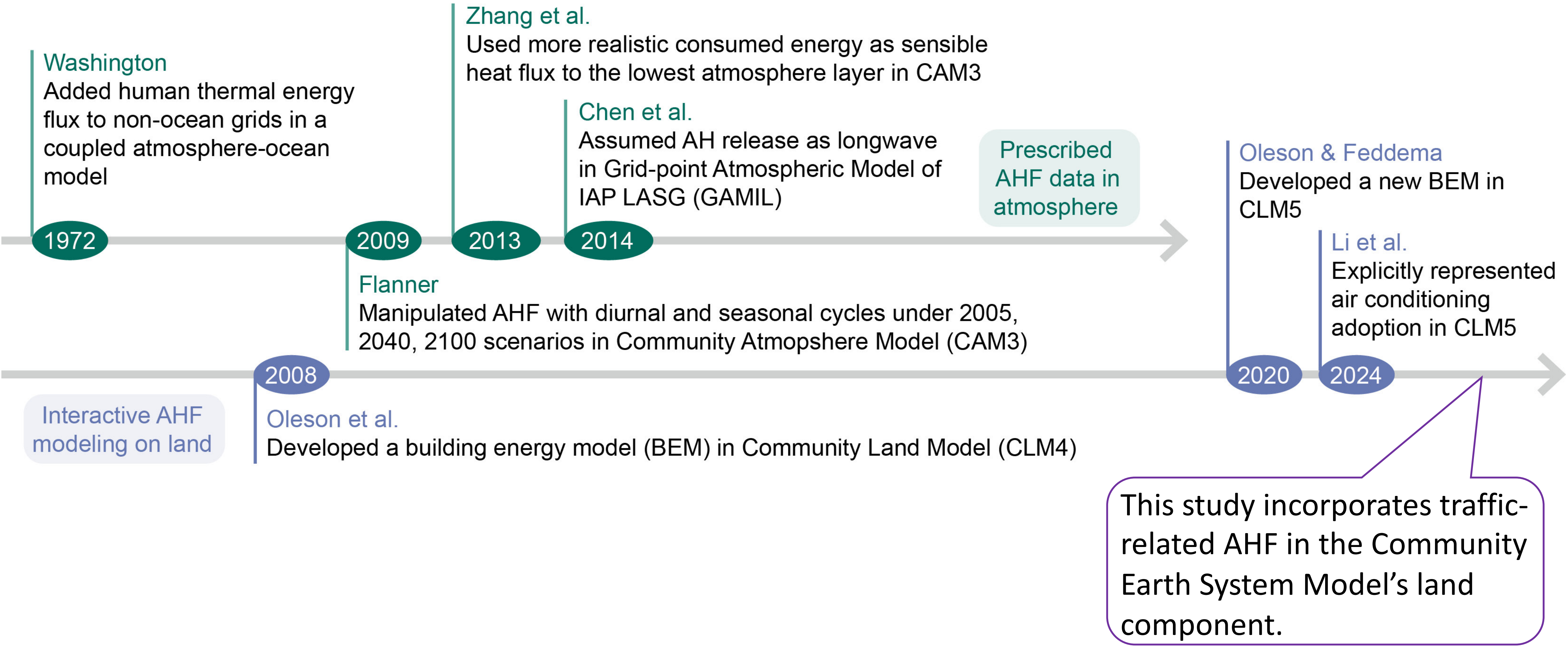
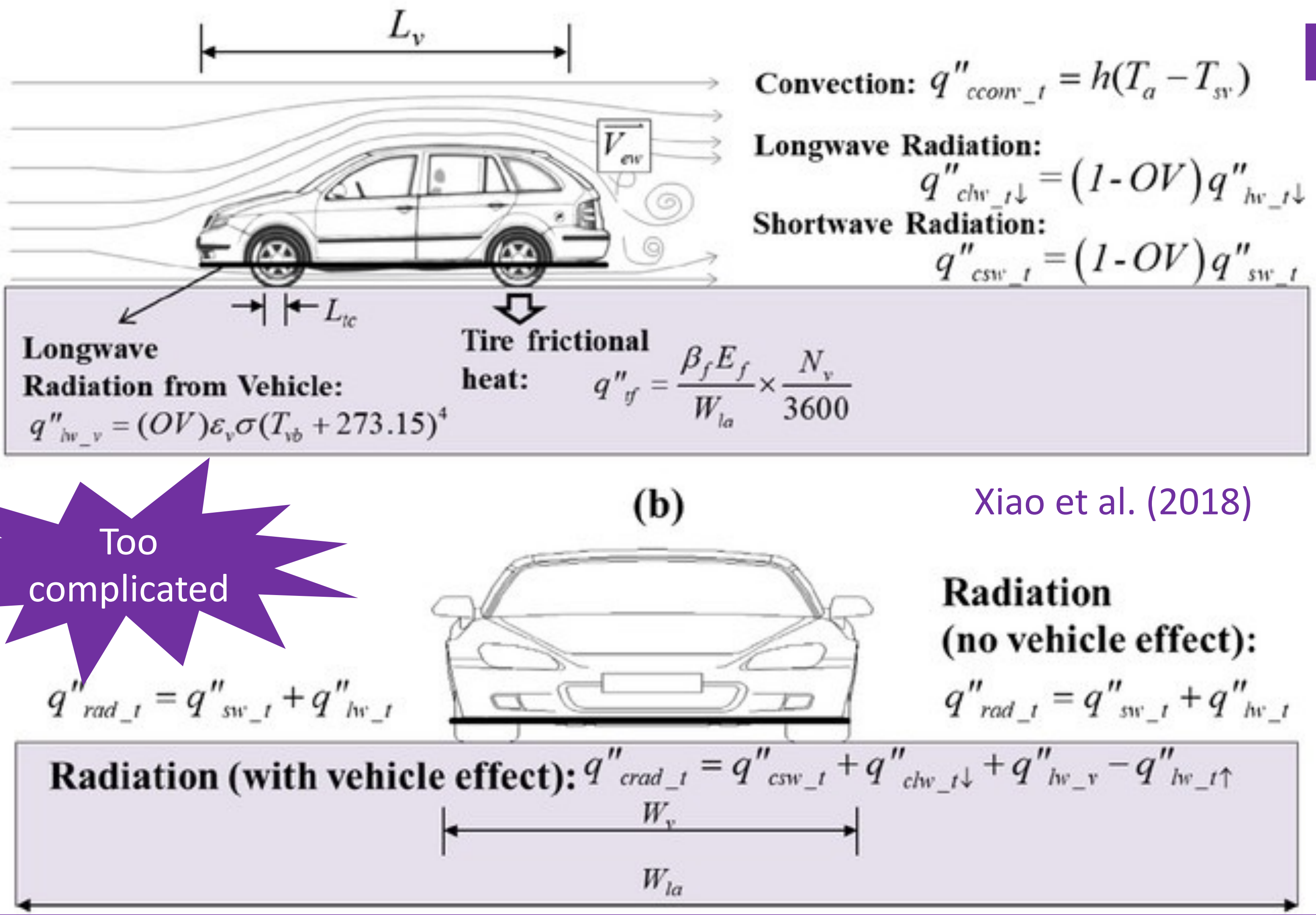



Fig. Timeline of incorporating anthropogenic heat in global climate simulation.

# Why? How? So What?

# Step1: Representation and parameterization of traffic-related processes




Xiao et al. (2018)

Too complicated

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

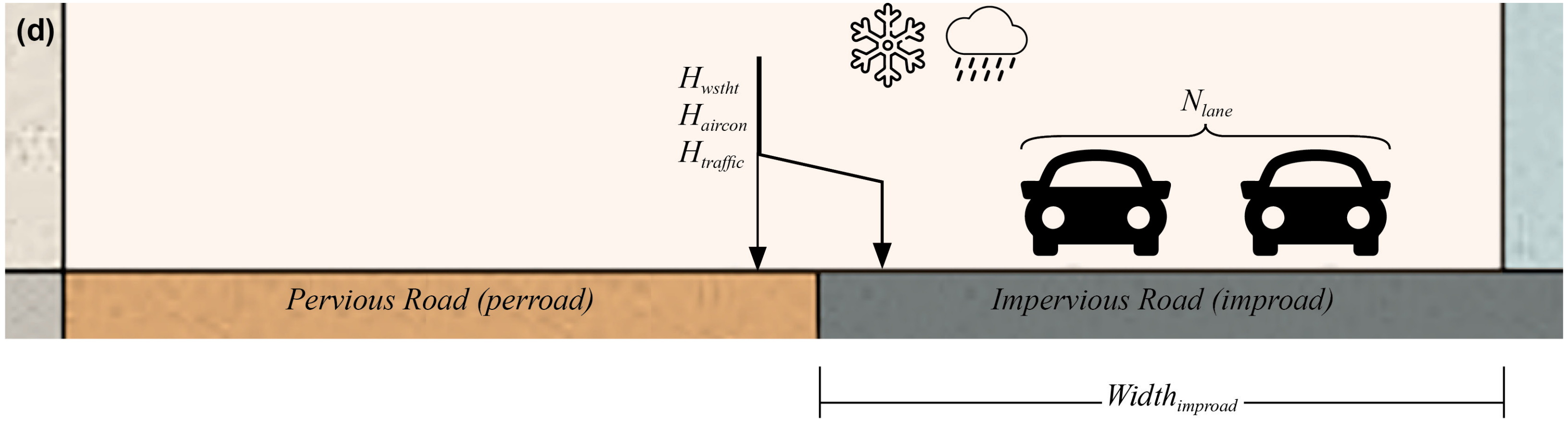
**Simplified**

$Q_{traffic}$

A trade-off between model complexity and practicability
- Availability of global input data
- Computational load for global simulations

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

# Step1: Representation and parameterization of traffic-related processes




Biogeophysical processes

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

**Simplified**

**$Q_{traffic}$**

$$R_n = SW_{down} - SW_{up} + LW_{down} - LW_{up}$$
$$= Q_h + Q_{le} + Q_g - Q_{ac} - Q_w - Q_v - \boxed{Q_{traffic}}$$

Added to the surface energy balance equation

Fig. Adding $Q_{traffic}$ into the canyon floor of a single-layer urban canopy model.

# Step2: Online $Q_{traffic}$ estimation in a bottom-up approach

$$Q_{traffic}(g,l,t) = \frac{E_{total}}{A_{improad}} = \frac{E_{vehicle}(g,t) \cdot N_{lane}(g,l) \cdot F_{vehicle}(g,l,t)}{S_{vehicle}(g,t) \cdot W_{improad}(g,l) \cdot 3600},$$

- $Q_{traffic}$: 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
- $F_{vehicle}$: Number of vehicles per hour per lane (vehicles/hour-lane)
- $S_{vehicle}$: Vehicle speed (m/s)
- $W_{improad}$: Width of impervious road (m)

Constant

$$N_{lane}(g,l) = \begin{cases} 0, & \frac{W_{improad}(g,l)}{W_{lane}} < 0.5 \\ 1, & 0.5 \le \frac{W_{improad}(g,l)}{W_{lane}} < 2 \\ \lfloor \frac{W_{improad}(g,l)}{W_{lane}} \rfloor, & \end{cases}$$

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

Constant

$$W_{improad}(g,l) = \frac{H_{roof}(g,l)}{HWR(g,l)} \cdot (1 - F_{perroad}(g,l)),$$

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

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

# Step2: Online $Q_{\text{traffic}}$ estimation in a bottom-up approach

$$Q_{\text{traffic}}(g,l,t) = \frac{E_{\text{total}}}{A_{\text{improad}}} = \frac{E_{\text{vehicle}}(g,t) \cdot N_{\text{lane}}(g,l) \cdot F_{\text{vehicle}}(g,l,t)}{S_{\text{vehicle}}(g,t) \cdot W_{\text{improad}}(g,l) \cdot 3600},$$

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- $S_{\text{vehicle}}$: Vehicle speed (m/s)
- $W_{\text{improad}}$: Width of impervious road (m)

Annual

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

$$E_{\text{vehicle}}(g,t) = \frac{\sum_{v=1}^{4} p_v(g,t) \cdot E_v \cdot R_v}{\sum_{v=1}^{4} p_v(g,t)},$$

$p$: Fraction of a vehicle type.

$E \cdot R$: Heat release per vehicle.

| Vehicle type |
| --- |
| Gasoline |
| Diesel |
| Hybrid electric |
| Electric |

Annual & hourly

$$F_{\text{vehicle}}(l,t) = \text{AADT}(l,t) \cdot \beta(h),$$

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

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

# Step2: Online $Q_{traffic}$ estimation in a bottom-up approach

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Model time step

$$S_{vehicle}(g,t) = S \cdot \alpha_{pr}(g,t) \cdot \alpha_{sn}(g,t),$$

$S$: Constant vehicle speed (40 km/h). $\alpha_{pr}$: Scale factor of rain. $\alpha_{sn}$: Scale factor of snow.

Rakha et al. (2012)

$$\alpha_{pr}(g,t) = \begin{cases} 1.0, & pr(g,t) = 0 \\ 1.0 - 60 \cdot pr(g,t), & 0 < pr(g,t) \leq 8.3 \times 10^{-4} \\ 1.0 - (90 \cdot pr(g,t) + 0.0425), & pr(g,t) > 8.3 \times 10^{-4} \end{cases}$$

Liu et al. (2017)

$$\alpha_{sn}(g,t) = \begin{cases} 1.0, & sn(g,t) = 0 \\ 0.96, & 0 < sn(g,t) \leq 3.53 \times 10^{-4} \\ 0.92, & 3.53 \times 10^{-4} < sn(g,t) \leq 7.06 \times 10^{-4} \\ 0.91, & 7.06 \times 10^{-4} < sn(g,t) \leq 3.53 \times 10^{-3} \\ 0.87, & sn(g,t) > 3.53 \times 10^{-3} \end{cases}$$

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

# Step3: Model code modification


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

# Step3: Model code modification

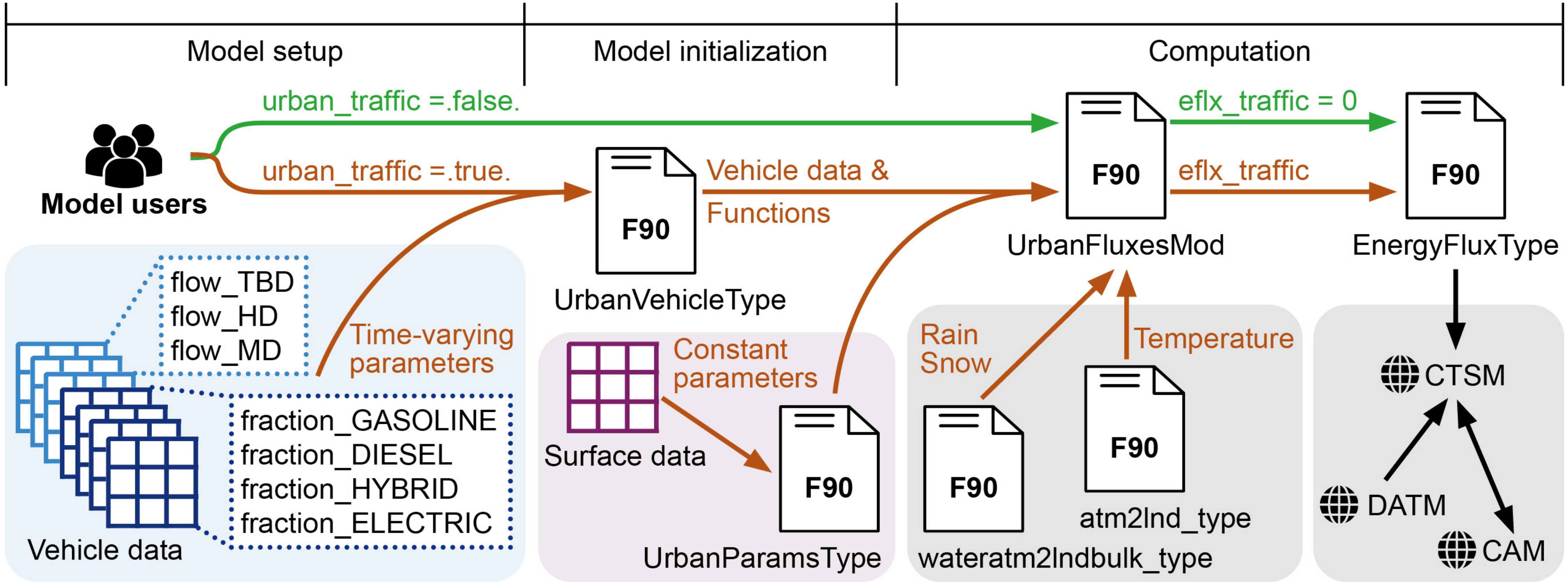
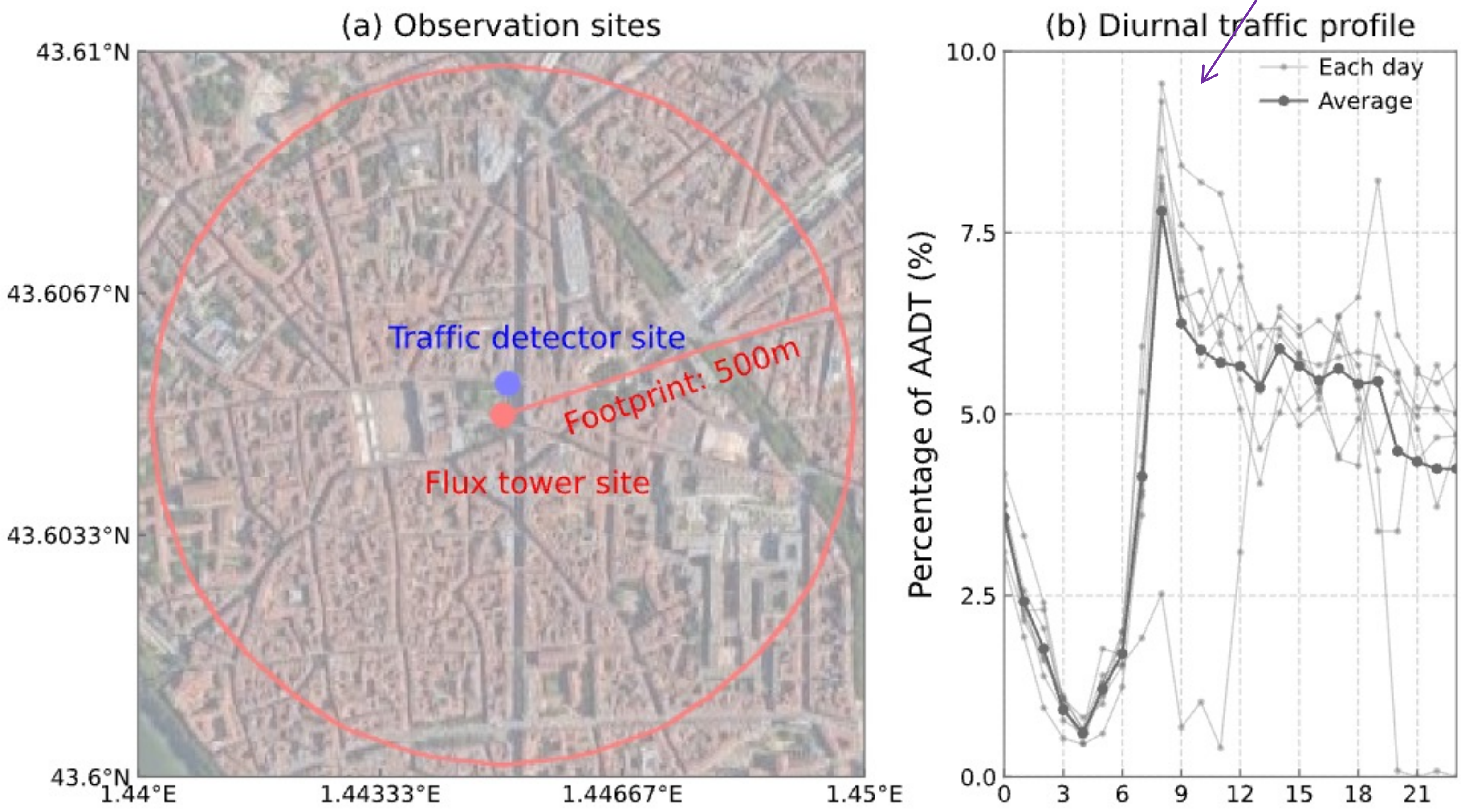



Fig. Workflow of incorporating urban traffic modeling in the Community Terrestrial Systems Model (CTSM).

# Why? How? So What?

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

Traffic rush in the **morning**



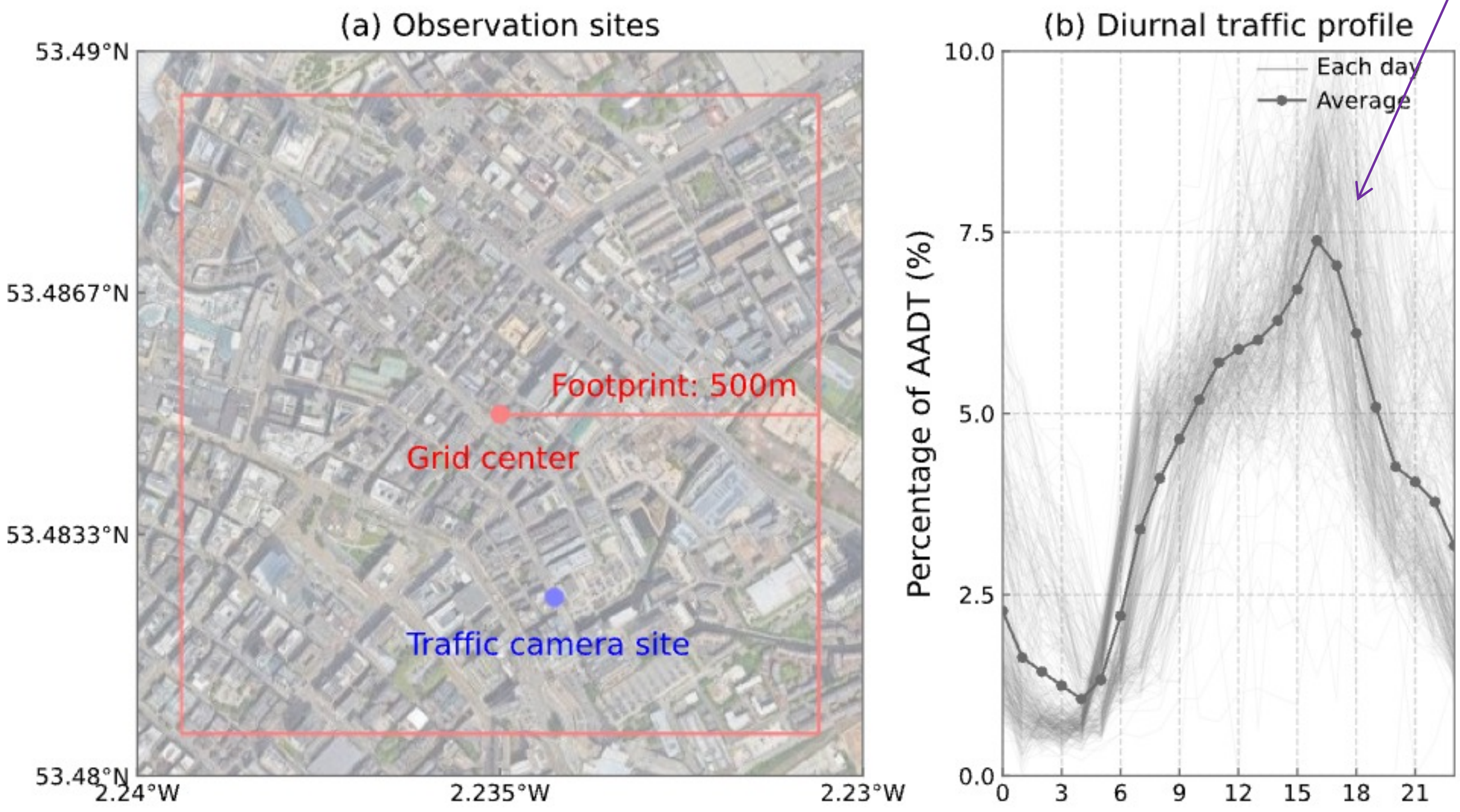

- Atmospheric data came from the **Urban-PLUMBER** flux tower site.
- Traffic volume came from the **UTD19** dataset.

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

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


Loder et al. (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




Traffic rush in the **afternoon**

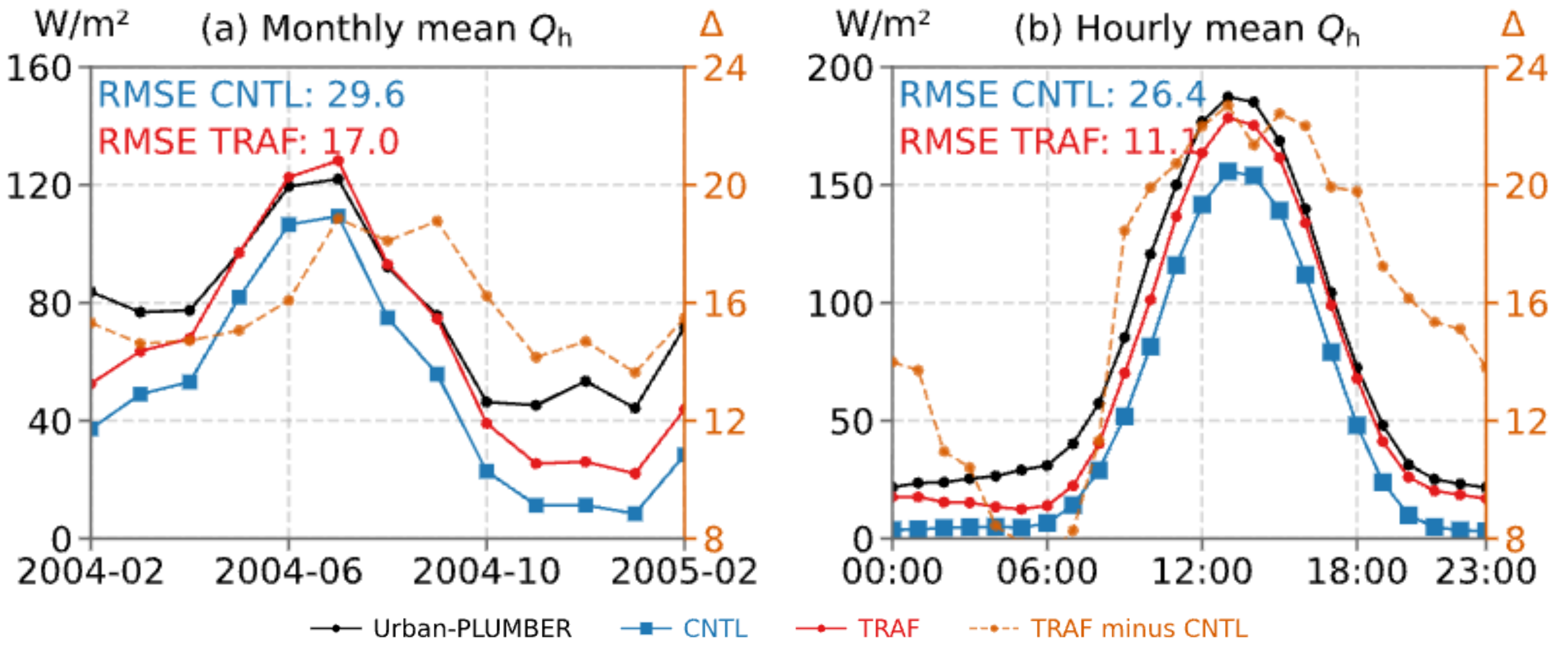
- Atmospheric data came from the HadUK-Grid.
- Traffic volume came from a **VivaCity** camera.

| | |
|---|---|
| **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.

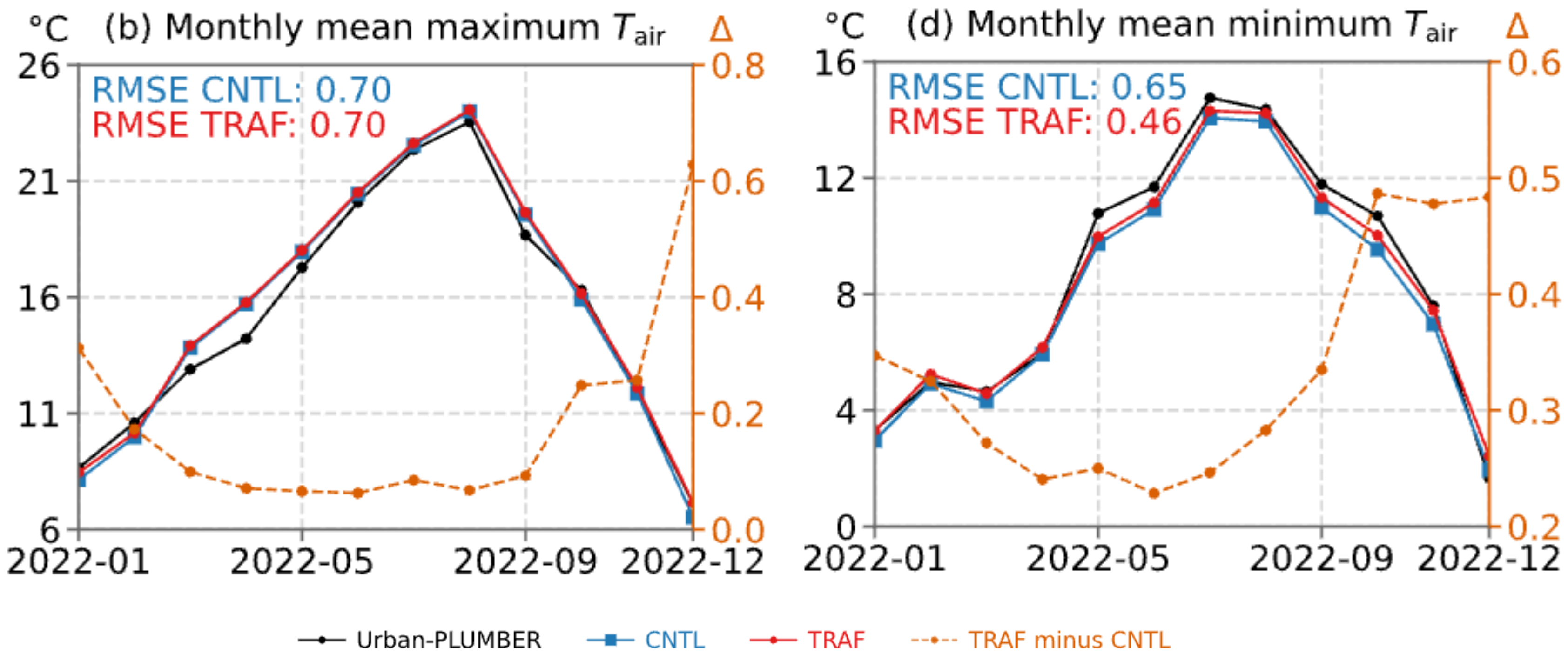
# Improved turbulent heat flux at FR-Capitole




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

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

# Improved 2 m air temperature at UK-Manchester




- Higher $\Delta T_{air}$ (TRAF minus CNTL) in winter than in summer
- Higher $\Delta T_{air}$ at night than during the day

Fig. 2 m air temperature ($T_{air}$) 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$^2$).

# Future directions

Scan me!
(JAMES 2026)

## Global traffic input data development

- Time-varying traffic volume
- Time-varying vehicle distribution

## Global climate simulations

- (Coupled simulation) Atmospheric responses to traffic-related AHF
- Urban heat mitigation under energy transition/transport electrification scenarios
- Intercomparison with existing inventory-based global AHF datasets

## Single-point simulations

- Model validation at more urban sites such as the Urban-PLUMBER, with different traffic and climate conditions (i.e., tropical, arid, temperate, cold)

Thanks! Any questions or comments?

Contact us: yuan.sun@manchester.ac.uk, oleson@ucar.edu, zhonghua.zheng@manchetser.ac.uk