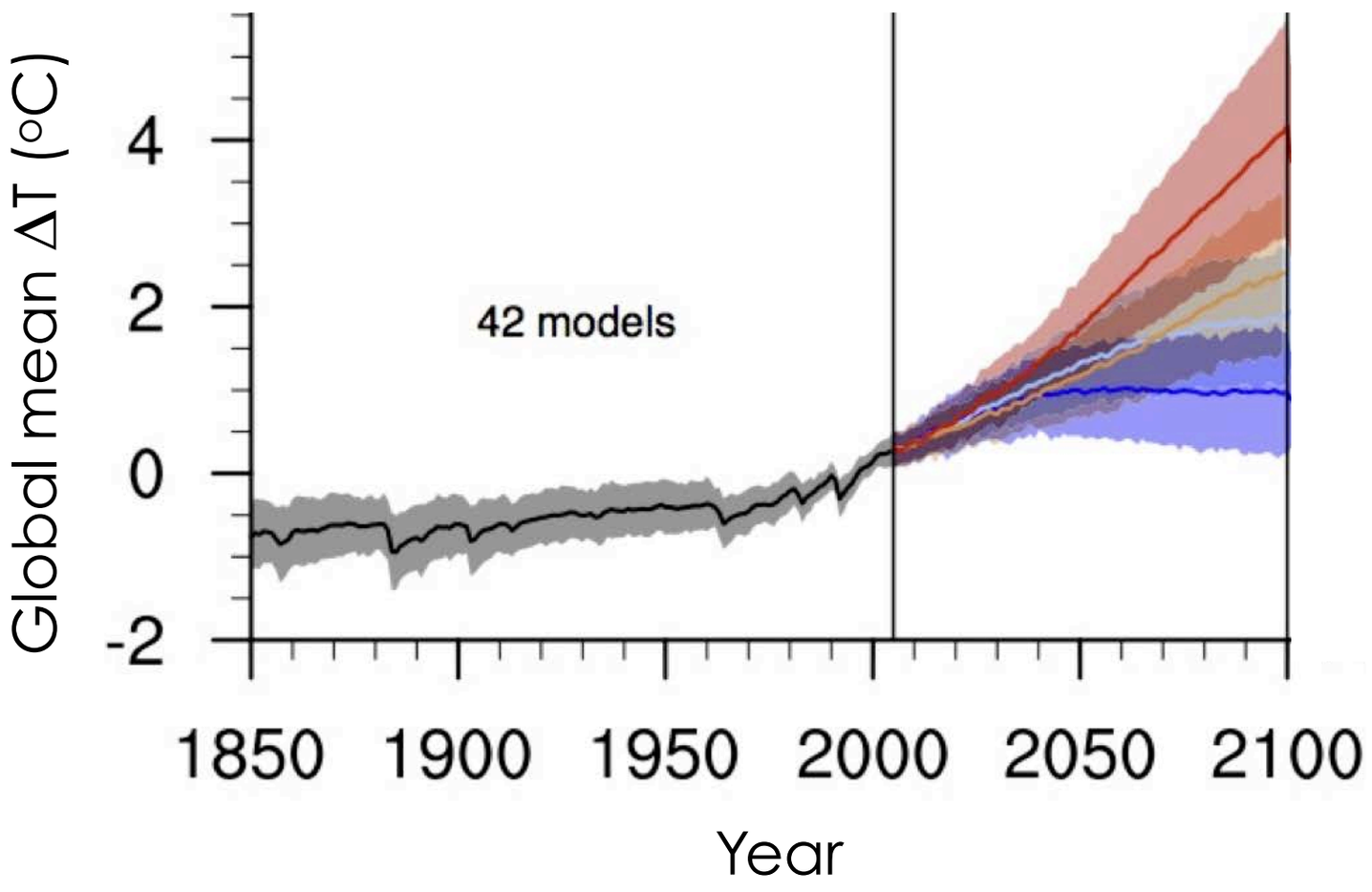
Regional 21st century warming determined by low-latitude cloud feedbacks & mediated by large-scale heat transport

CFMIP 2019, Mykonos, Greece
Cristian Proistosescu, David Battisti, Gerard Roe, Kyle Armour, Nick Lutsko, Paolo Ceppi, Aaron Donohoe

What index is most useful for projections?

If we want to know how much a model warms over the 21st century* is it better† to know its

- TCR
- ECS
- ?



Grose et al 2018

What index is most useful for projections?

If we want to know how much a model warms over the 21st century* is it better to know its

- TCR 59 % variance explained
- ECS 90 % variance explained

?

What Climate Sensitivity Index Is Most Useful for Projections?

Michael R. Grose[1], Jonathan Gregory[2], Robert Colman[3], and Timothy Andrews[4]

[1]CSIRO Climate Science Centre, Hobart, Tasmania, Australia, [2]University of Reading, Reading, UK, [3]Bureau of Meteorology, Docklands, Victoria, Australia, [4]Met Office, Exeter, UK

Grose et al 2018

We DO live in the long-term global mean

CFMIP 2019, Mykonos, Greece
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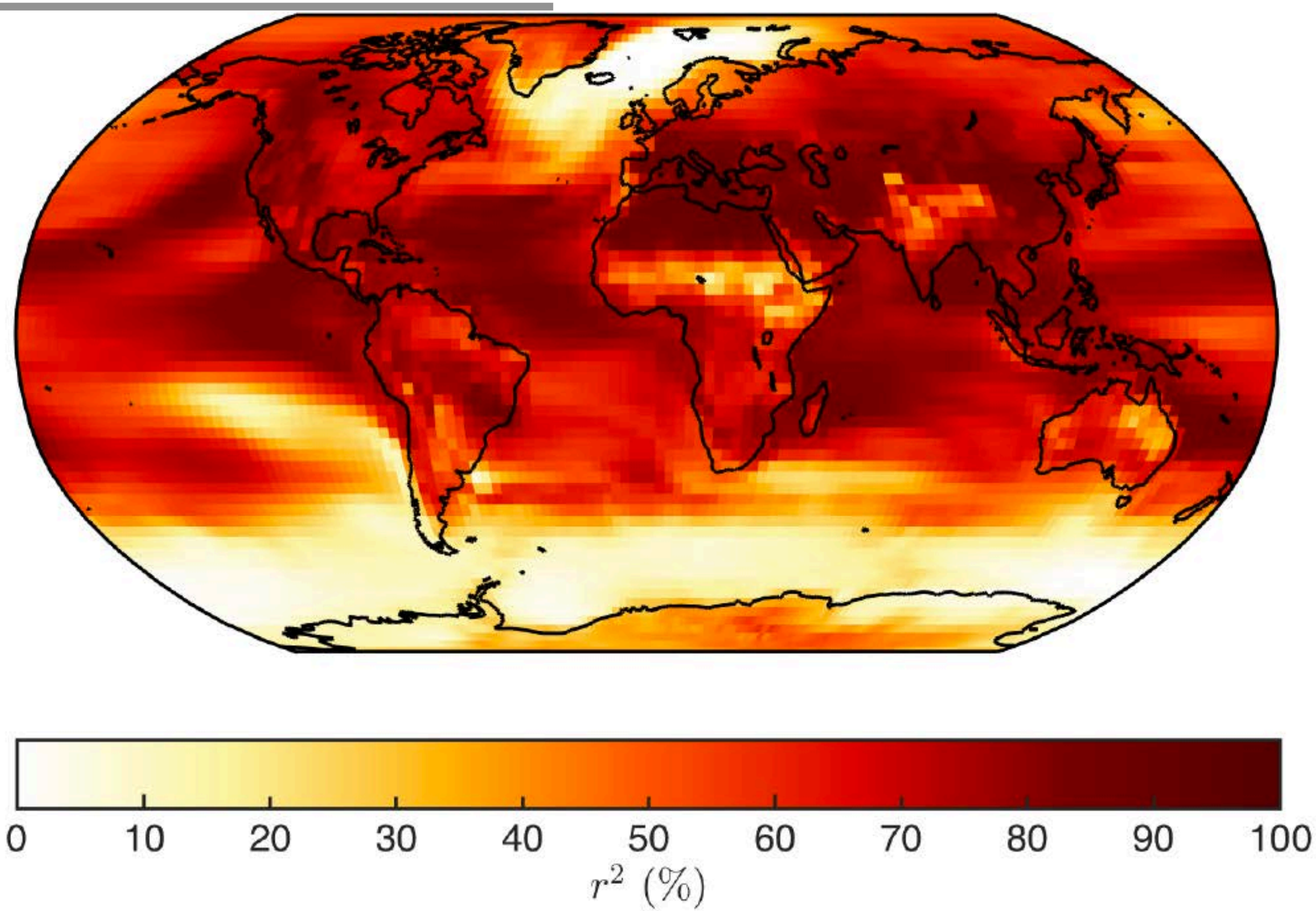
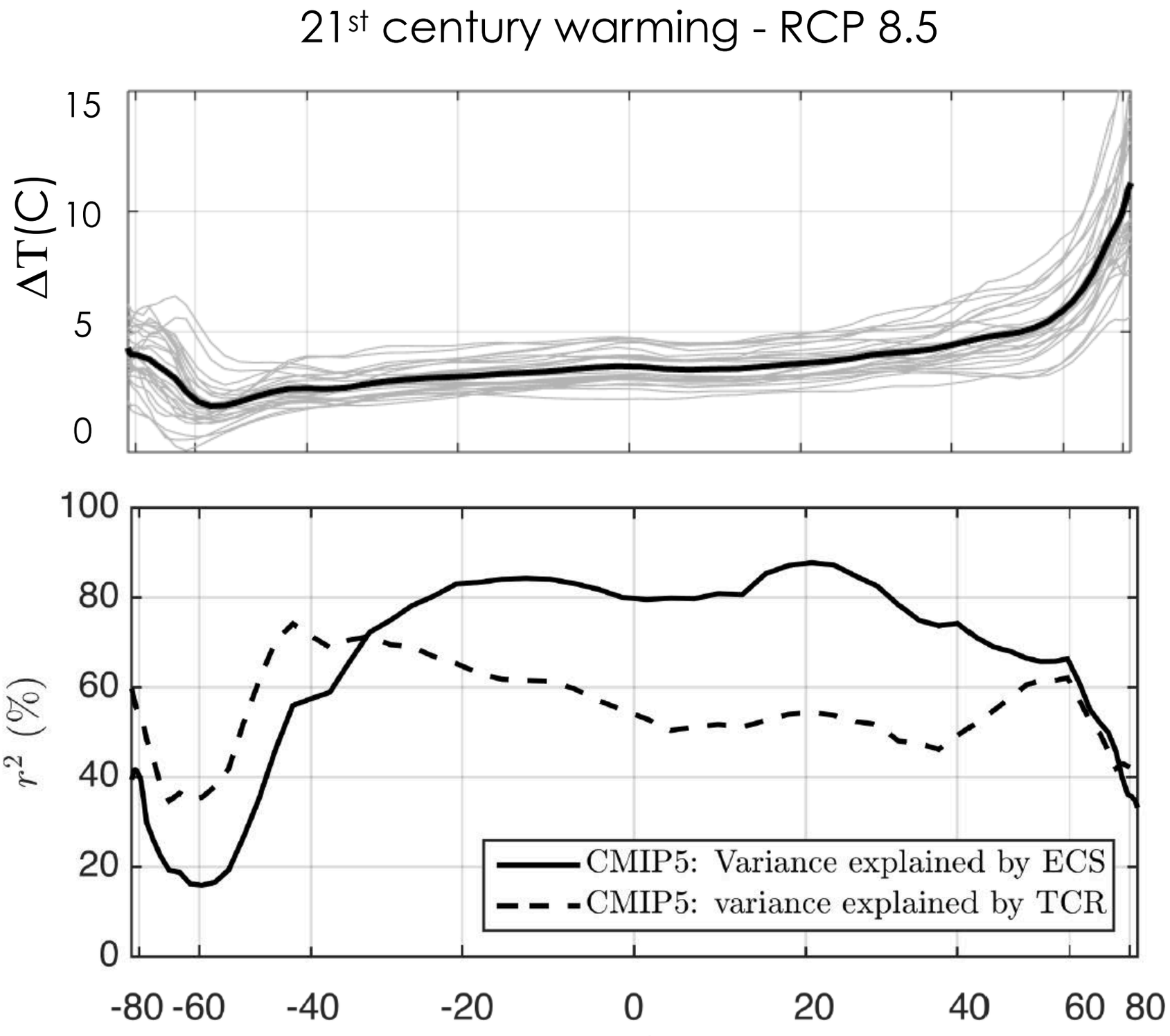
Q: What do I do to improve projections of 21st century warming in Greece (or Iowa)?
A: Fix ECS! (…and whatever fixes ECS)



- Variance of model projections of local warming explained by ECS
- Warning: do not attempt for precipitation

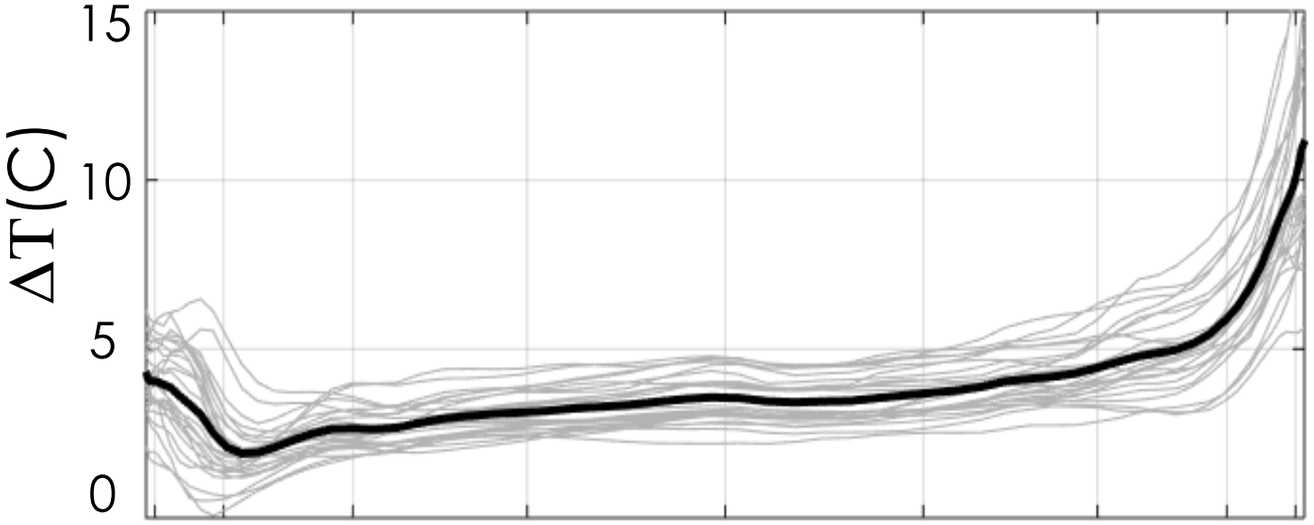
Grose et al 2018
Proistosescu et al in prep

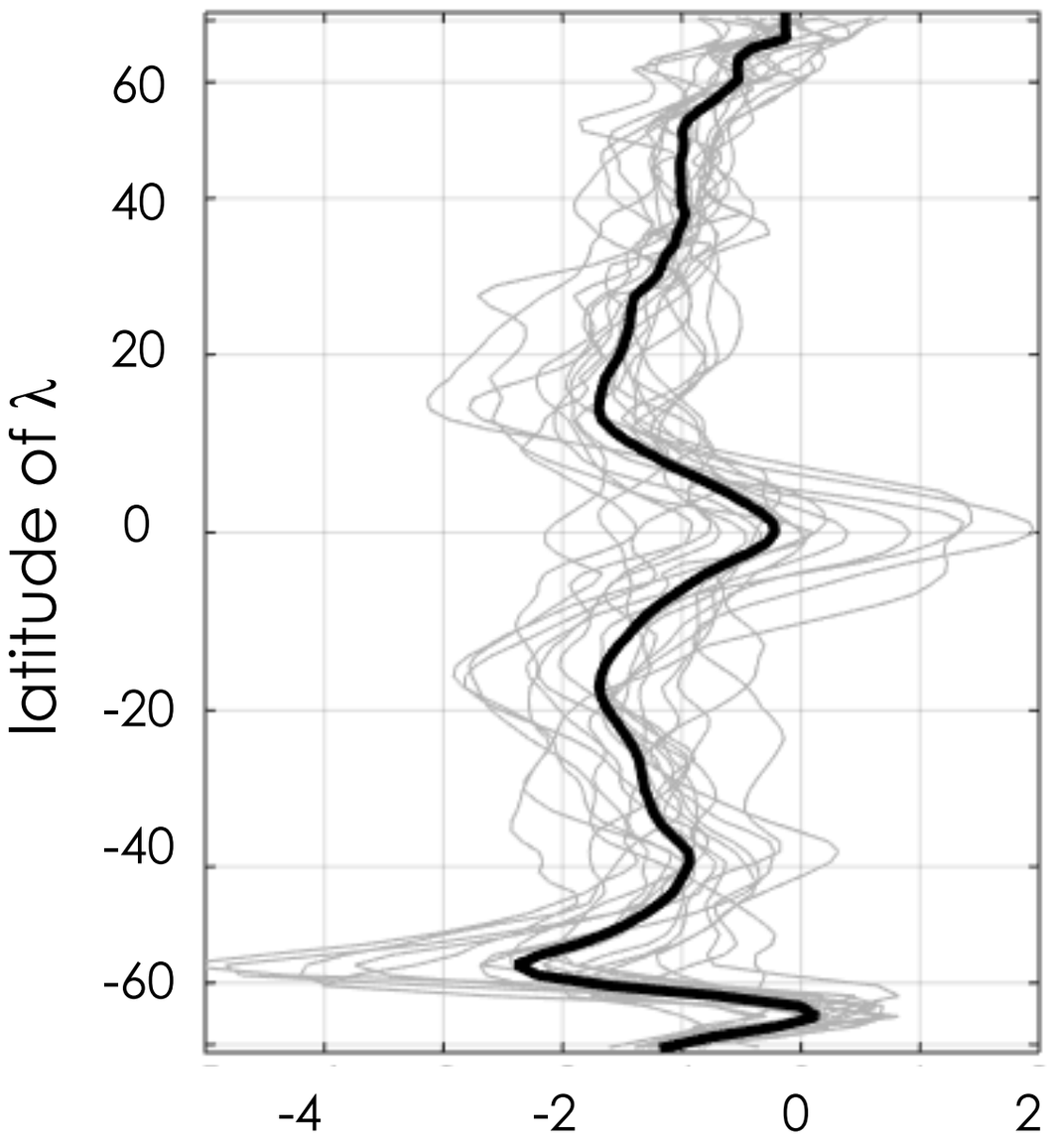
Spread in ECS determines spread in regional end-of century warming.

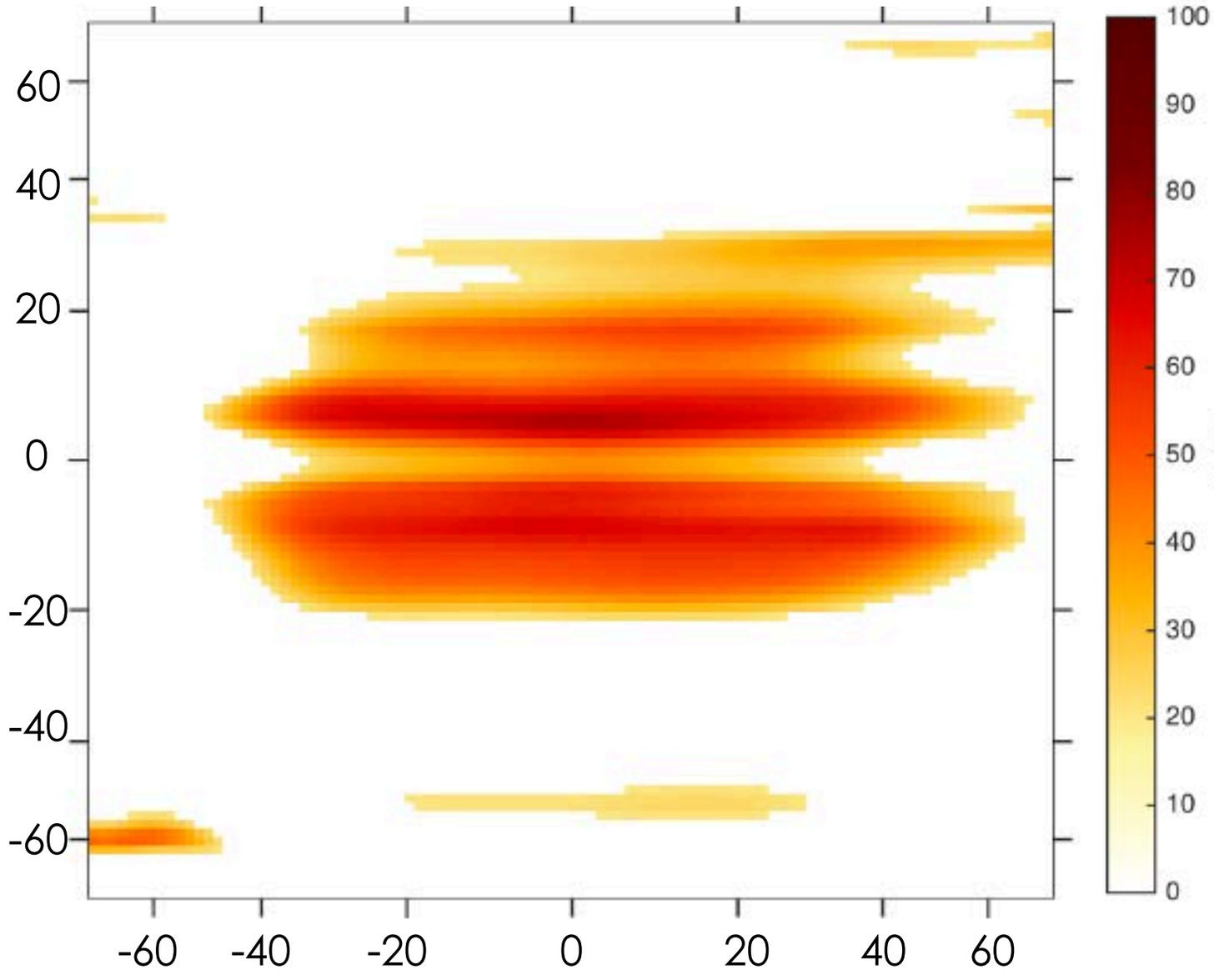


Regional warming uncertainty determined by low-lat feedbacks

Non-diagonal: ~1 DOF in low lats local feedback uncertainty propagates non-locally.







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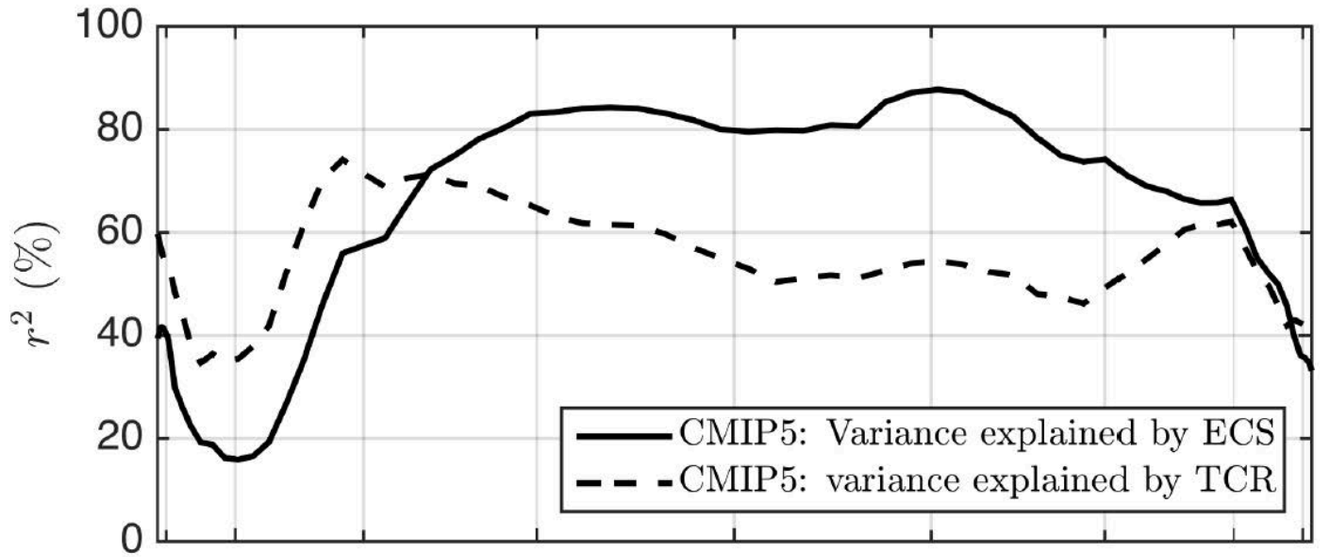
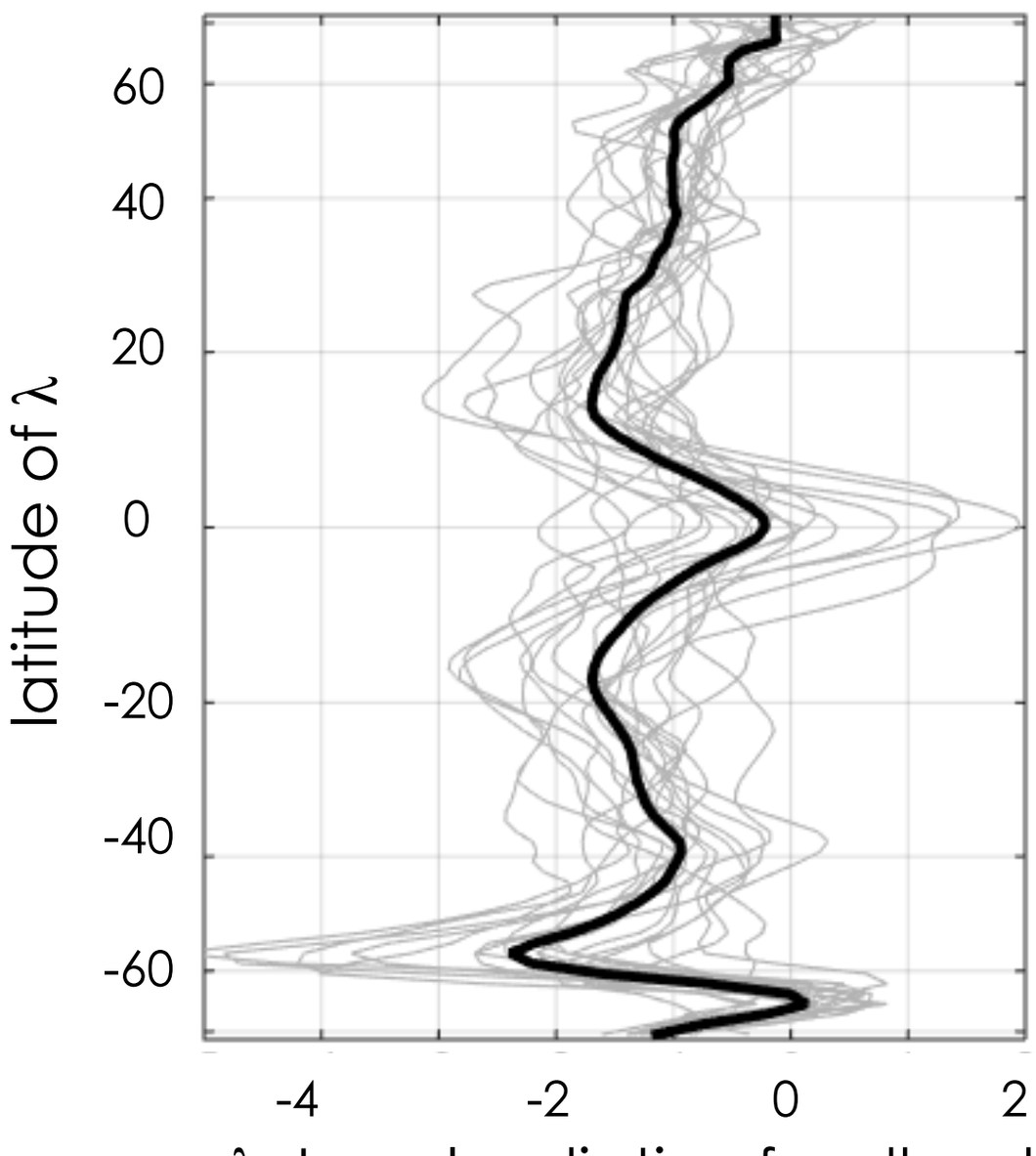
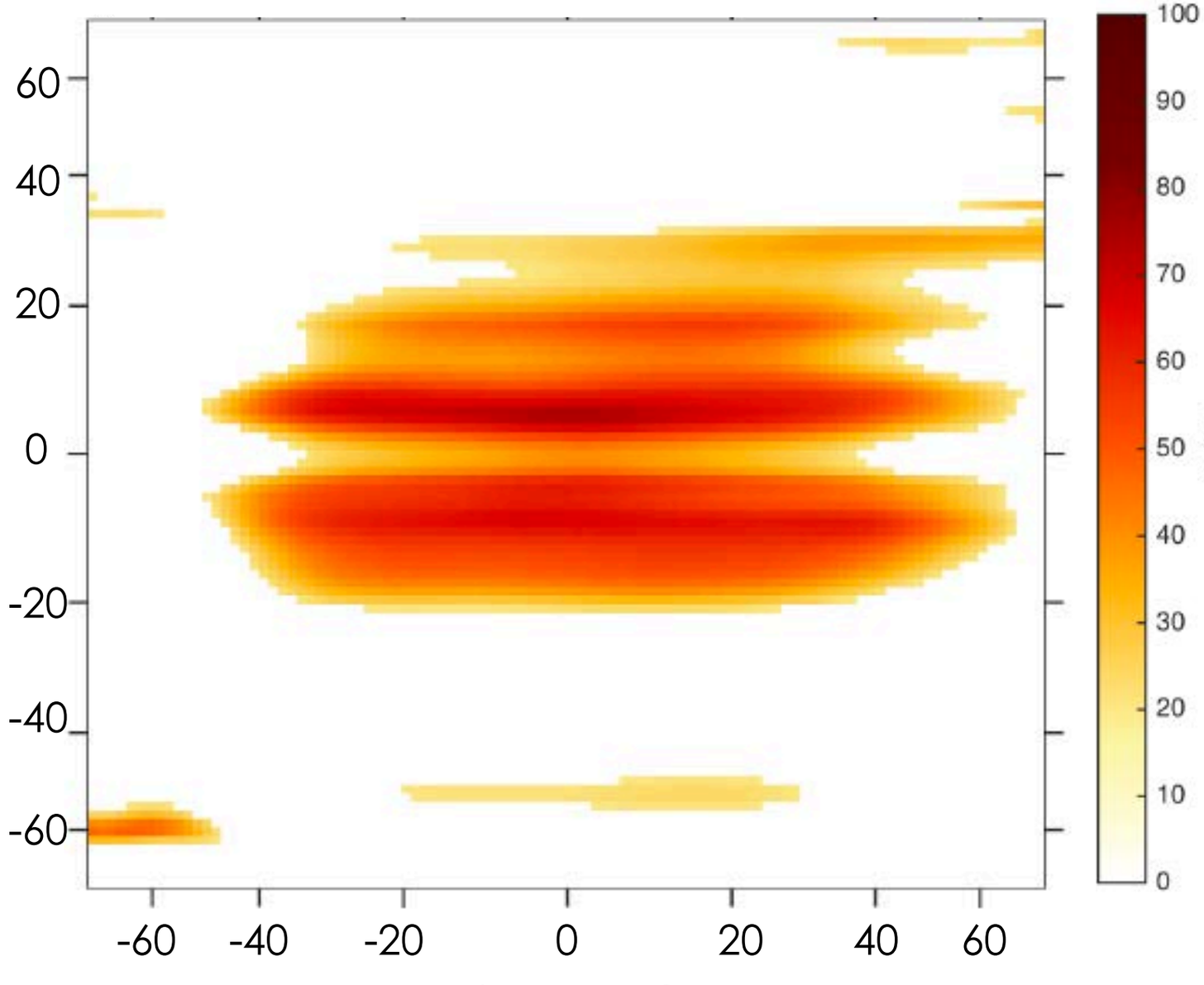
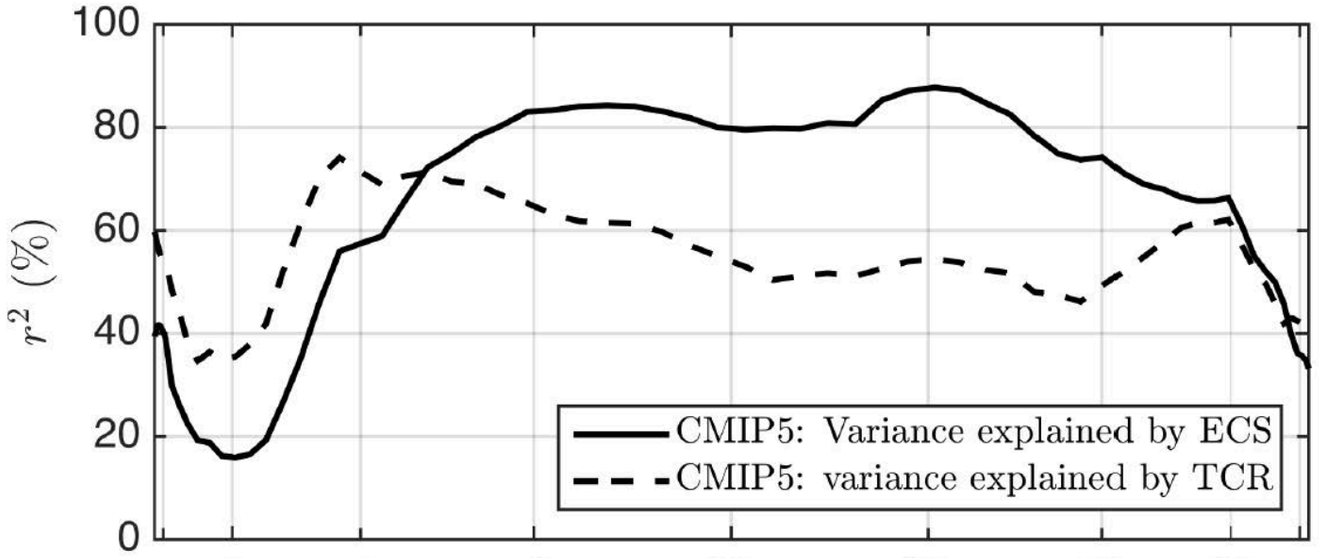
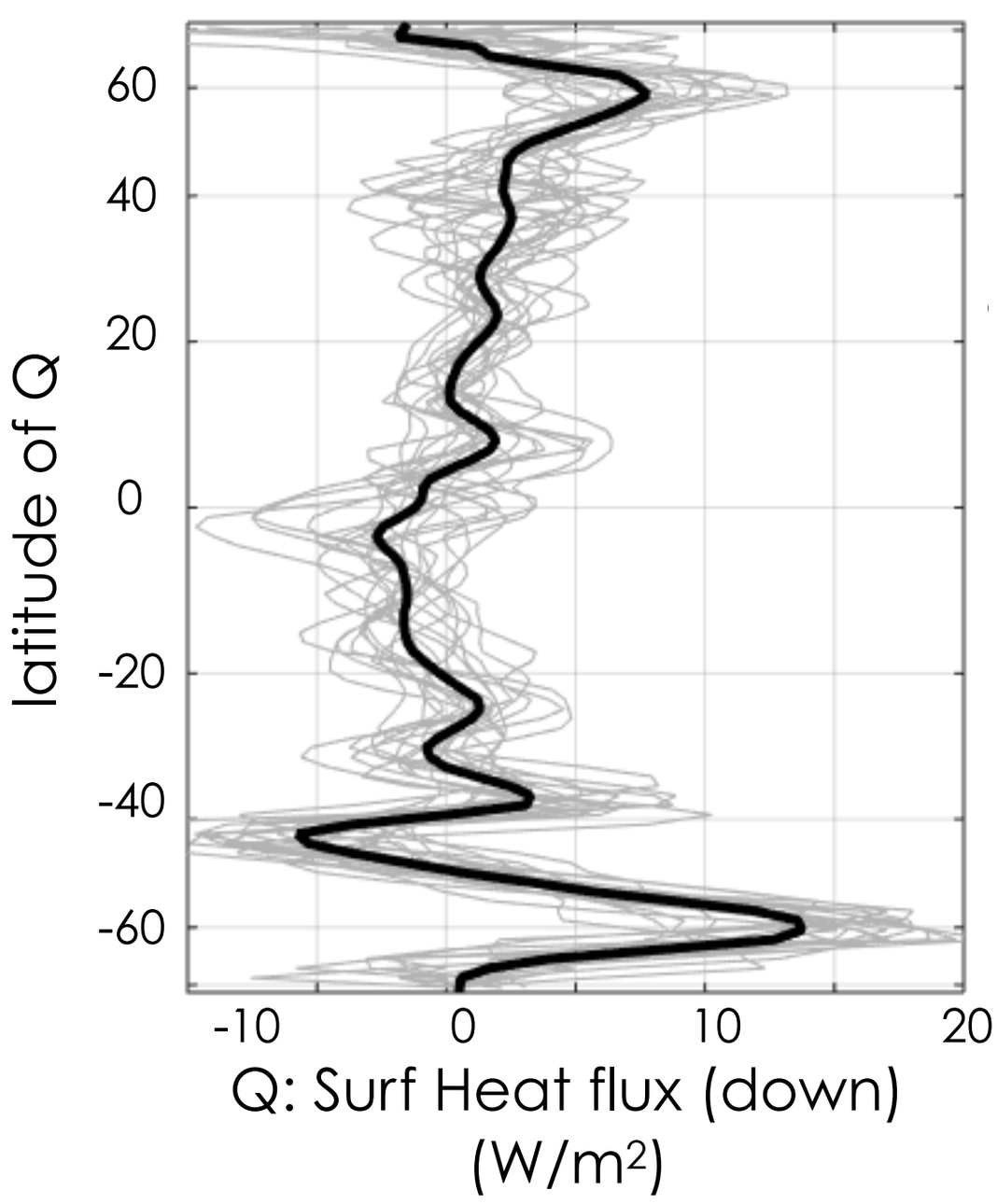


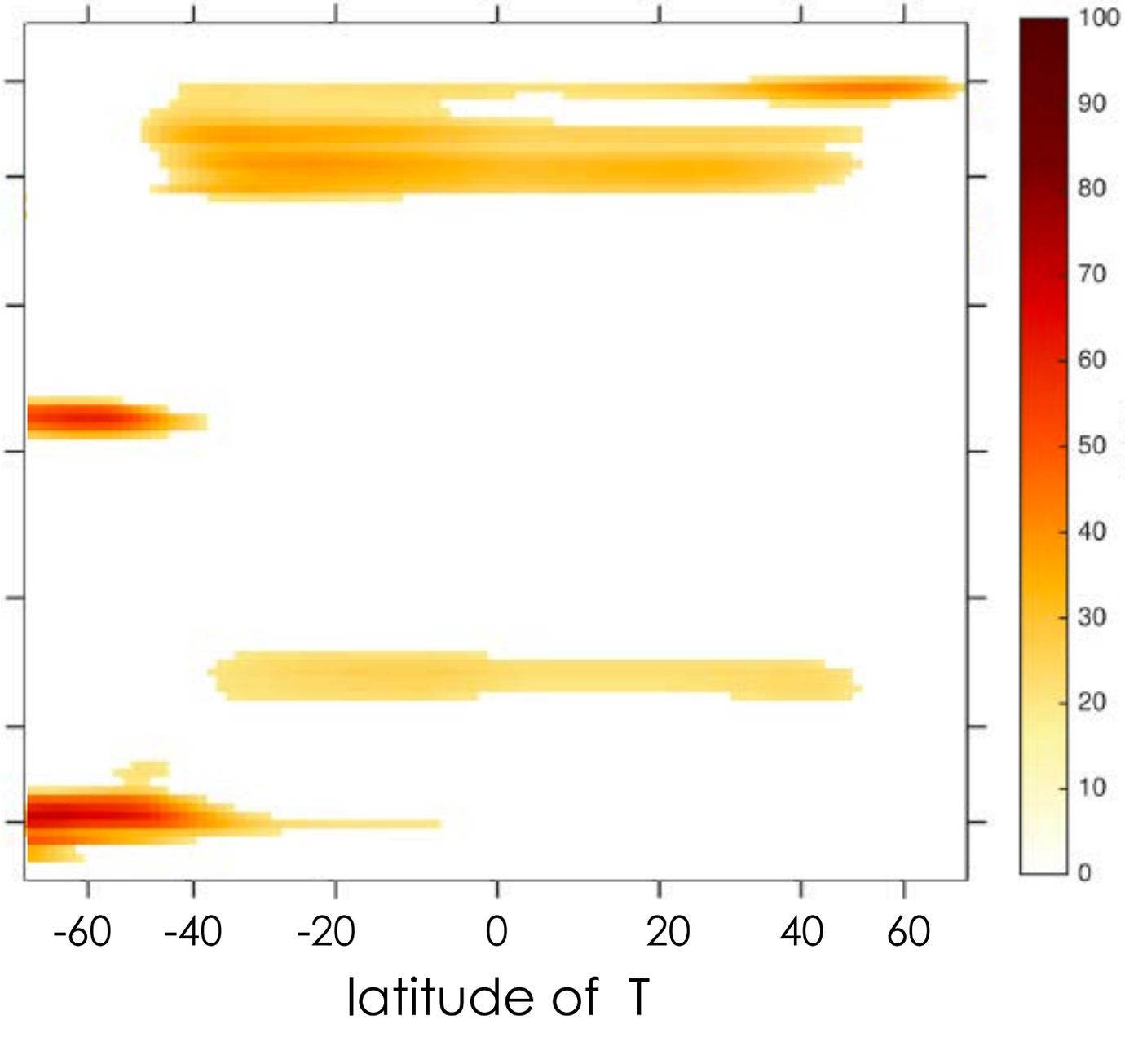




Heat uptake only dominates in Southern Ocean

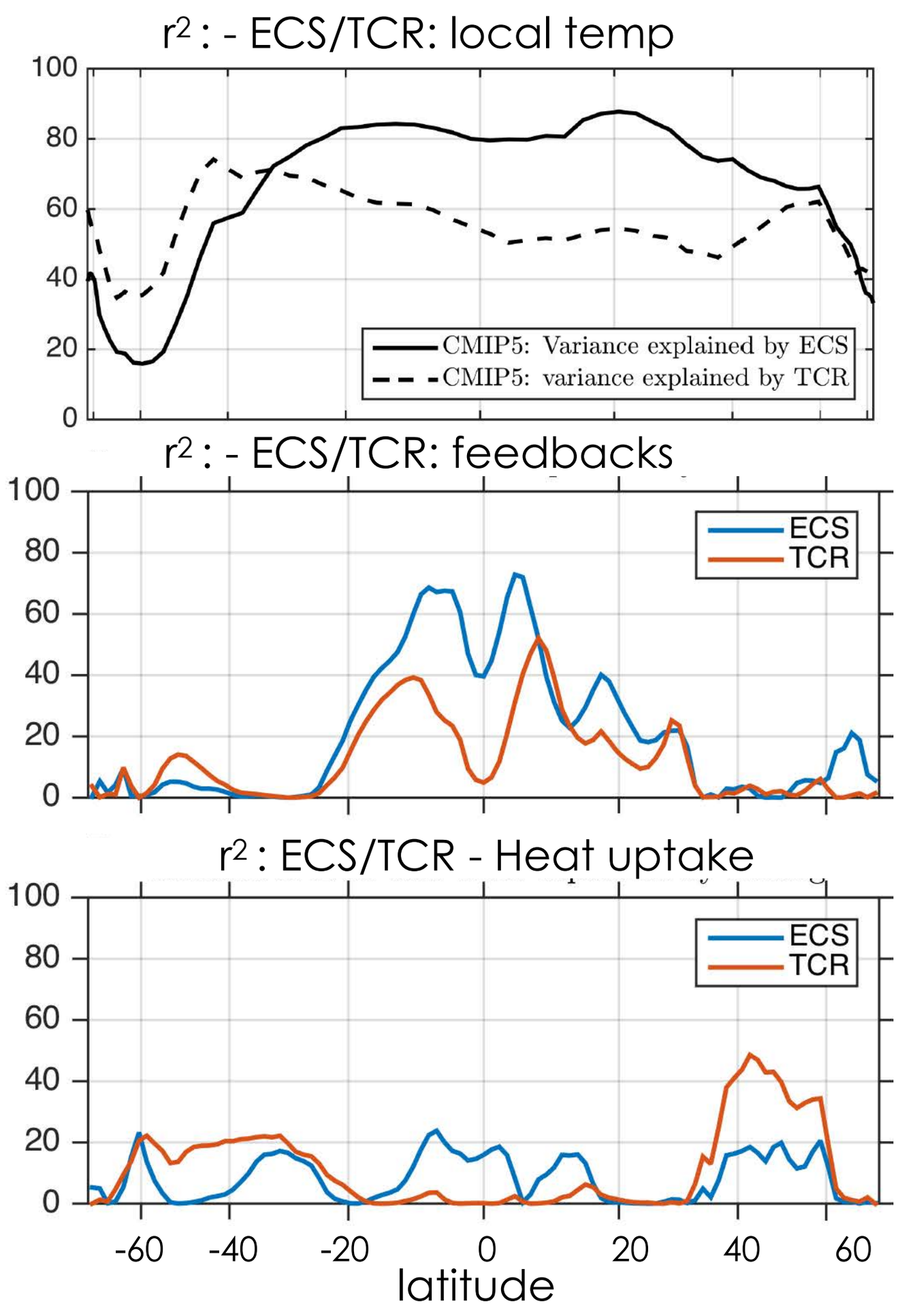






What drives regional temperature and warming indices?

- Low-lat feedbacks important for ECS & 21st century warming
- Heat uptake important for TCR, not for ECS & 21st century warming
- Tropical feedbacks have broad impacts: 50S-60N
- High-latitude feedbacks and heat uptake have local impacts



Crook and Forster 2011
Grose et al 2018

A simple model of local energy balance

$$R_f - Q_o = \lambda \cdot T - \nabla \cdot \mathbf{F}_a$$

radiative forcing

Surface heat flux

radiative damping

atmospheric heat-flux div

A simple model of local energy balance:
MSE diffusion rule for atmospheric heat transport

$$R_f - Q_o = \lambda \cdot T + D\nabla_\phi^2 h$$

radiative forcing

Surface heat flux

radiative damping

atmospheric heat-flux div

prescribed from CMIP5

MSE diffusion

A simple model of local energy balance:
Large diffusive length-scales in low-latitude

$$R_f - Q_o = \lambda \cdot T + \nabla^2_\phi \left(D(\phi) T \right)$$

radiative forcing

Surface heat flux

prescribed from CMIP5

radiative damping

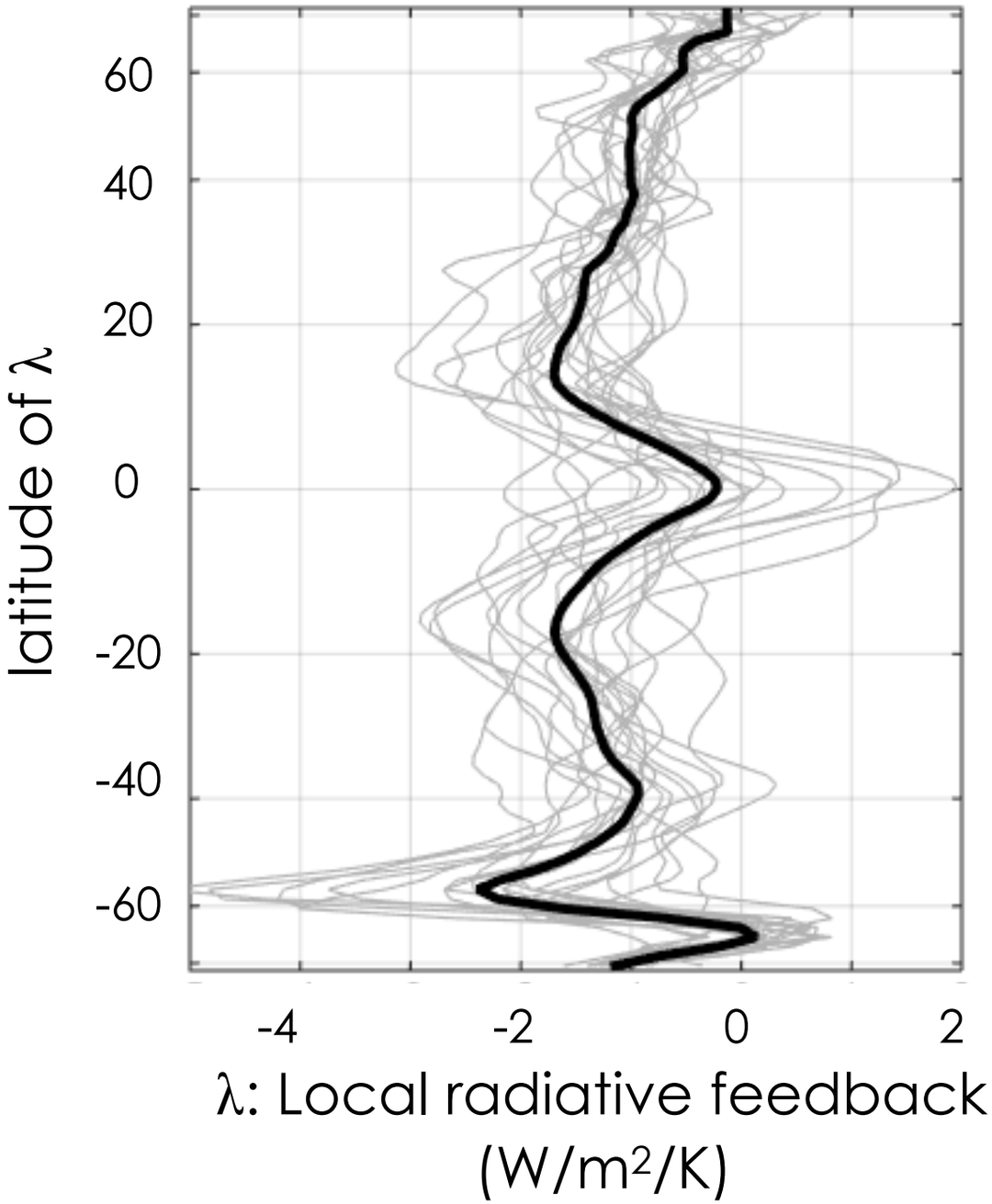
MSE

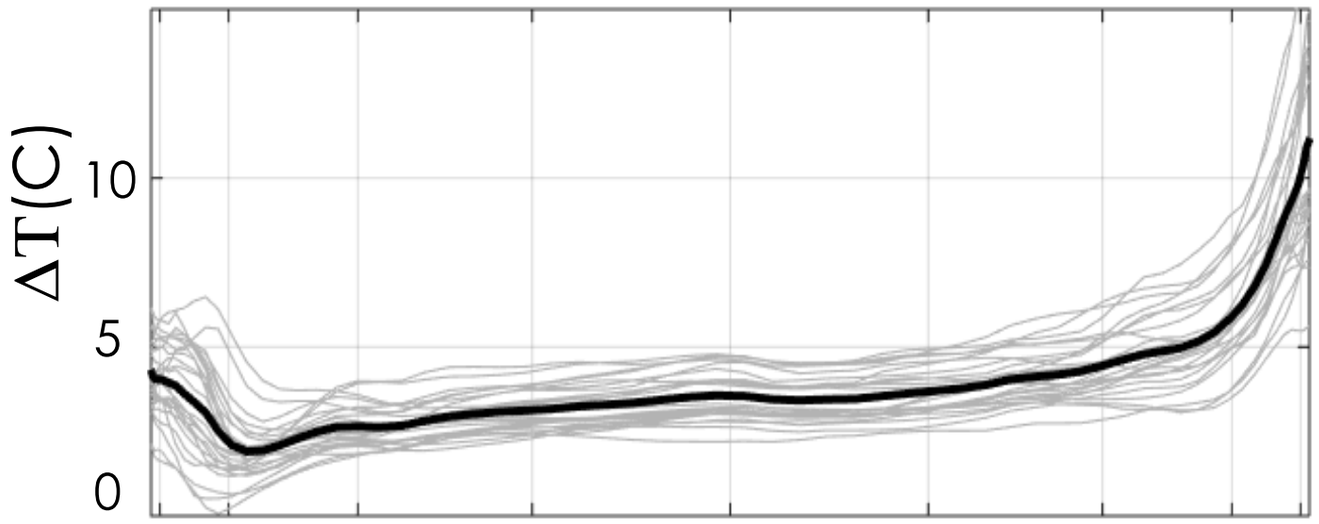
atmospheric heat-flux div

diffusion

Uncertainty as perturbations from ensemble mean

Non-diagonal: ~1 DOF in low lats local feedback uncertainty propagates non-locally.





$$T = \langle T \rangle + \delta T$$
$$\lambda = \langle \lambda \rangle + \delta \lambda$$
$$Q_o = \langle Q_o \rangle + \delta Q_o$$
$$R_f = \langle R_f \rangle + \delta R_f$$

How does uncertainty in forcing, heat uptake and feedbacks translate to warming uncertainty?

Uncertainty in forcing, heat uptake, feedbacks | Uncertainty in warming

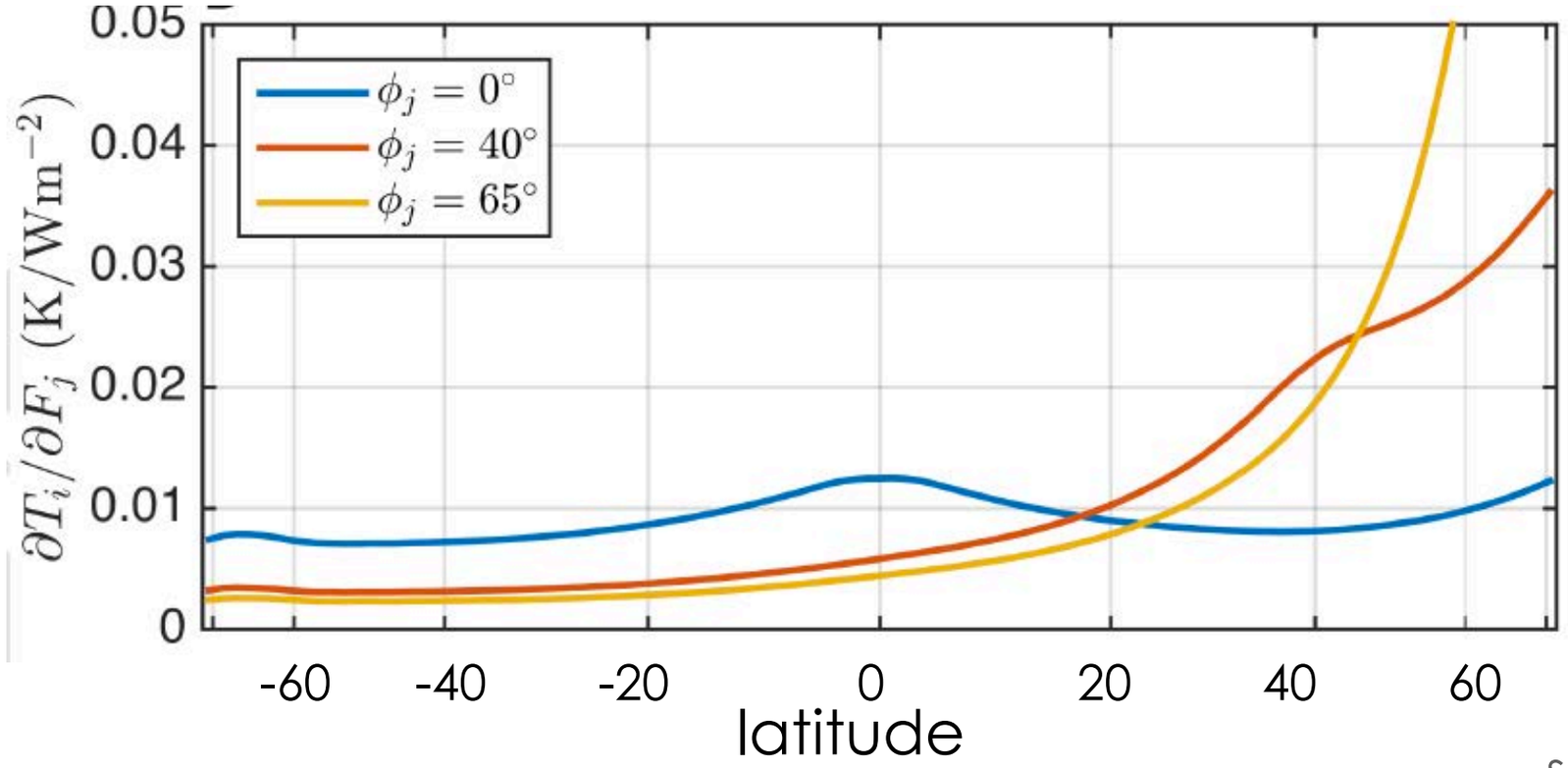
$$\delta R_f - \delta Q_o - \delta\lambda \langle T \rangle = \langle \lambda \rangle \delta T + \nabla_\phi^2 D(\phi) \delta T$$

Tropical energetic perturbations have broad response
High-latitude perturbations have strong, but localized response

Uncertainty in forcing, heat uptake, feedbacks | Uncertainty in warming

$$\delta R_f - \delta Q_o - \delta\lambda \langle T \rangle = \langle \lambda \rangle \delta T + \nabla_\phi^2 D(\phi)\delta T$$

δT



see also Stuecker et al 2018

The relative importance of feedback uncertainty increases with ensemble mean-temperature

Uncertainty in forcing, heat uptake, feedbacks	Uncertainty in warming

$$\delta R_f - \delta Q_o - \delta\lambda \langle T \rangle = \langle \lambda \rangle \delta T + \nabla_\phi^2 D(\phi)\delta T$$

Relative importance of heat-uptake:

$$\rho = \frac{\sigma_Q^2}{\sigma_Q^2 + \langle T \rangle \sigma_\lambda^2} \approx \frac{\langle Q \rangle^2}{\langle Q \rangle^2 + \langle T \rangle^2 \sigma_\lambda^2}$$

The relative importance of feedback uncertainty increases with ensemble mean-temperature

Uncertainty in forcing, heat uptake, feedbacks | Uncertainty in warming

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Very important initially: $T \approx 0$

Not important at equilibrium: $Q \approx 0$

The relative importance of feedback uncertainty increases with ensemble mean-temperature

Uncertainty in forcing, heat uptake, feedbacks	Uncertainty in warming

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Very important initially: $T \approx 0$

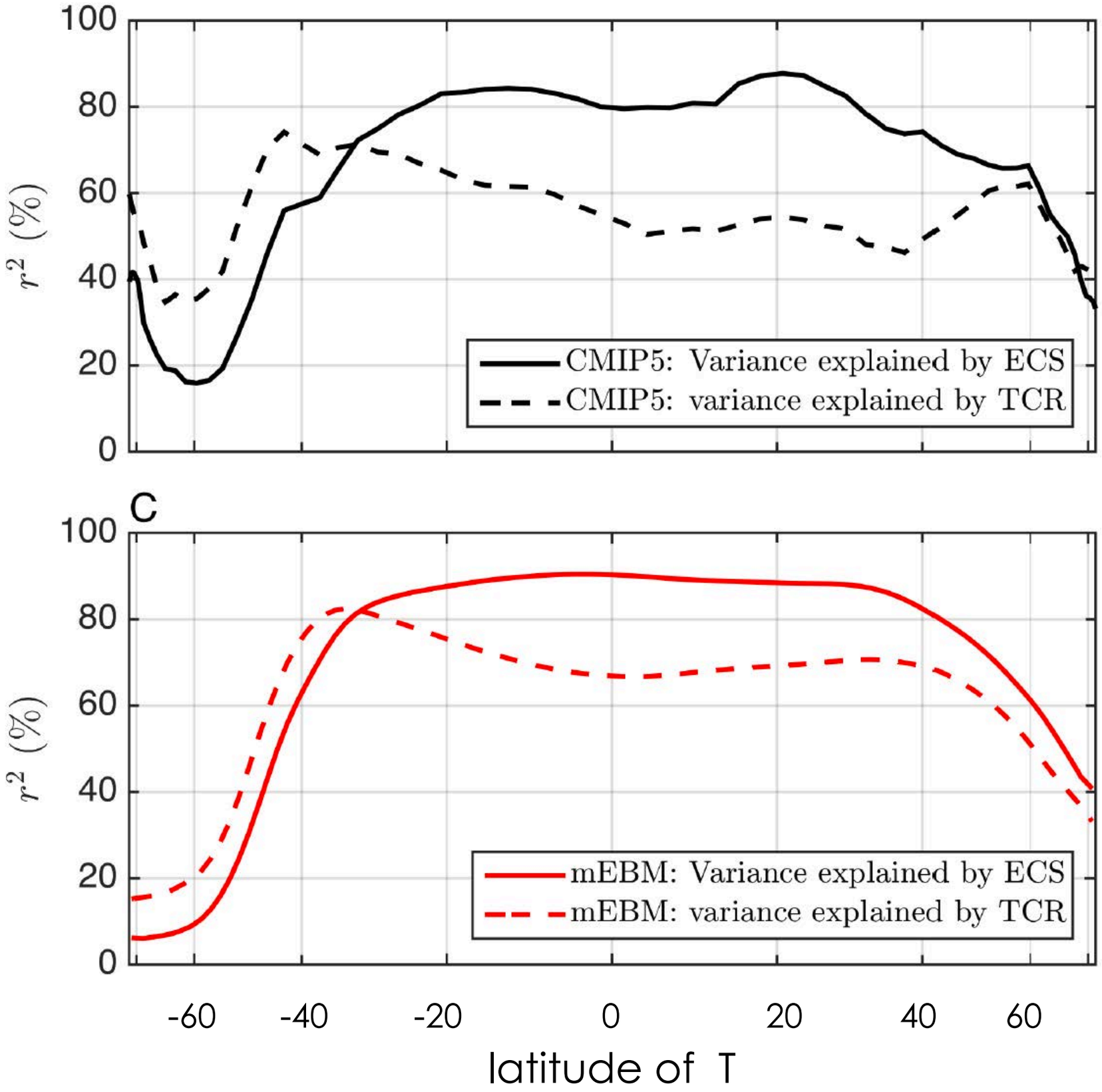
Not important at equilibrium: $Q \approx 0$

RCP 8.5: $T \propto t$; $Q \propto C_{\text{eff}} dT/dt$

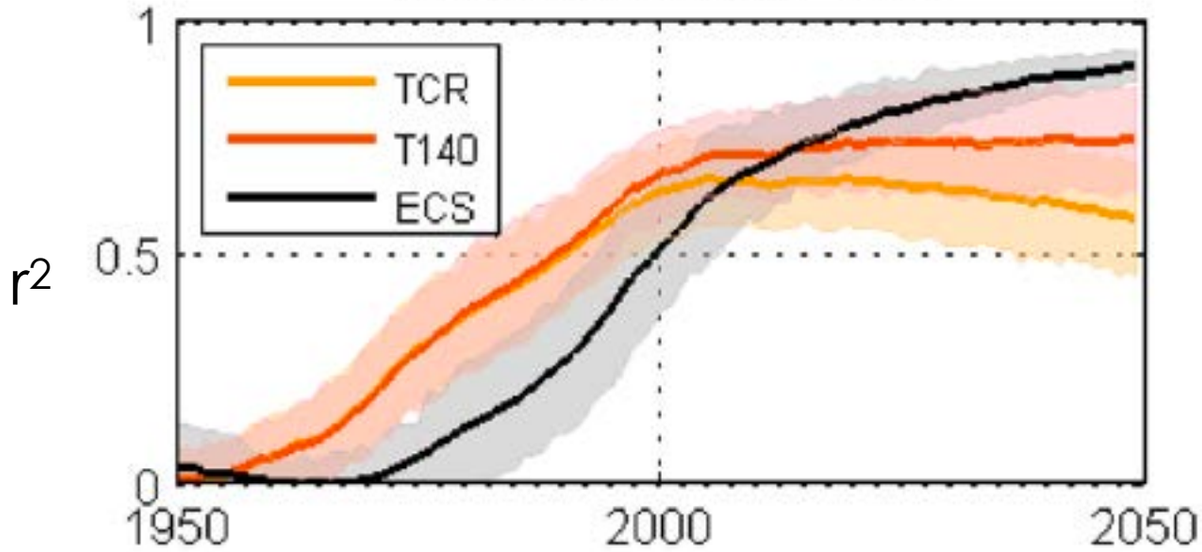
21st century warming $\rho = 0.14$

TCR (1pctCO2) $\rho = 0.38$

Regional energy balance & MSE diffusion reproduces the structure of ECS/TCR & warming



Summary: Why does ECS become more and more important for transient, reginal warming?

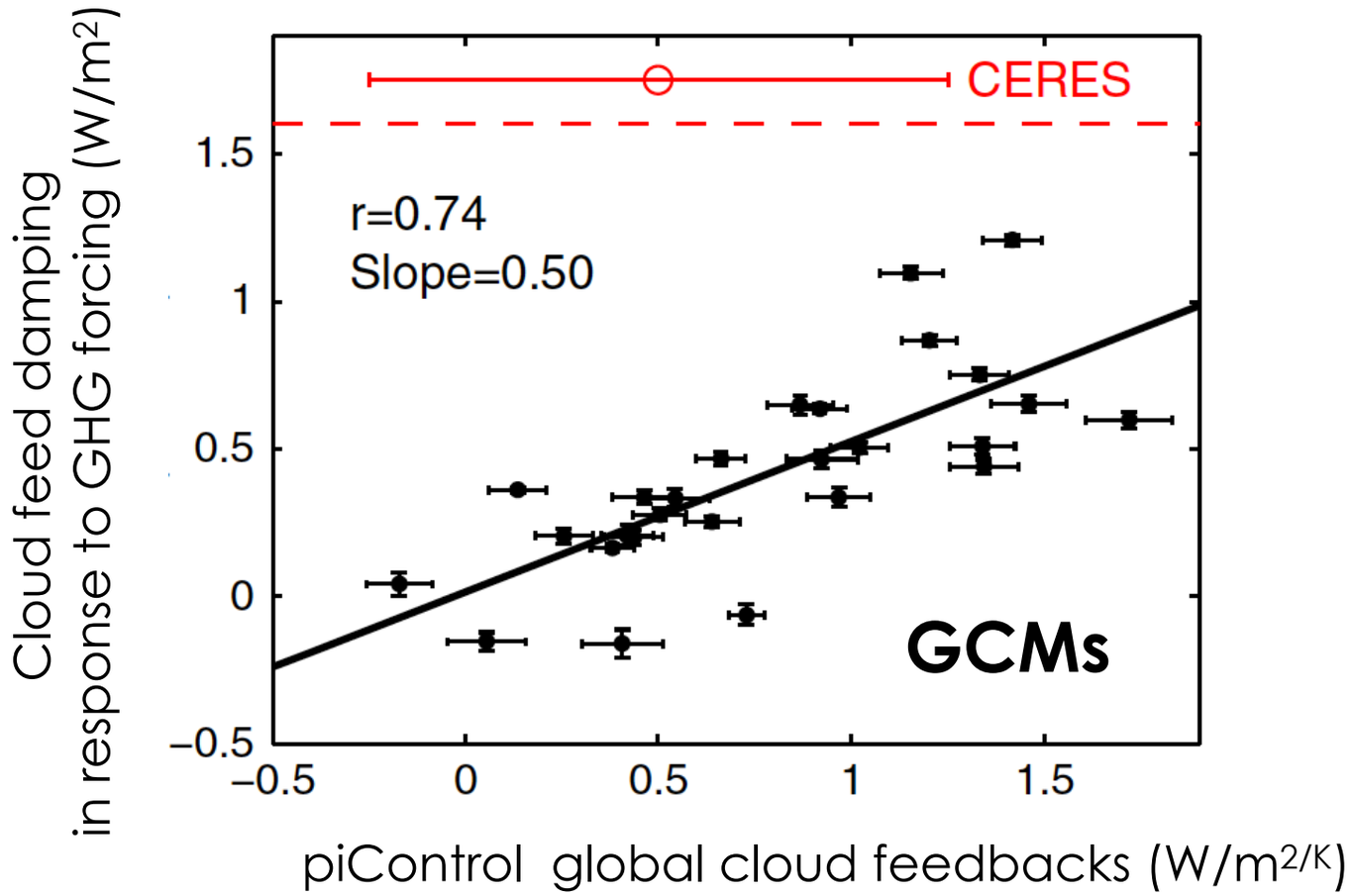


Grose et al 2018

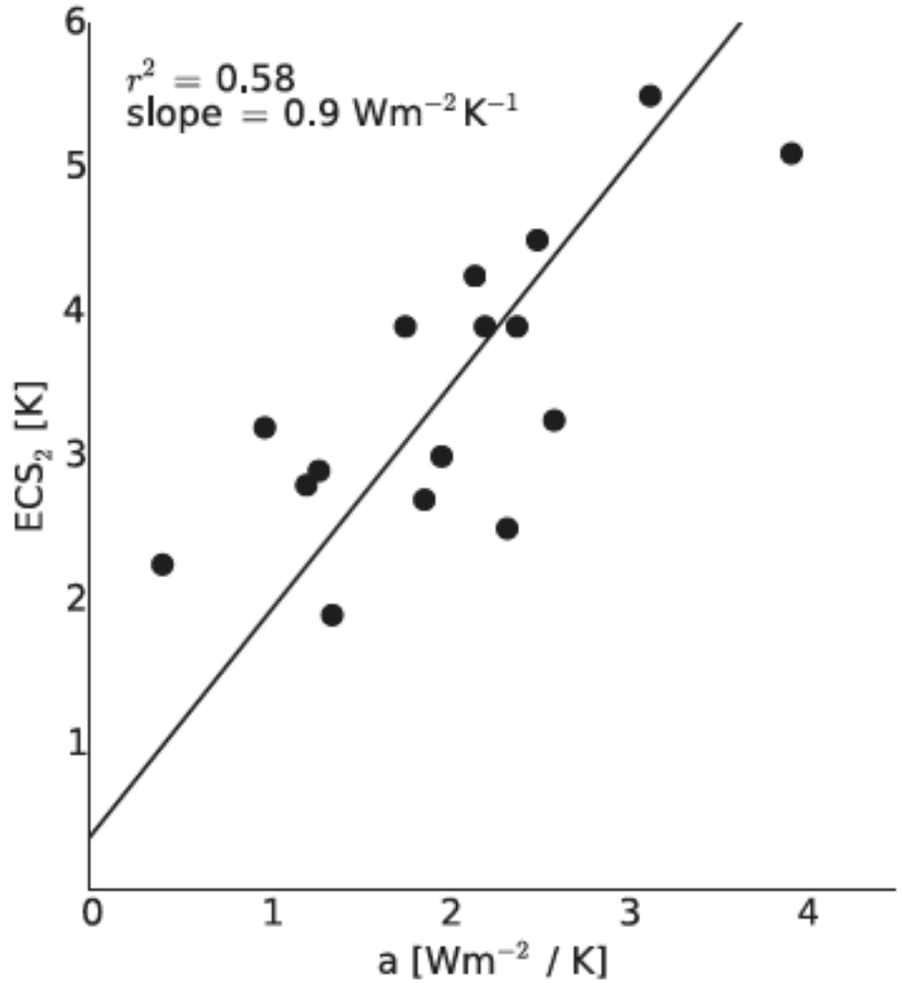
- Relative importance of heat uptake decreases with warming.
- By the end of the 21st century, feedbacks matter more than heat uptake or forcing.
- Fitting to historical warming we may be fitting to aerosol forcing and heat uptake. (Crook and Forster 2011). We need to fit to feedbacks
- Efforts go into understanding model-obs discrepancy in Temp and Q. Models do poor job at reproducing radiative feedbacks (though that is not necessarily due to cloud physics).
- Caveat: pattern effect

So what does all that teach us about how to diagnose feedbacks?

Zhou et al 2015



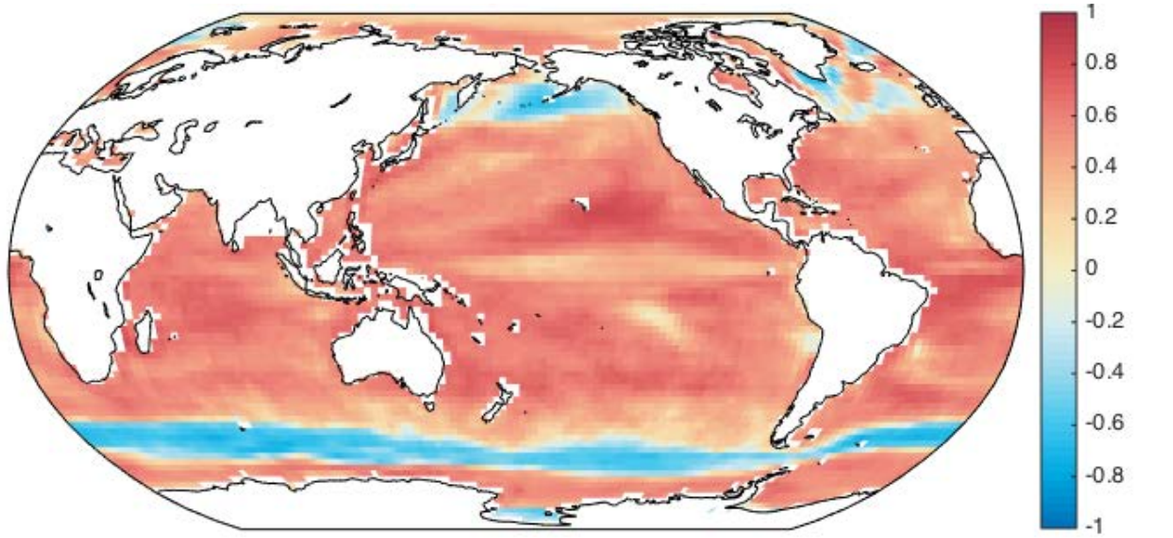
Lutsko and Takahashi 2018, Lutsko 2018



Cloud feedbacks in ENSO freq band

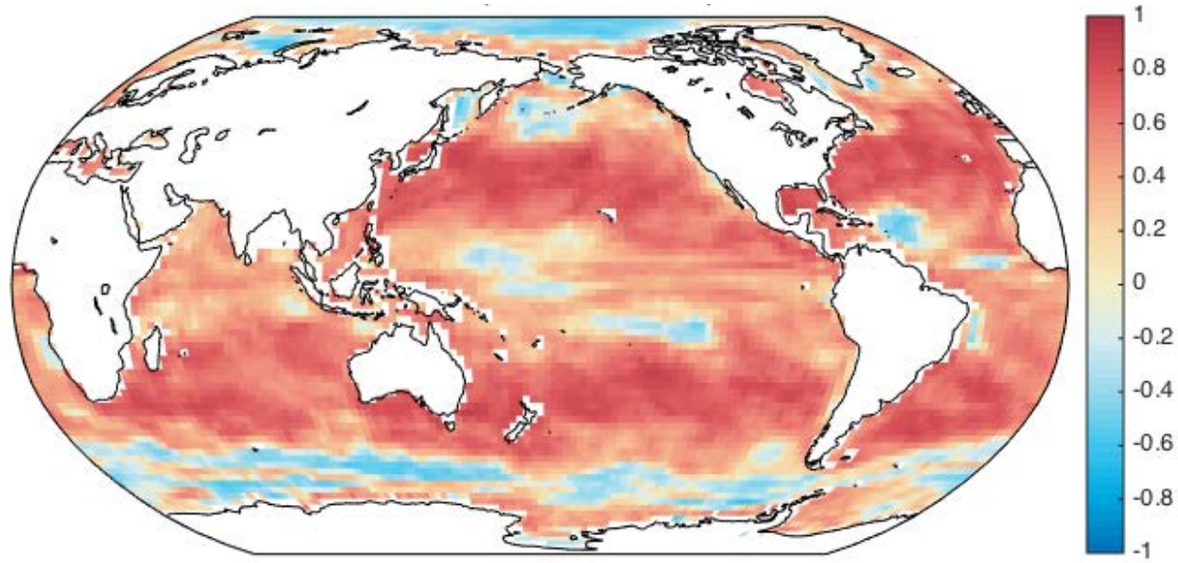
Correlation between local cloud feedbacks and ECS (CMIP5)

piControl



500 years
different SST patterns for variability

AMIP



~30 years, observed SST patterns.

Correlation between local cloud feedbacks and ECS (CMIP5)

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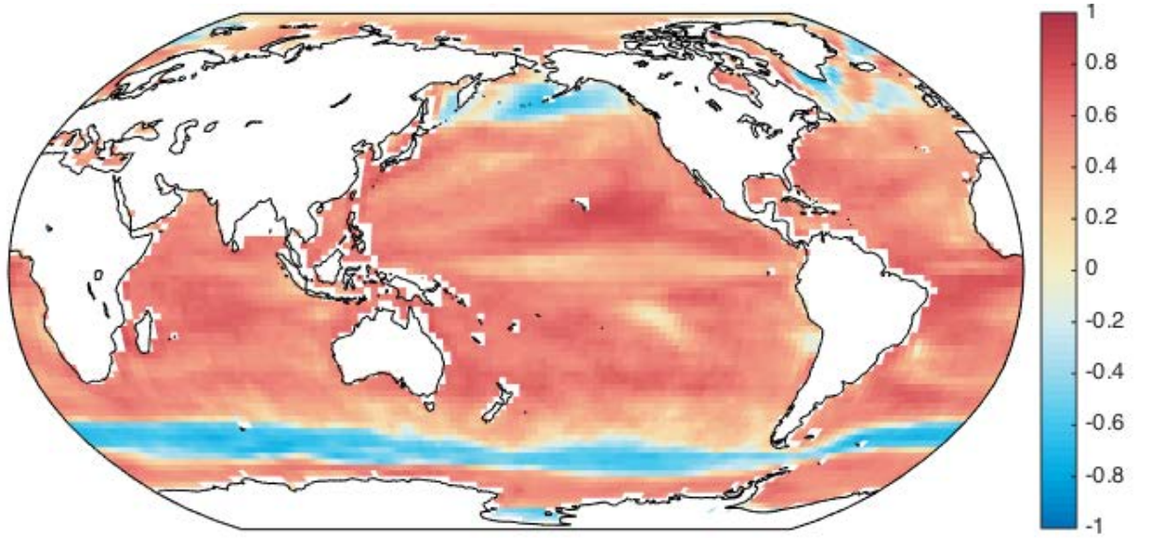

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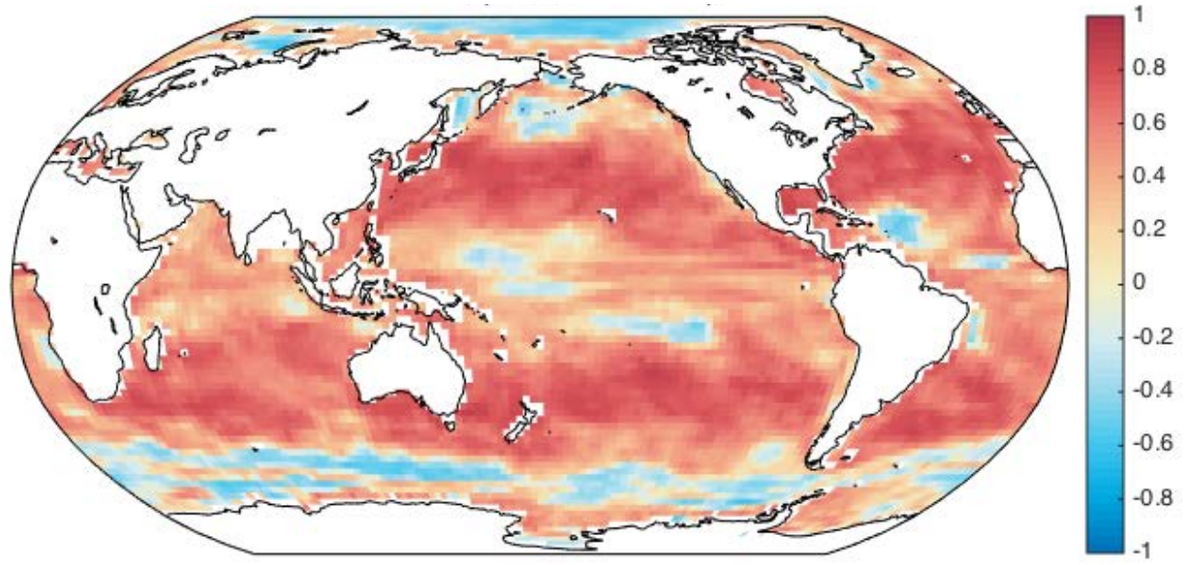
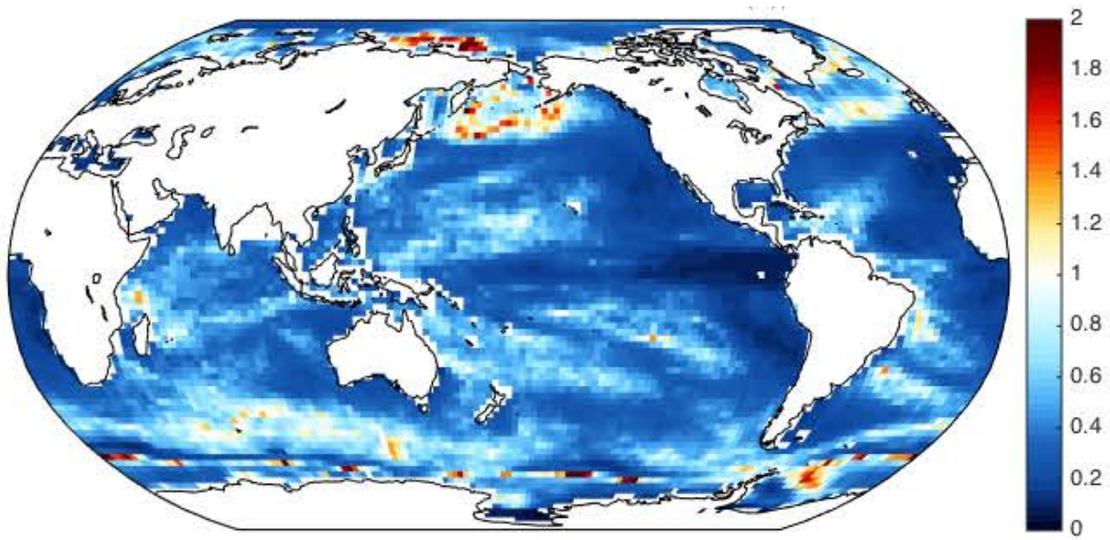


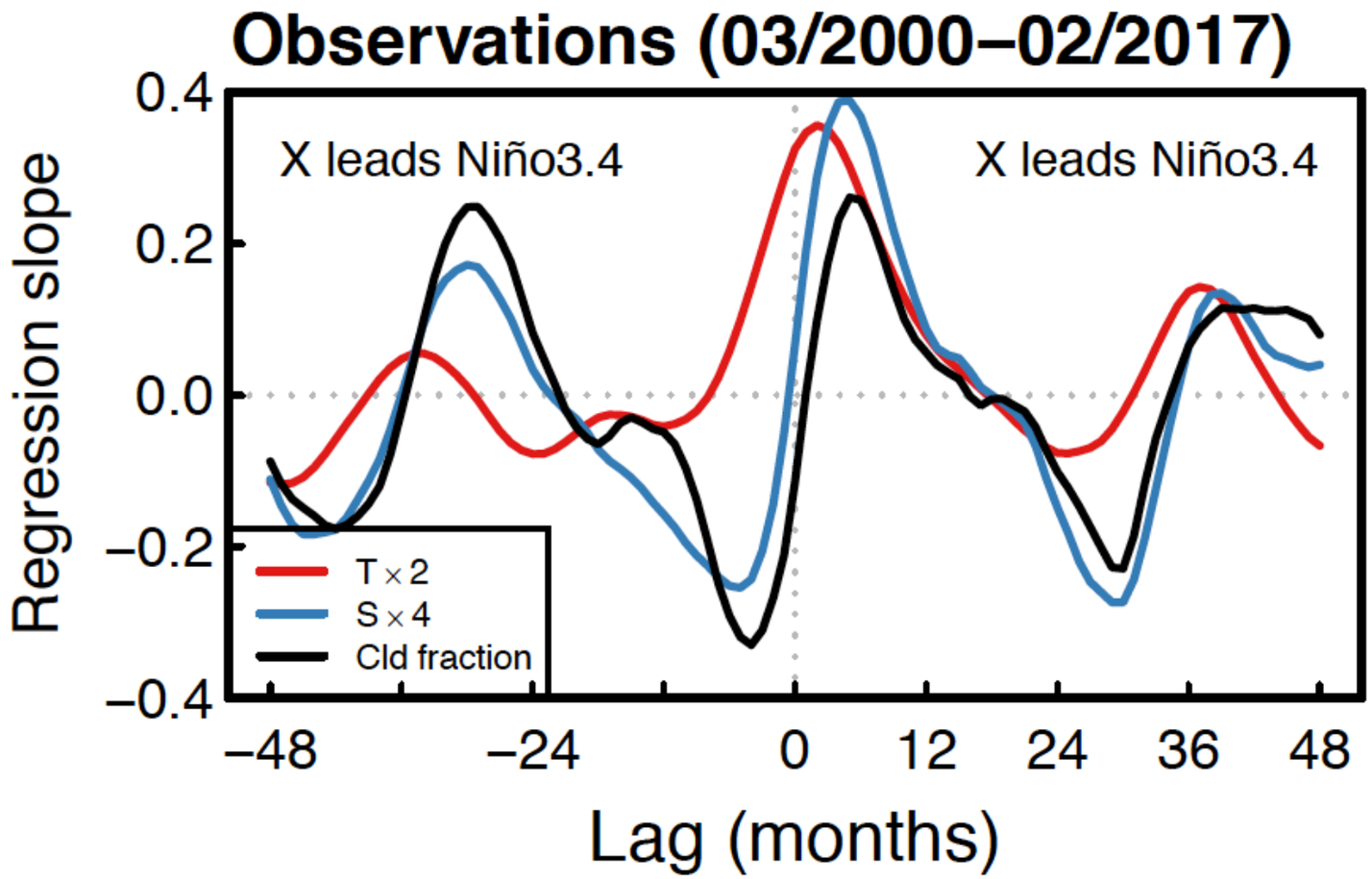
~30 years, observed SST patterns.

Relative error: blue is good!



$$\varepsilon = \left\langle \frac{\sigma(\lambda_n)}{\lambda_n} \right\rangle$$

ENSO cloud changes driven by stability and at lag



T (ERA 5)

S - stability (ERA 5)

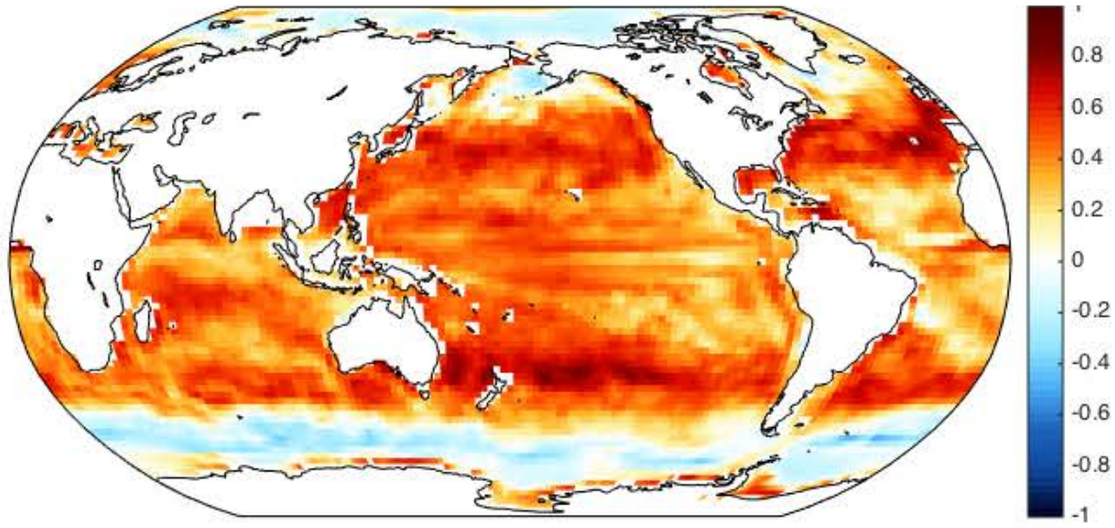
Low Cld Fraction (MODIS)

P. Ceppi

Correlation between local cloud feedbacks and ECS (CMIP5)

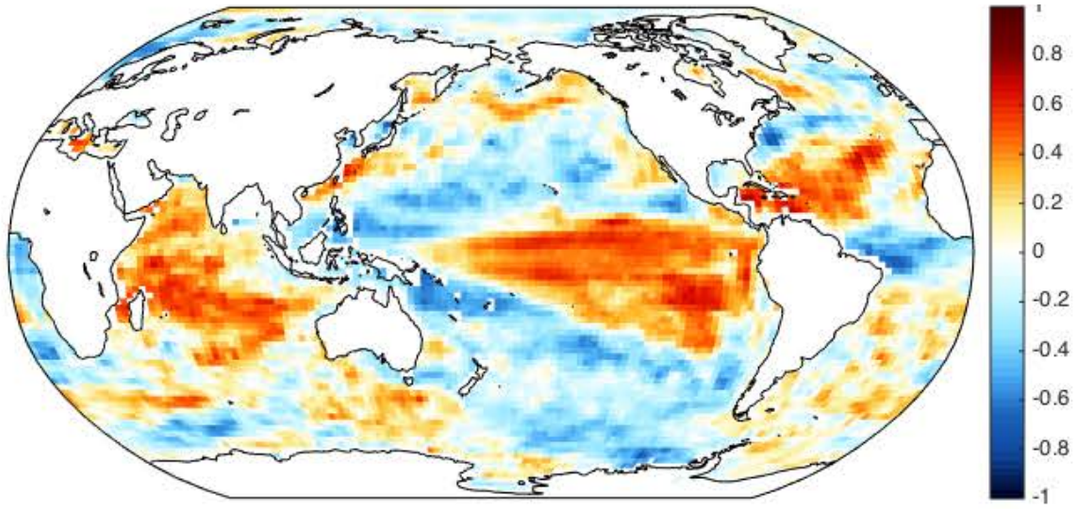
$$\lambda_n(x) = \frac{dR_{\text{cld}}(x)}{dT(x)}$$

Local Cloud feedback vs ECS

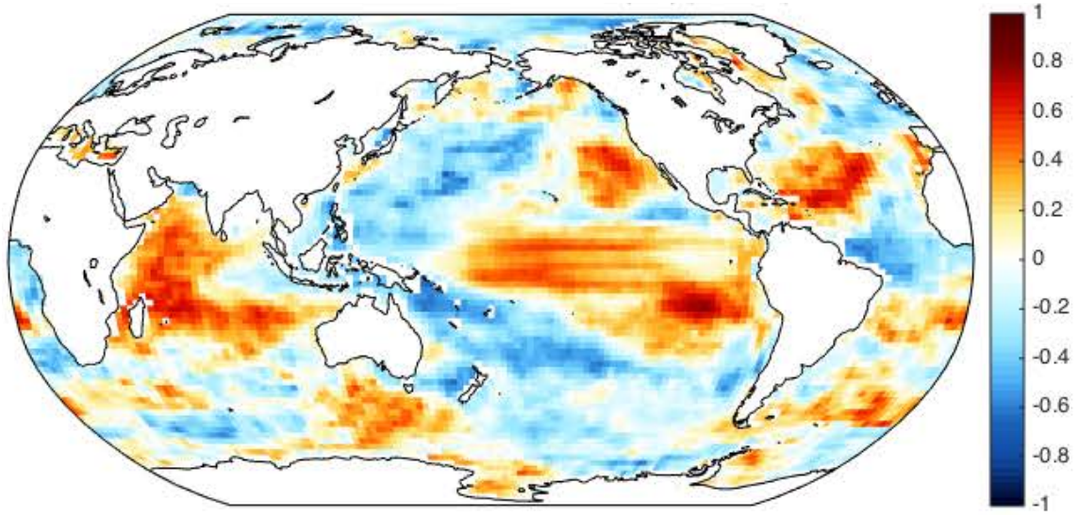


$$\lambda_{\text{ENSO}}(x,\tau) = \frac{dR_{\text{cld}}(x,t+\tau)}{d\text{NINO3.4}(t)}$$

5 months after peak nino3.4



Peak ENSO



Thank you!
Questions?

- Relative importance of heat uptake decreases with warming.

- By the end of the 21st century, feedbacks dominate warming uncertainty.

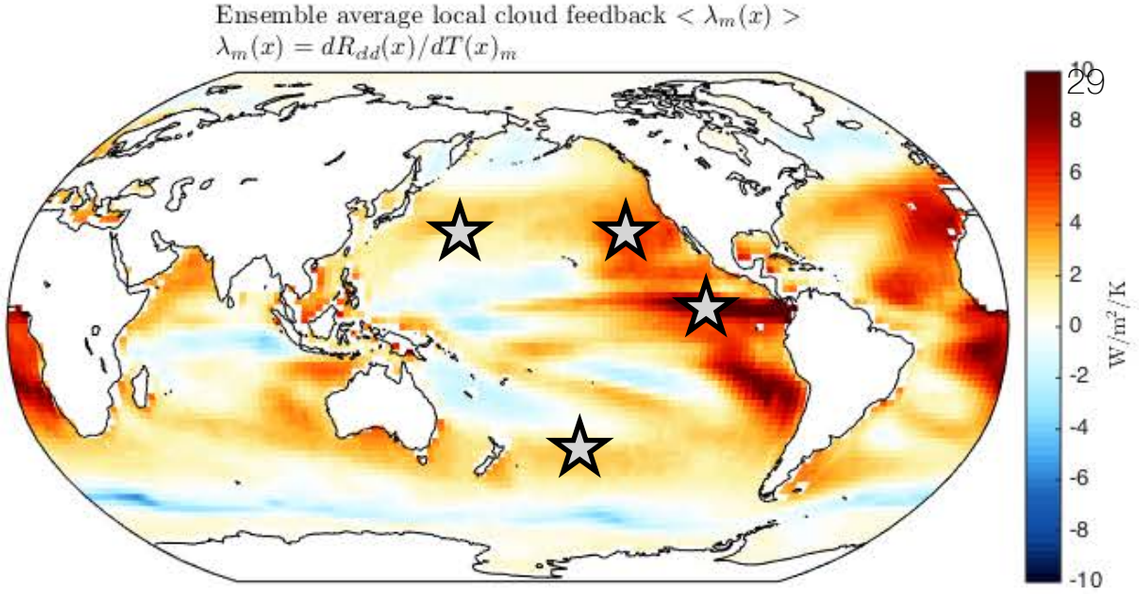
- Fitting to historical warming we may be fitting to aerosol forcing and heat uptake. (Crook and Forster 2011). We need to fit to feedbacks

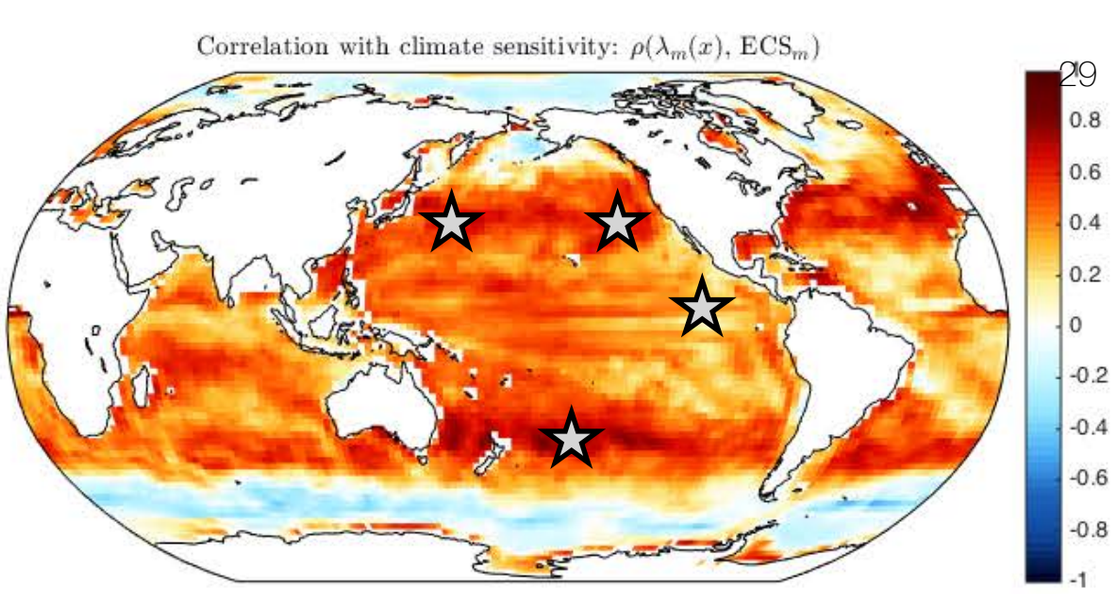
- Efforts go into understanding model-obs discrepancy in Temp and Q. Models do poor job at reproducing radiative feedbacks (though that is not necessarily due to cloud physics).

- Caveat: pattern effect

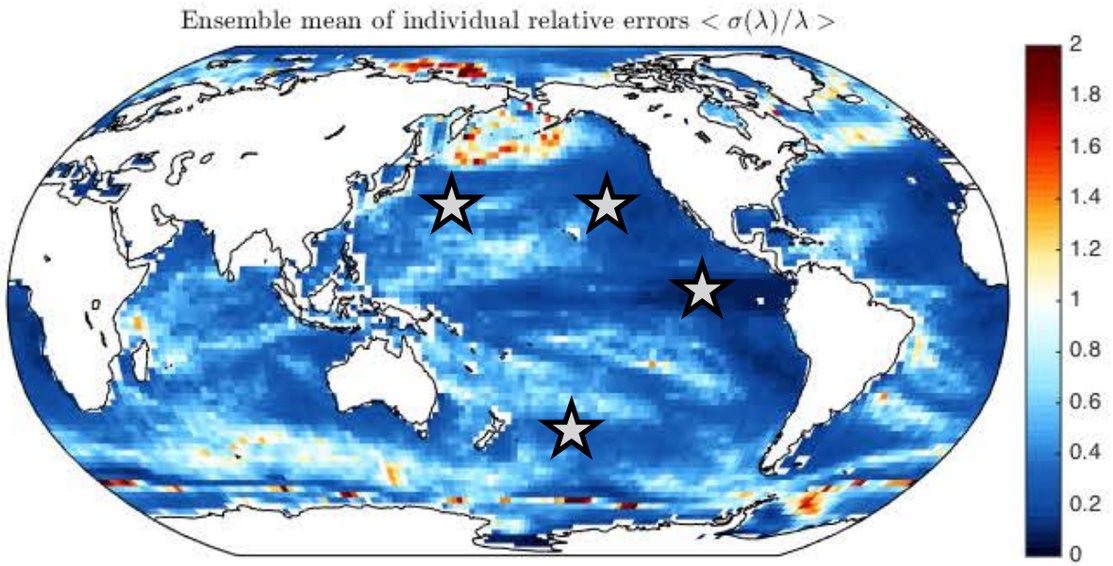
- AMIP simulations might isolate interannual feedbacks better than piControl

Supplementary Slides





What is driving cloud feedbacks? Let's look at TAS and cloud radiative forcing (CRF) in four regions



CCSM4: Nino3.4

CCSM4: N Decks

CCSM4: Kuroshio

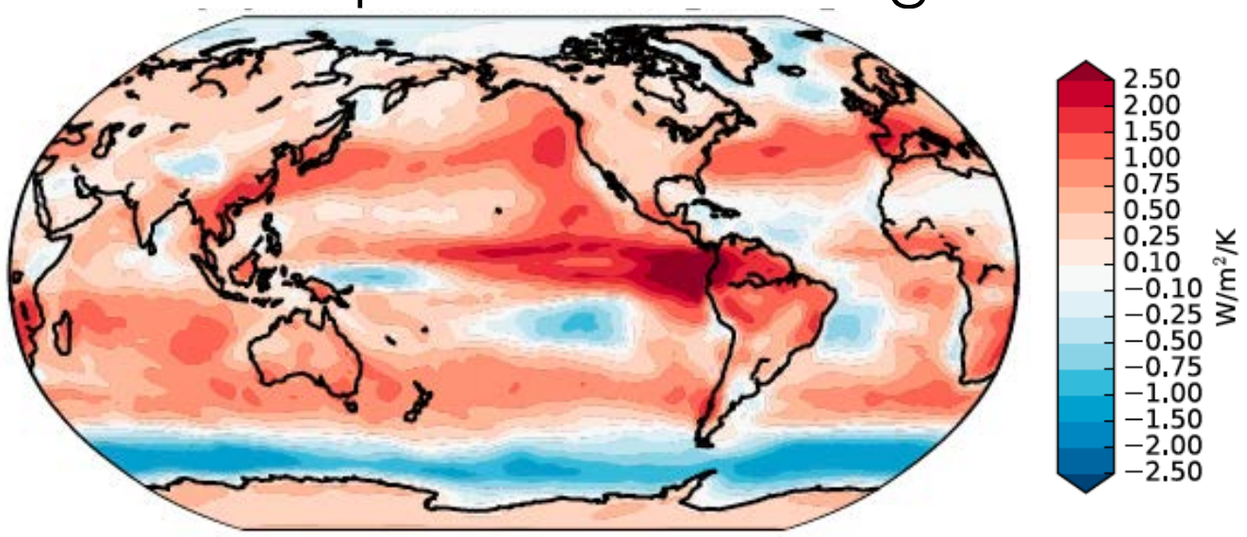
CCSM4: Southern Ocean

coherence

phase

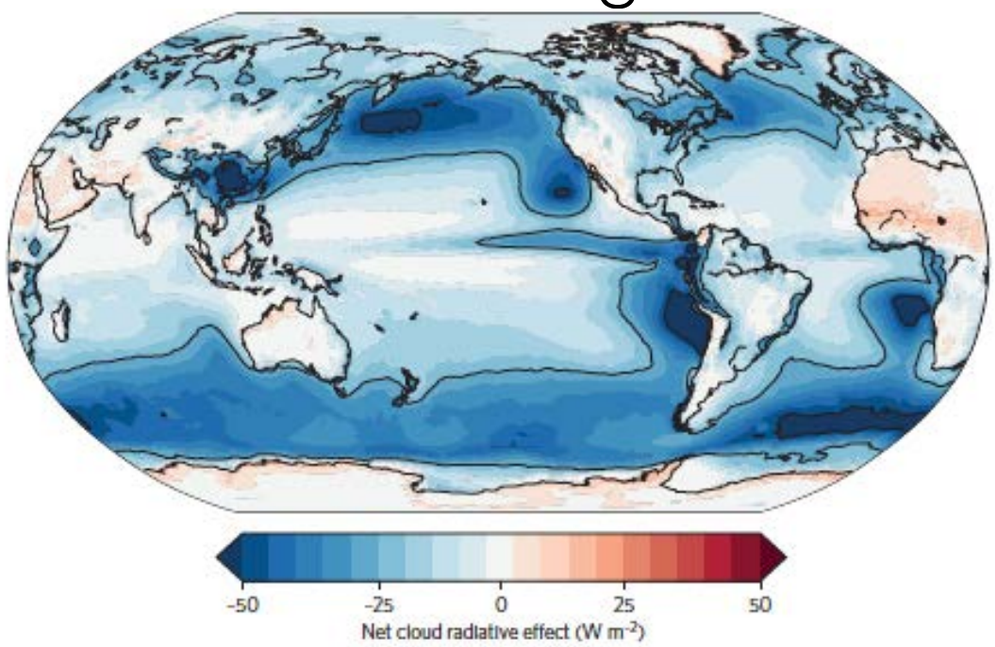
AMIP

CFMIP: response to doubling of CO2



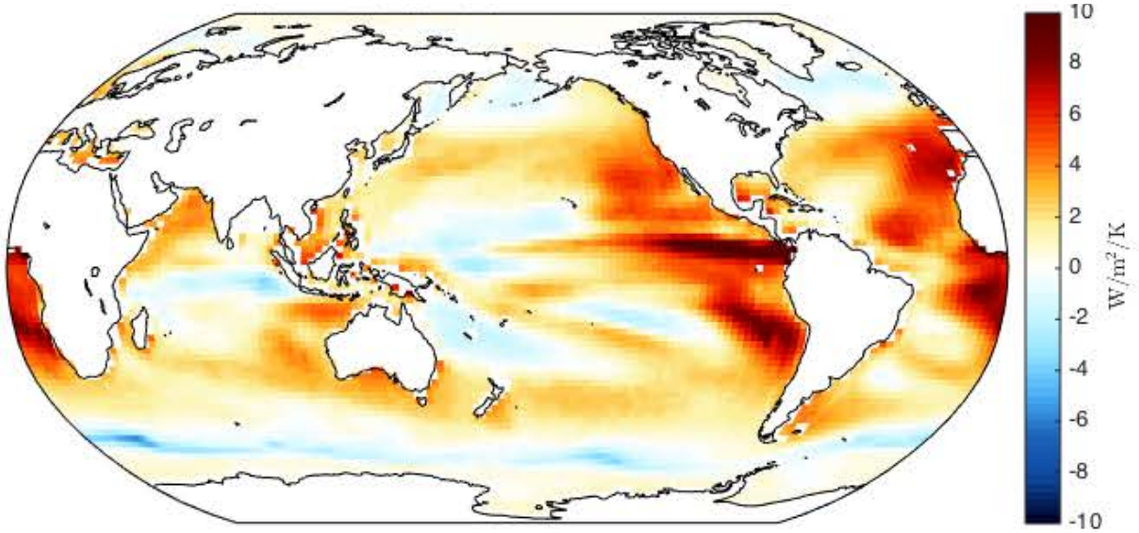
Zelinka et al 2016

Climatological CRE

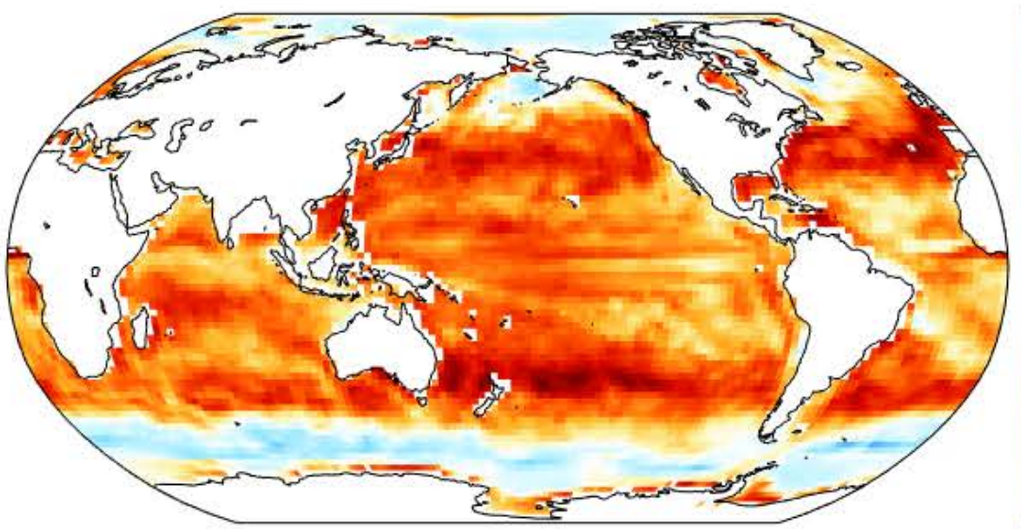


Zelinka et al 2017

AMIP: Interannual cloud feedbacks



AMIP: Correlation w/ ECS



$G_{i,j} = \delta T(\phi_i)/\delta\lambda(\phi_j)$

ϕ_j $(\delta\lambda)$

K/(W/m^2/K)

ϕ_i (δT)

$C_{i,k}$ =COV$(T(\phi_i), \delta\lambda(\phi_k)) = \sum_j G_{i,j}\Lambda_{j,k}$

ϕ_k $(\delta\lambda)$

(W/m^2)

Variance of $T(\phi_i)$ explained $\lambda(\phi_k)$

r^2

ϕ_i (δT)

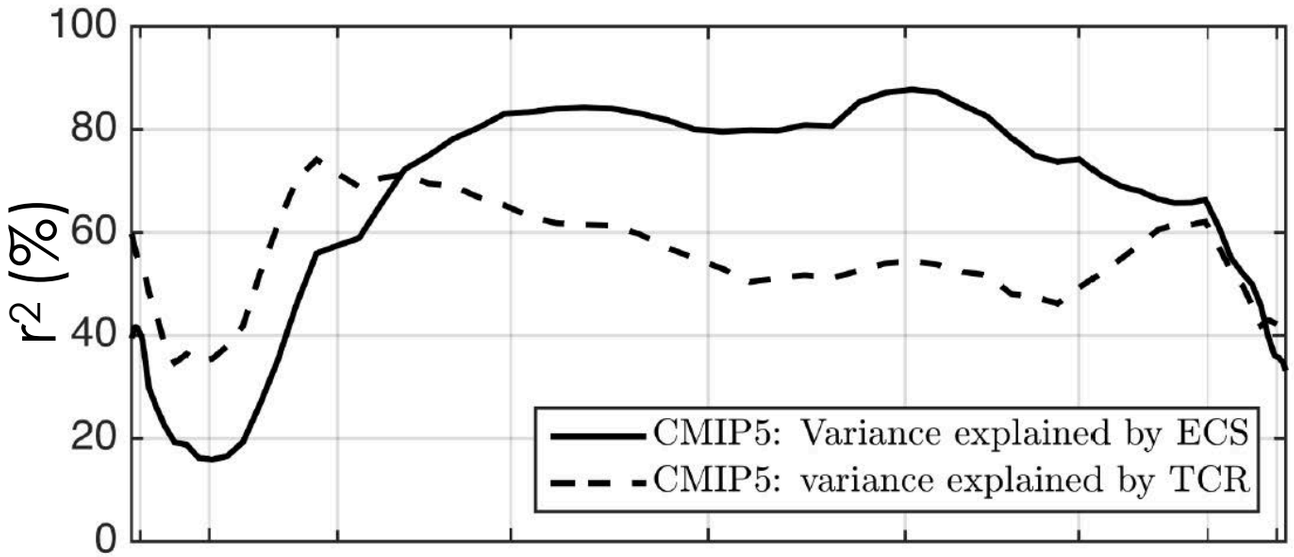
ϕ_k $(\delta\lambda)$

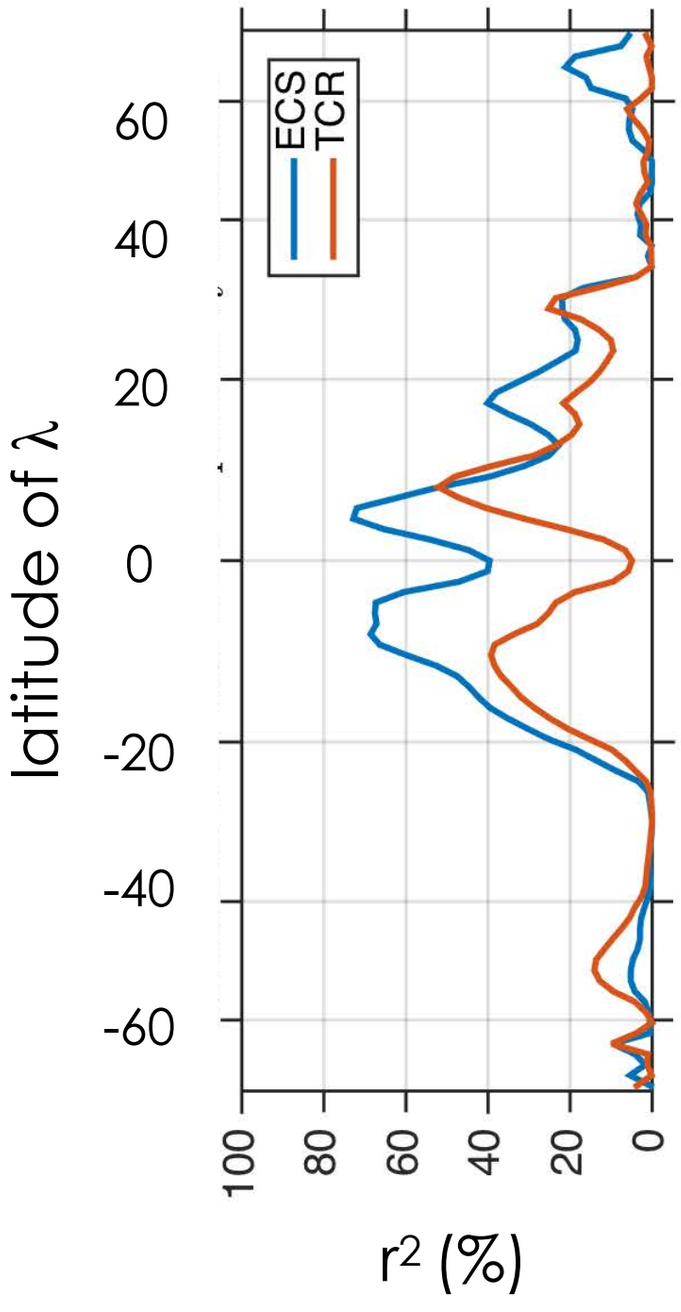
$\Lambda_{j,k}$ =COV$(\lambda(\phi_j), \delta\lambda(\phi_k))$

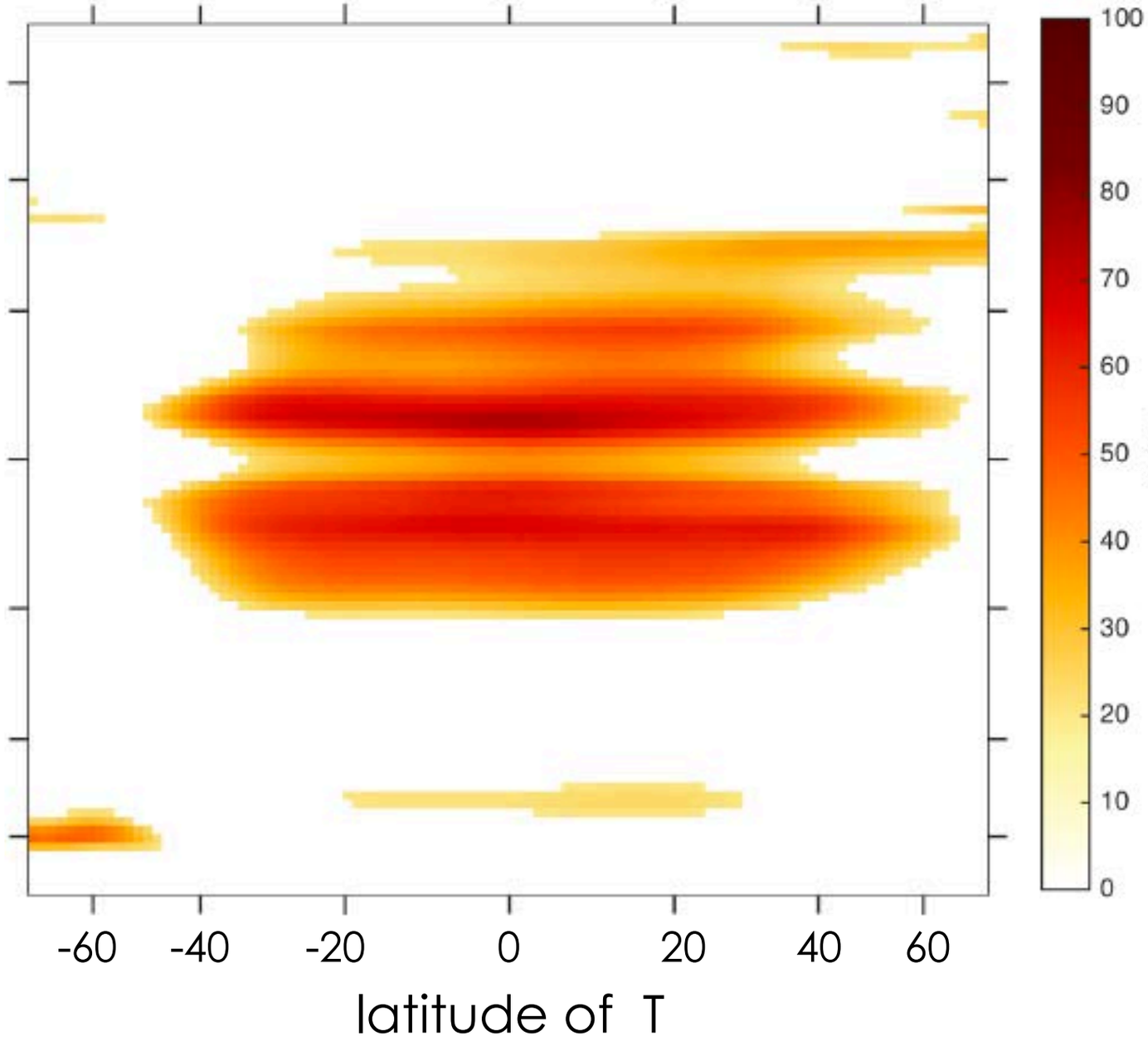
ϕ_j $(\delta\lambda)$

(W/m^2/K)^2

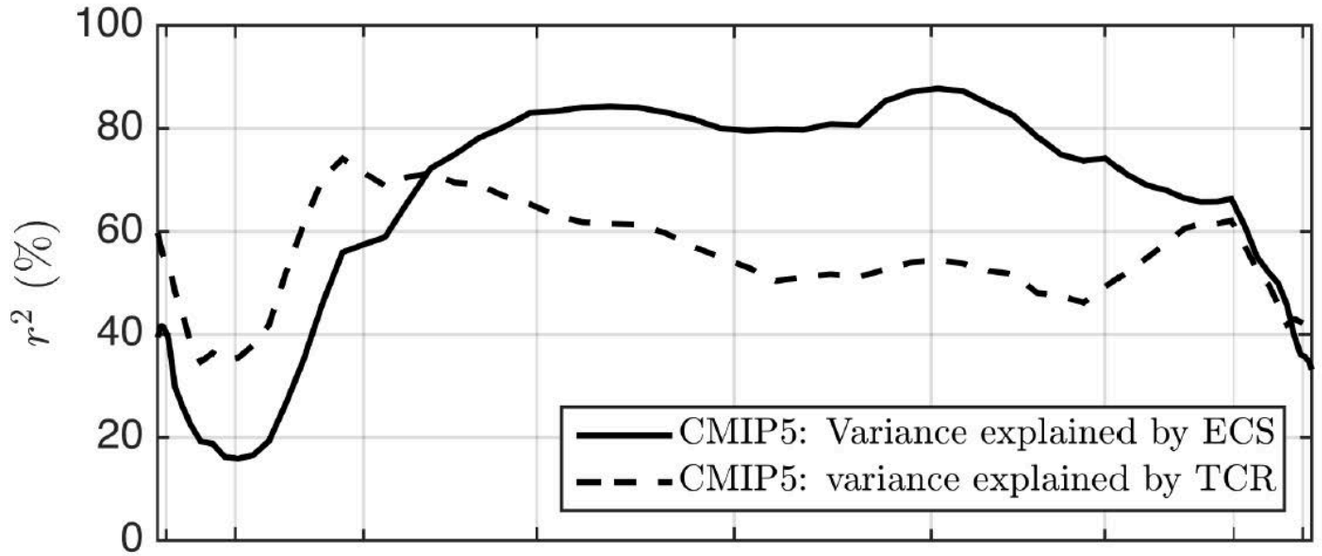
ECS and 21st century warming both determined by low-lat feedbacks.

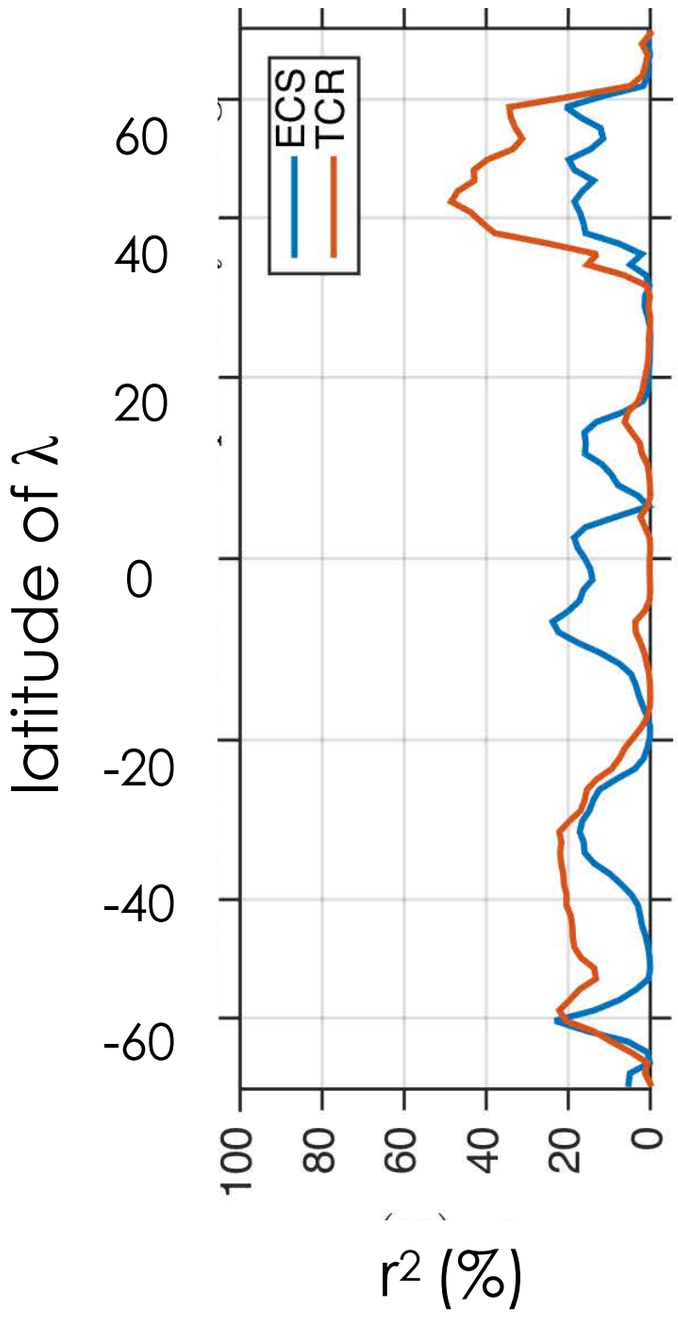


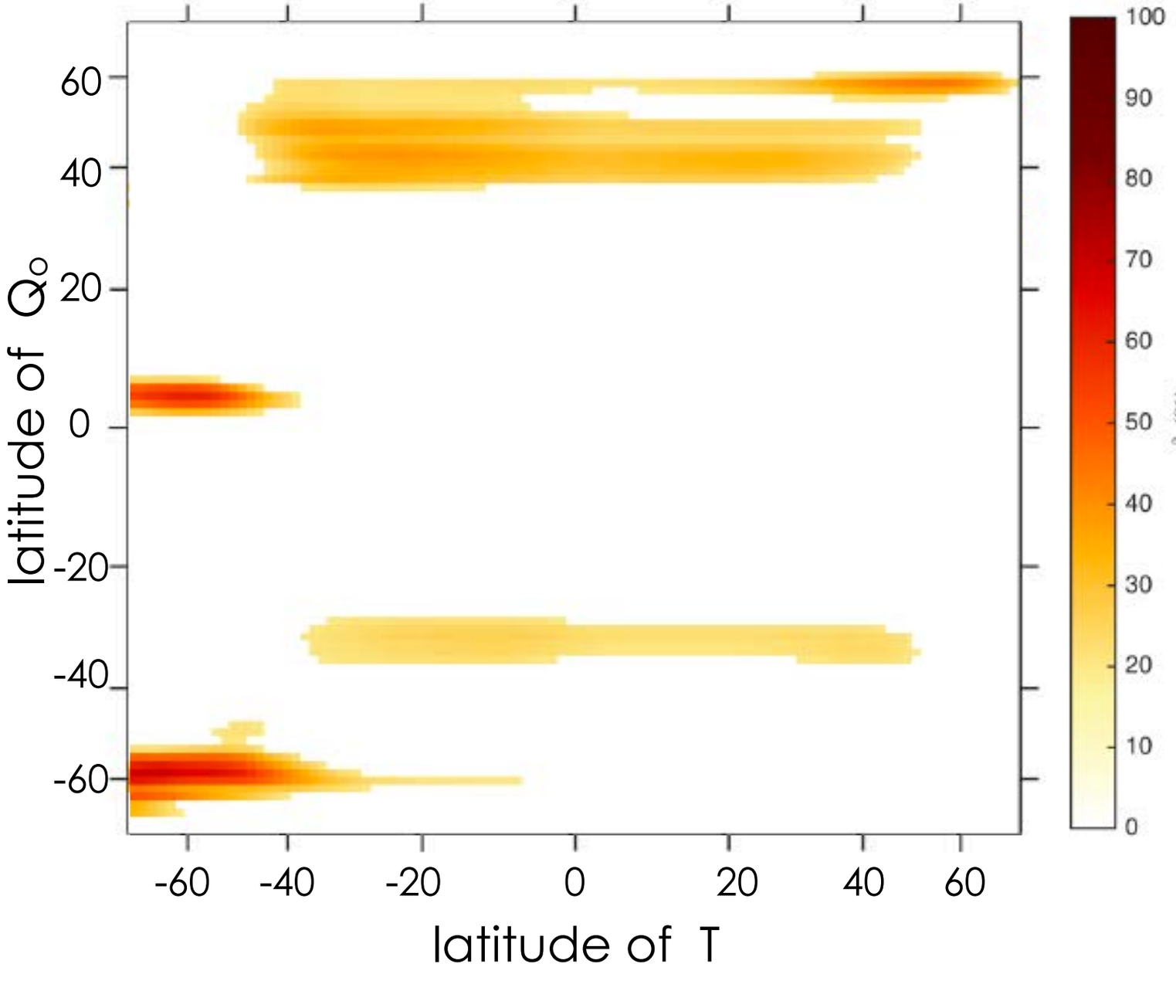




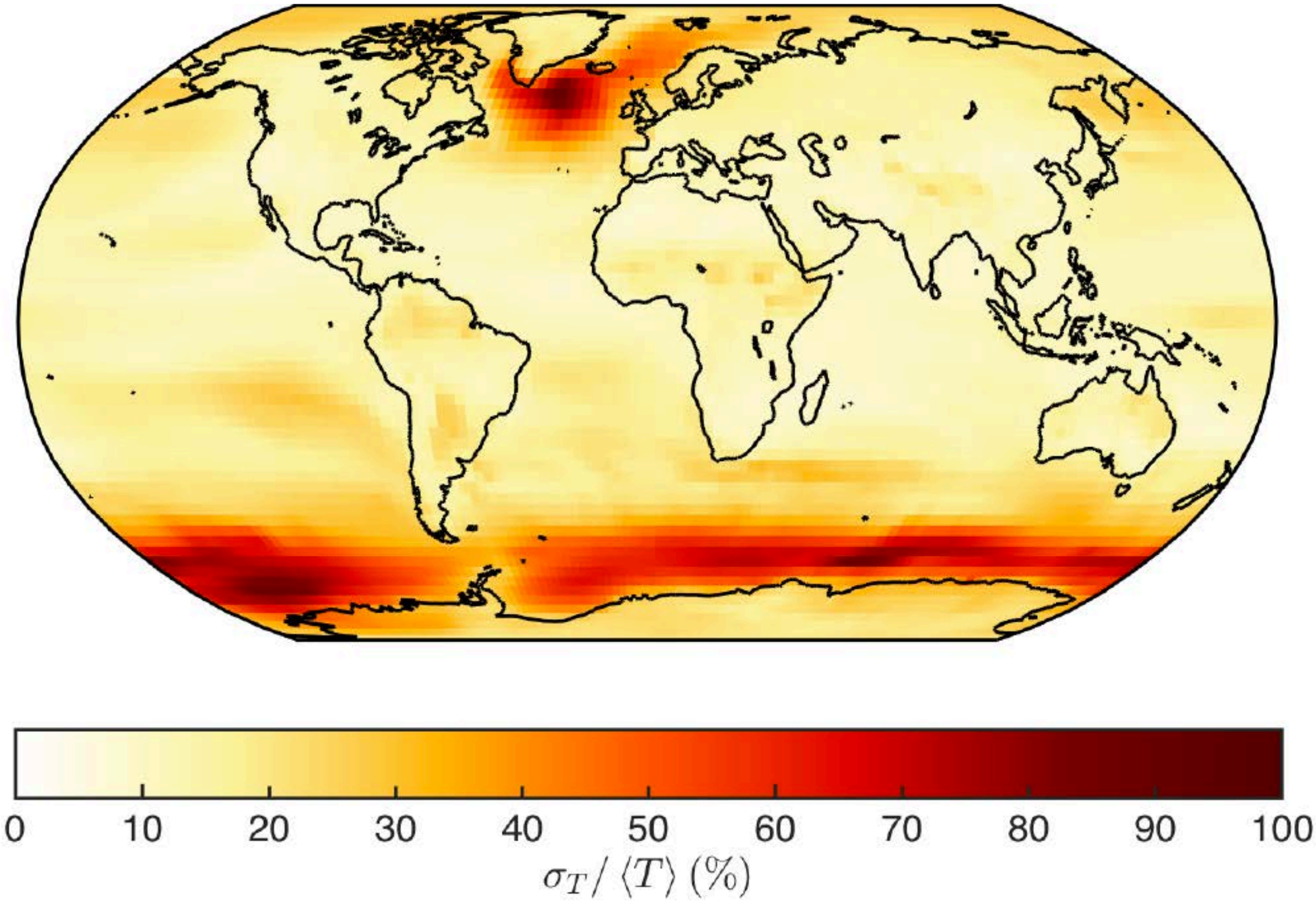
Spread in heat uptake important for TCR, but not for 21st century T







Q: What do I do to improve projections of 21st century warming in Greece (or Iowa)?
A: Fix ECS! (…and whatever fixes ECS)



- Local processes are only important if they contribute to fixing ECS
- Caveat: at least amongst the "known-unknowns"