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Fine-Scale Projections of Elderly Heat Stress and Associated Adaptation Costs in Japan

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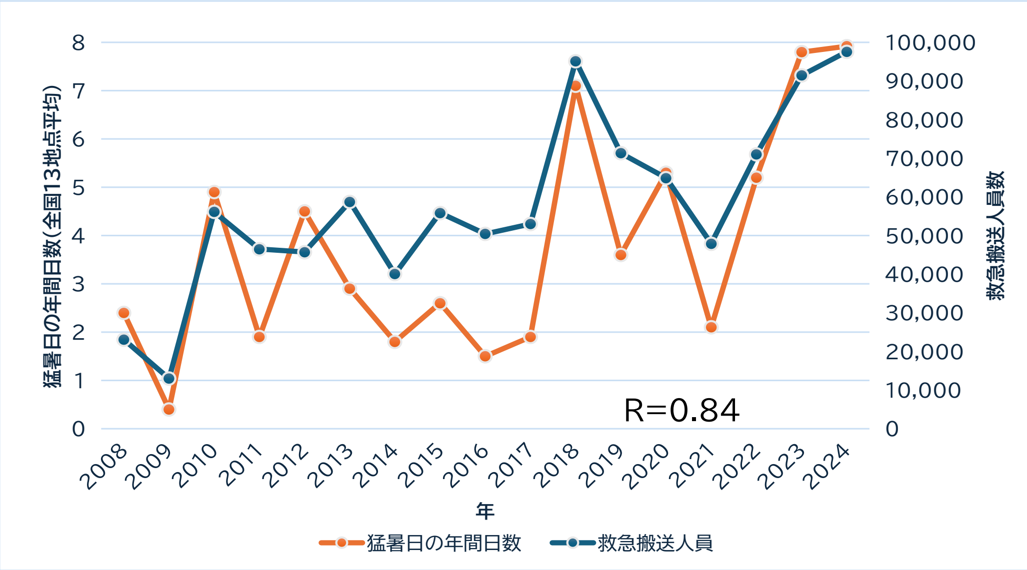
Background

- Heat illness is becoming increasingly serious in Japan due to rising temperatures.
  - ➢ Mortality: often exceeds 1,000 per year—even 2,000 in 2024—surpassing deaths from natural disasters.
  - ➢ Emergency transport: tens of thousands per year, nearing 100,000 in 2018 and 2024.
- The heat illness risk will be made even worse by temperature rise and population aging.



Annual number of 35°C+ days and emergency transport cases (2008–2024)

Source: JMA(1), JMA(2), FDMA

Background

- Declines in mobility of elderly population and a severe shortage of care workers in Japan, underscore the need for fine-scale mapping of heat stress.
- Still, most existing studies have been conducted at the prefectural level.

Japan faces 570,000 care worker shortage in fiscal 2040

By AYAKA KIBI/ Staff Writer

July 14, 2024 at 12:45 JST

Source: Asahi Shimbun (2024/7/14)

Nearly 70% of care service providers in Japan face labor shortage

KYODO NEWS - Oct 07, 2023 - 07:20 | All , Japan

Source: Kyodo News (2023/10/7)

Nursing Care Worker Numbers Fall to 2.13 Million; Demand is Growing Higher, but Pay Remains Low

Source: The Japan News (2025/3/19)

Objective

To project:

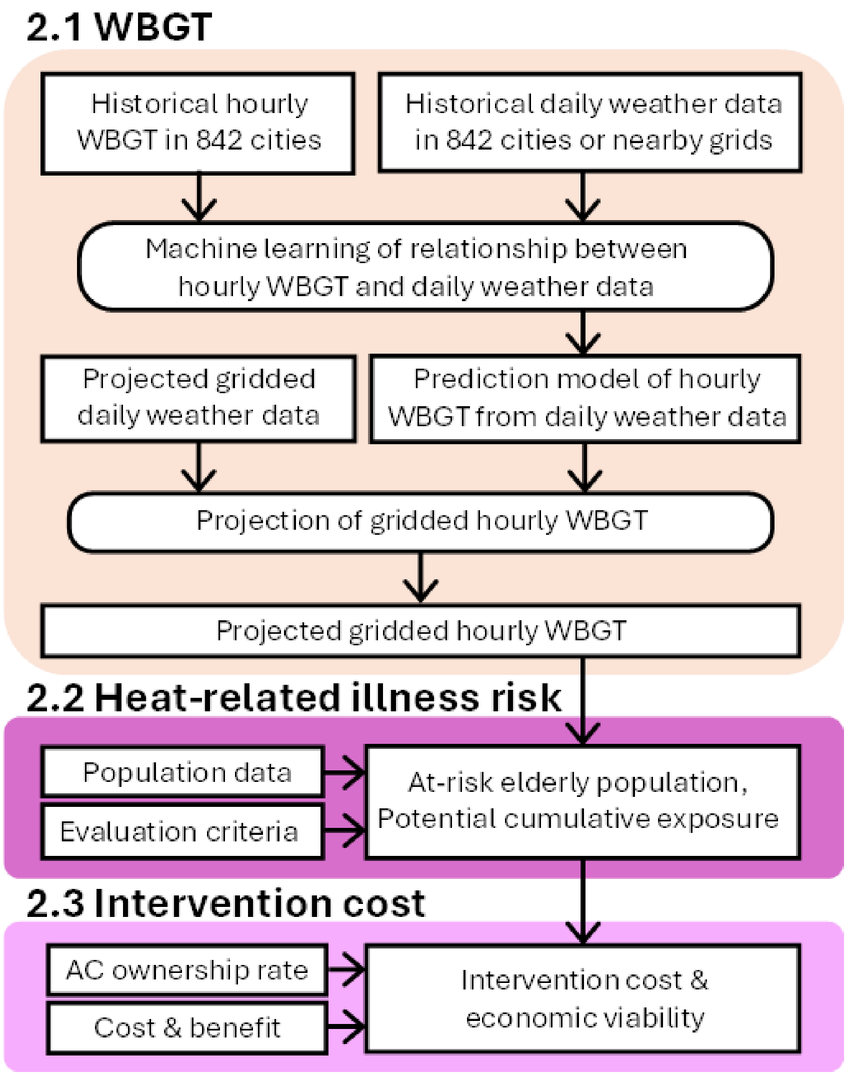
1. Distribution of at-risk elderly populations (AREP)* and cumulative exposure

   * elderly populations in grids reach the current alert threshold (WBGT 33℃) or region-specific thresholds

2. Intervention costs (here, household AC installation and electricity subsidies)

Method (1): WBGT projection

- We developed a model to estimate hourly WBGT from daily weather data using machine-learning.
- Then, applied the model to CMIP6-based climate projections (NIES2020) (Ishizaki, 2021) to project hourly WBGT at high resolution (1-km grid).



Process overview

Method (1): WBGT projection

- For machine learning to construct a prediction model, two modeling approaches were compared:
  1. Extreme gradient boosting (XGBoost) model (Chen and Guestrin, 2016)
  2. Generalized linear model (with L1:LASSO and L2:Ridge regularization)
- Concept (Takakura et al., 2019) :

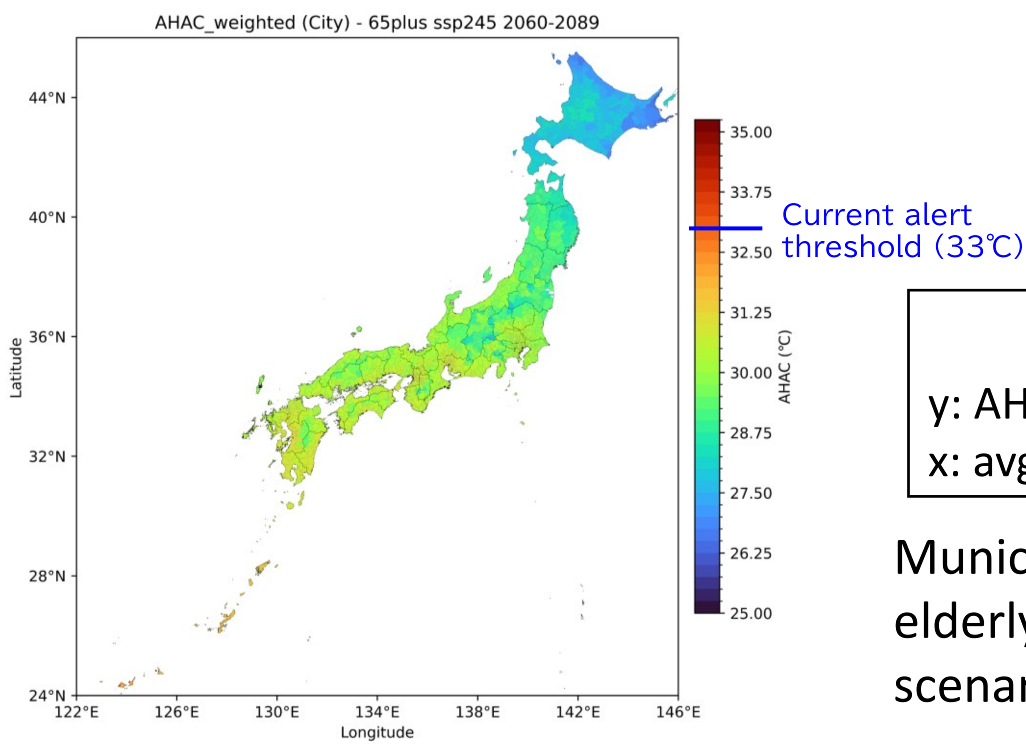
$$WBGT_{c,d,hh} = f_{hh}\left(x_{c,d-1}, x_{c,d}, x_{c,d+1}, cos\theta_{c,d}\right)$$

✓ $x_{c,d} = (T_{a,c,d}, T_{a(max),c,d}, T_{a(min),c,d}, RH_{c,d}, WS_{c,d}, SR_{c,d})$
where each variable represents city-level daily average / max / min temperature, relative humidity, wind speed, and solar radiation on day *d* in city *c*.

✓ $\cos\theta_{c,d} = (\cos\theta_{c,d,0}, \ldots, \cos\theta_{c,d,23})$
where $\theta_{d,hh}$ is the solar zenith angle at hour *hh* on day *d*. If $\cos\theta_{d,hh} < 0$, it is set to zero.

Method (2): Heat illness risk distribution

- We estimated the distribution of at-risk elderly populations (AREP) by integrating projected WBGT and population.
  - AREP: elderly individuals (age≥65) in grids, which reach the current alert threshold (WBGT 33℃), or the region-specific thresholds (AHAC) (Oka et al. 2023).



$$y = 0.4514x + 18.211$$

y: AHAC threshold for the age group of 65y+

x: avg daily max WBGT from May to Sep

Municipality-specific WBGT thresholds for elderly individuals (period: 2060–2089; scenario: SSP2–4.5; avg of 5 GCMs)

Method (3): Intervention cost & benefit

- Costs
  - Air conditioner (AC) installation for AREP households w/o AC.
    Unit: US$700 per household, 10 years
  - Electricity subsidy (ES) for AREP households to lower financial barriers
    Unit: US$167 per household, year
  - Cooling shelter (CS) scenario, where the CS houses AREP w/o AC, was also considered
  - A conventional discount rate for Japanese public investment (4%) is adopted (Otani et al. 2023).

Method (3): Intervention cost & benefit

- Benefits (avoidable risk)
  - ➢ Heatstroke deaths
    - ✓ 2.57 × 10^{-5} deaths per elderly person (2010–2022 avg)

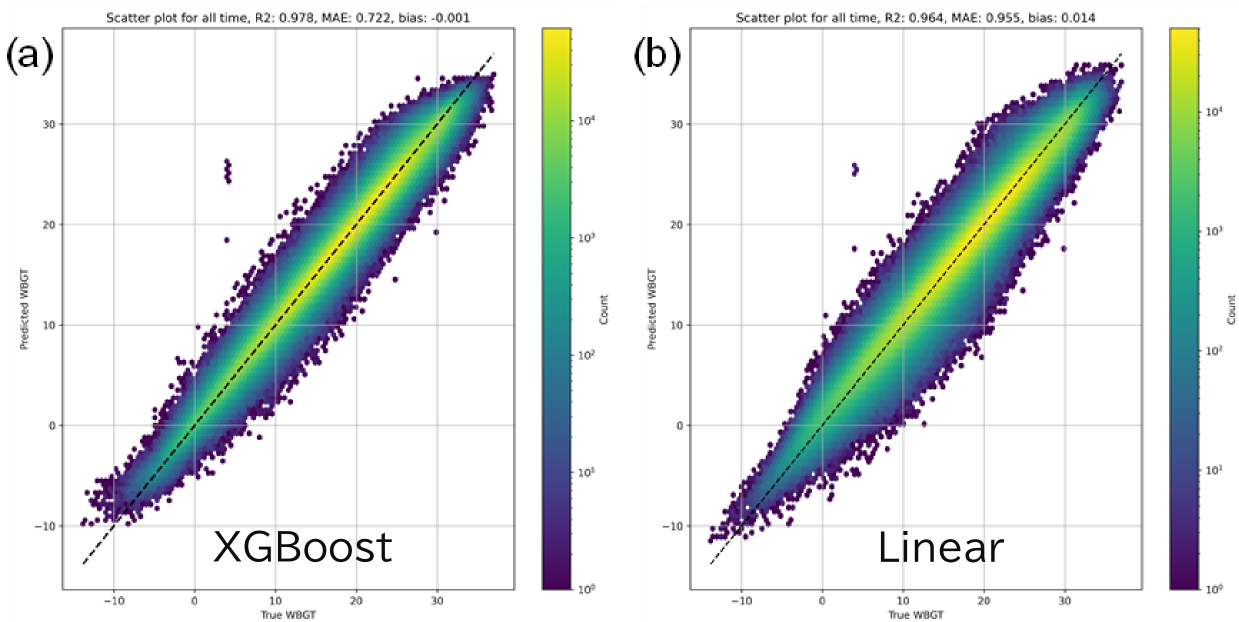
      ⇒˜969/year in 2030-2059, ˜840/year in 2060-2089
    - ✓ Unit: 1.33M USD/person (Fujimi et al., 2023)
  - ➢ Emergency transports
    - ✓ 1.04 × 10^{-3} cases per elderly person (2010–2024 avg)

      ⇒˜39,414/year in 2030-2059, ˜34,187/year in 2060-2089
    - ✓ Unit: 890 USD/case (Beniko & Nakai, 2022; Tokyo Gov., 2004)
  - ➢ Risk reduction assumption
    - ✓ AC-free households: 12.5% reduction (25%* total avoidable risk × 50% usage)
    - ✓ AC-equipped households: 37.5% reduction (75%* total avoidable risk ×50% usage), source same as above.

      * Based on Tokyo Medical Examiner (n.d.)
    - ✓ Adjusted by AREP share in population
    - ✓ Two discount rates are adopted (4% and 0.1% (Stern, 2006)).

Results (1): Accuracy of WBGT Prediction Models

ML	XGBoost	Linear regression
All hours	R^2=0.98, MAE=0.74(℃)	R^2=0.96, MAE=0.95(℃)
By hour	R^2=0.96～0.99, MAE: 0.55～0.95, RMSE: 0.8～1.3, bias: -0.005～0.002	R^2=0.93～0.97, MAE: 0.79～1.21, RMSE: 1.1～1.5, bias: 0.001～0.027

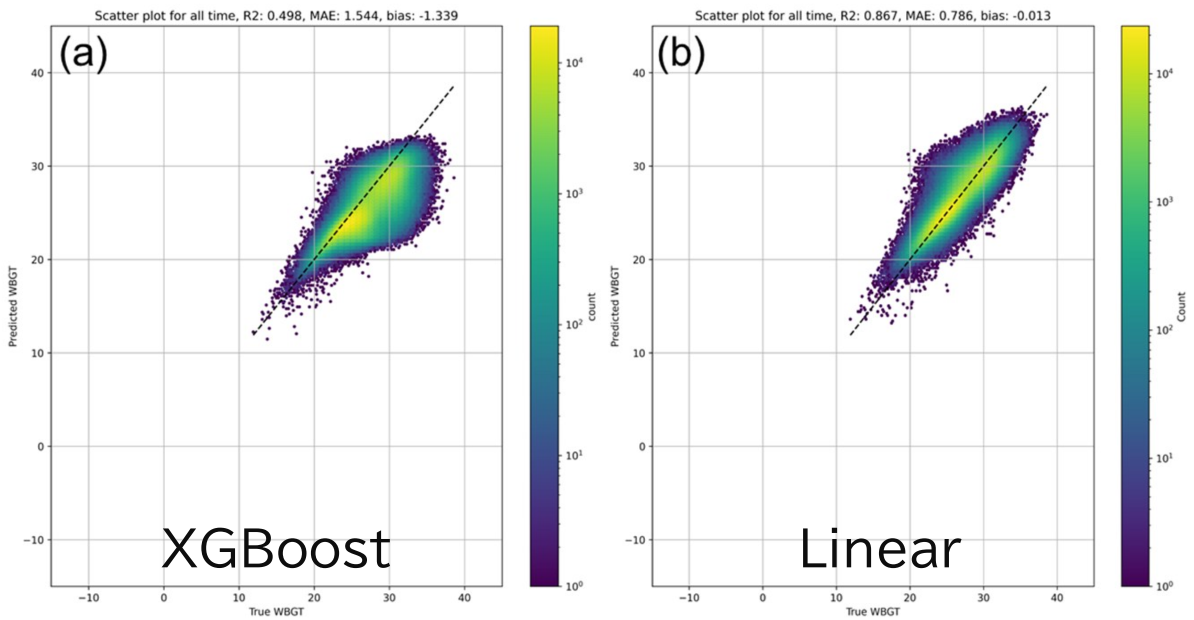


(10M test data)

⇒ Both models were highly accurate, with MAE within ±1°C; XGBoost performed slightly better.

Results (1): Stress test for external validity

- We trained models using datasets with low T_a (< 90^{th} PCTL), then tested using datasets with high T_a(≧ 90^{th} PCTL).



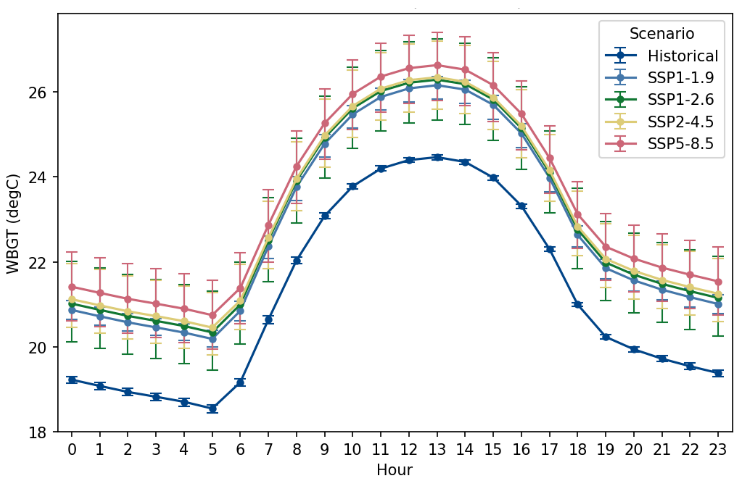
⇒XGB: Limited accuracy when T_a is high,
Linear: Relatively stable 〃

⇒For applicability to unlearned conditions in future, we adopted the linear model.

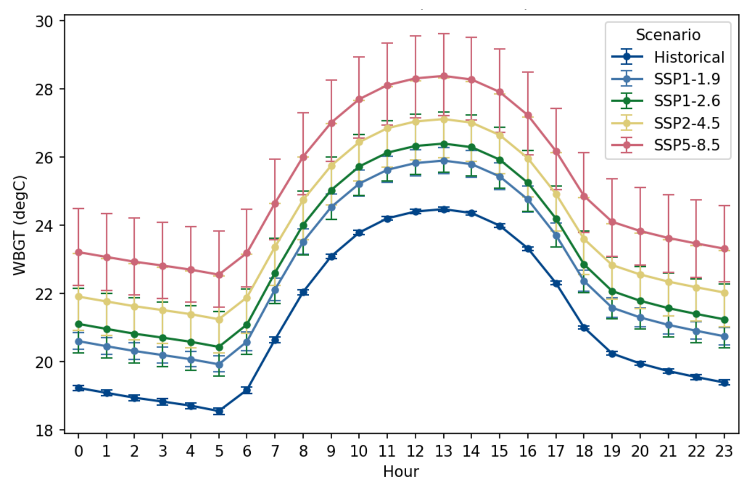
Results (1): Projection of hourly WBGT

- We applied the prediction model to NIES2020 dataset to project future hourly WBGT.
  - ✓ Global Climate Models (GCMs): MIROC6, MRI-ESM2-0, ACCESS-CM2, IPSL-CM6A-LR, MPI-ESM1-2-HR
  - ✓ Emission Scenarios (SSP): SSP1-1.9/1-2.6/2-4.5/5-8.5
  - ✓ Periods: 2030–2059, 2060-2089
- Example: National mean WBGT in August (GCMs mean)
  - ✓ WBGT notably increased under higher-emission scenarios in 2060–2089. Peak occurs around 13:00.

2030-2059



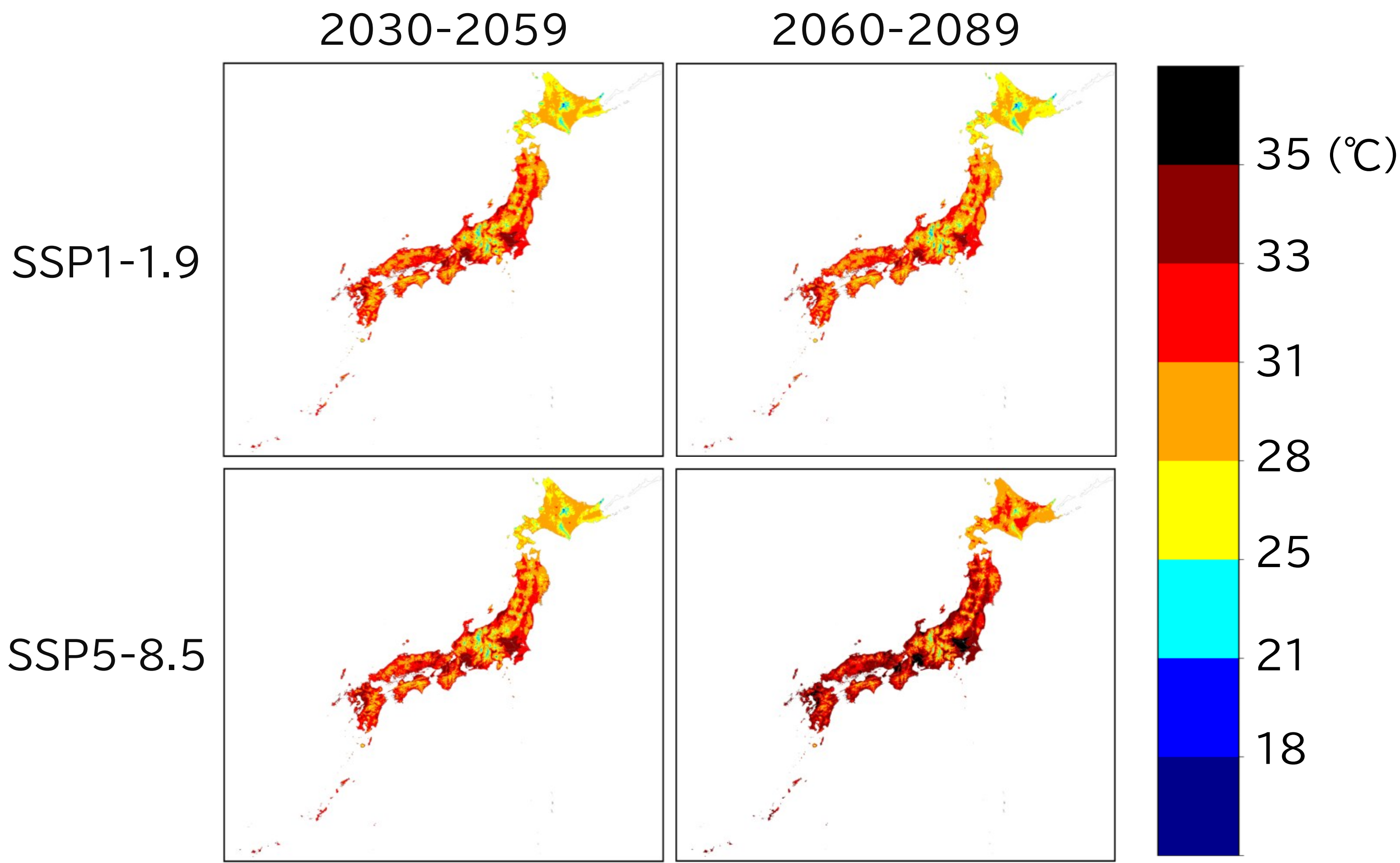
2060-2089



**Error bars represent GCM range (min–max).*

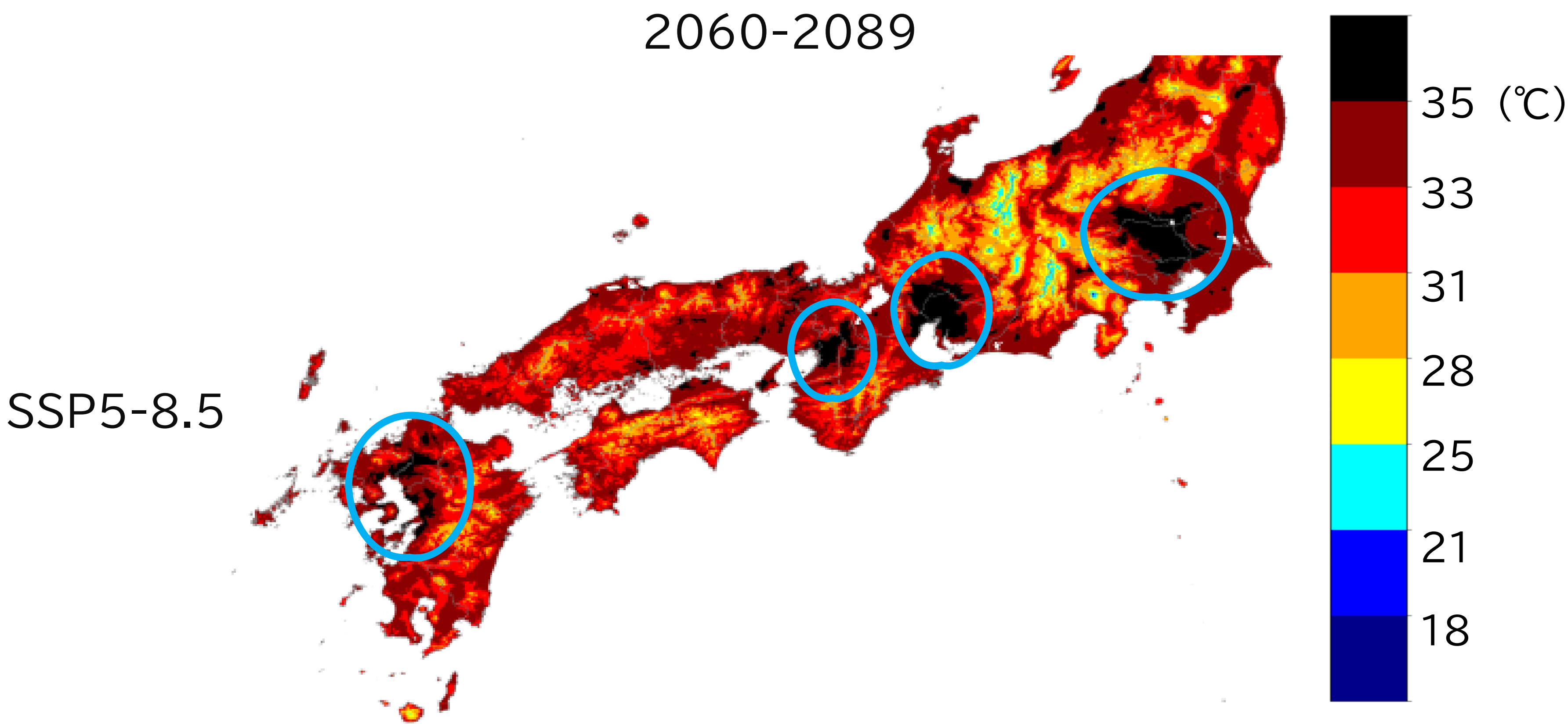
Results (1): Projection of hourly WBGT

- Example: Monthly maximum WBGT at 13 JST in August (5GCMs mean)
  - ✓ Higher under higher-emission scenarios, especially in low-latitude and urban areas.



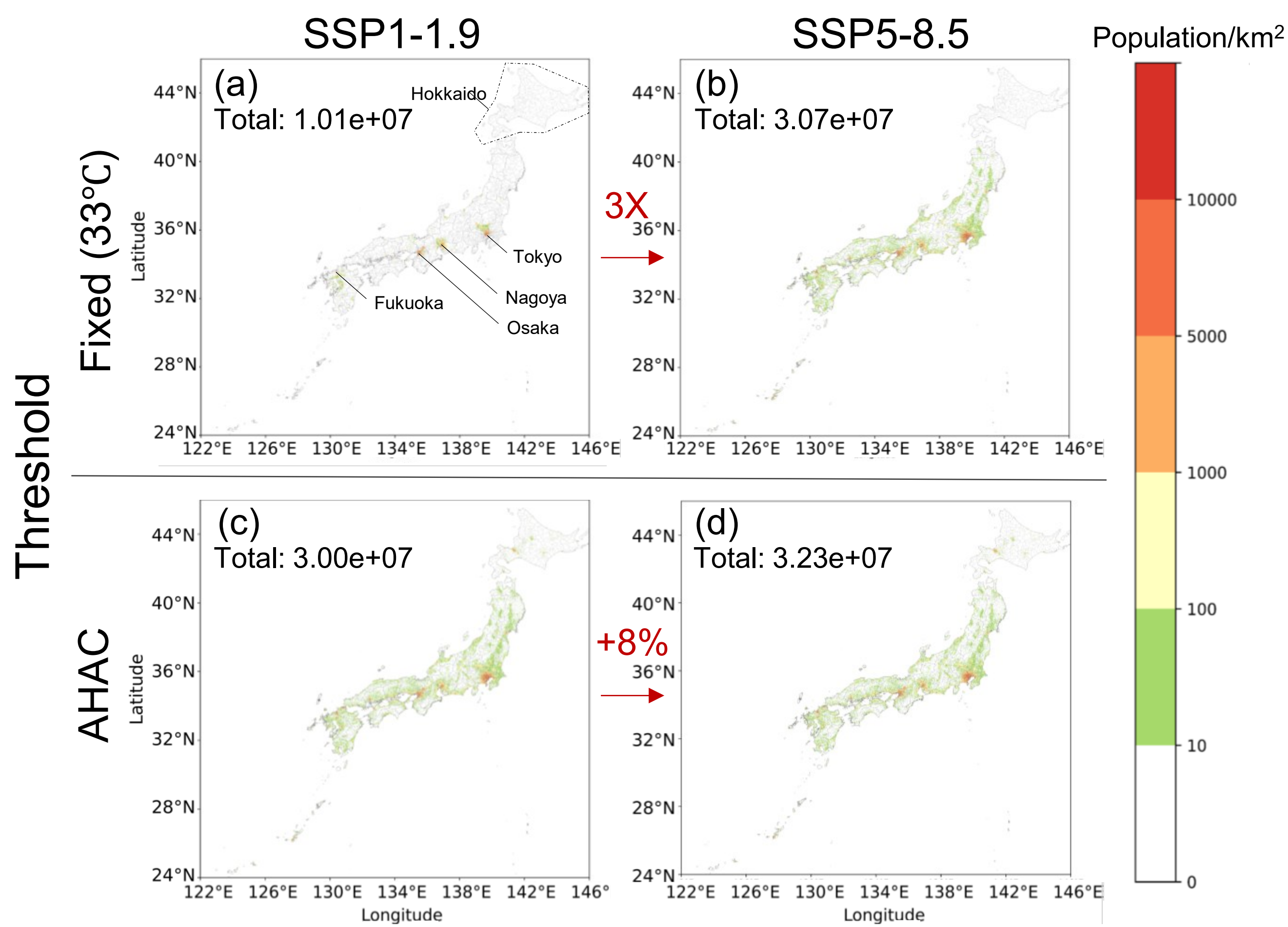
Results (1): Projection of hourly WBGT

- Example: Monthly maximum WBGT at 13 JST in August (5GCMs mean)
  - ✓ Projected to exceed 35 °C in many areas under SSP5-8.5 (2060–2089).



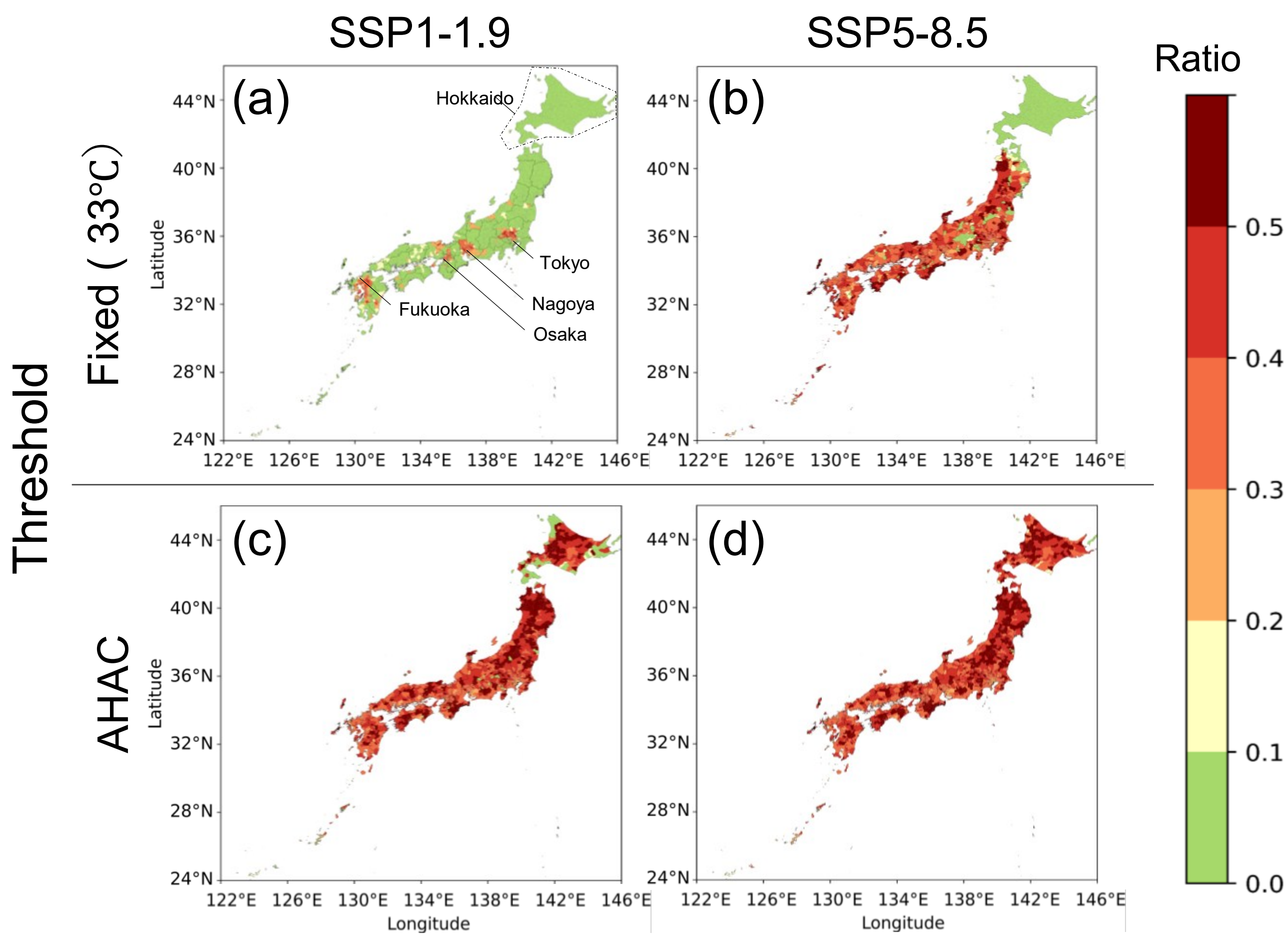
Results (2): AREP distribution (5GCMs mean, 2060–2089)

- Mainly concentrated in major urban areas.
  - Fixed: 10 million (SSP1-1.9) to 31 million (SSP5-8.5)
  - AHAC: 30 million (SSP1-1.9) to 32 million (SSP5-8.5)



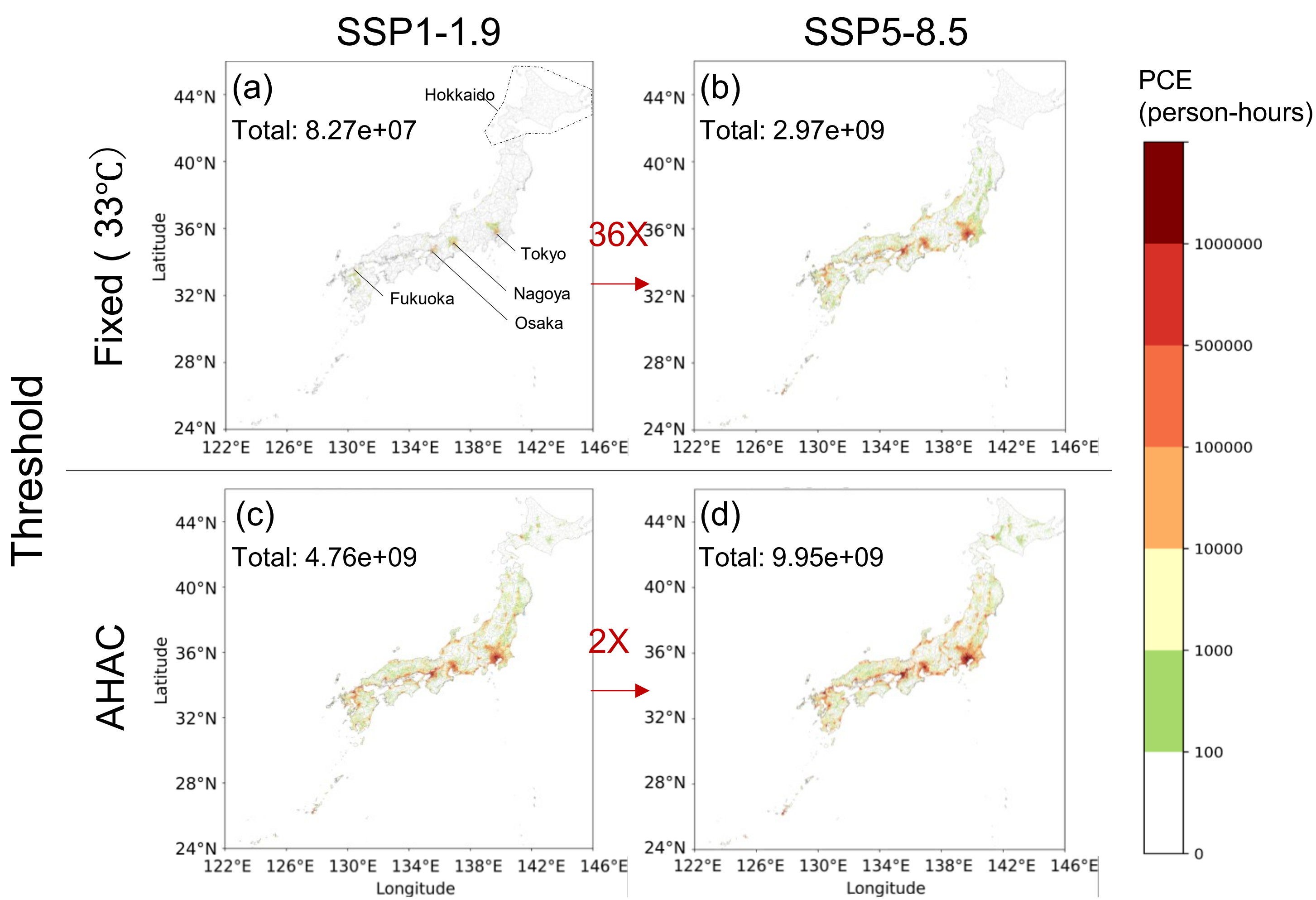
Results (2): AREP proportion (5GCMs mean, 2060–2089)

- Fixed: SSP1-1.9: 40%+ is limited to metro regions.
  SSP5-8.5: 〃 expands to broader area but Hokkaido.
- AHAC: 〃 across the country, including Hokkaido.



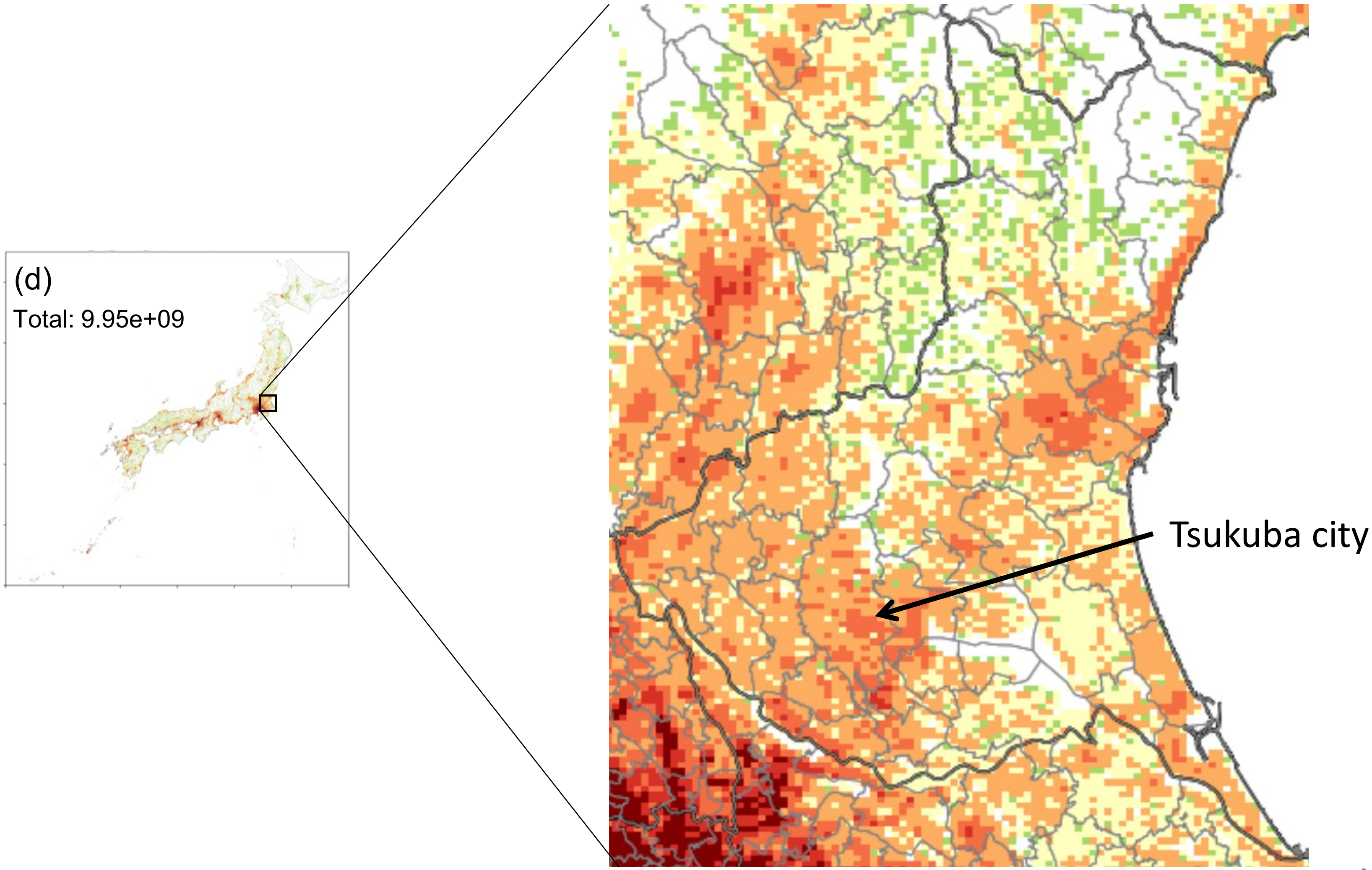
Results (2): Population exposure (5GCMs mean, 2060–2089)

- Fixed: 83 million (SSP1-1.9) to 3.0 billion (SSP5-8.5)
- AHAC: 4.8 billion (SSP1-1.9) to 10.0 billion (SSP5-8.5)



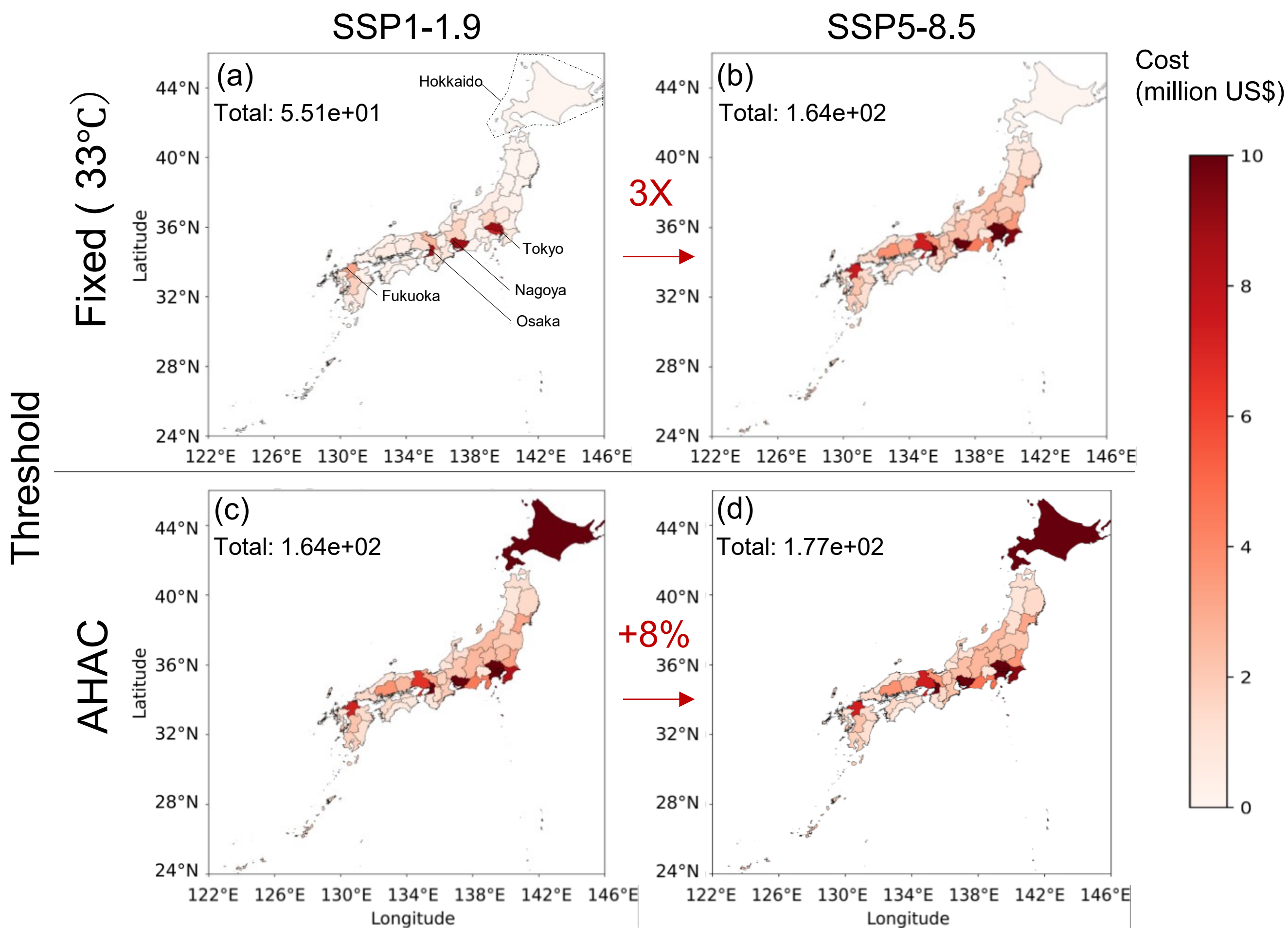
Results (2): Population exposure (5GCMs mean, 2060–2089)

- If zoomed to Ibaraki Prefecture:



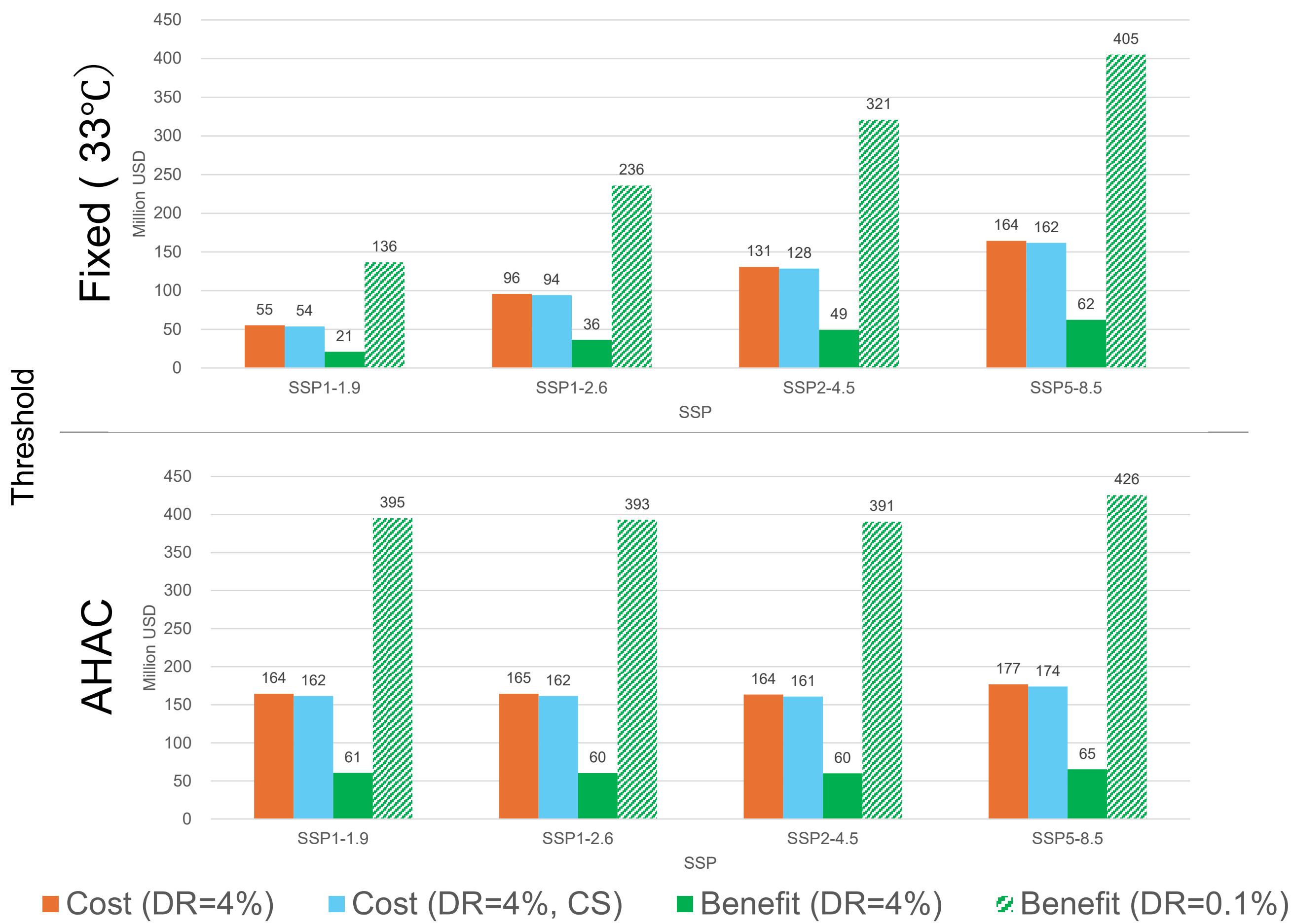
Results (3): Intervention Cost (5GCMs mean, 2060-2089)

- Fixed: 55 million (SSP1-1.9) to 164 million (SSP5-8.5)
- AHAC: 164 million (SSP1-1.9) to 177 million (SSP5-8.5), prominent in Hokkaido, where AC ownership is low (40%)



Results (3): Cost and benefit (5GCMs mean, 2060-2089)

- Under both thresholds, the costs were offset only under a low discount rate (0.1%) for future health impacts.
- Housing AREP to CS decreased the cost only by 2%.



Discussion: Key findings and implications

- Hourly and 1-km grid WBGT projections enable targeted and effective interventions for heat-related risks.
- AREP is projected to reach at least 10 million (SSP1-1.9). Under SSP5-8.5 or with region-specific thresholds, the number could reach 32 million, over 40% of the pop in most municipalities.
- The current uniform threshold (WBGT 33°C) may underestimate the magnitude and spatial extent of heatstroke risk compared to AHAC. This is particularly critical in cooler regions and among vulnerable populations such as the elderly.
- Intervention costs are substantial (55–177 million USD per year), yet justifiable under low discount rate, highlighting the importance of ethical considerations for future generations.

Discussion: Next steps

- Evaluate heat environments in specific activities using high-resolution WBGT data (e.g., school activities, labor, outdoor events)
- Validate the epidemiological relevance of indicators such as AREP and cumulative heat exposure
- Incorporate more sustainable cooling strategies, especially for elderly care facilities (e.g., rooftop sprinklers, outdoor shading devices, electric fans) (Jay et al. 2021)
- Extend the approach to other countries/regions and apply alternative thermal indices (e.g., UTCI, SET*)

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