Integrating anthropogenic heat flux with global climate models

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AHF or "Waste heat"

- **All** human energy use is dissipated as heat within Earth's land-atmosphere-ocean system
  - Second Law of Thermodynamics, entropy tendency
  - Opacity of Earth's land/atmosphere to most radiation
- Heat conversion (Example: coal->electricity)
  - 1) Combustion at plant, waste heat
  - 2) Transmission inefficiency
  - 3) Mechanical work, incandescent light, etc
    - Work generally done against friction, dissipated as heat
    - No/temporary change in net gravitational, electrical, chemical, mechanical potential energy of Earth
  - LED light: p-n junction emits photon, but 99.9% of these photons are absorbed within planet
- Primary energy consumption = heat energy

AHF as a climate forcer

- Non-renewable sources of chemical & atomic energy (coal, oil, gas, nuclear) are being converted to heat orders of magnitude more quickly than in the absence of humans
  - Anthropogenic climate forcing term
  - “Thermal” rather than “radiative” forcing
- Renewable sources (wind, hydro) are redistributed kinetic and potential energy, and thus do NOT introduce excess heat to the Earth system
  - Exception 1, Solar: Altered surface albedo from inefficient photovoltaic panels
  - Exception 2, Geothermal: Enhanced “conductivity” of heat to Earth's surface from interior

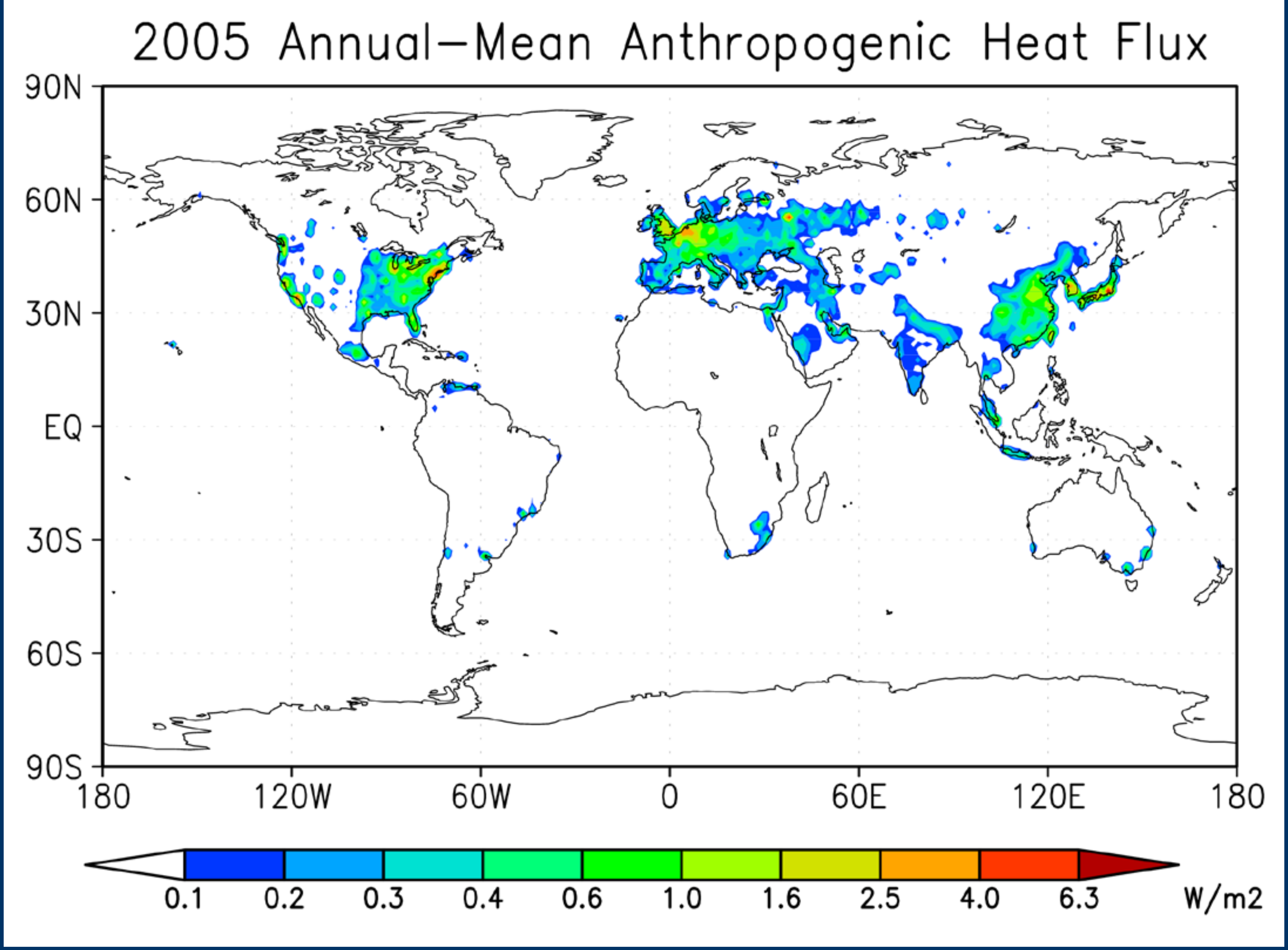
Methods for incorporating AHF into GCMs

- A) Prognostic scheme
  - e.g., embedded in urban model (*Oleson et al., 2008*), function of desired building environment relative to ambient
  - Advantages:
    - Sensible, latent heat flux changes are consistent with the "urban fabric"
    - Captures important feedback (e.g., enhanced A/C use from warmer ambient air induced by A/C use)
    - Will simulate enhanced AHF from increasing urbanization in land-use change simulations
- B) Prescribe "top-down" estimates of AHF
  - Advantages
    - Includes all primary energy (e.g., transportation, agricultural, industrial)
    - Yields most realistic present-day spatial distribution of AHF to test climate sensitivity

Methods for Approach B

- Country- and source-specific primary energy consumption data
  - e.g., chemical energy released from combustion
  - Source: U.S. Energy Information Administration
- Apportion energy dissipation within each nation according to population density
  - Source: Columbia University, 2.5-minute resolution
  - Most energy is dissipated quickly, and close to human settlement. Coarse GCM resolution averages out errors
- Prescribe crude annual and diurnal cycles to dissipated energy
- Introduce all energy to lowest layer of atmosphere
  - Future sensitivity studies: Heat dissipation in urban fabric, ground, different heights in atmosphere

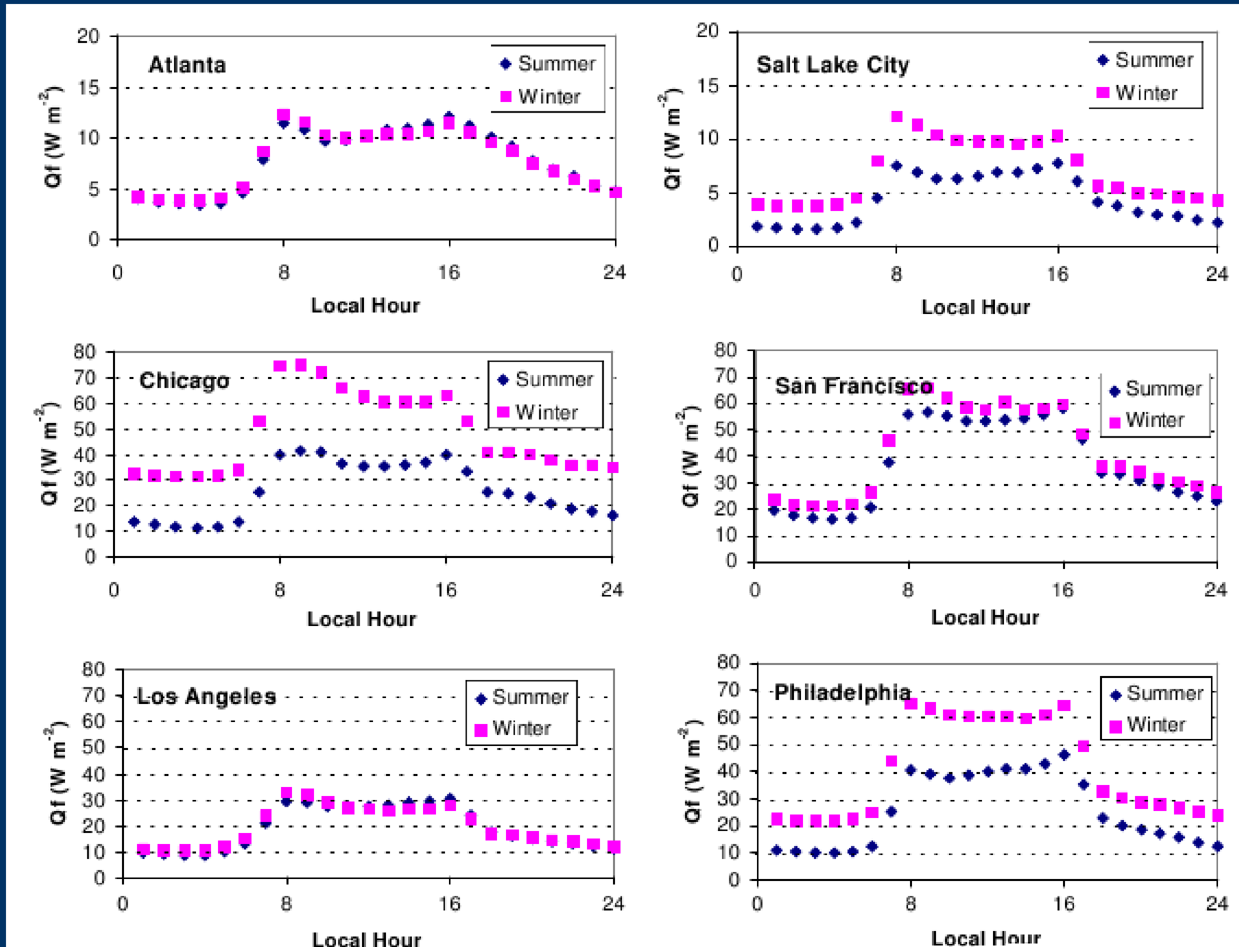
Results



Flanner (2009), *Geophys. Res. Lett.*

- Global, 2005: +0.028 W/m^2
  - Continental U.S: +0.39 W/m^2
  - Western Europe: +0.68 W/m^2
  - Netherlands: 4.2 W/m^2 (*de Laat et al.*, 2008)
  - Japan: 2.1 W/m^2

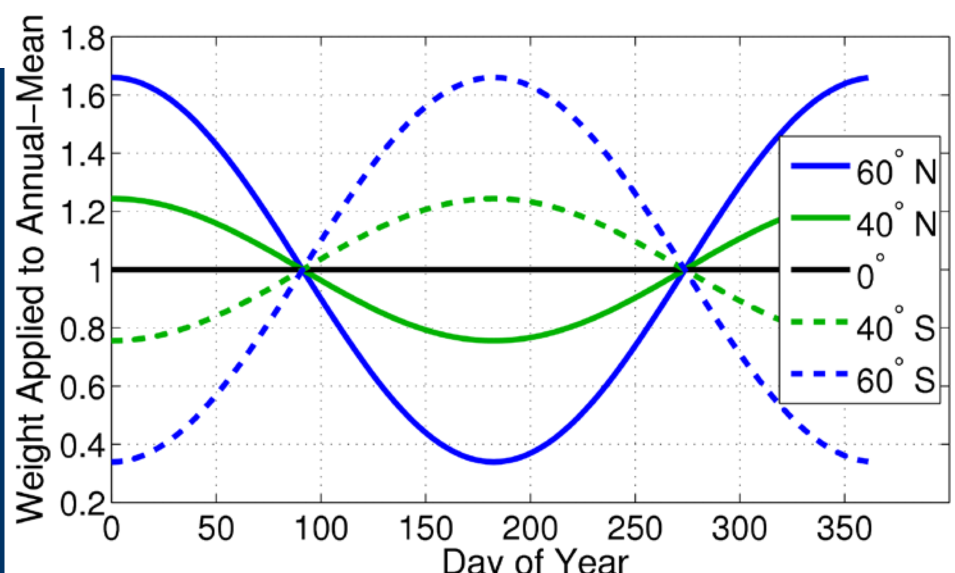
Temporal Variability

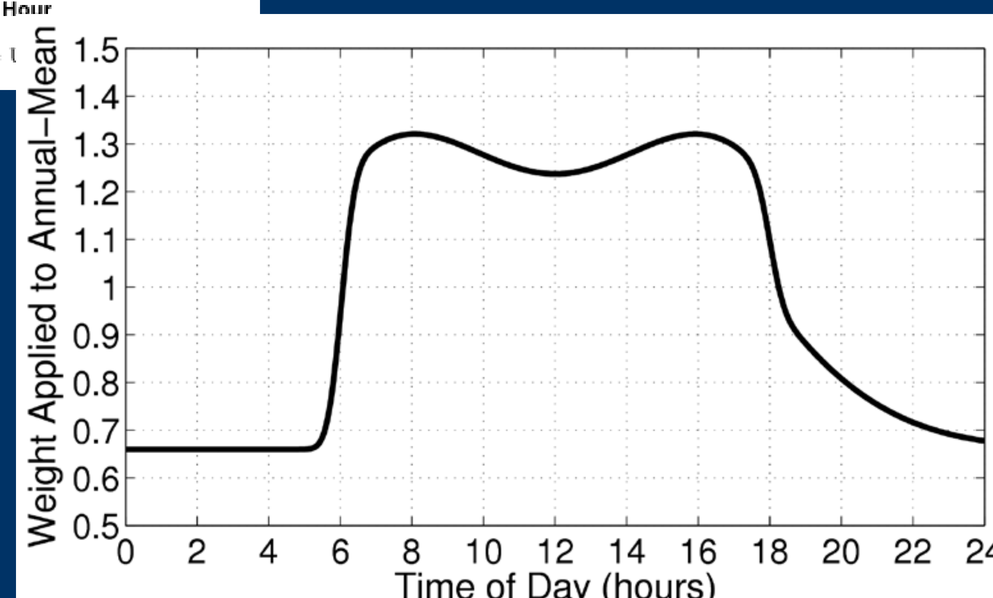


Sailor and Lu (2004), *Atmos. Environ.*

$$Q_{\mathrm{H}}(t_{\mathrm{d}}, t_{\mathrm{y}}) = \overline{Q_{\mathrm{H}}}\, w_{\mathrm{d}}(t_{\mathrm{d}}) w_{\mathrm{y}}(t_{\mathrm{y}})$$

Flanner (2009), *Geophys. Res. Lett.*



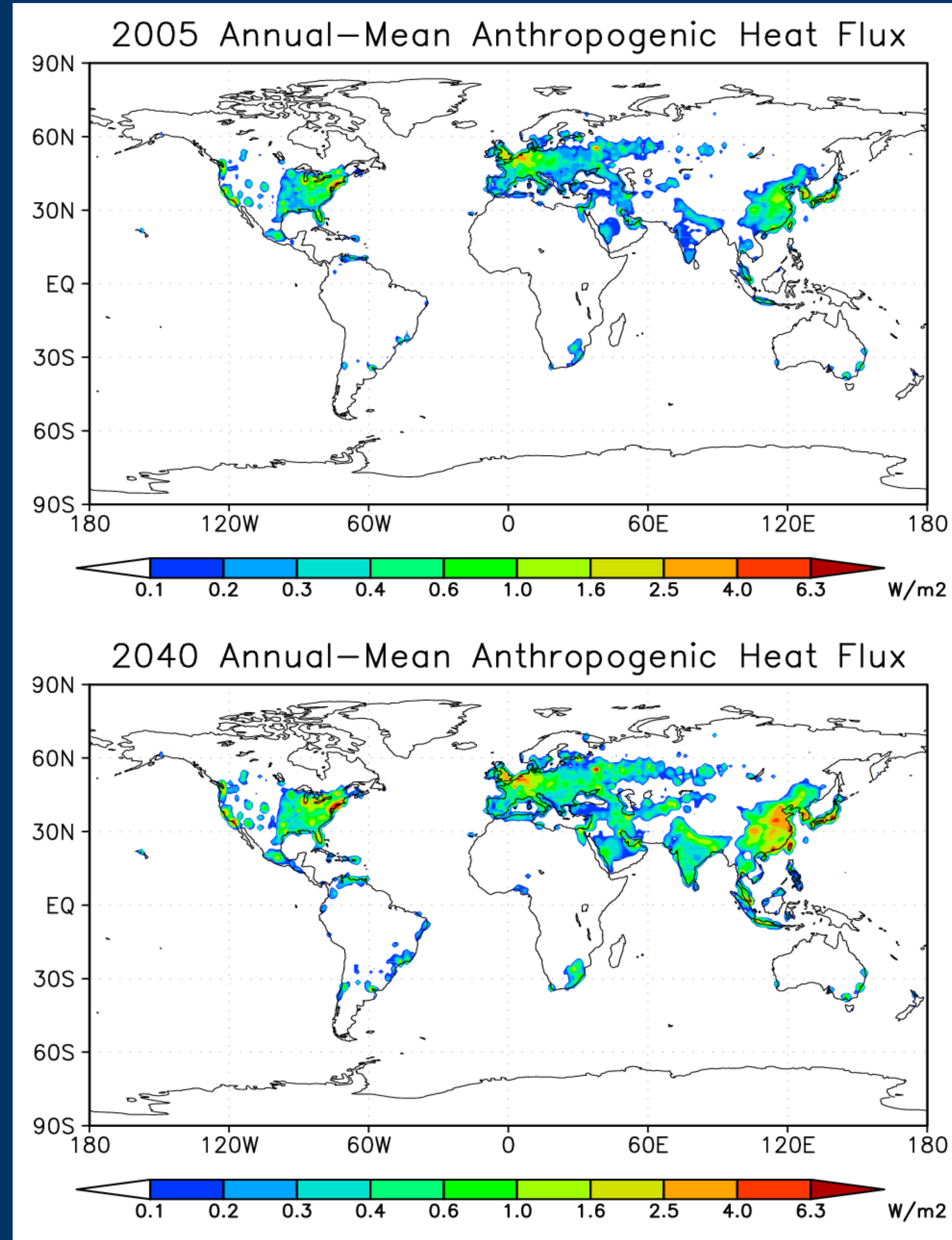


Future AHF

Table 1. Projected Non-Renewable Energy Growth Rates Through 2030[a]

Country Classification	Annual Growth Rate (% yr^{-1})
OECD[b] North America	1.2
OECD Europe	0.8
OECD Asia	1.0
non-OECD Eurasia	1.7
non-OECD Asia	3.6
non-OECD Middle East	2.4
non-OECD Africa	2.5
non-OECD Central and S. America	2.5

[a]Source: EIA International Energy Outlook: "High Economic Growth Case," Report #: DOE/EIA-0484(2008).
[b]Organization for Economic Co-operation and Development.



Flanner (2009), *Geophys. Res. Lett.*

2005 global-mean AHF: 0.03 W/m^2
2040 global-mean AHF: 0.06 W/m^2
2100 global-mean AHF: 0.19 W/m^2

Equilibrium temp, PBL height change

Over what scales does this effect matter?

Table 2. Statistically Significant Equilibrium Climate Changes[a]

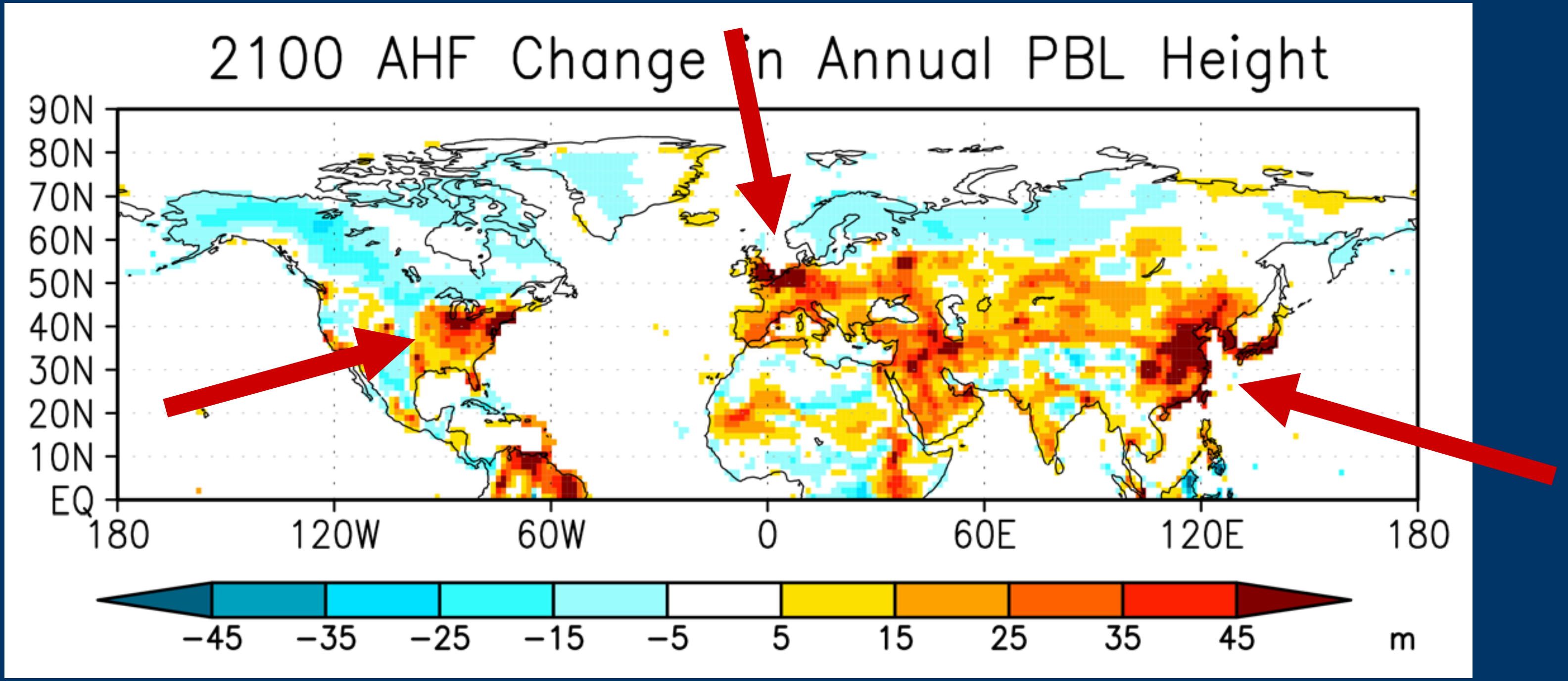
	Continental United States	Europe	East Asia	Gridcells With $\overline{Q}_H > 3.0$ W m^{-2}
2005 Annual-mean T_s (°C)	–	–	–	+0.15 (n = 14)
2005 Annual-mean h_{pbl} (m)	+16	–	–	+32
2040 Annual-mean T_s (°C)	–	–	–	+0.24 (n = 60)
2040 Annual-mean h_{pbl} (m)	–	–	–	+29
2040 Aerosol residence time	–	–	–	+2.5%
2100 Annual-mean T_s (°C)	+0.44	+0.54	+0.88	+0.76 (n = 414)
2100 Annual-mean h_{pbl} (m)	+15	+21	+45	+53

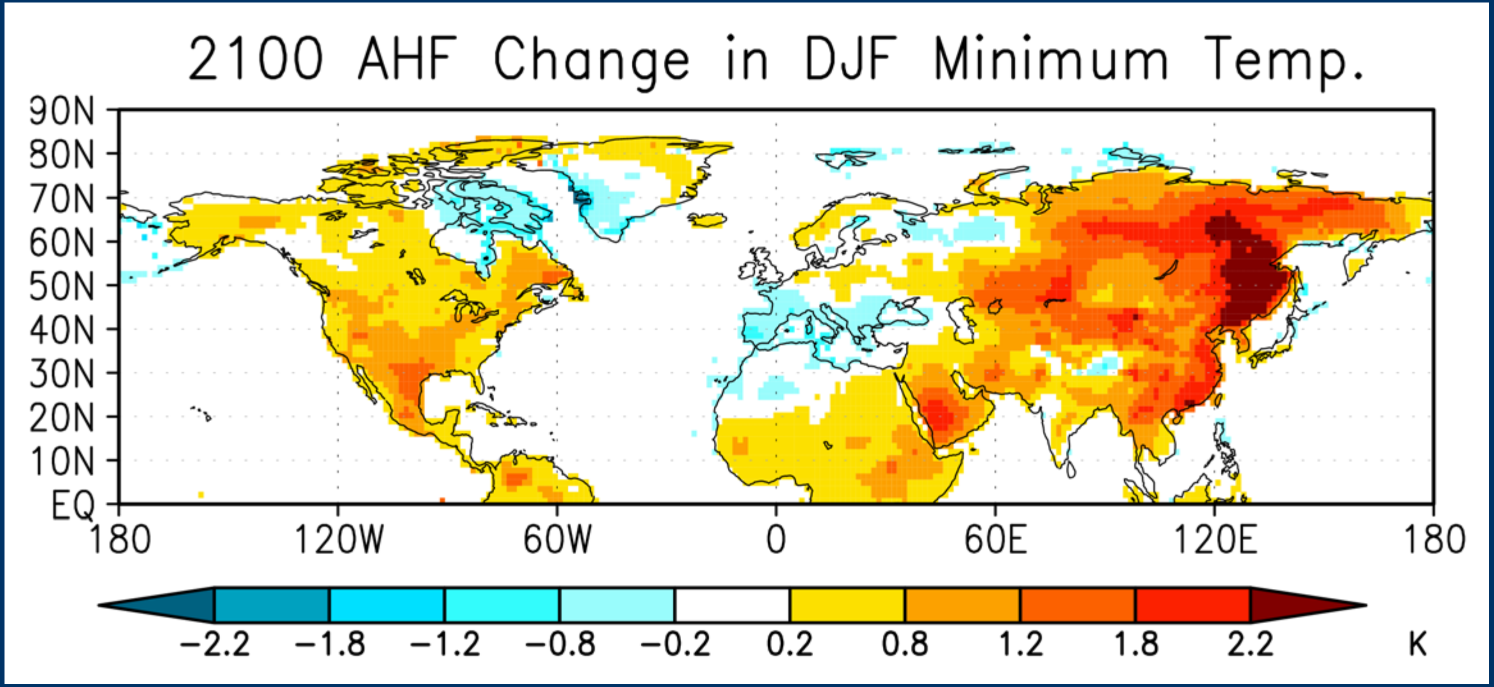
[a]Changes significantly different from zero at the 0.05 level. T_s, 2-meter air temperature; h_{pbl}, Planetary boundary layer height.

- Continental-scale warming is not apparent until 2100
- Local (gridcell)-scale warming and PBL expansion are apparent now
- Most pollutants are emitted from high-AHF regions

Large ensemble needed to answer when/where effects are most important.

Geographic pattern of changes





Conclusions

- AHF is a small, but “missing” energy term in contemporary climate models
- AHF is a climate forcing term:
  - All non-renewable primary energy use
  - 2005 global-mean: +0.03 W/m^2
  - 2005 Netherlands: +4.2 W/m^2
  - 2100 global-mean: +0.19 W/m^2 (= present N_2O forcing)
- Significant present-day warming and PBL expansion in gridcells with AHF > 3.0 W/m^2
  - Most pollutants emitted concurrently with combustion (e.g., large AHF); may be lofted higher in atmosphere
- Current energy growth rates produce continental-scale surface warming of 0.4-0.9°C around 2100
  - No significant signal produced from 2005 or 2040 scenarios
- Could be important for regional climate projections

Original work

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Numerical Climatic-Change Experiments: The Effect of Man's Production of Thermal Energy

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ABSTRACT

We describe in this paper a set of general circulation model experiments on possible climatic changes caused by man's generation of thermal energy or pollution. Three experiments were carried out: one in which we introduced only a small initial error, one in which we added the expected ultimate levels of thermal energy generation, and one in which we added a *negative* amount of thermal energy. In all three experiments, we obtained the same results, indicating that the thermal pollution effect is probably small compared to the natural fluctuations of the model. We also discuss some limitations of the present model for inferring the proper climatic-change response.