U.S. summertime surface warm bias in models – A summary from the CAUSES project

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with

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CESM Atmosphere Model Working Group Meeting, Boulder, CO

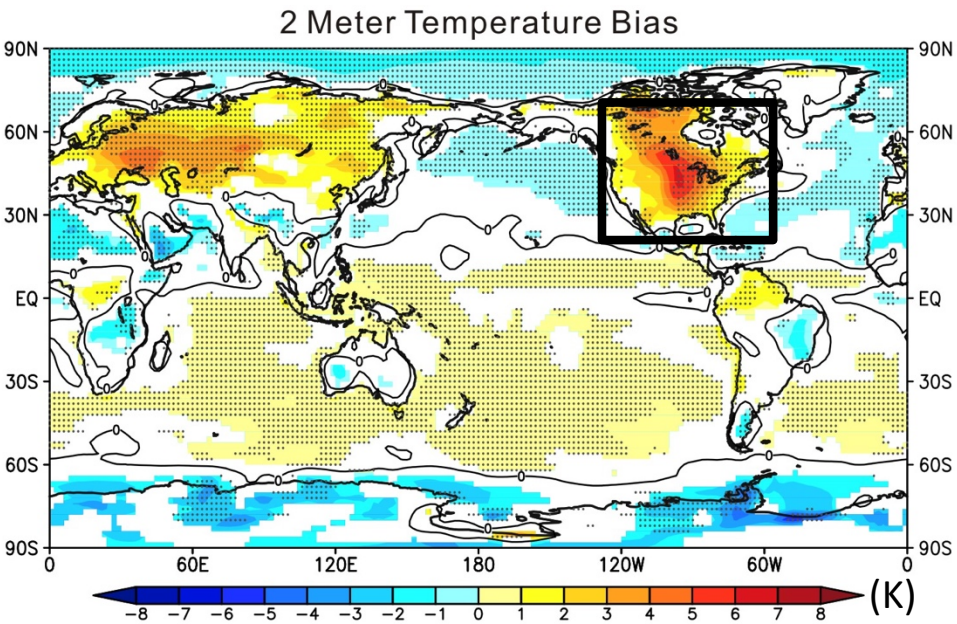
February 12 - 14, 2018

LLNL-PRES-746118

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Systematic T_{2m} bias in global climate models

CMIP5/AMIP Multi-Model Mean JJA T2m bias

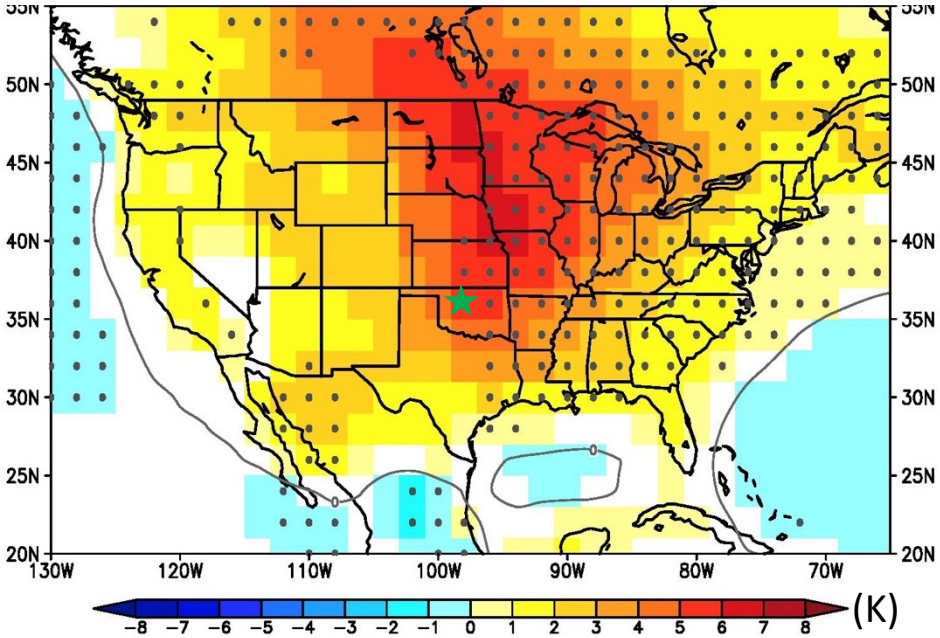


Ma et al. (2014 JCLI)

- Contemporary global climate models (or weather forecasting models) show large systematic bias in surface air temperatures over land during northern summer.
- Large systematic biases in climate models hinder the fidelity of climate simulations and their future projections (e.g., Cheruy et al GRL 2014; Lin et al. Nat Commun 2017).

What is CAUSES (Cloud Above the United States and Errors at the Surface)?

CMIP5/AMIP Multi-Model Mean JJA T2m bias



- The role of precipitation and surface energy budget (led by LLNL)
- The role of clouds and radiation (led by U.K. Met Office)

- CAUSES is an multi-model intercomparison project aiming to understand the contributors to the robust warm-bias in modeled summertime surface air temperature over the Central U. S. using hindcast approach.
- Hindcasts from 9 global models (2 NWP, 8 climate) and 1 regional model (2 versions), supplemented by an analysis of AMIP integrations from 23 CMIP5 models

GASS GEWEX WCRP Global Atmospheric System Studies

RGCM

ASR Atmospheric System Research

Met Office

Science Questions to Address

- What is the role of cloud and radiation errors?
  - (1) What is the contribution of radiation errors to the temperature errors?
  - (2) How much of the errors in radiation result from errors in clouds and their properties?
  - (3) Which cloud regimes contribute most the radiation errors?
- What is the role of precipitation and surface energy budget errors?
  - (1) Does this atmosphere provide the correct amount of precipitation for the soil?
  - (2) Does the surface energy balance reveal signs that evaporation is underestimated due to the lack of soil moisture?

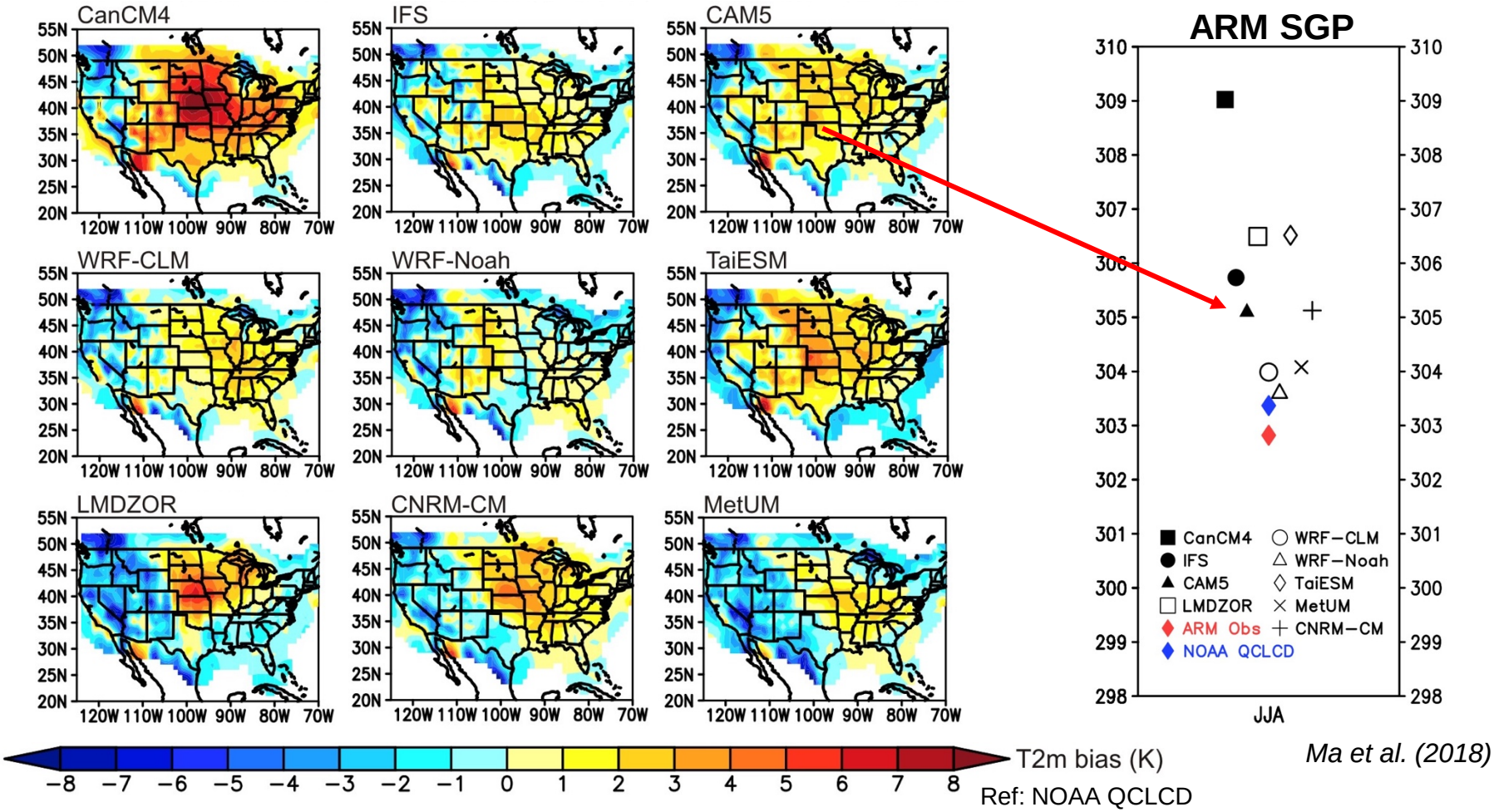
Outline

- Warm bias characteristics
- Surface energy budget analysis
- Attribution of radiation errors to clouds and other causes
- Theoretical interpretation of warm bias contribution
  - Based on four manuscripts accepted by JGR (Morcrette et al. 2018; Ma et al. 2018; Van Weverberg et al. 2018; Zhang et al. 2018)
  - CAUSES Web Page

    http://portal.nersc.gov/project/capt/CAUSES/

Warm bias characteristics

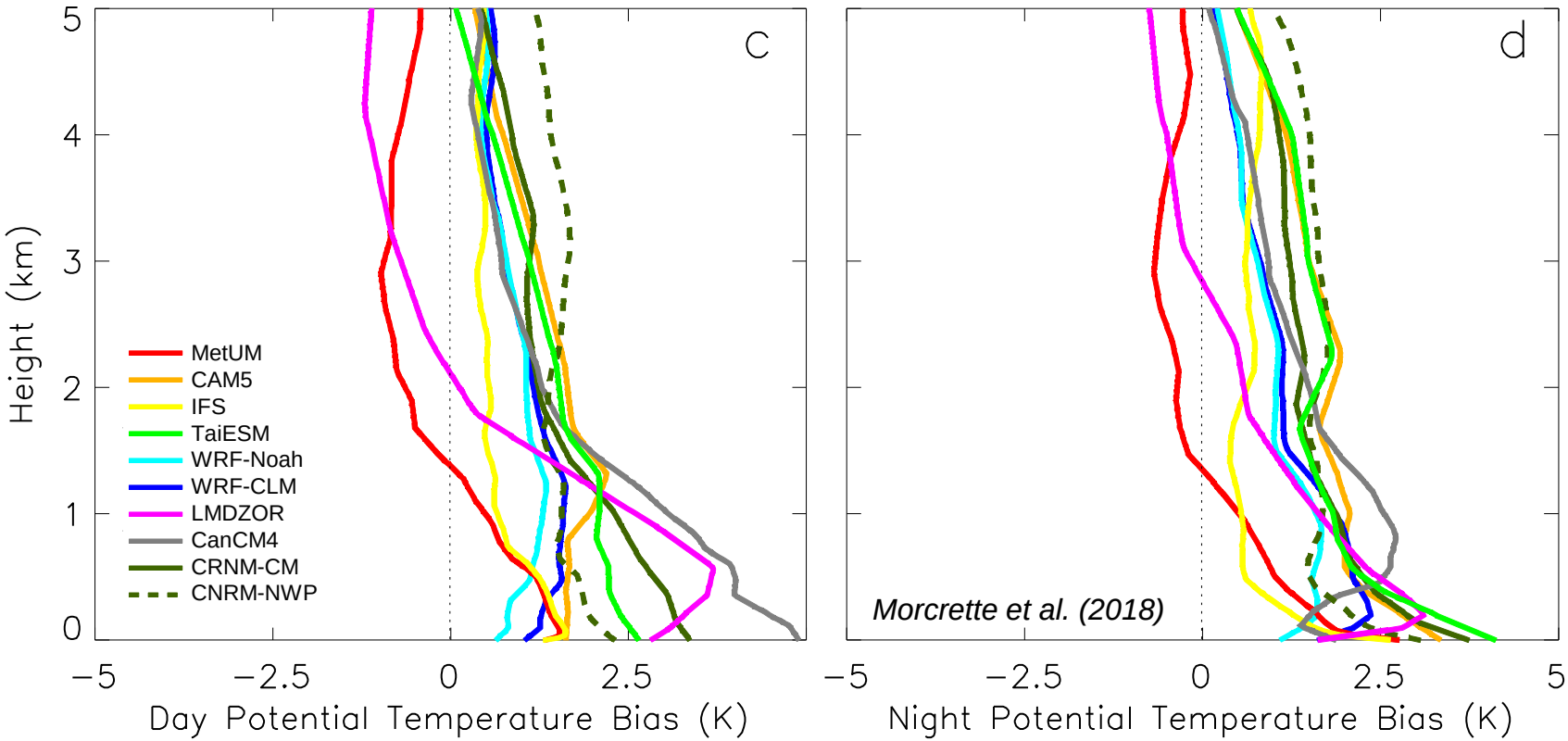
2 meter temperature bias (2011, Day 2-5 JJA mean)



Ma et al. (2018)

- All model simulate warm T2m bias over the central U.S. (CAM5 ~ +2.2K)
- Warm bias is more significant in June-August than in April-May.

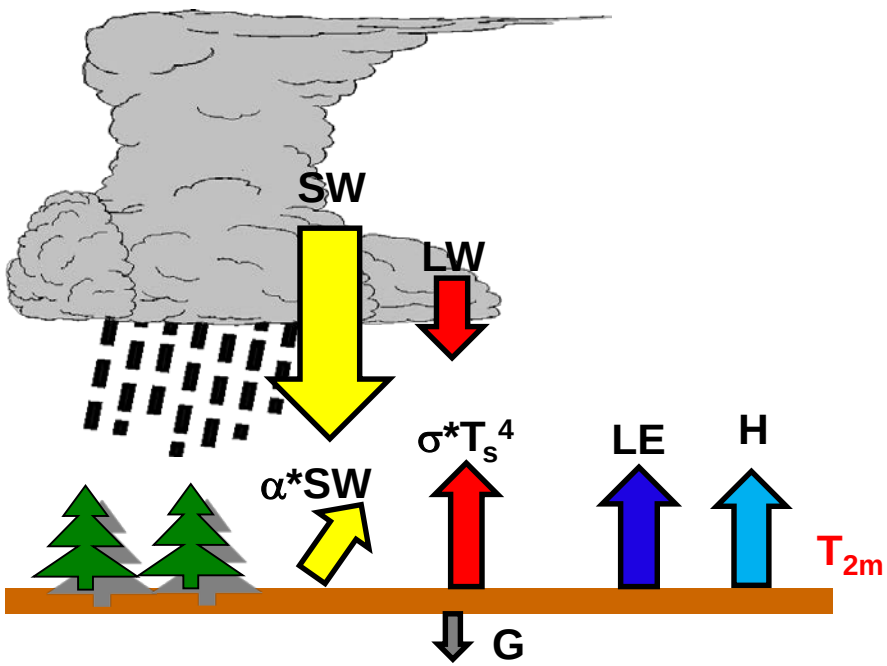
Vertical structure of potential temperature bias over the SGP



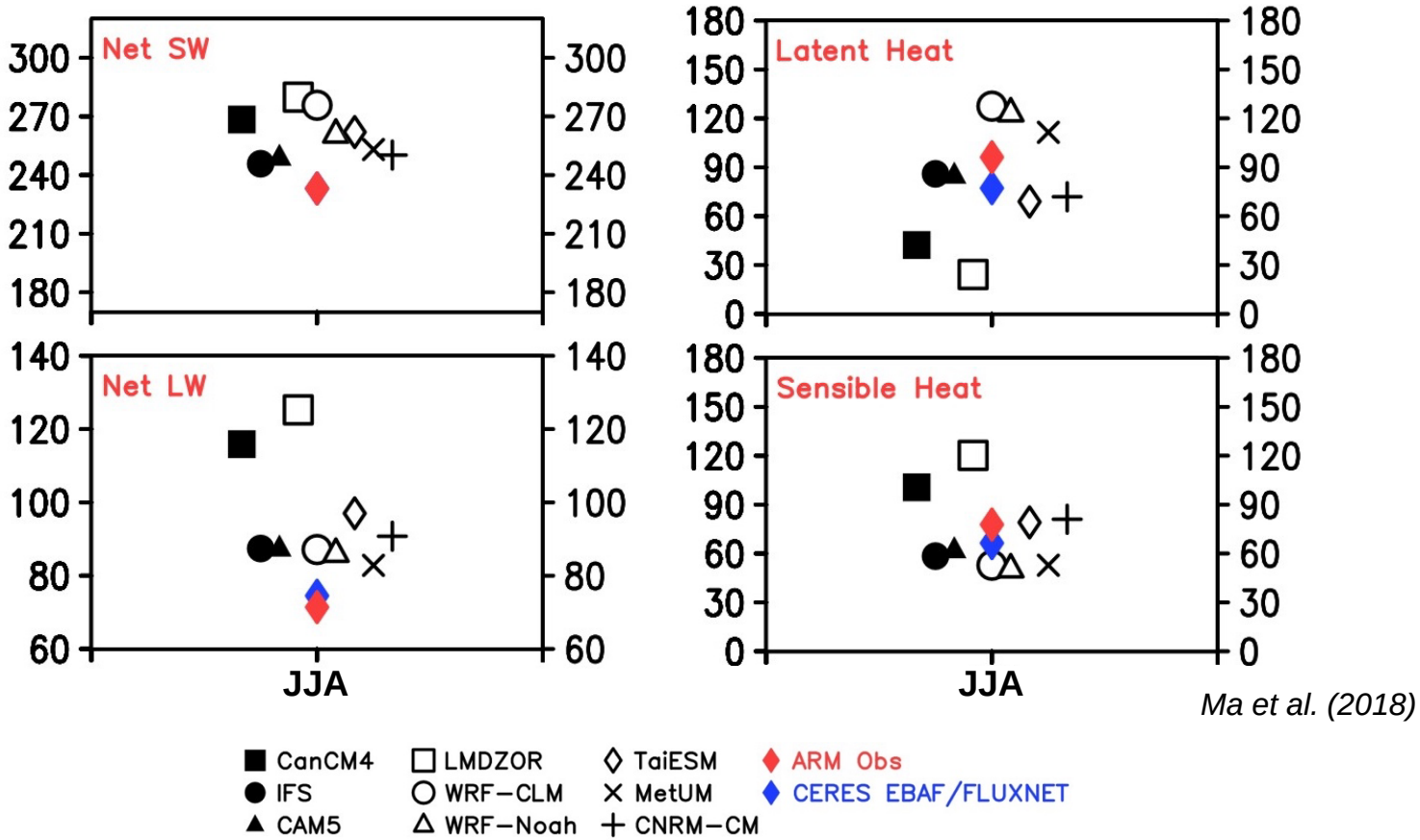
- The warm bias not only occurs near the surface but also in the lower atmosphere during day and night throughout the Central U. S. including at ARM's SGP site.
- There is also diurnal variation in the bias magnitude.

(Obs: Soundings from MC3E Campaign at ARM SGP, April 22 – June 6, 2011)

Surface energy budget analysis



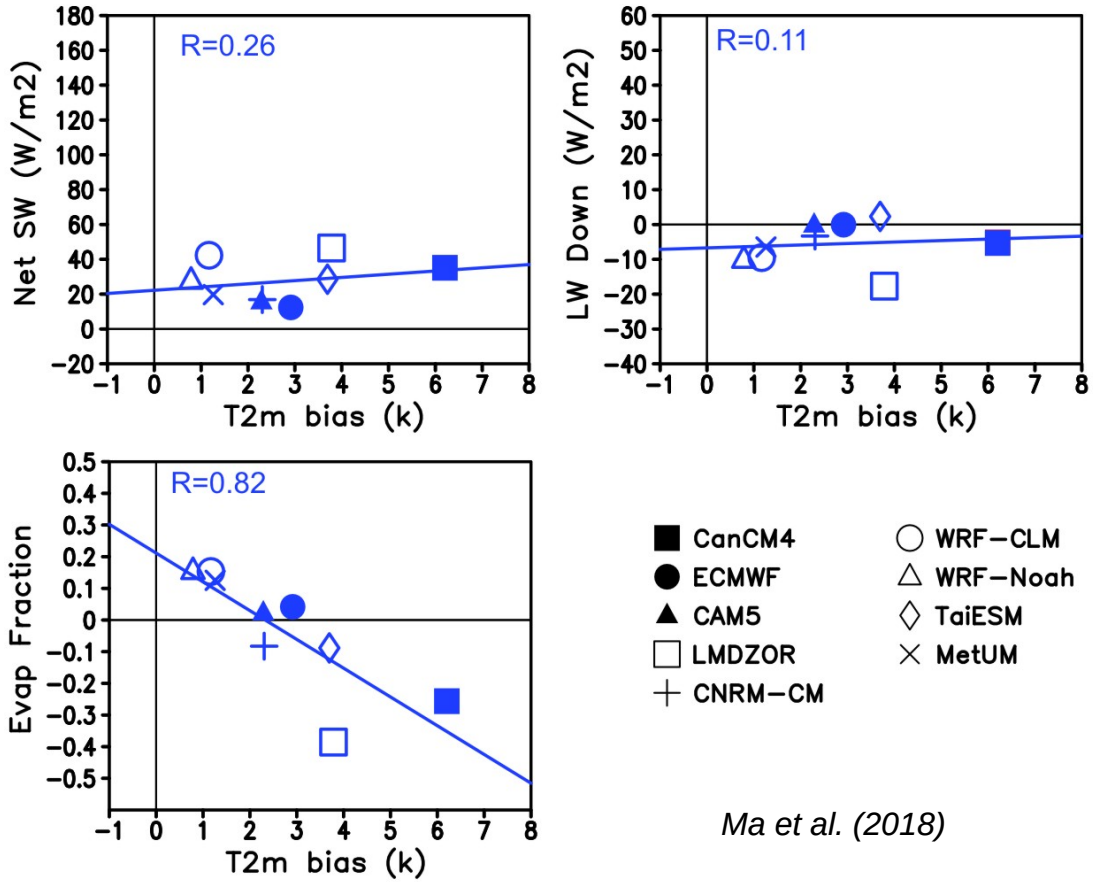
JJA mean surface energy budget at ARM SGP



Ma et al. (2018)

- All models overestimate surface net shortwave flux mostly due to cloud problems.
- All models overestimate surface net longwave flux consistent with warm T_{2m} bias.
- There is no consistent mean bias sign in the sensible or latent heat fluxes.

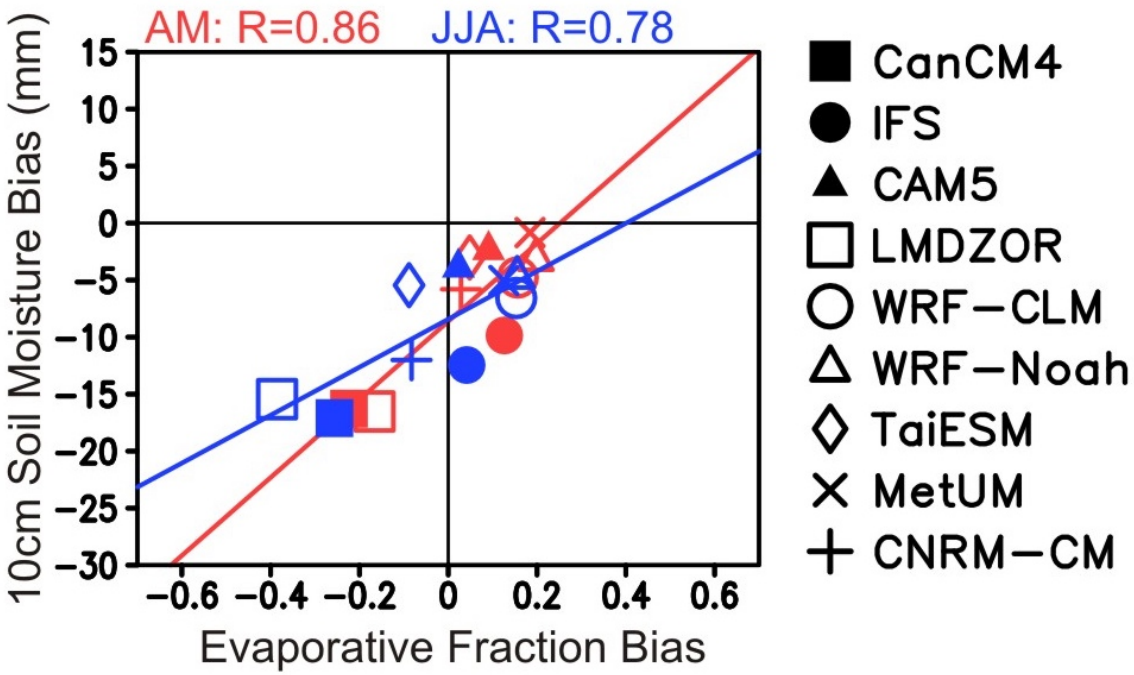
Connection between T_{2m} bias and surface energy budget bias



Ma et al. (2018)

- Models with larger negative evaporative fraction (EF: latent/(latent+sensible)) bias magnitudes are likely to simulate larger T_{2m} mean bias on seasonal time scales.

Water budget analysis



Ma et al. (2018)

- EF mean bias is largely correlated with soil moisture mean bias.
- Day-to-day changes in the soil moisture are largely affected by the seasonal accumulated precipitation minus accumulated evaporation (P-E).

Attribution of radiation errors to clouds and other causes

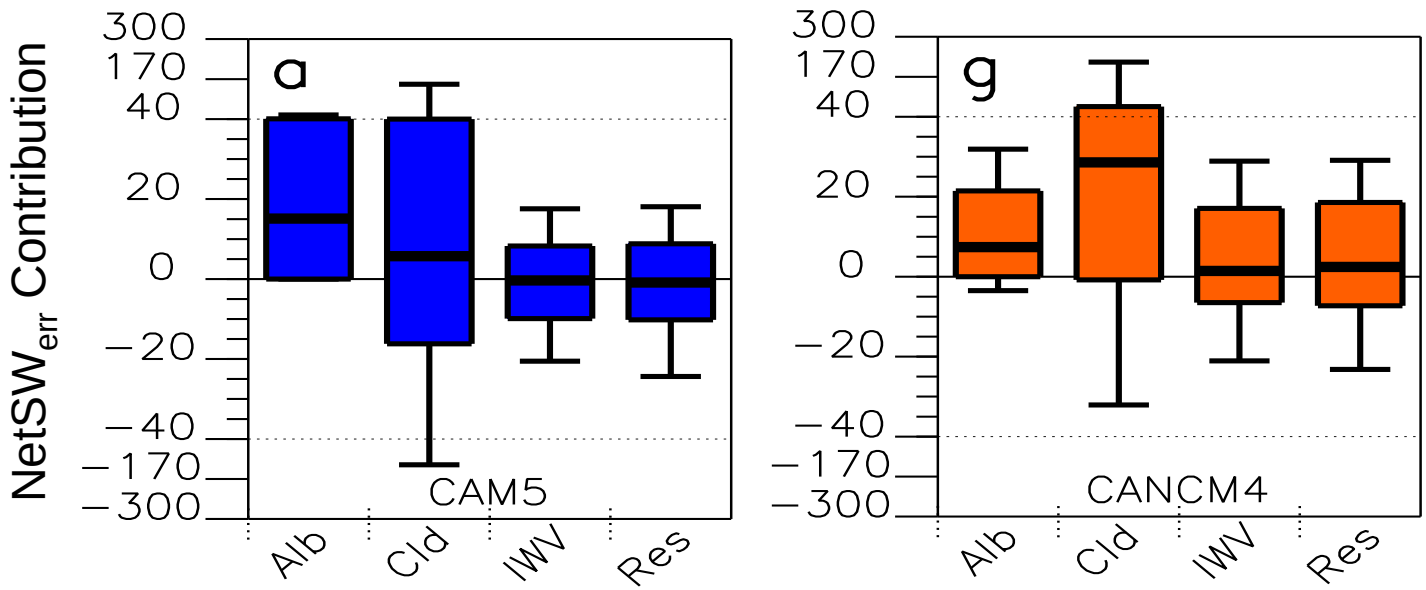
Decomposition of radiation biases

$$NetSW_{err} = SWDN_{mod} - SWUP_{mod} - (SWDN_{obs} - SWUP_{obs}) \quad (1)$$

…

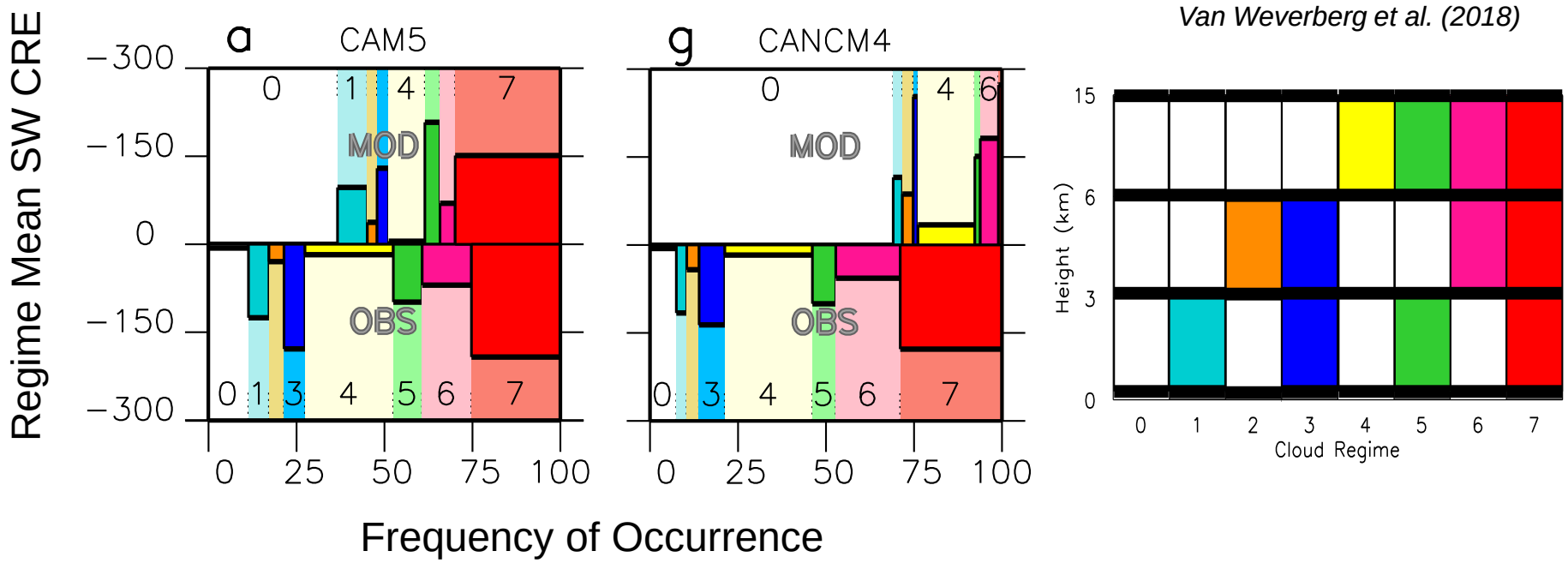
$$NetSW_{err} = \underbrace{(1 - \alpha_{obs}) * SWDN_{clr,\,err}}_{\text{SW clear-sky error}} + \underbrace{(1 - \alpha_{obs}) * SWDN_{cre,\,err}}_{\text{SW cloud radiative effect error}} - \underbrace{\alpha_{err} * SWDN_{obs}}_{\text{Surface albedo effect error}} \quad (2)$$

Van Weverberg et al. (2018)
Zhang et al. (2018)



- The NetSW is overestimated in all models: (1st) cloud radiative effect (CRE), (2nd) surface albedo.

SW_{cre} from different cloud regimes



- CRE associated with deep cloud regime (regime 7) dominates the total CRE error in CAM5 and other models.
- Small error of total CRE in CAM5 is due to compensating errors between a too large frequency and a too small CRE with deep cloud regime.

Theoretical interpretation of warm bias contribution

- Excess radiation absorbed directly heats the surface causing a warm bias.
- If evaporation is suppressed, radiative heating (even if unbiased) will be used to heat the surface instead of evaporating water causing a warm bias.

Theoretical interpretation of warm bias

$$SW + LW = SH + LH, \quad (1)$$

$$SW' + LW' = SH' + LH', \quad (2)$$

$$SW' + LW' = (\gamma SH)', \qquad \gamma = 1 / (1 - EF) \quad (3)$$

$$(SW' + LWDN') - SH_{mod}\gamma' = LWUP' + \gamma_{obs} SH', \quad (4)$$

$$(SW' + LWDN') - SH_{mod}\gamma' = \left(\frac{\partial LWUP}{\partial T_{2m}} + \gamma_{obs}\frac{\partial SH}{\partial T_{2m}}\right) T'_{2m}, \quad (5)$$

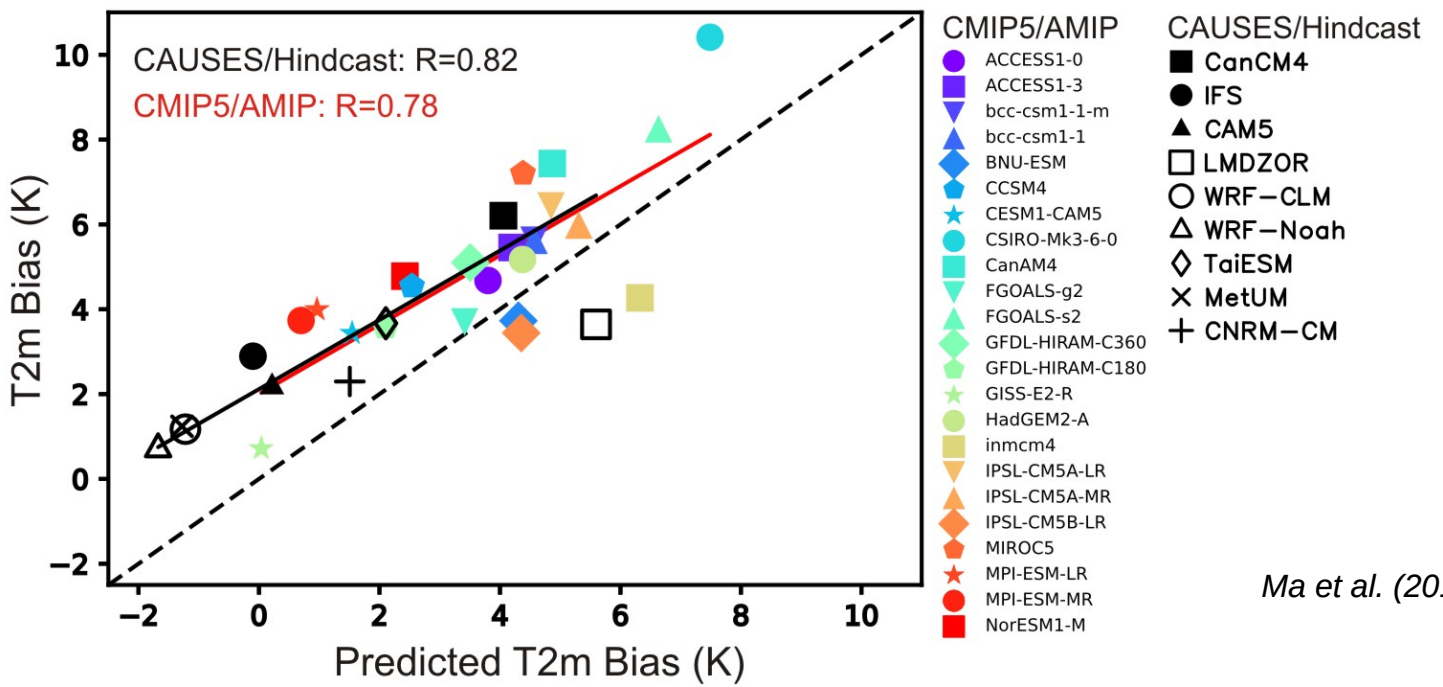
$$(SW' + LWDN') - EF'\gamma_{obs}(SH_{mod} + LH_{mod}) = \left(\frac{\partial LWUP}{\partial T_{2m}} + \gamma_{obs}\frac{\partial SH}{\partial T_{2m}}\right) T'_{2m}, \quad (6)$$

$$T'_{2m} = \frac{(SW' + LWDN')}{\frac{\partial LWUP}{\partial T_{2m}} + \gamma_{obs}\frac{\partial SH}{\partial T_{2m}}} - \frac{EF'\ \gamma_{obs}(SH_{mod} + LH_{mod})}{\frac{\partial LWUP}{\partial T_{2m}} + \gamma_{obs}\frac{\partial SH}{\partial T_{2m}}}, \quad (7)$$

Given $\frac{\partial LWUP}{\partial T_{2m}} = 7$, $\frac{\partial SH}{\partial T_{2m}} = 9$, γ_{obs}=2.5 from model values and observations,

Ma et al. (2018)

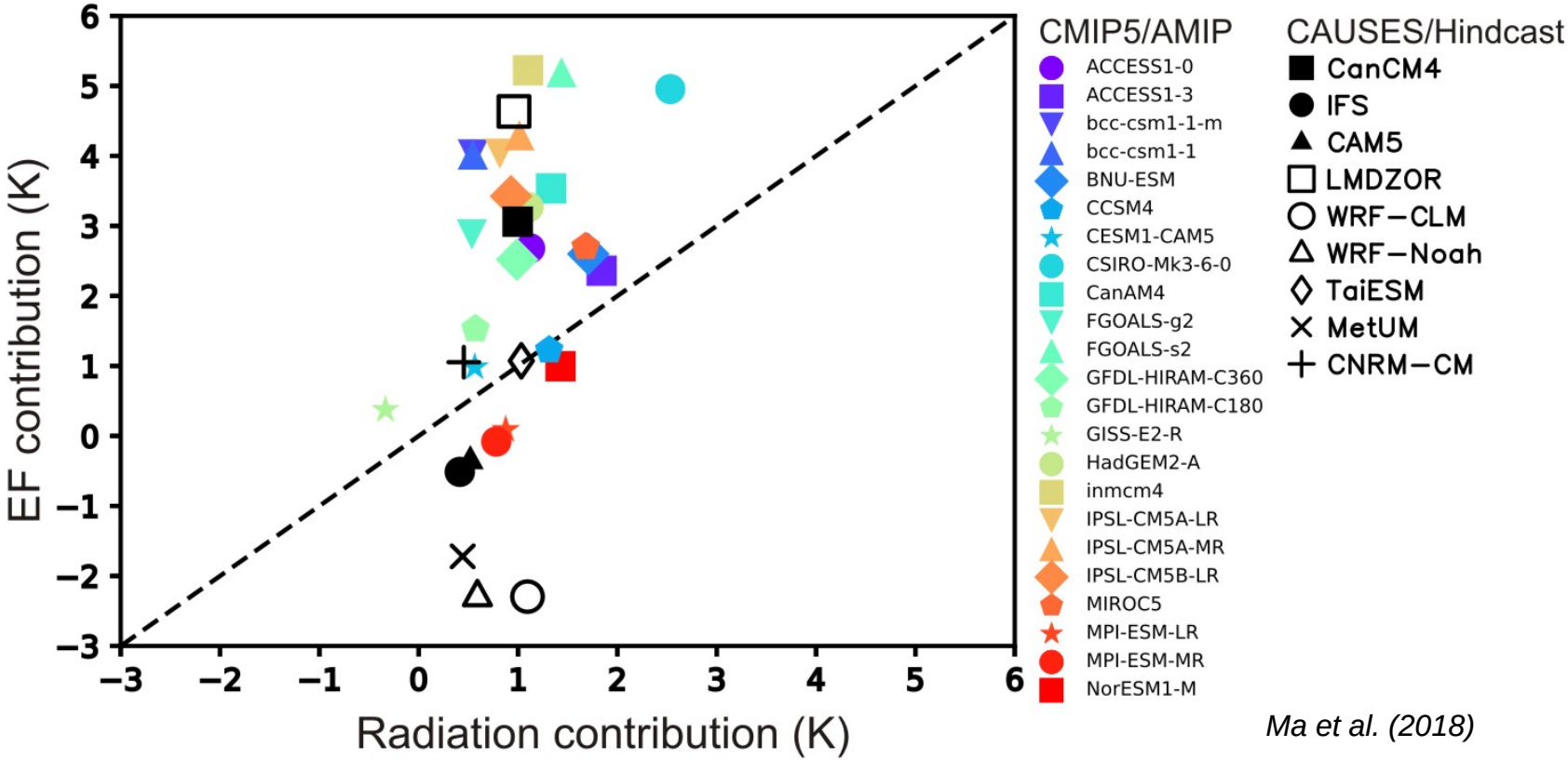
$$T'_{2m} = \underbrace{\frac{(SW' + LWDN')}{30\ W\ m^{-2}K^{-1}}}_{\text{Radiation Contribution}} - \underbrace{\frac{2.5\ EF'(SH_{mod} + LH_{mod})}{30\ W\ m^{-2}K^{-1}}}_{\text{Evaporative Fraction Contribution}} . \qquad (8)$$



Ma et al. (2018)

- The approximate equation predicts the T2m bias well with the biases estimated from radiation and evaporative fraction biases.

Relative contribution of radiation and evaporative fraction biases



Ma et al. (2018)

- Contribution from surface radiation biases (shortwave absorbed and downward longwave fluxes) is ~ 0.5 – 2 K for most models while contribution from evaporative fraction bias varies from ~ -2.5 to 5.5K.
- Long-term climate simulations (CMIP5/AMIP) show larger positive evaporative fraction biases than short-term hindcasts.

Summary

- Warm bias is present in the first few days of hindcasts, and occurs not only near the surface but also in the lower atmosphere during day and night.
- Warm bias is due to (1) too much SW (atmospheric model problem) and (2) too low evaporative fraction (atmospheric and land model problem).
- Too much SW are primarily due to underestimates in the radiative effects of deep convective clouds (Too infrequent deep convection or insufficiently reflective clouds when deep convection occurs).
- Too low EF are primarily due to low soil moisture and precipitation.
- Radiation errors explain 0-2 K of the warm bias but vary much less than EF errors. EF errors explain most of the temperature bias in the models with large warm biases, but they compensate for the radiation error in the models with small temperature bias.

Thank you and questions?

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