Modeling the Extratropical Jets: Connections between the mean climate, variability, and response to anthropogenic forcing

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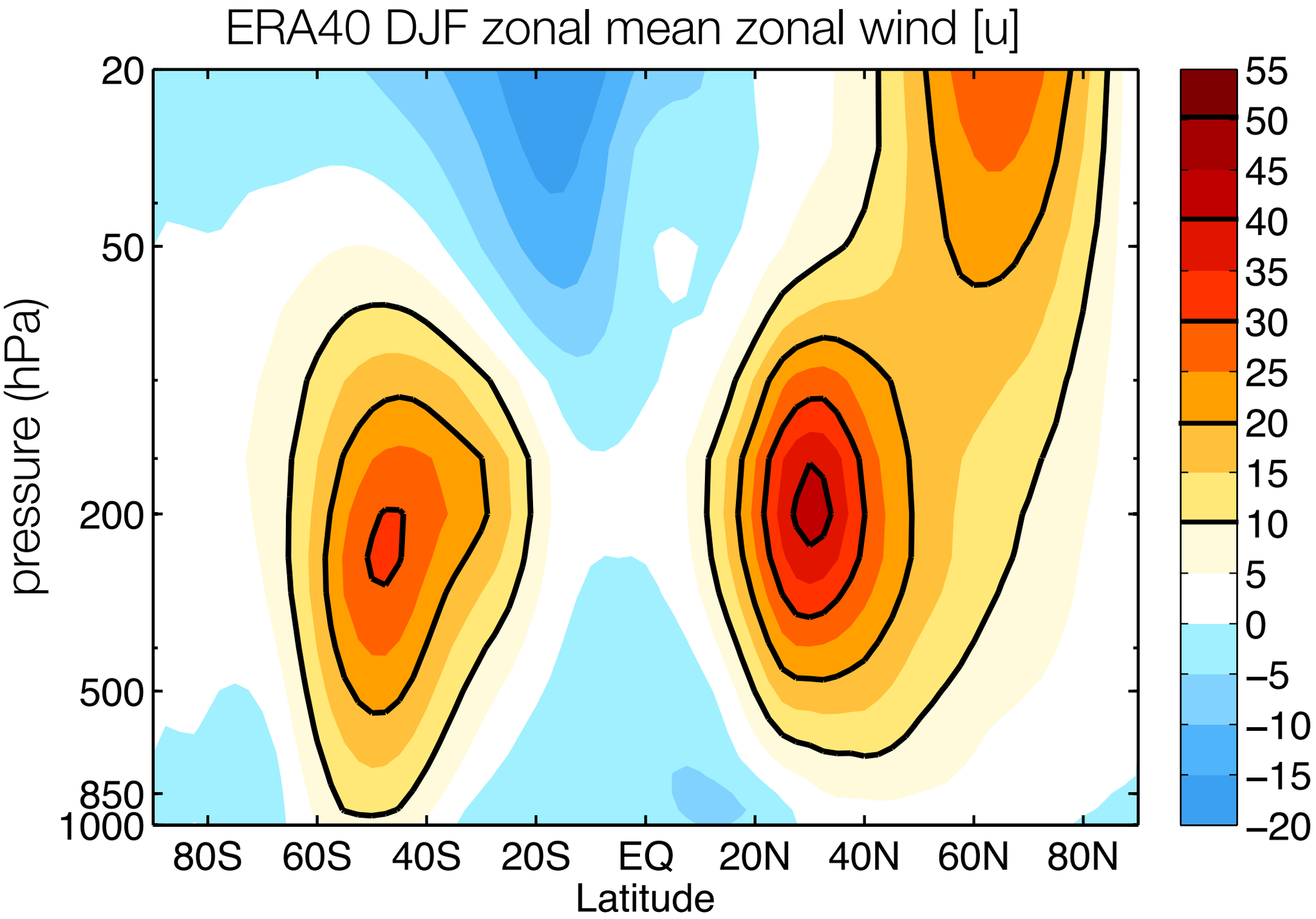
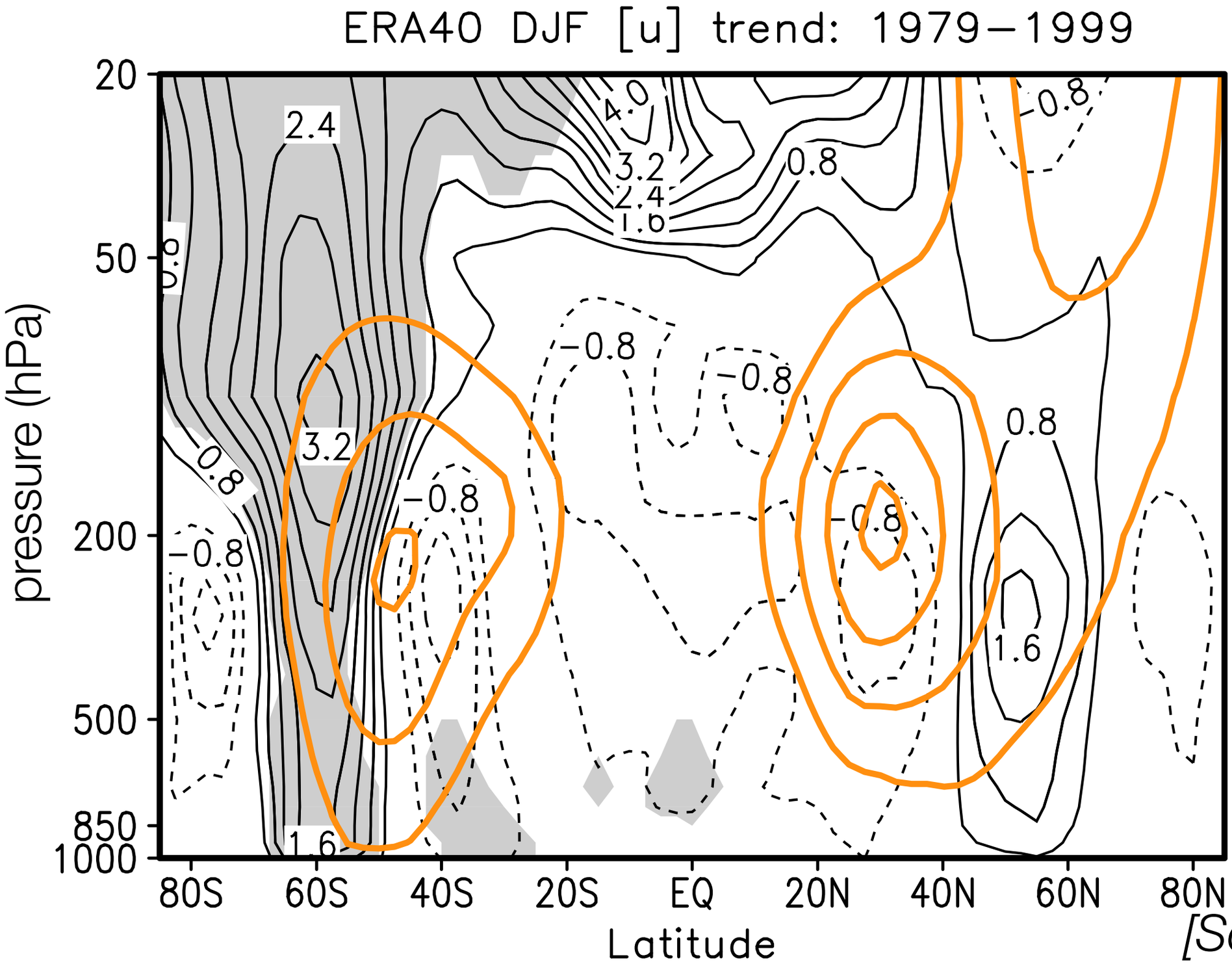
The extratropical jets in Austral summer



The extratropical jets in Austral summer: Recent trends



[Son et al. 2010]

Questions

- What are the relative roles of greenhouse gases (GHGs) and ozone in forcing Southern Hemisphere circulation changes?

- What causes uncertainty in the circulation response? (That is, why is there such variance in model projections?)

- How can we reduce the uncertainty in the circulation response?

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(cast, in order of decreasing CPU time)

- Coupled Climate Models: CMIP3, plus some tentative results from CMIP5
- Chemistry Climate Models (CCMs) from the CCMVal2 Project
    - simulate interactive ozone chemistry in the stratosphere
    - generally specified SSTs
- Dry Dynamical Cores
    - primitive equation dynamics on the sphere (guts of an atmospheric model)
    - simple *Held and Suarez 1994* climate physics (no radiation, convection)

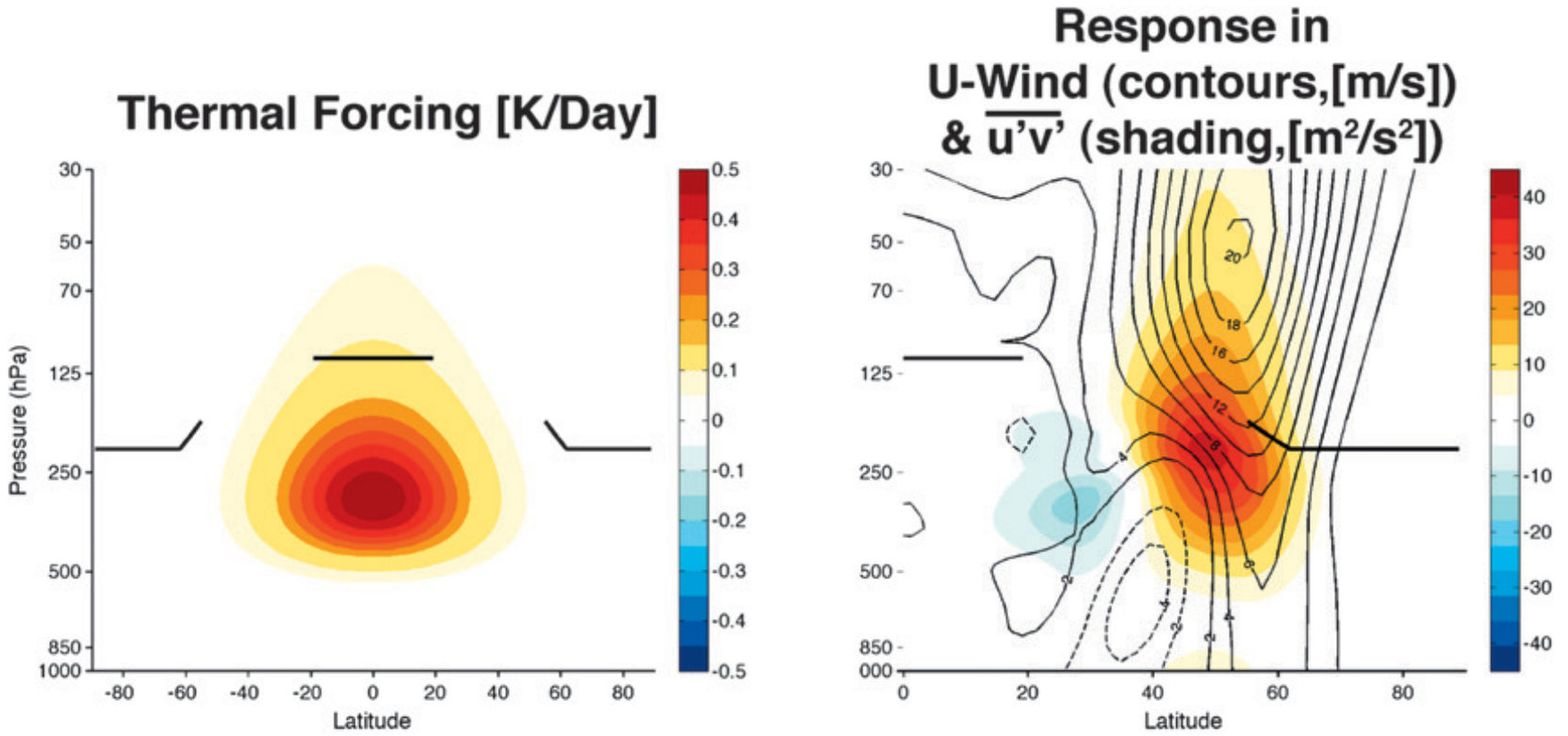
A GHG Push and Ozone Pull

- Green house gas induced warming can shift the jets equatorward *[Kushner et al. 2001]*

- Ozone induced cooling can shift the jet poleward *[Polvani and Kushner, 2002; Arblaster and Meehl, 2006]*

The circulation response to thermal forcing in a Dry Dynamical Core

GHG-like warming

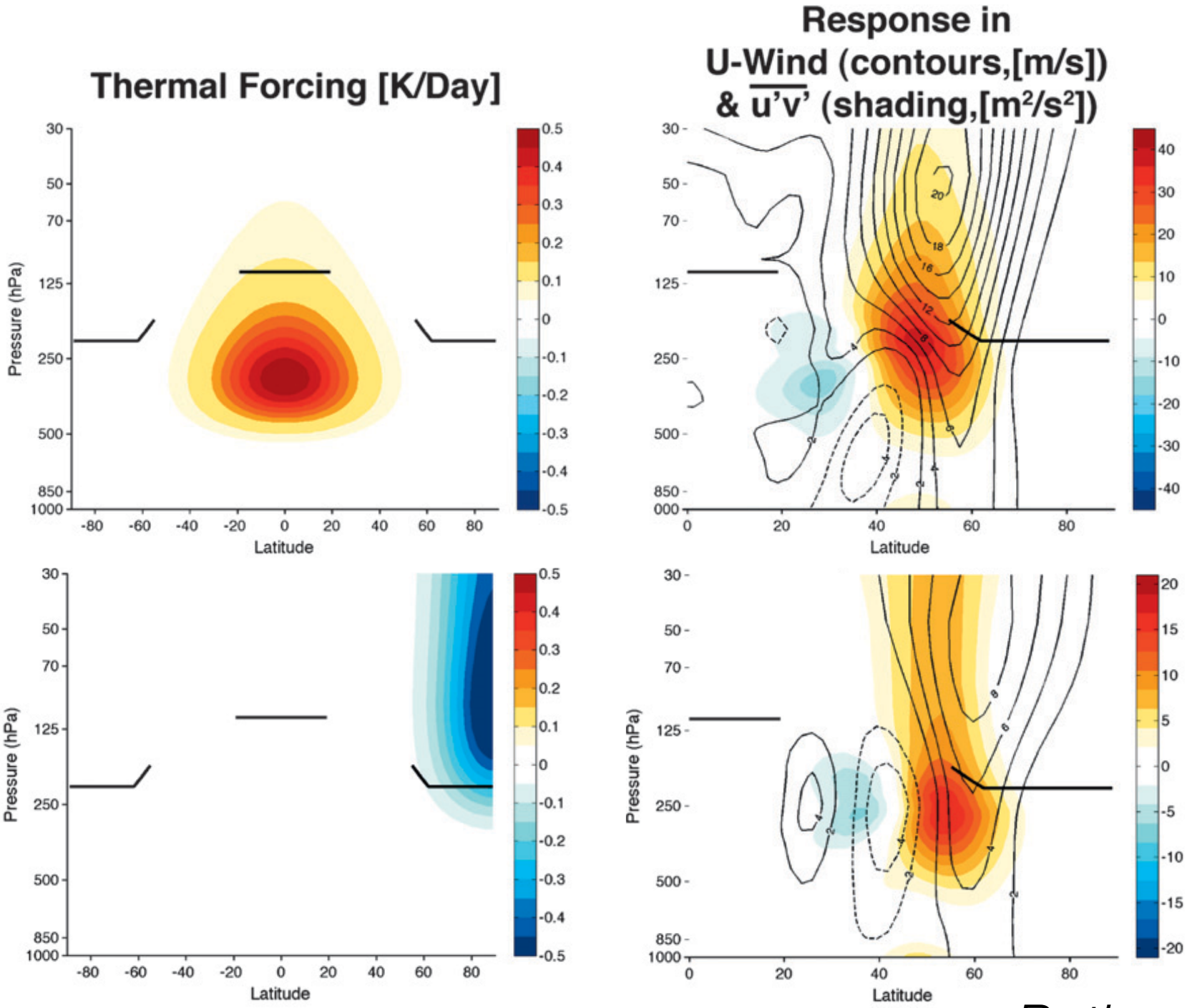


Butler et al. 2010

The circulation response to thermal forcing in a Dry Dynamical Core

GHG-like warming

ozone-like cooling



Butler et al. 2010

Quantifying the response:
Ozone critical for understanding SH trends in DJF

- Arblaster and Meehl 2006: ensemble of forcings with a coupled model
- Perlwitz et al. 2008: Chemistry Climate Model (CCM) study
- Son et al. 2008: CCMs and CMIP3 coupled models
- Polvani et al. 2011; McLandress et al. 2011 (detailed studies with individual GCMs)

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- Polvani et al. 2011; McLandress et al. 2011 (detailed studies with individual GCMs)
- Today: a simple approach that allows us explore the response in the both CCMVal2 and CMIP3 models

A Simple Model of the Jet Response

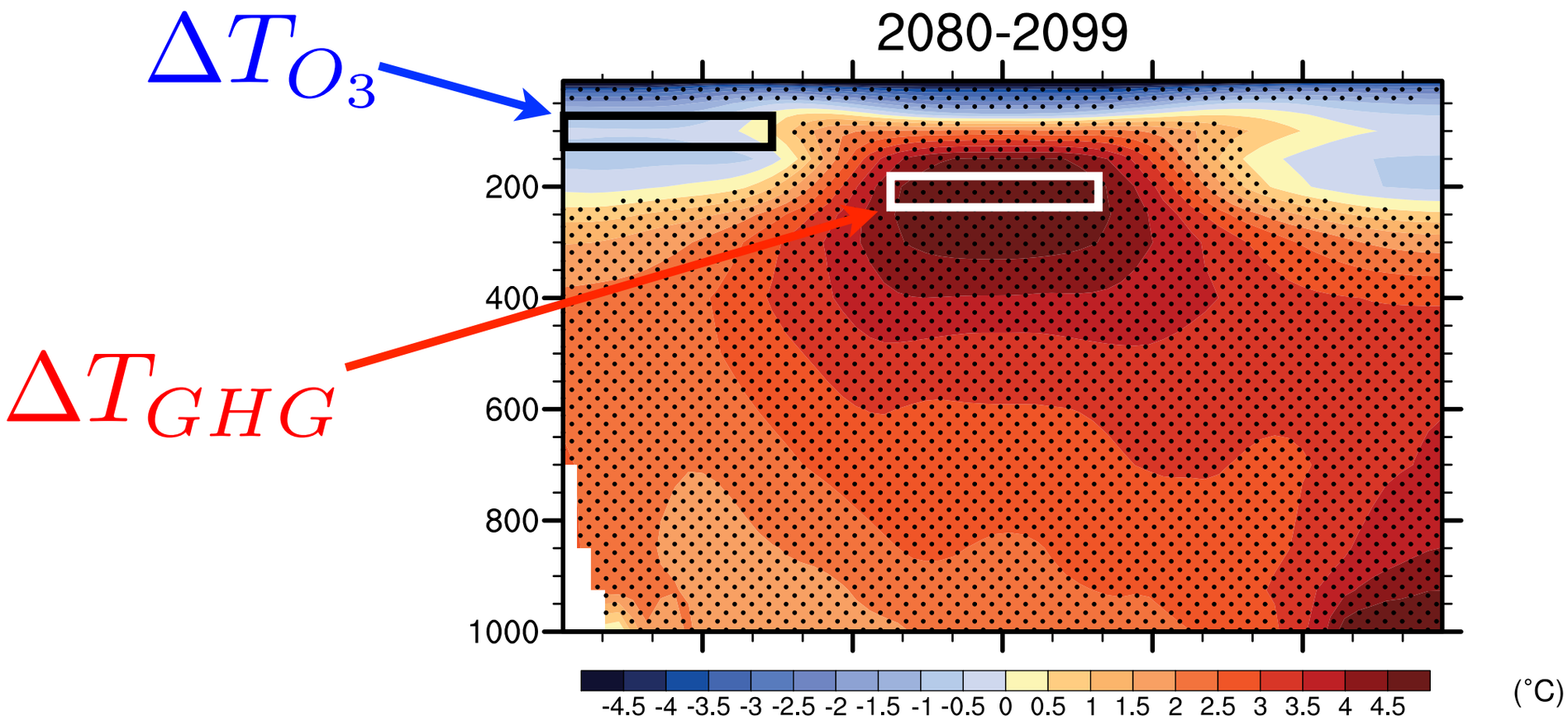
jet shift = ozone pull + GHG push

$$\Delta U_{lat} = r_{O_3} \cdot \Delta T_{0_3} + r_{GHG} \cdot \Delta T_{GHG}$$

model simulations give us the forcings and **response**

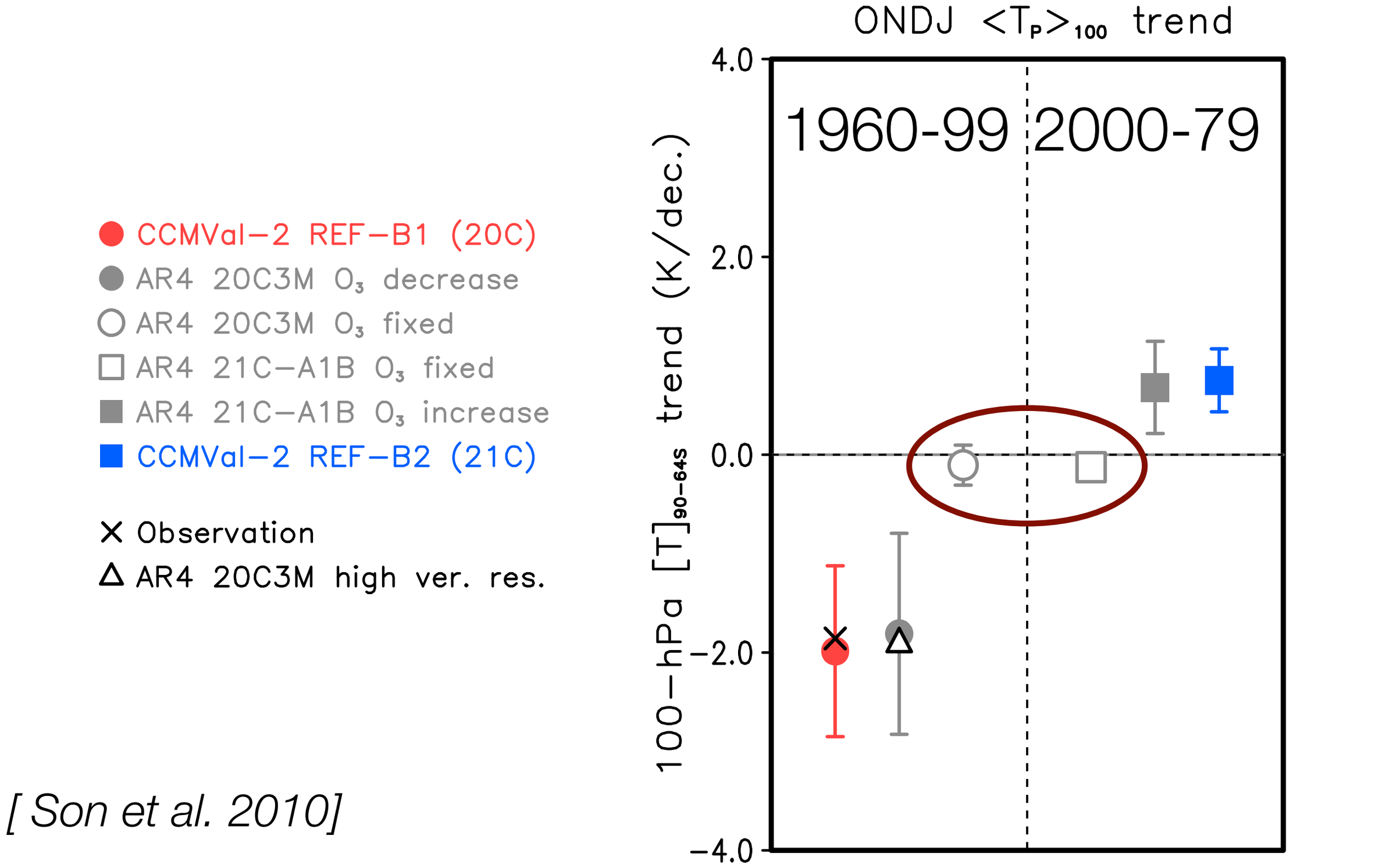
A Simple Model of the Jet Response

AR4 multimodel temp. change, A1B scenario



[IPCC AR4, Chp 10]

Polar cap temperature trends are very weak, absent ozone forcing



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A Simple Model of the Jet Response

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two unknowns

A Simple Model of the Jet Response

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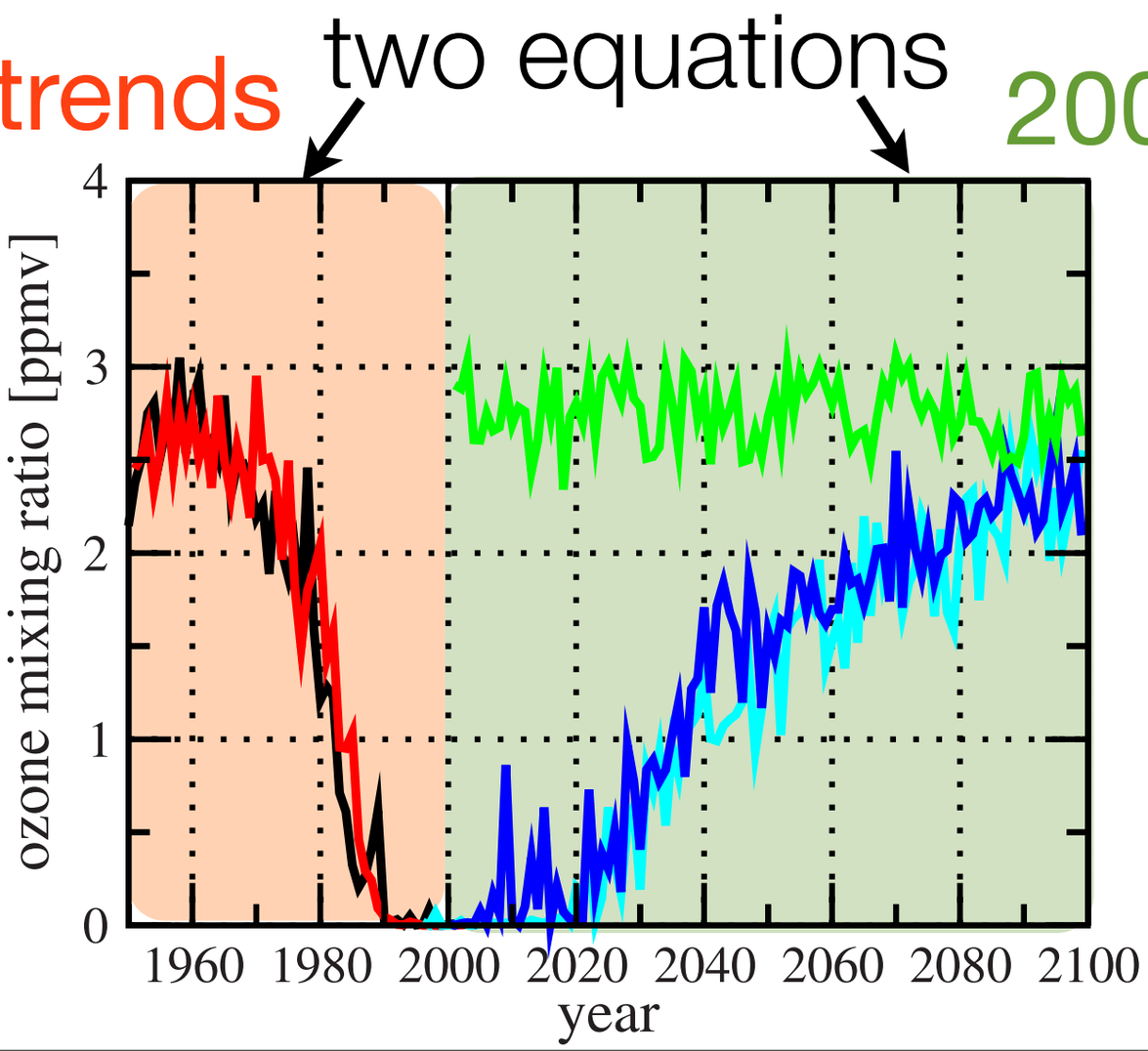
1960-1999 trends

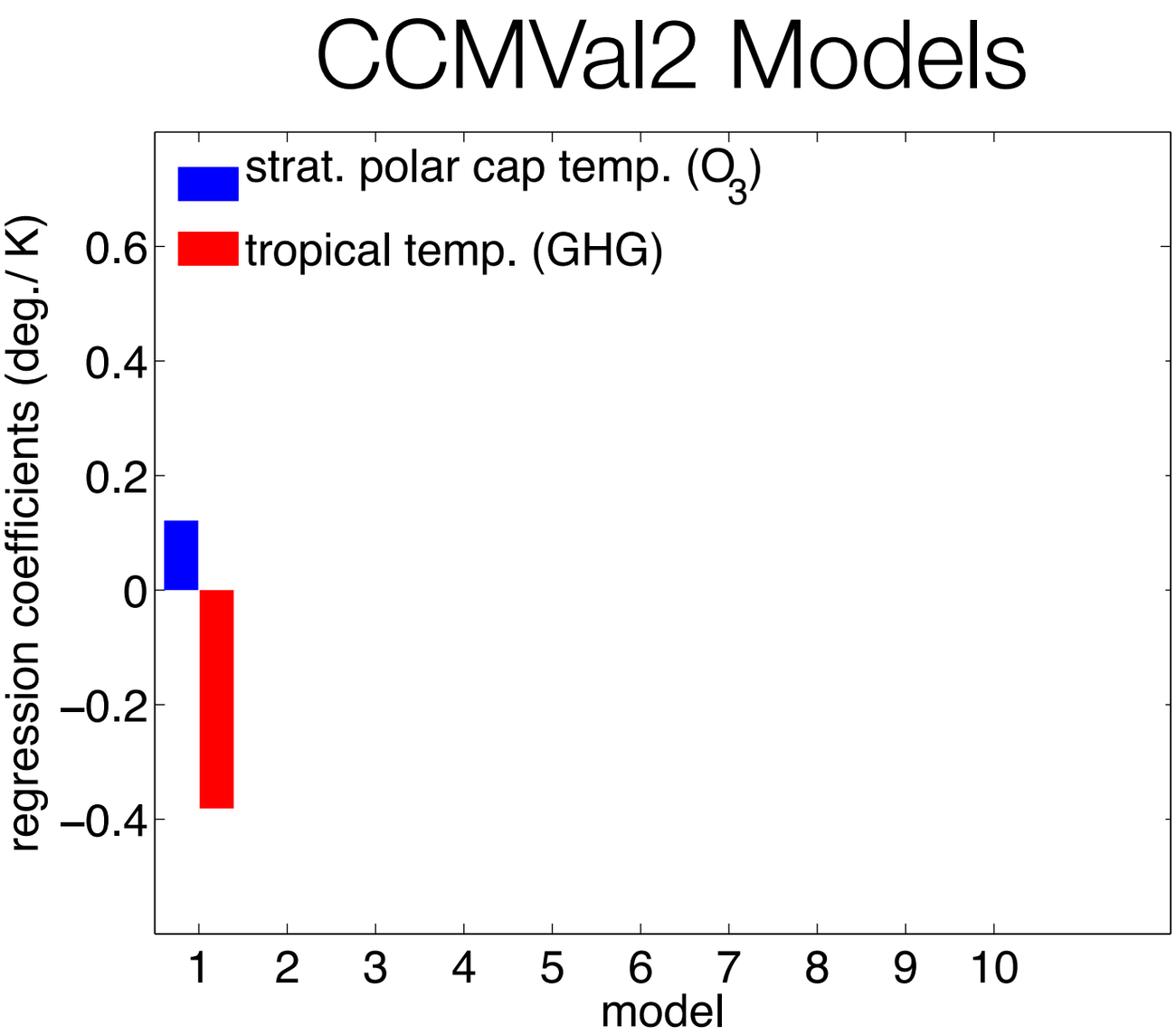
two equations

2000-2079 trends



[Perlwitz et al. 2008]

Regression Coefficients: Estimate of Sensitivity



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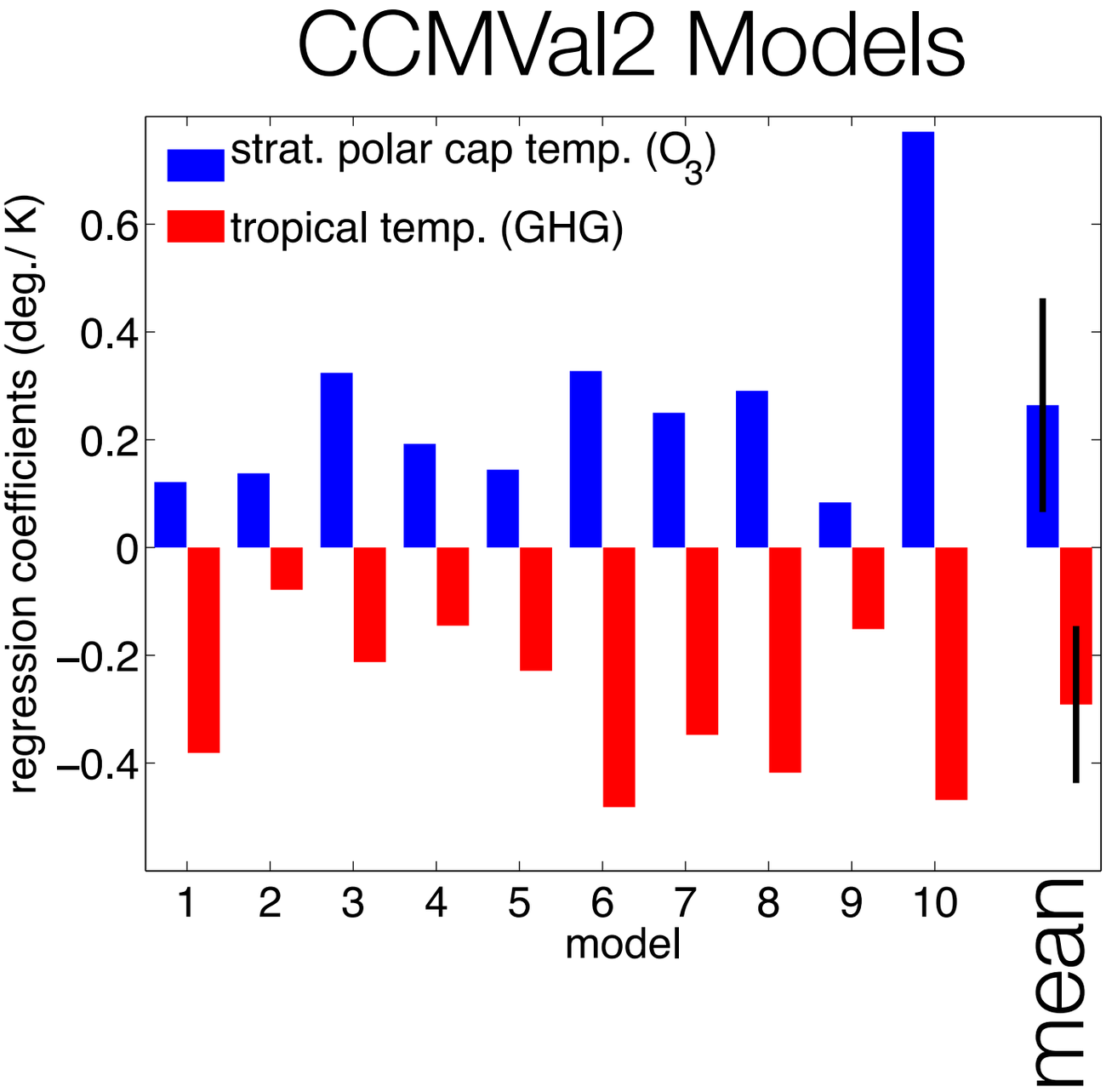

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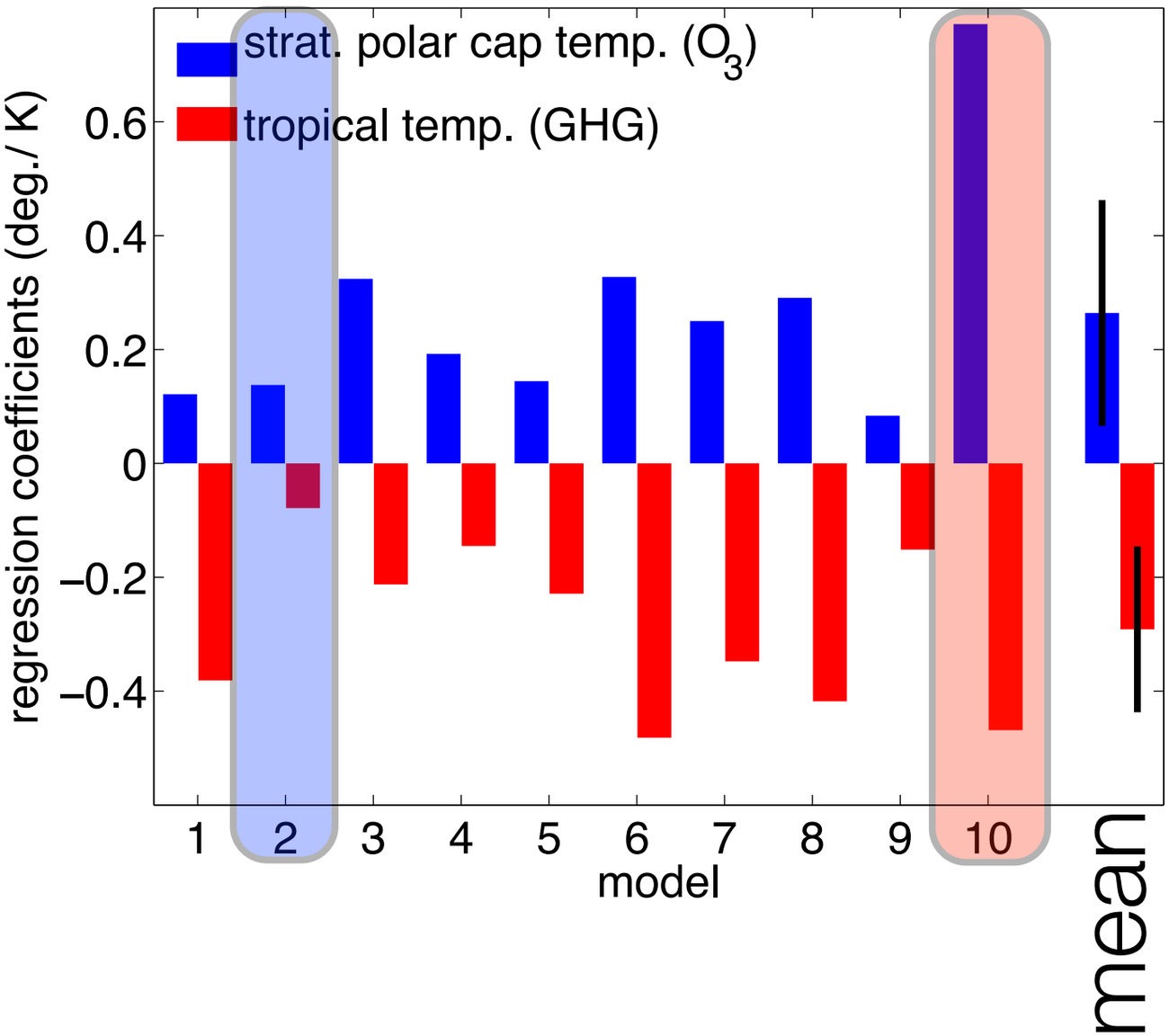
Regression Coefficients: Estimate of Sensitivity

CCMVal2 Models



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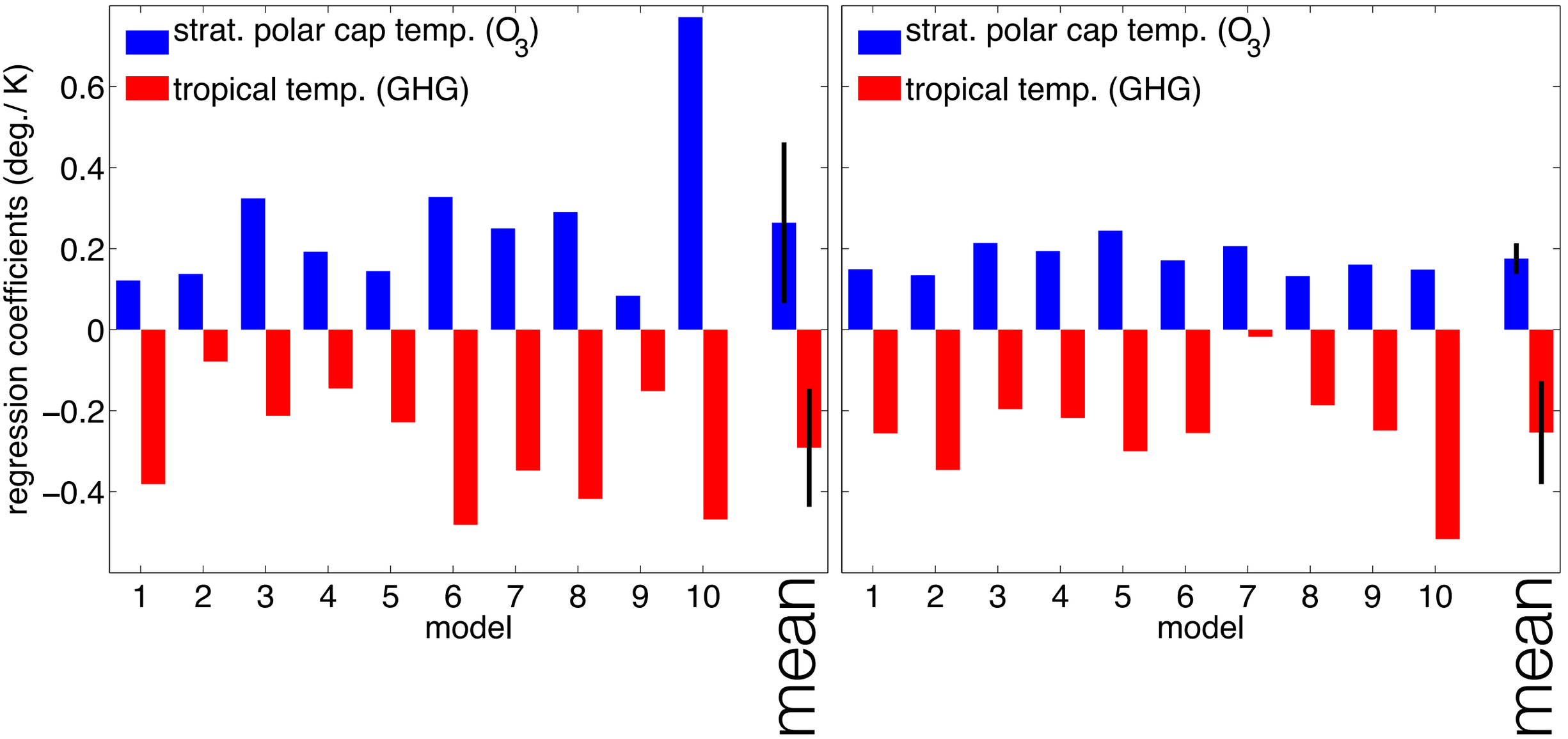

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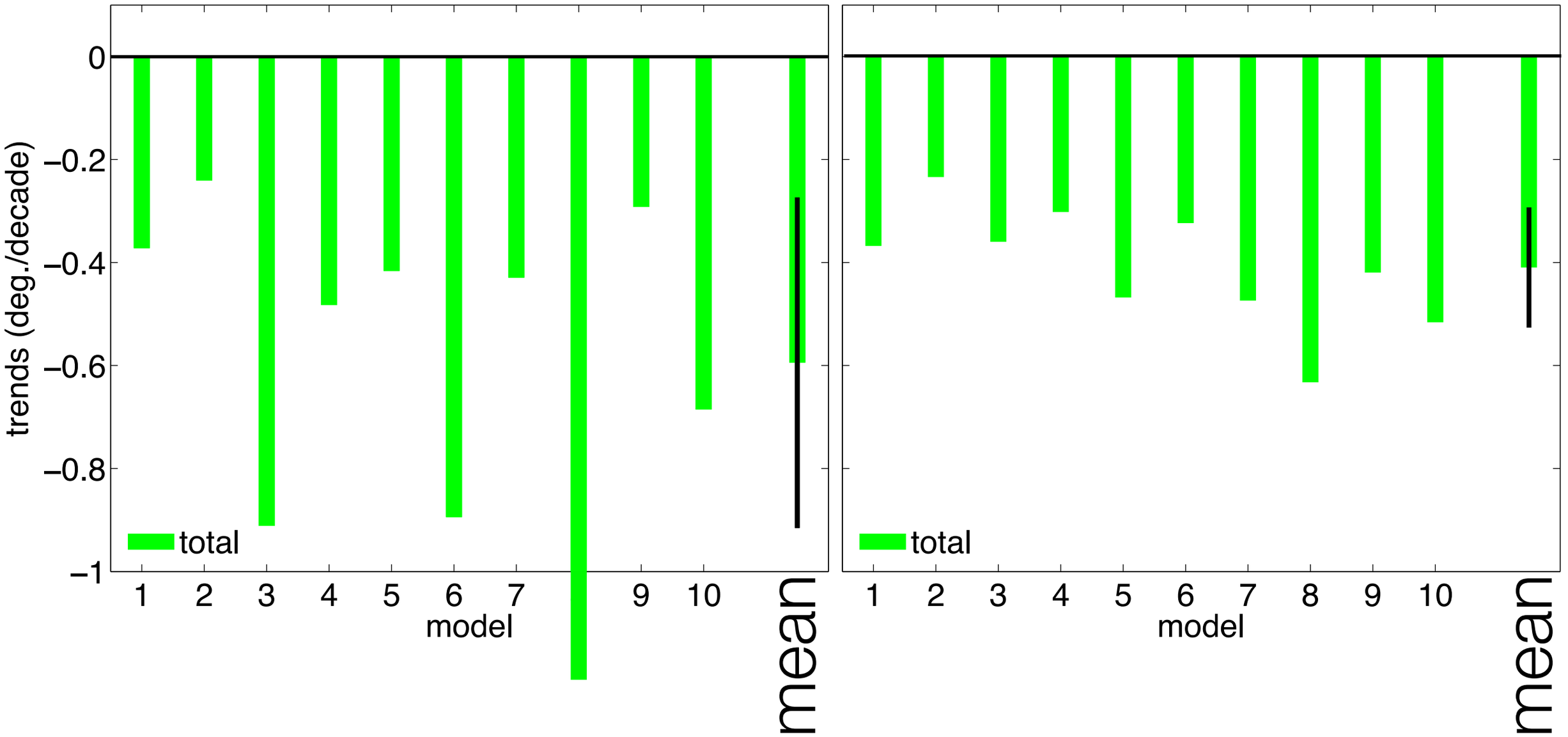
Attribution of 20 Century Climate Trends

CCMVal2 Models

CMIP3 Models



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Attribution of 20 Century Climate Trends

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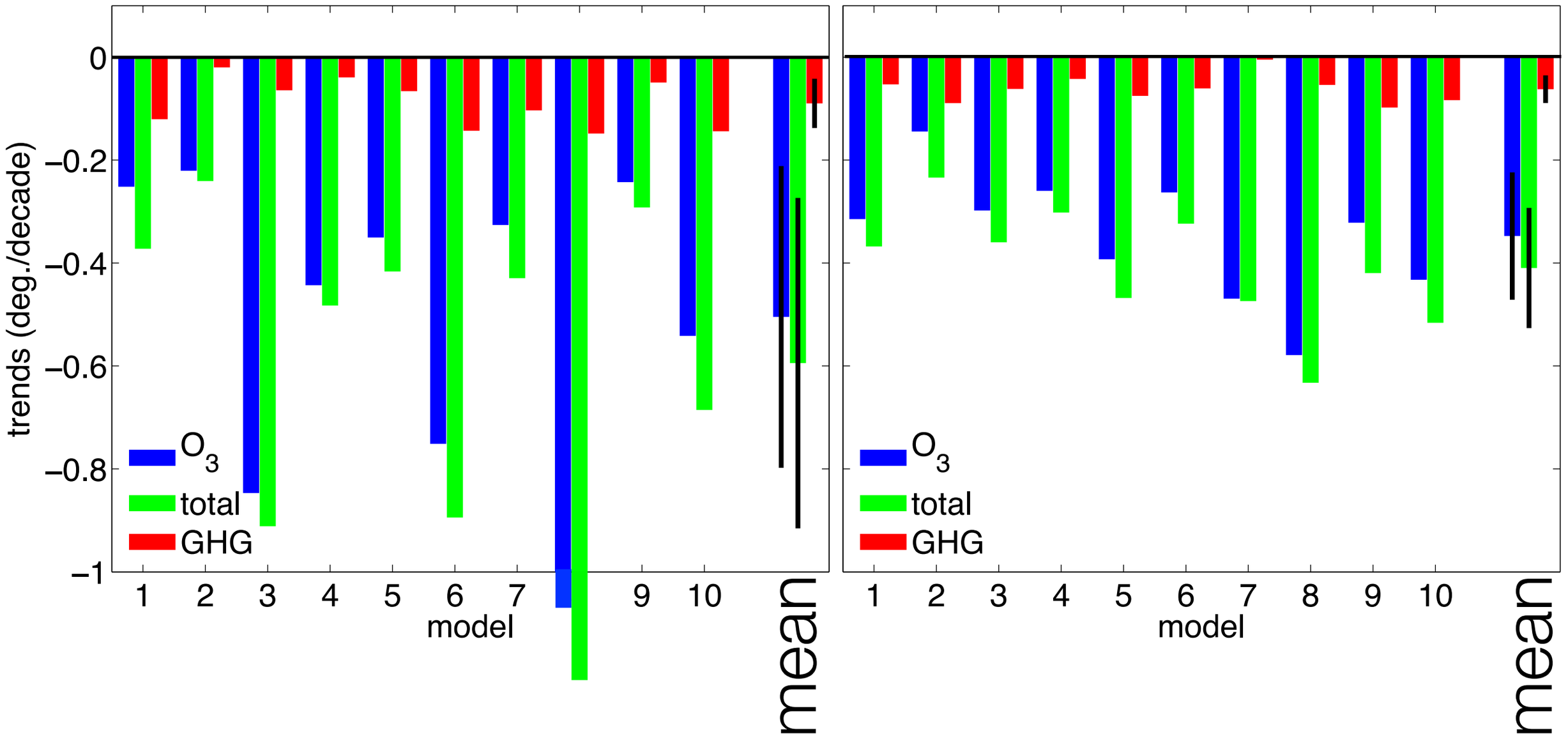

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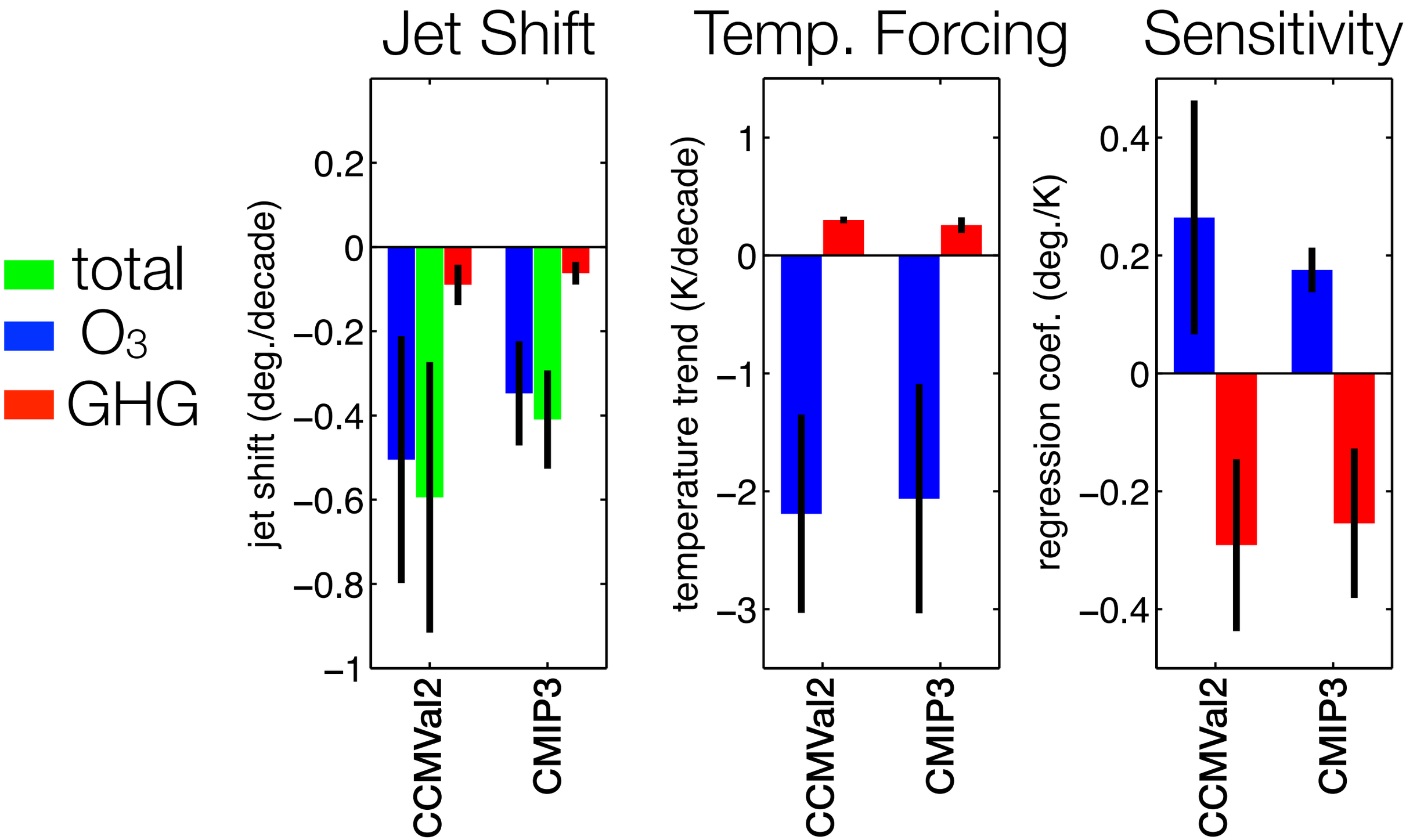
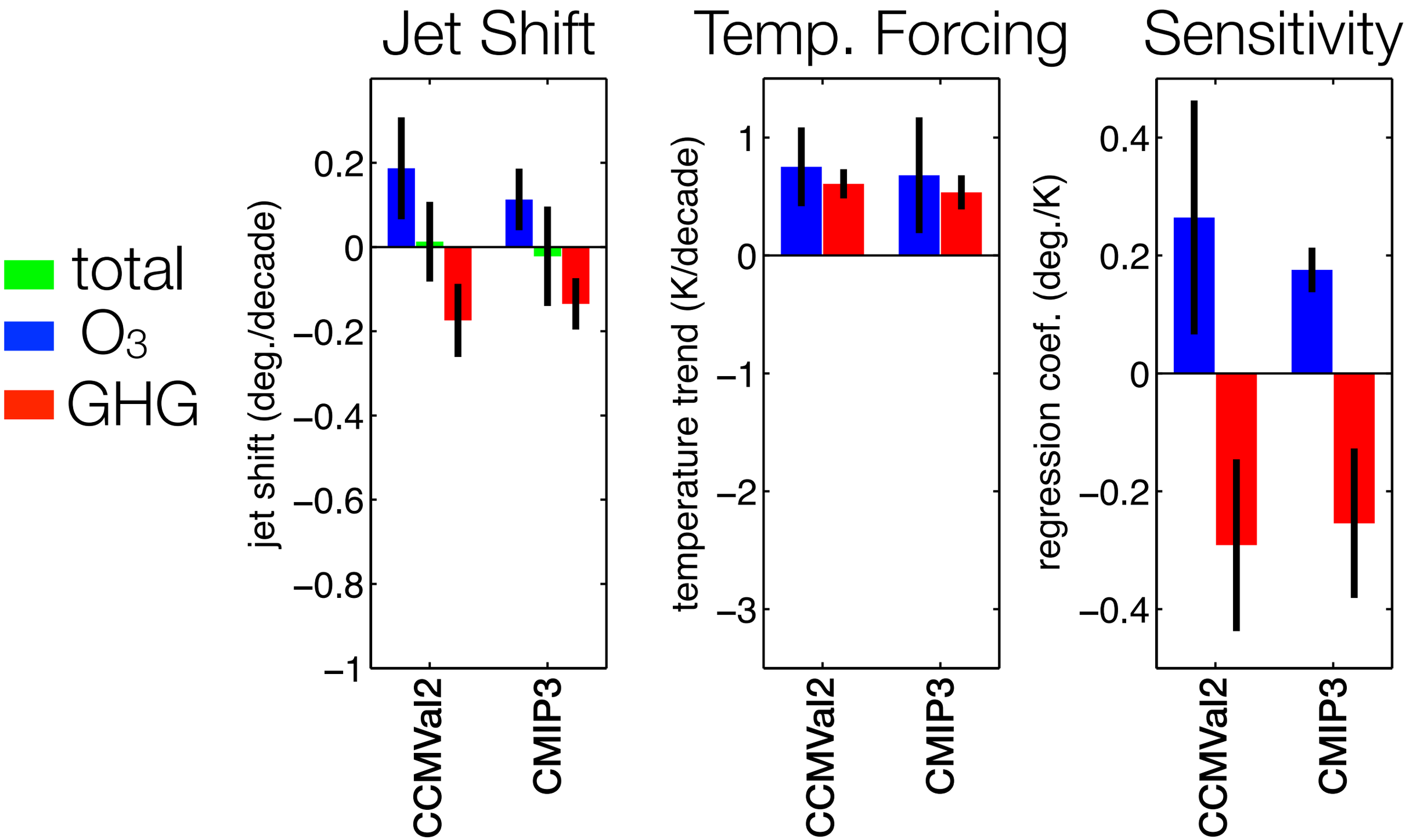
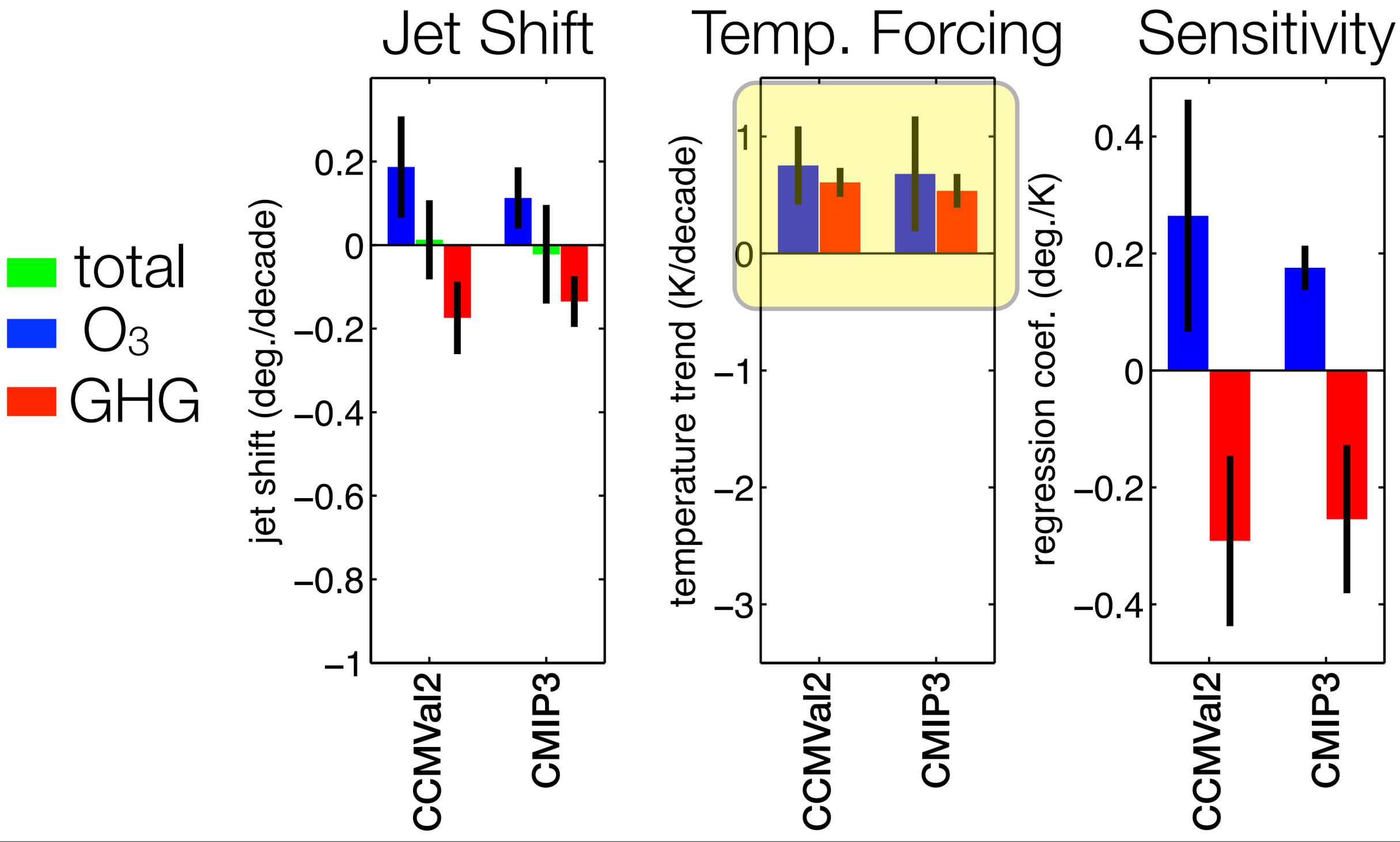
Summary of 20th Century Trends



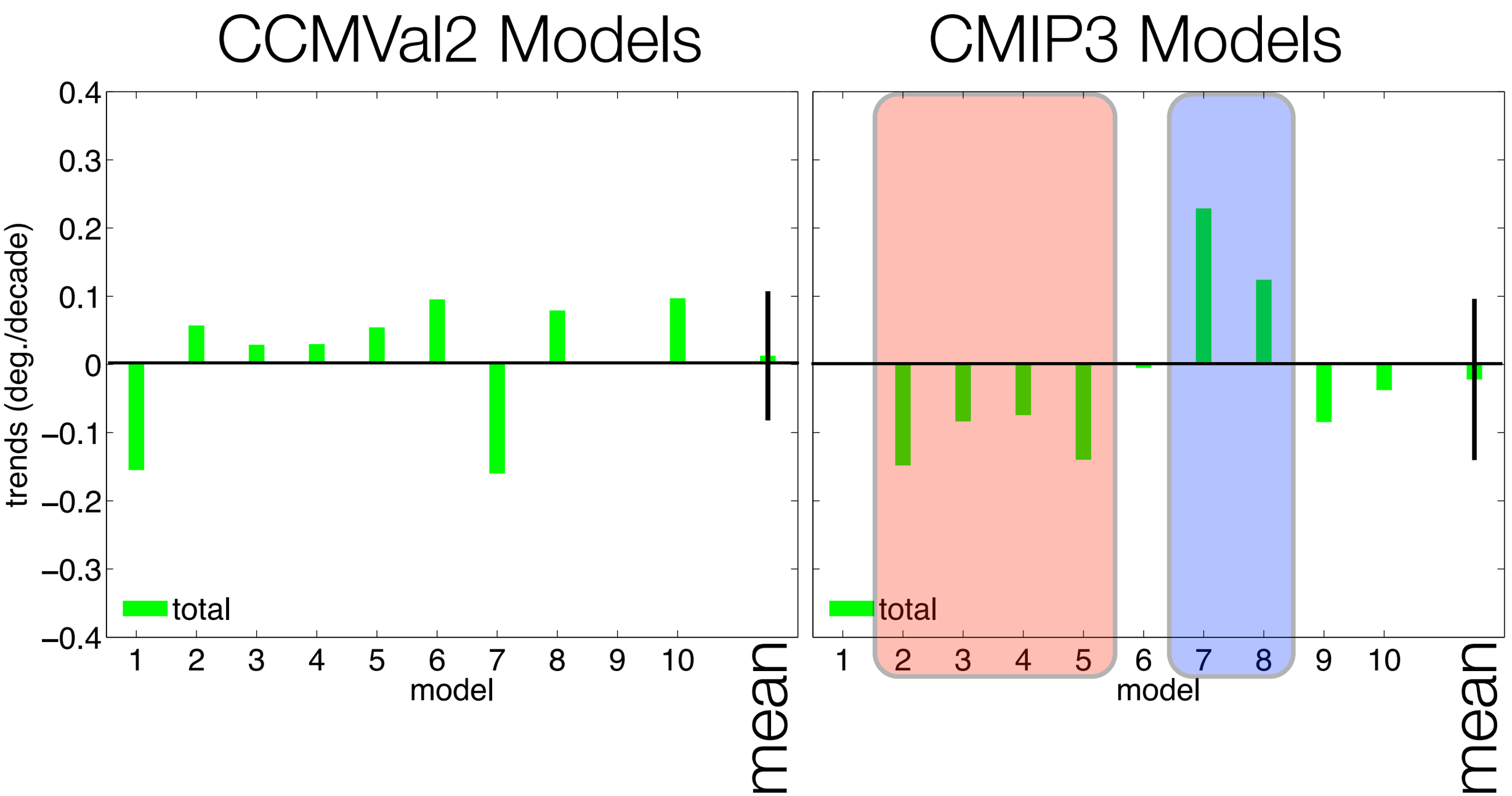
Summary of 21st Century Trends



Uncertainty in the thermal response to forcing



Uncertainty in the thermal response (21st Century Trends)



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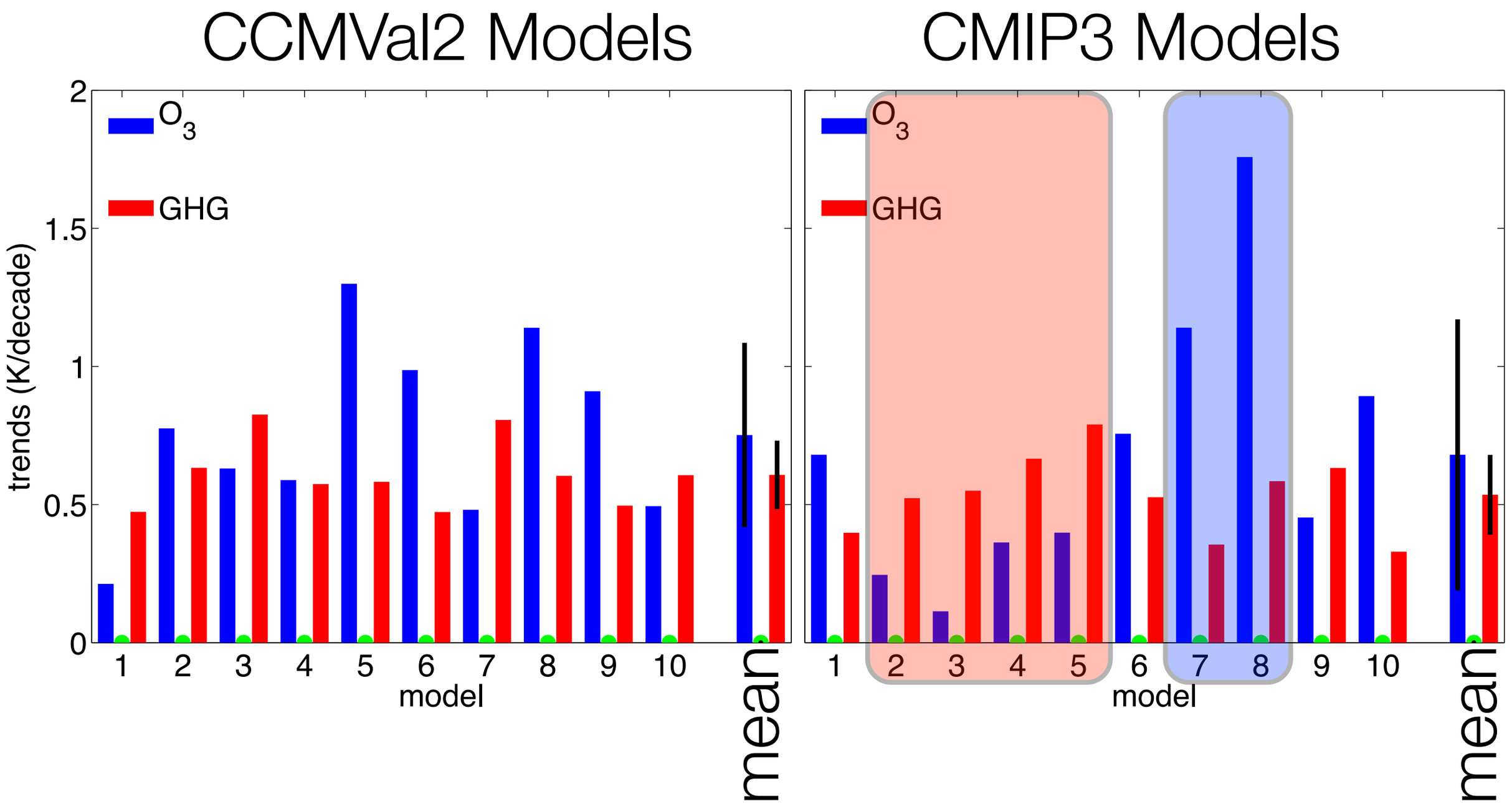

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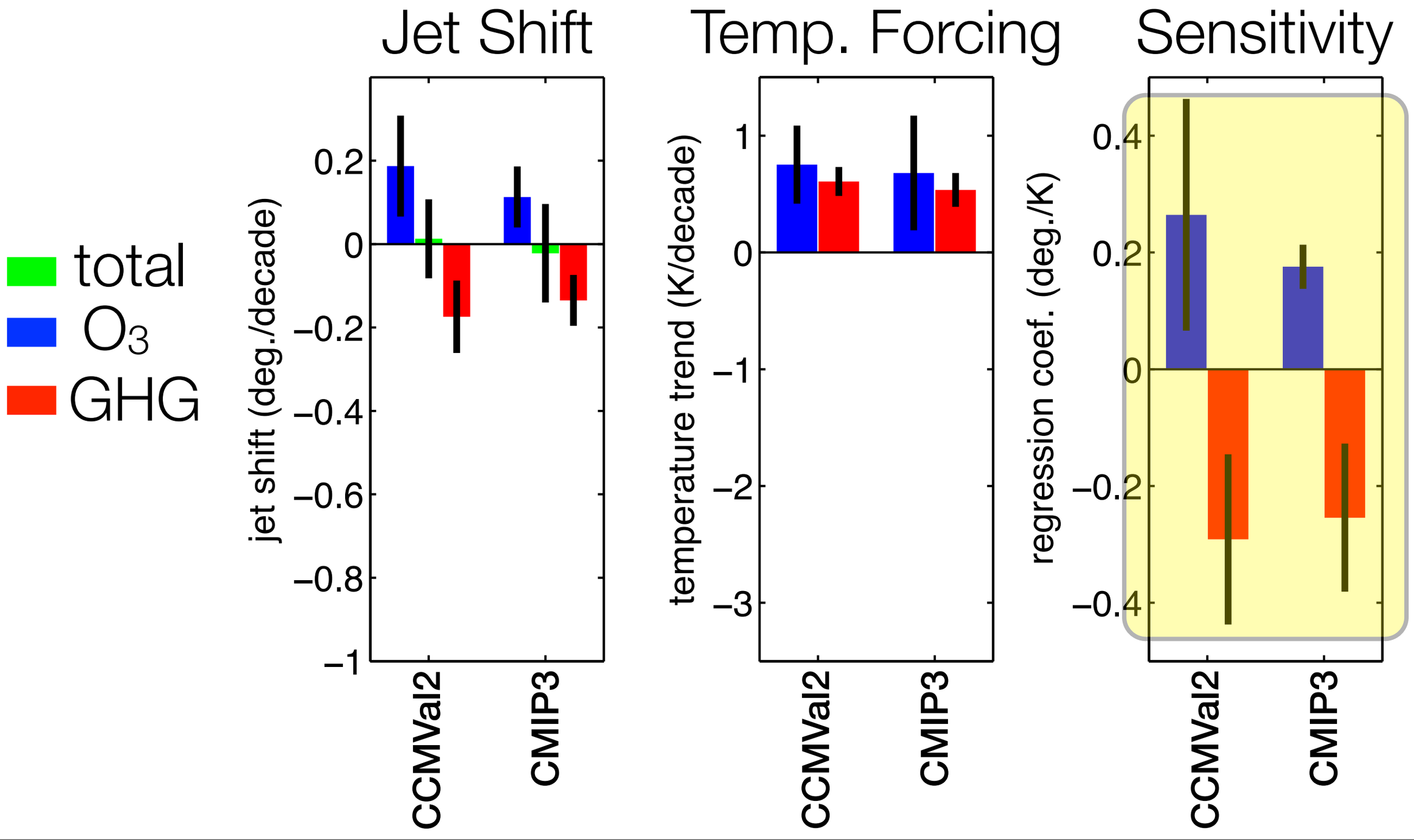

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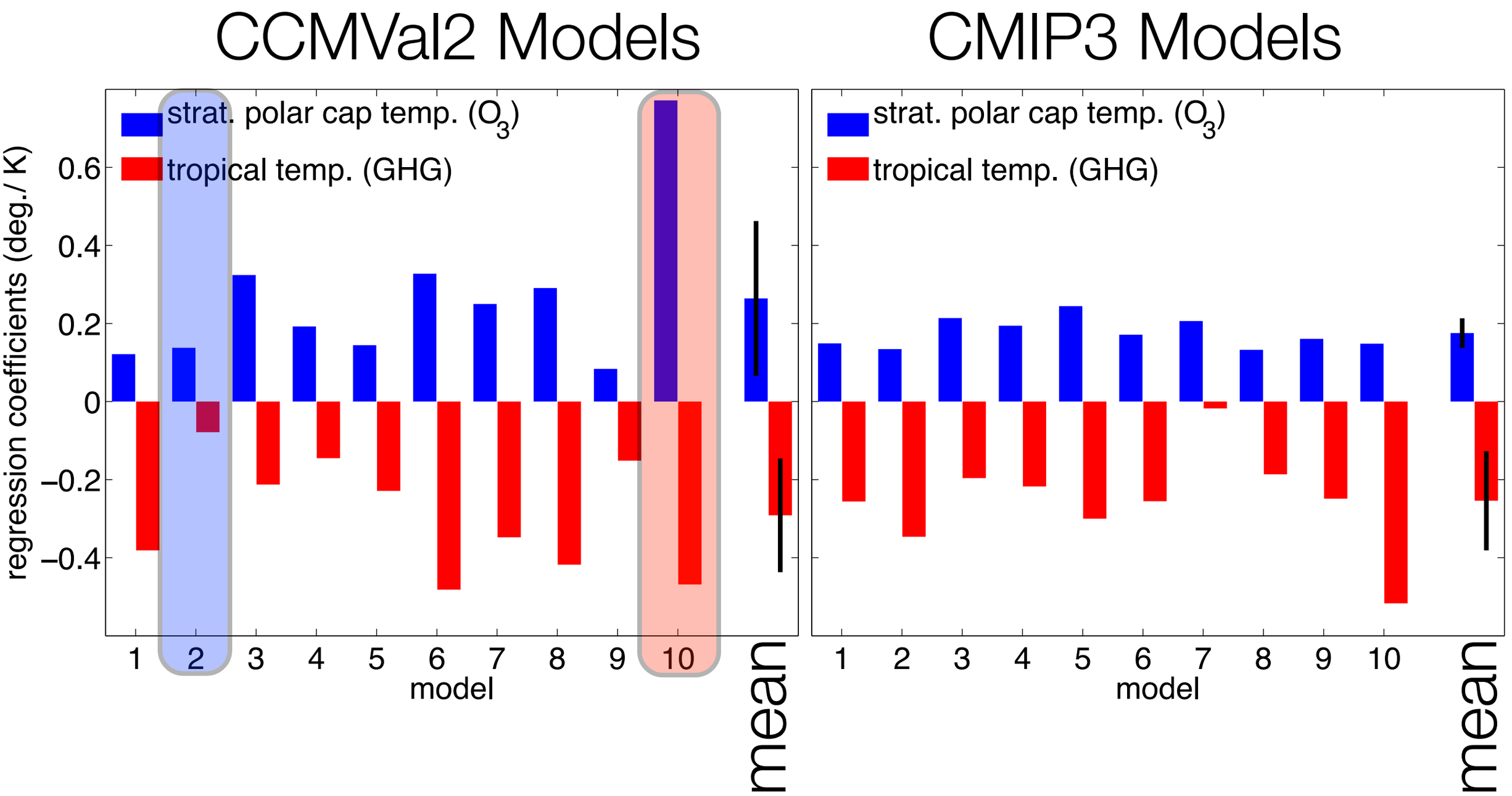

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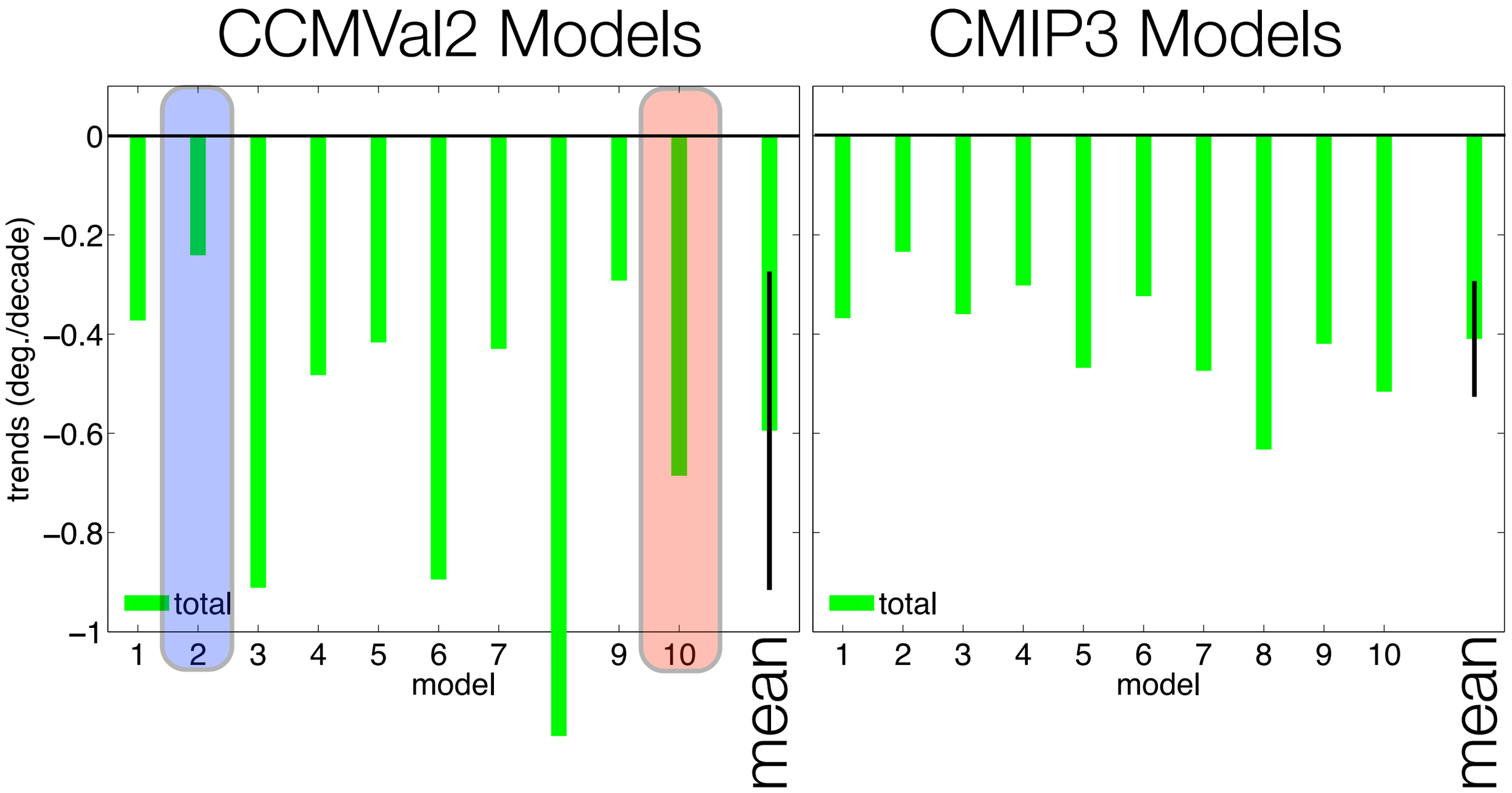

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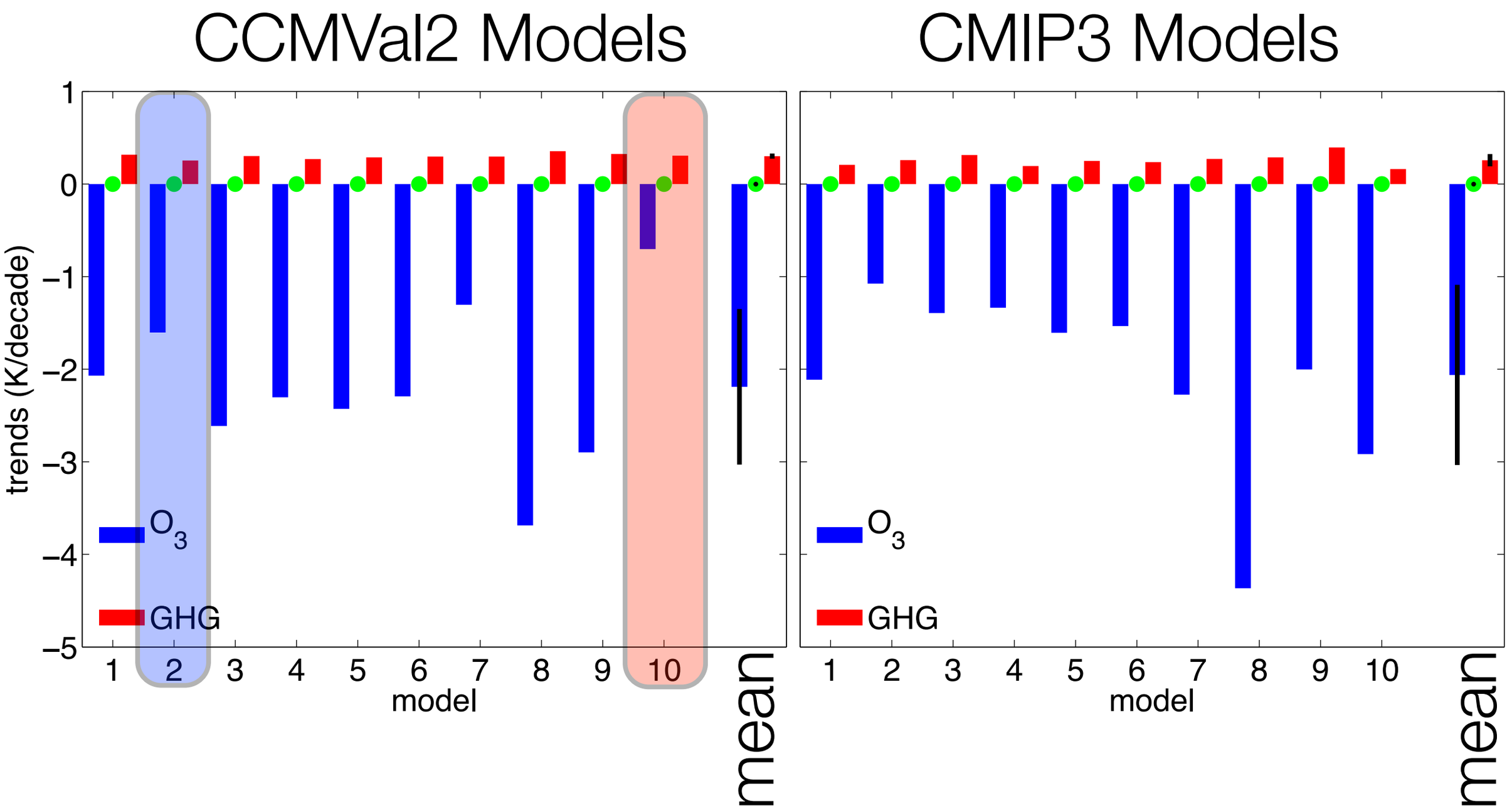


$$\Delta U_{lat} = r_{O_3} \cdot \Delta T_{0_3} + r_{GHG} \cdot \Delta T_{GHG}$$

Uncertain Forcing vs. Uncertain Dynamics

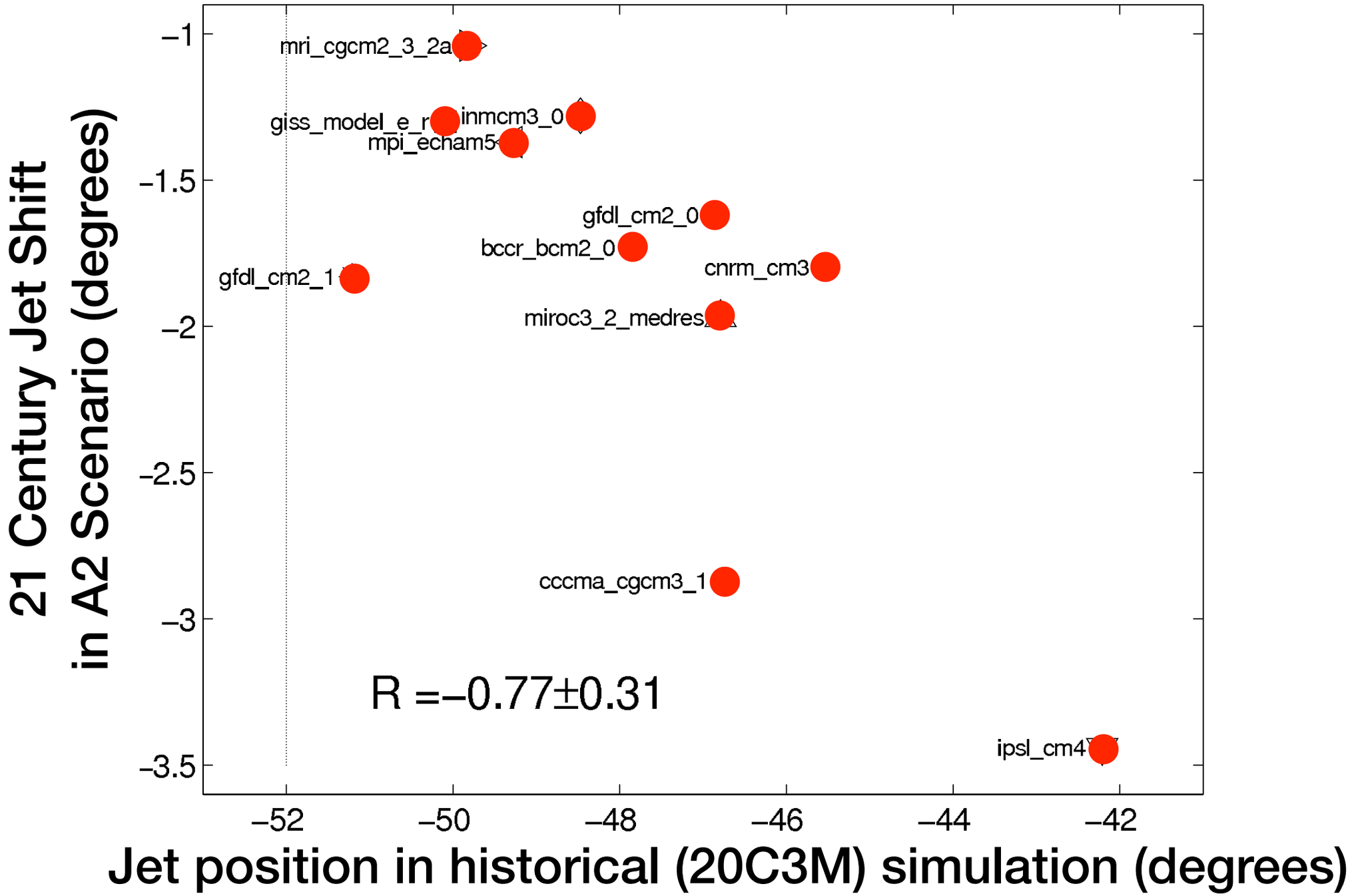
- 1K warming of tropical upper troposphere OR cooling in polar stratosphere causes ~ 0.2º shift in the SH jet: jet responds to temperature gradient

- Variability in modeled circulation response are due to

    - differences in thermal forcing by ozone and GHGs

    - differences in “circulation sensitivity”

Connection between 21st Century Jet Shift and 20th Century Climatology



[Kidston and Gerber 2010]

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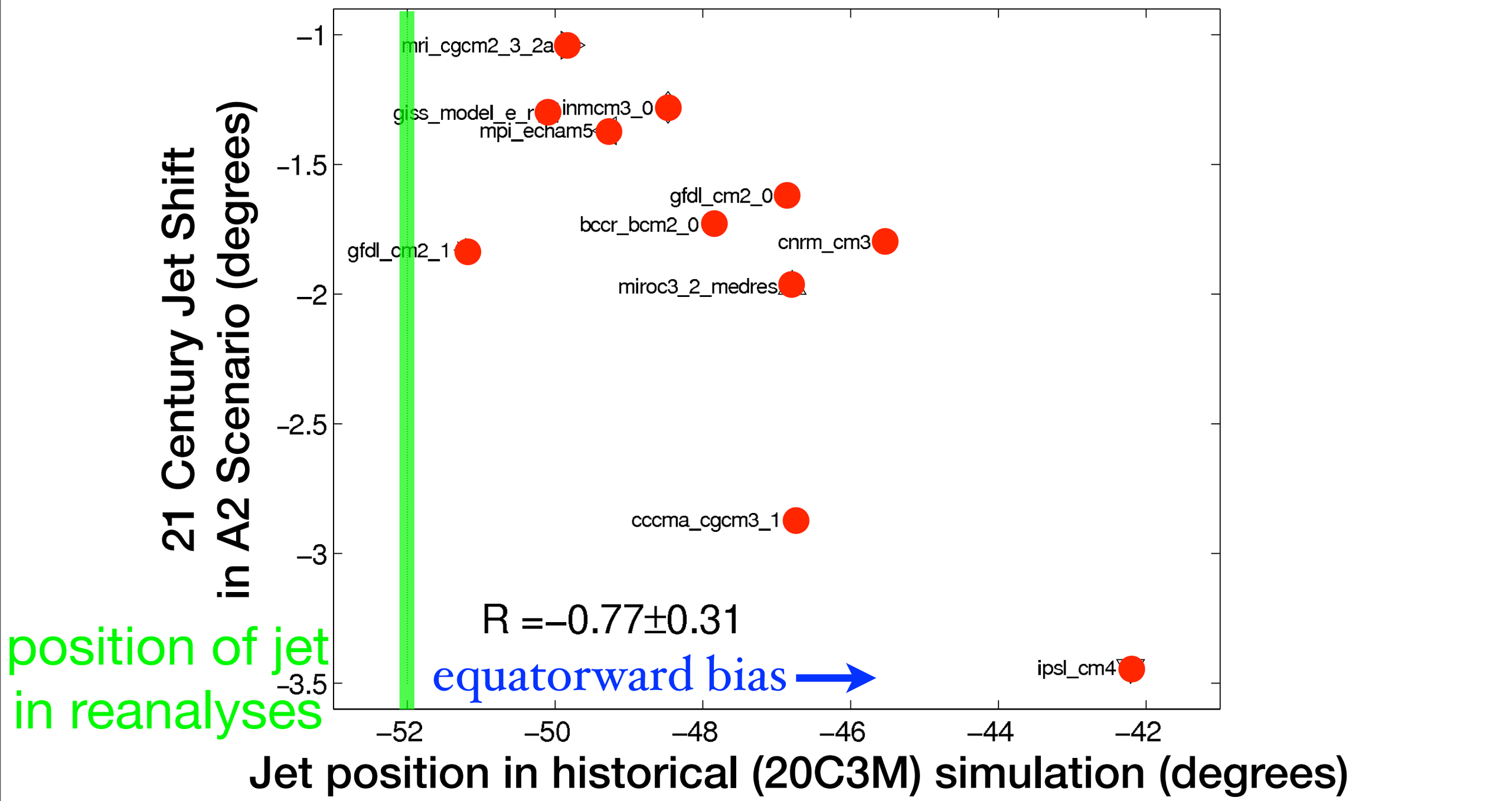

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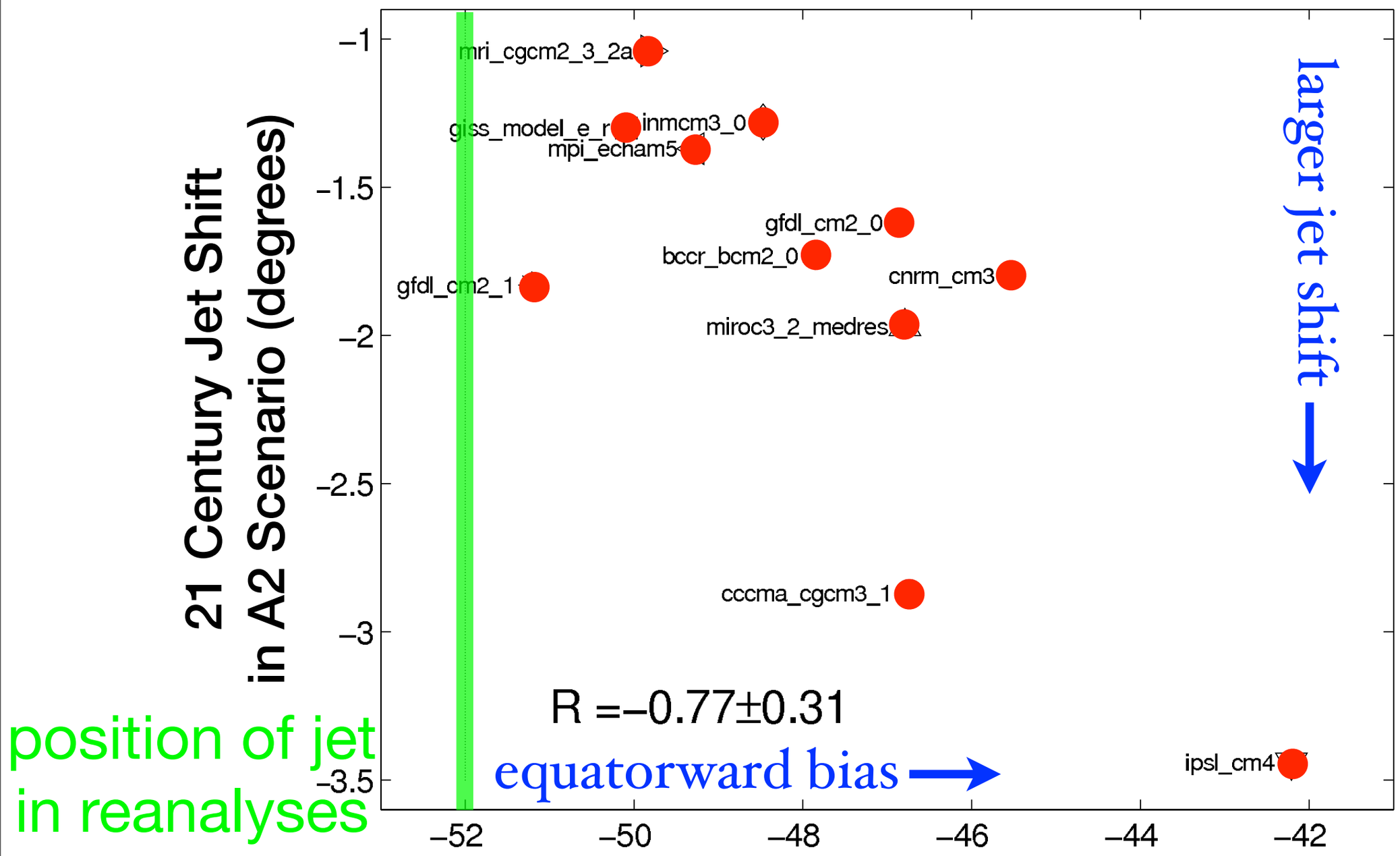
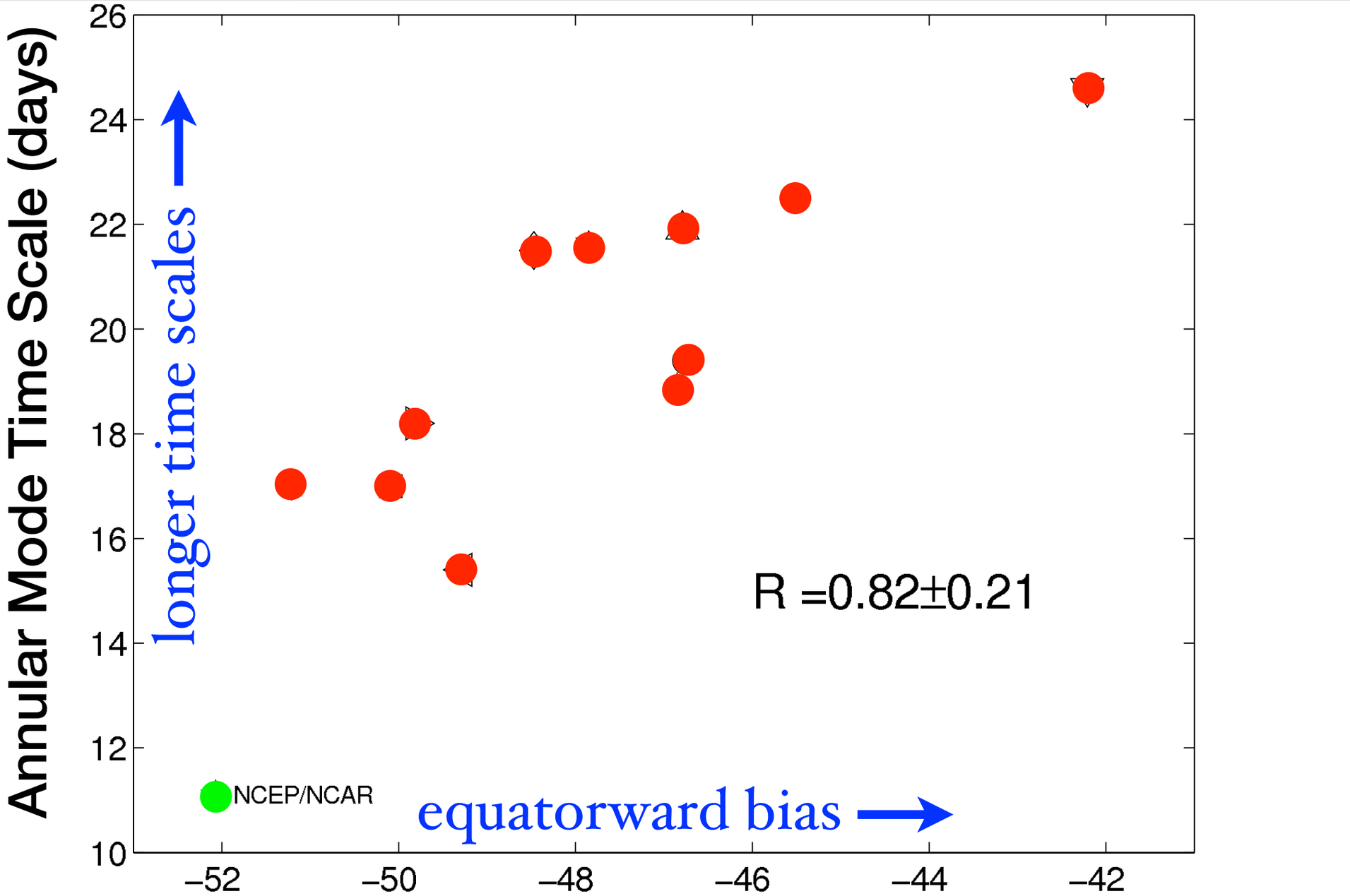


[Kidston and Gerber 2010]

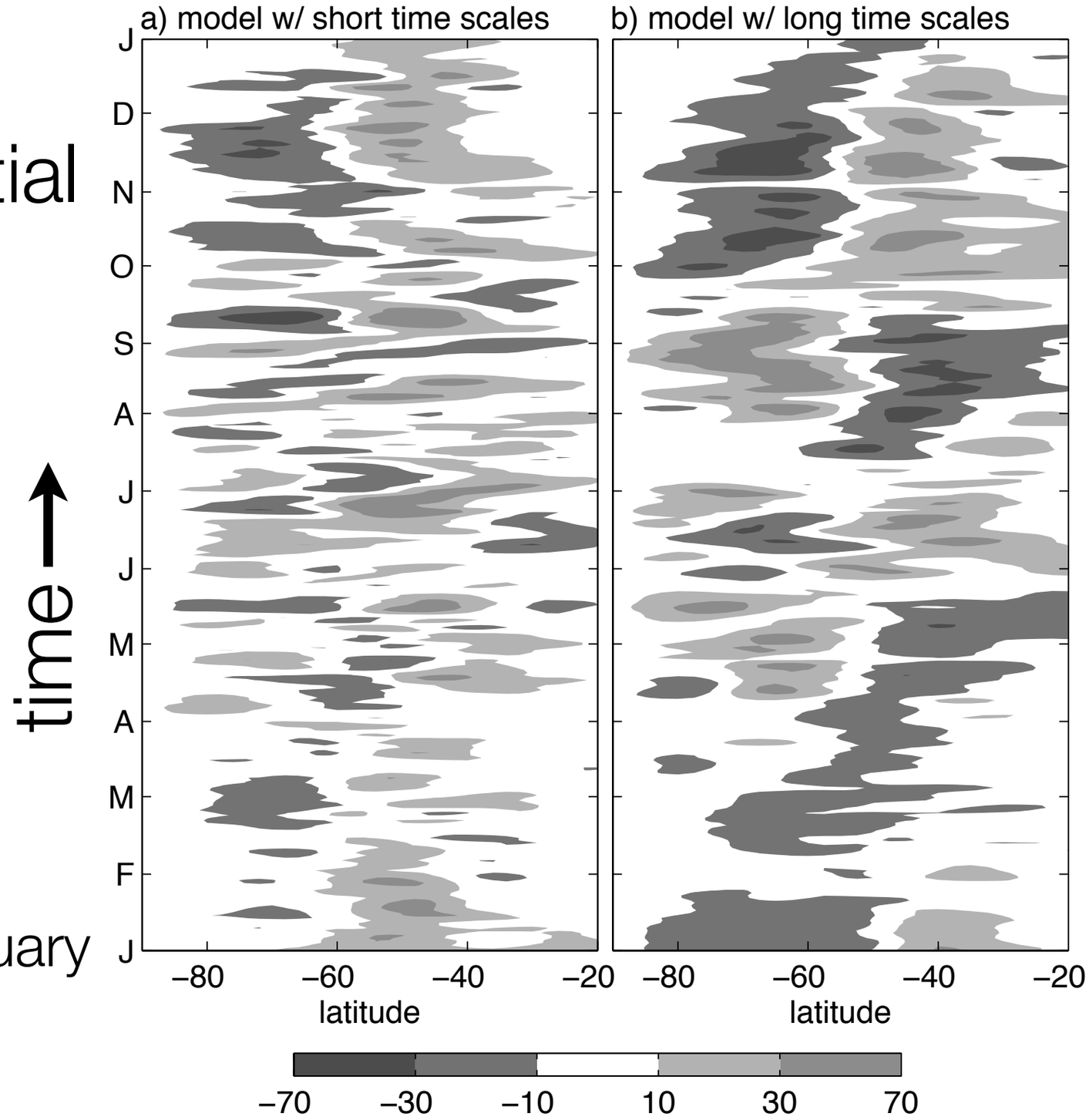
Connection between the Climatological Jet Position and Time Scales of Internal Variability



[Kidston and Gerber 2010]

What does this annular mode time scale represent?

500 hPa geopotential height anomalies in two models



[Gerber et al. 2010]

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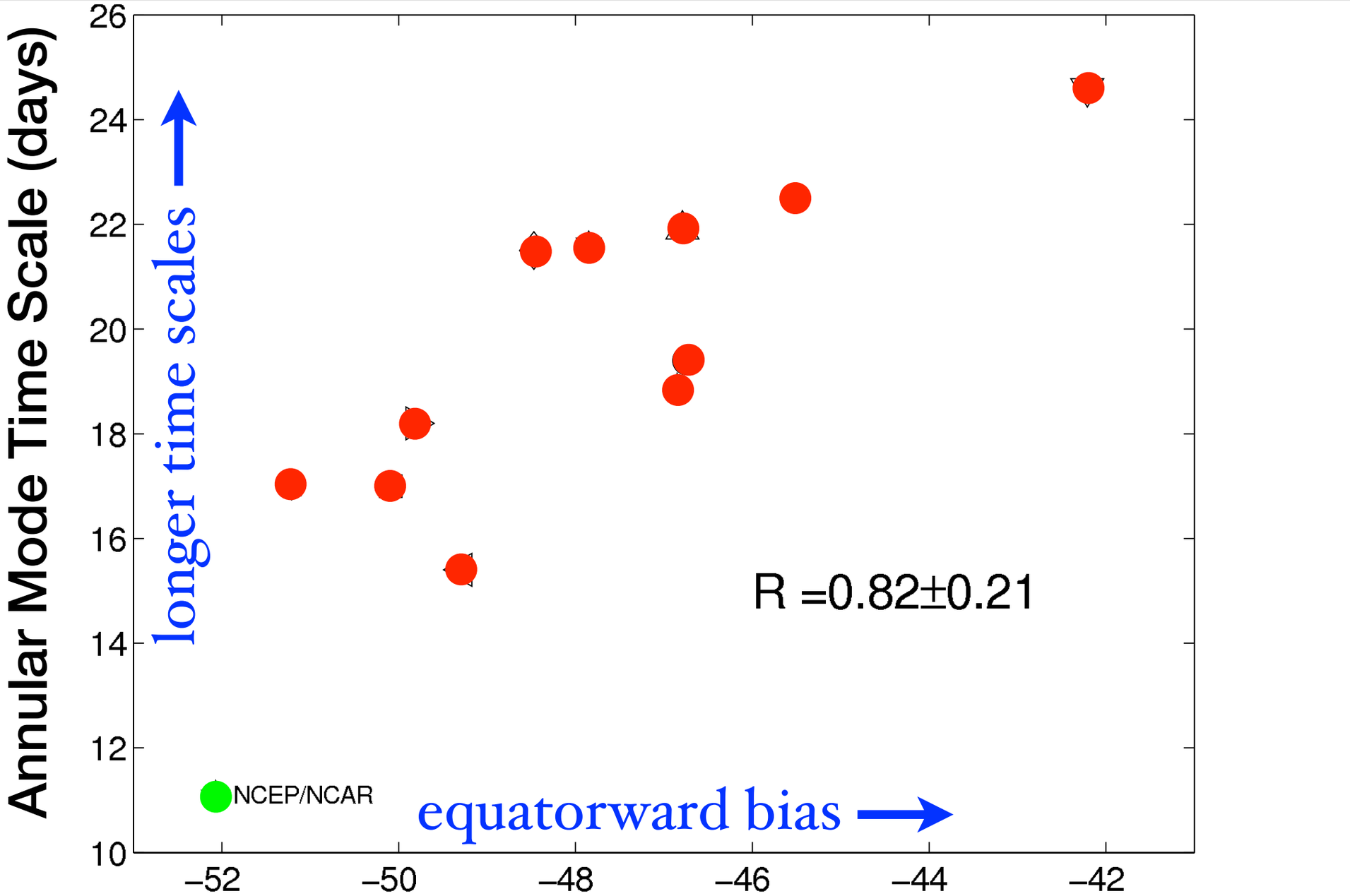
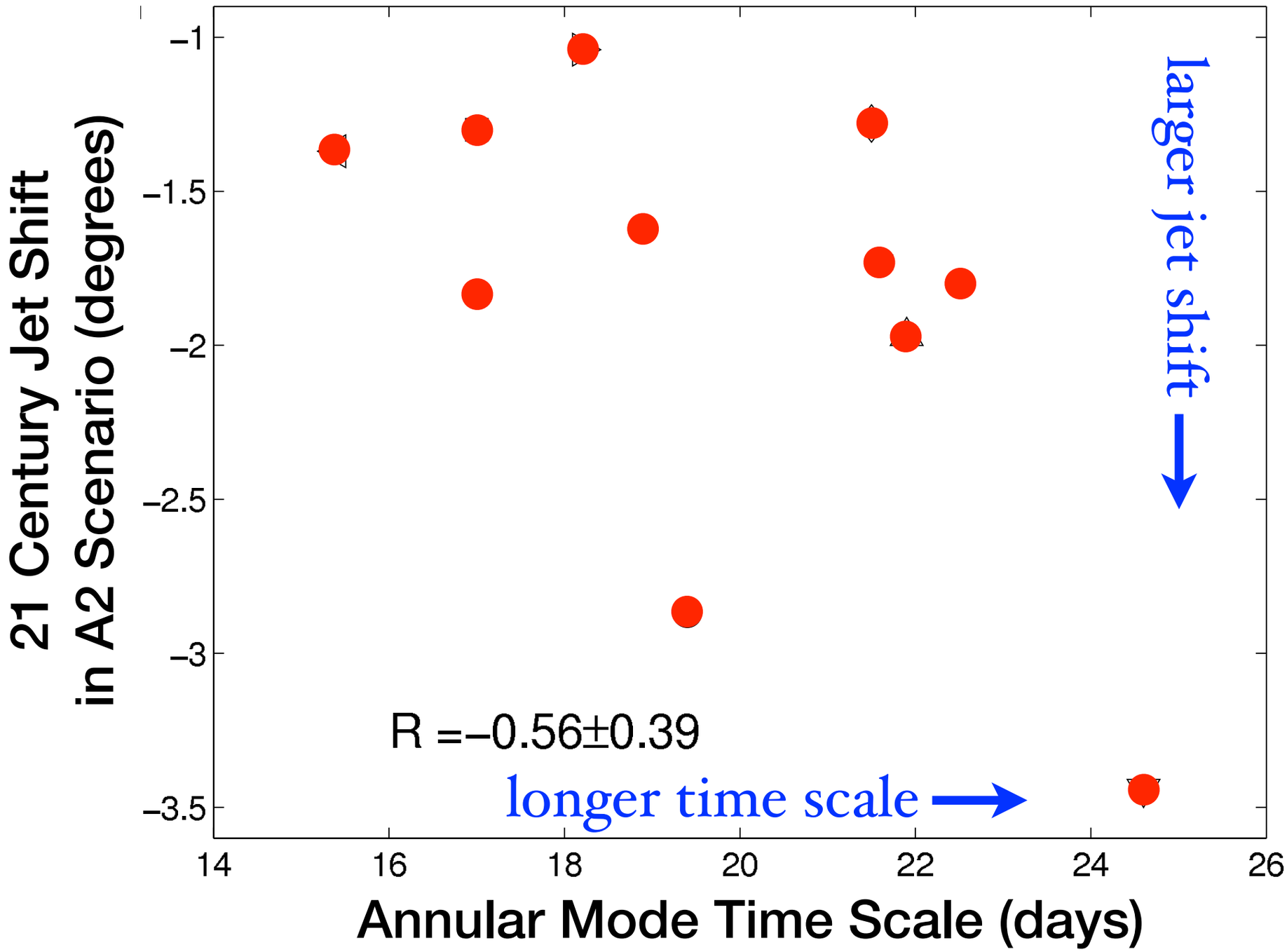


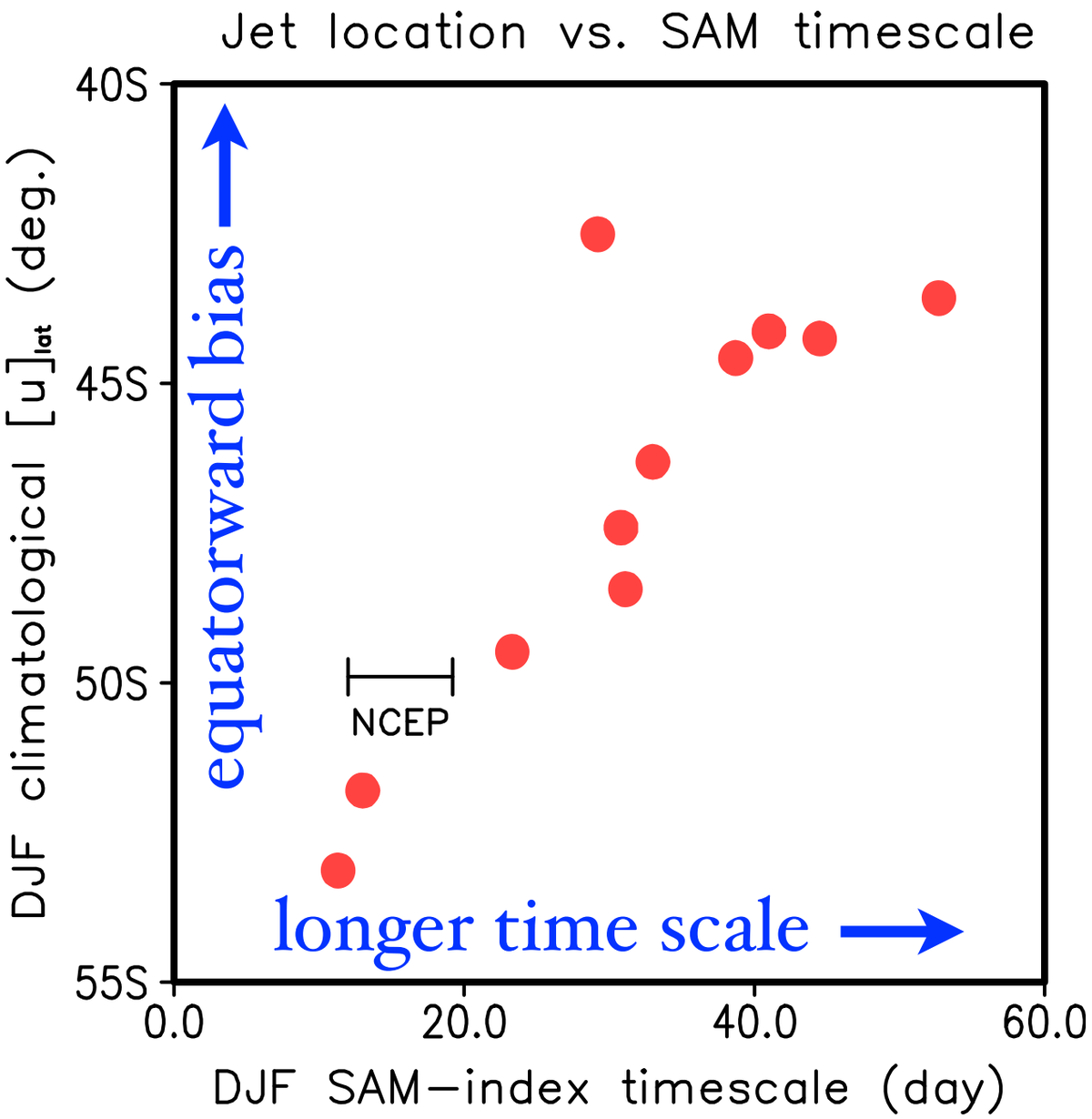
[Kidston and Gerber 2010]

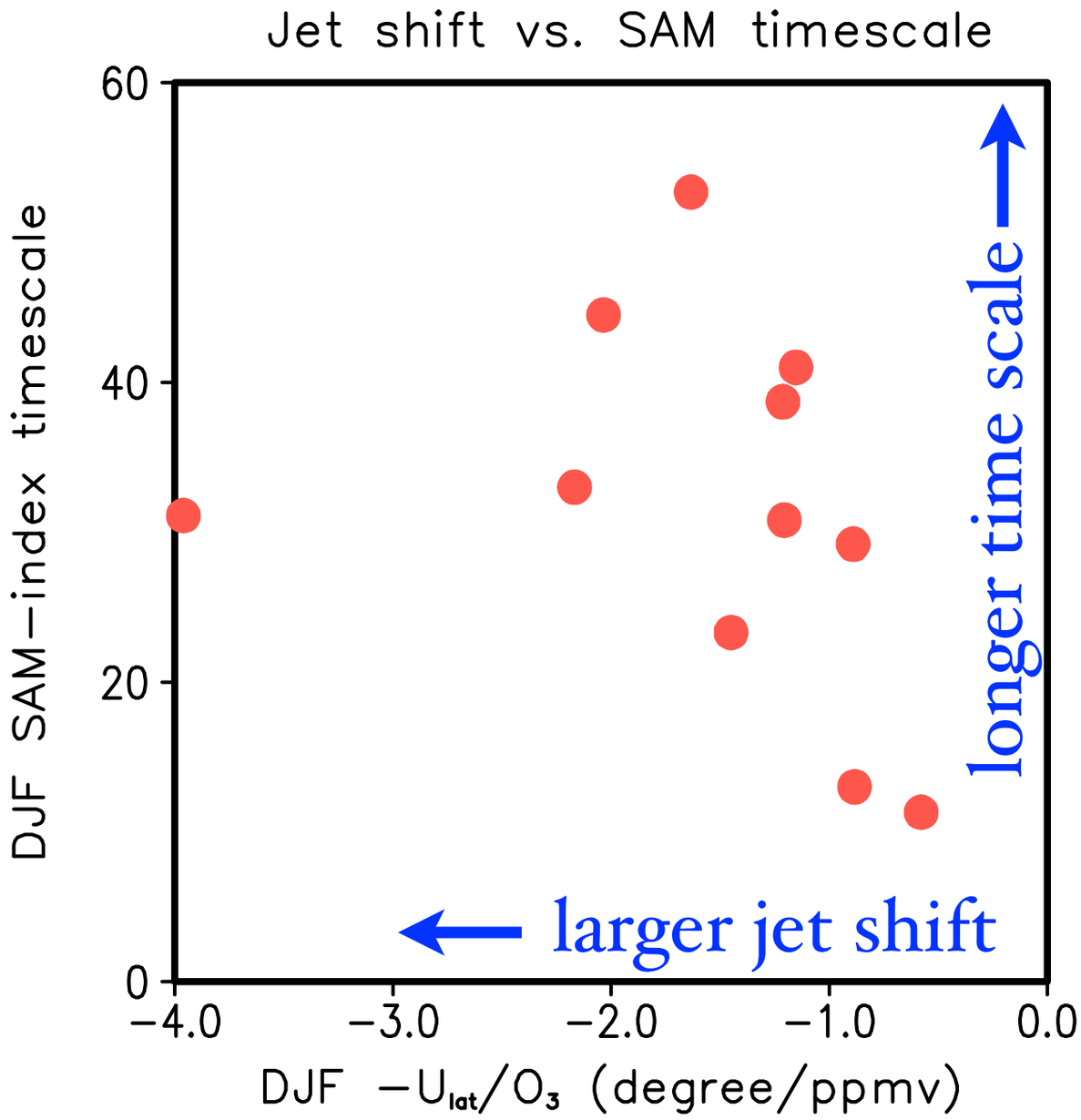
Internal Variability - Jet Shift Connection



[Kidston and Gerber 2010]

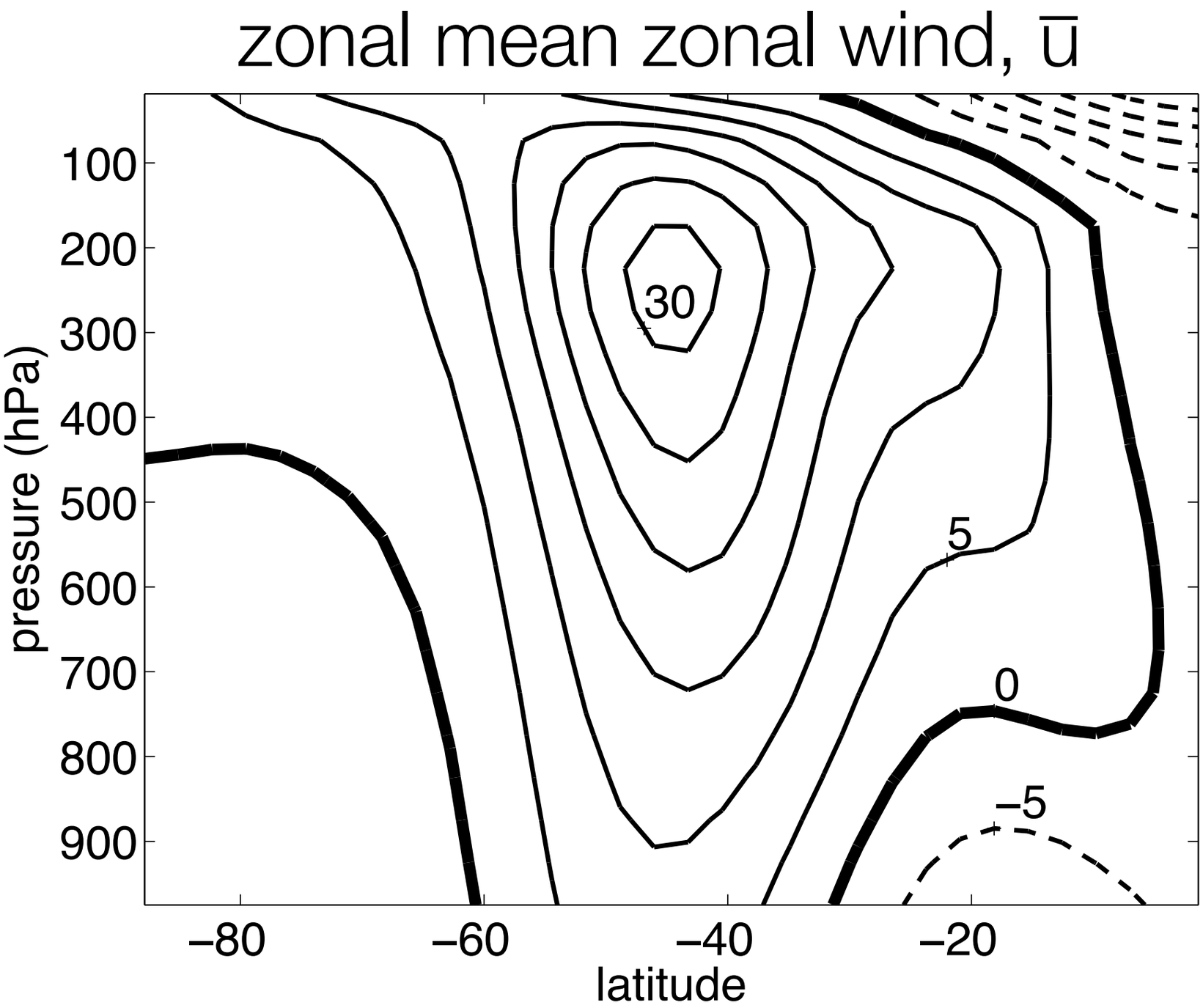
Similar Connections in CCMVal2 Models (20th Century)





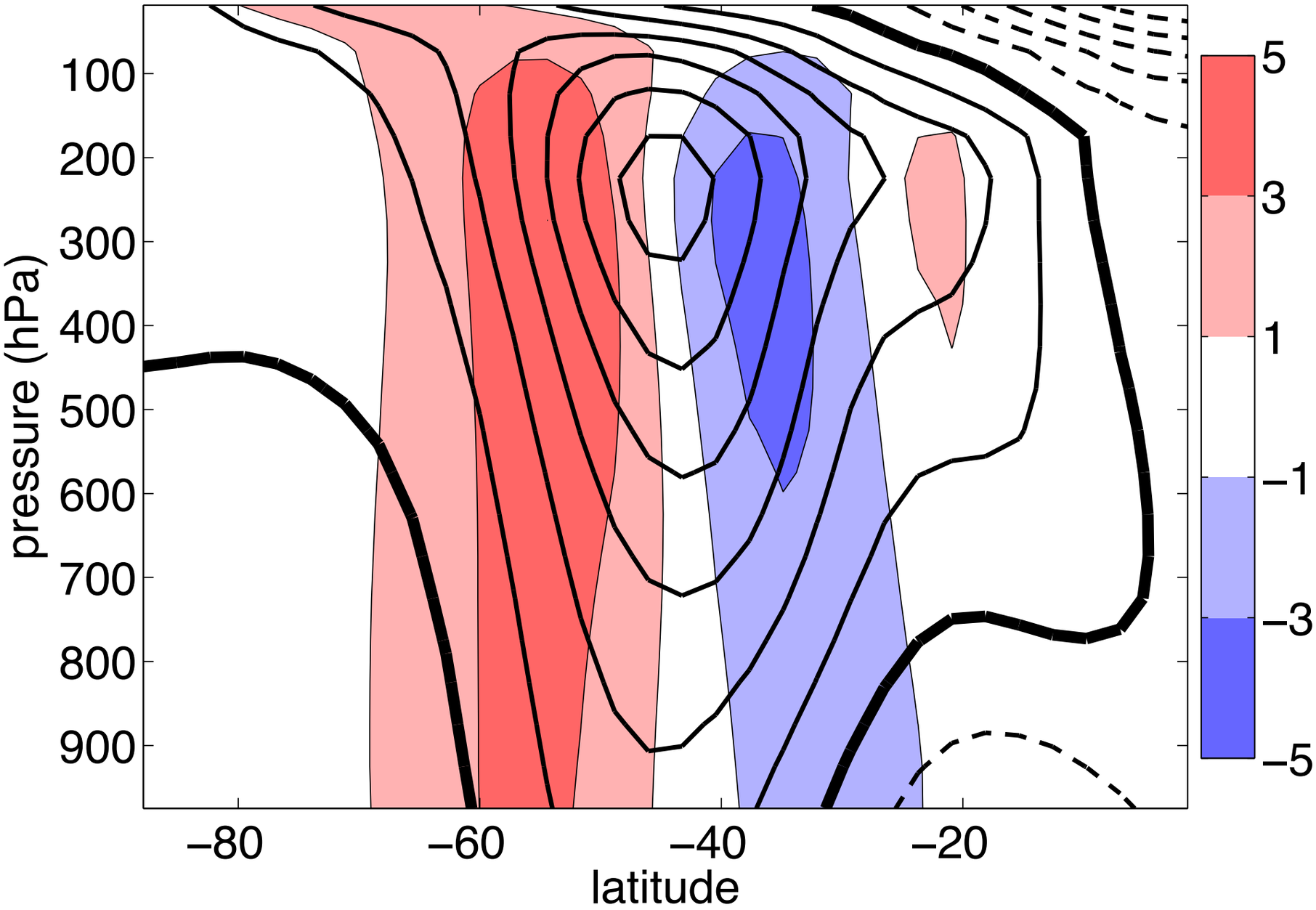
[Son et al. 2010]

Dry Dynamical Core Experiments

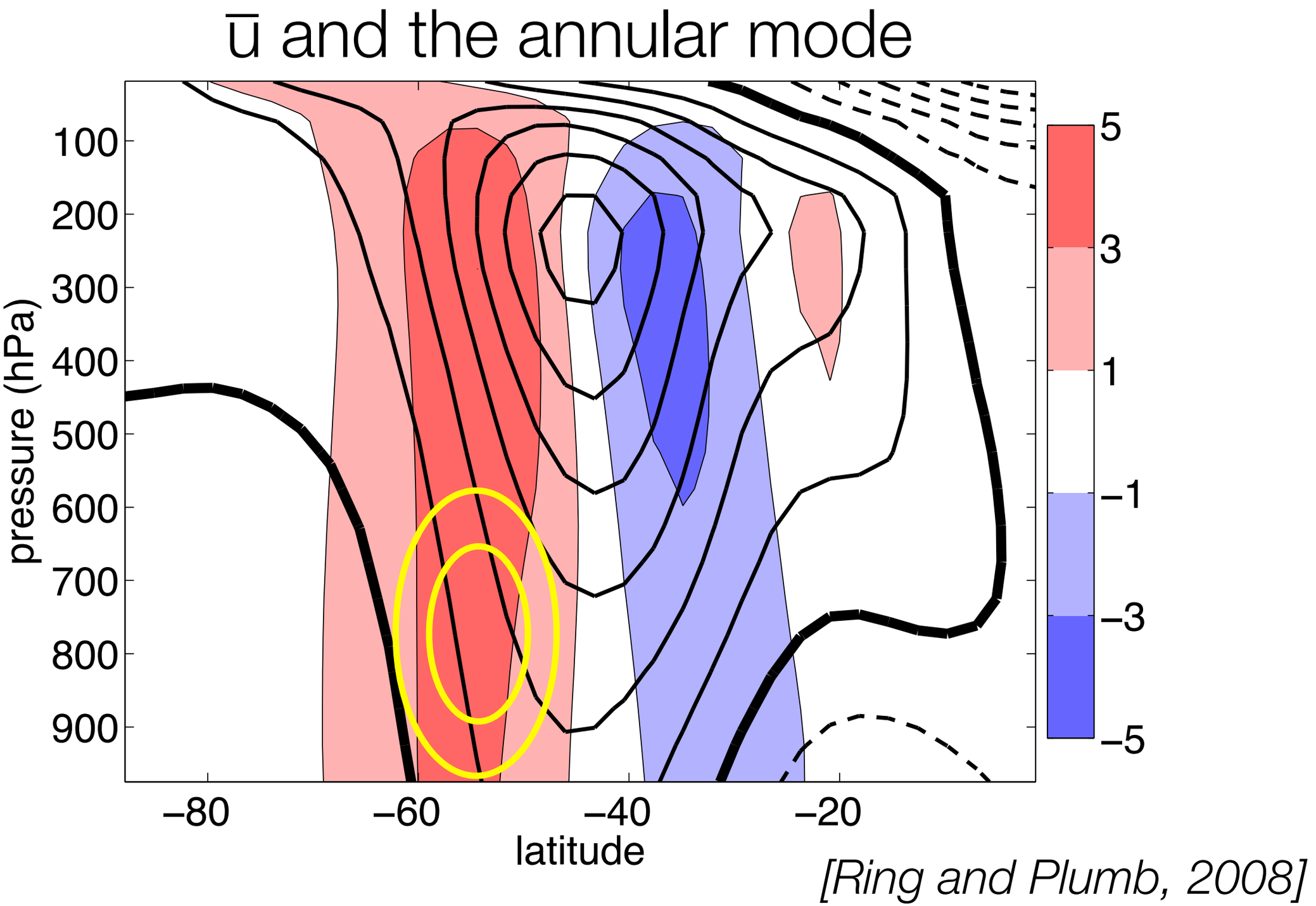


Dry Dynamical Core Experiments

ū and the annular mode



Apply torque that projects on internal variability



[Ring and Plumb, 2008]

System responds modally:
strong projection on to internal variability

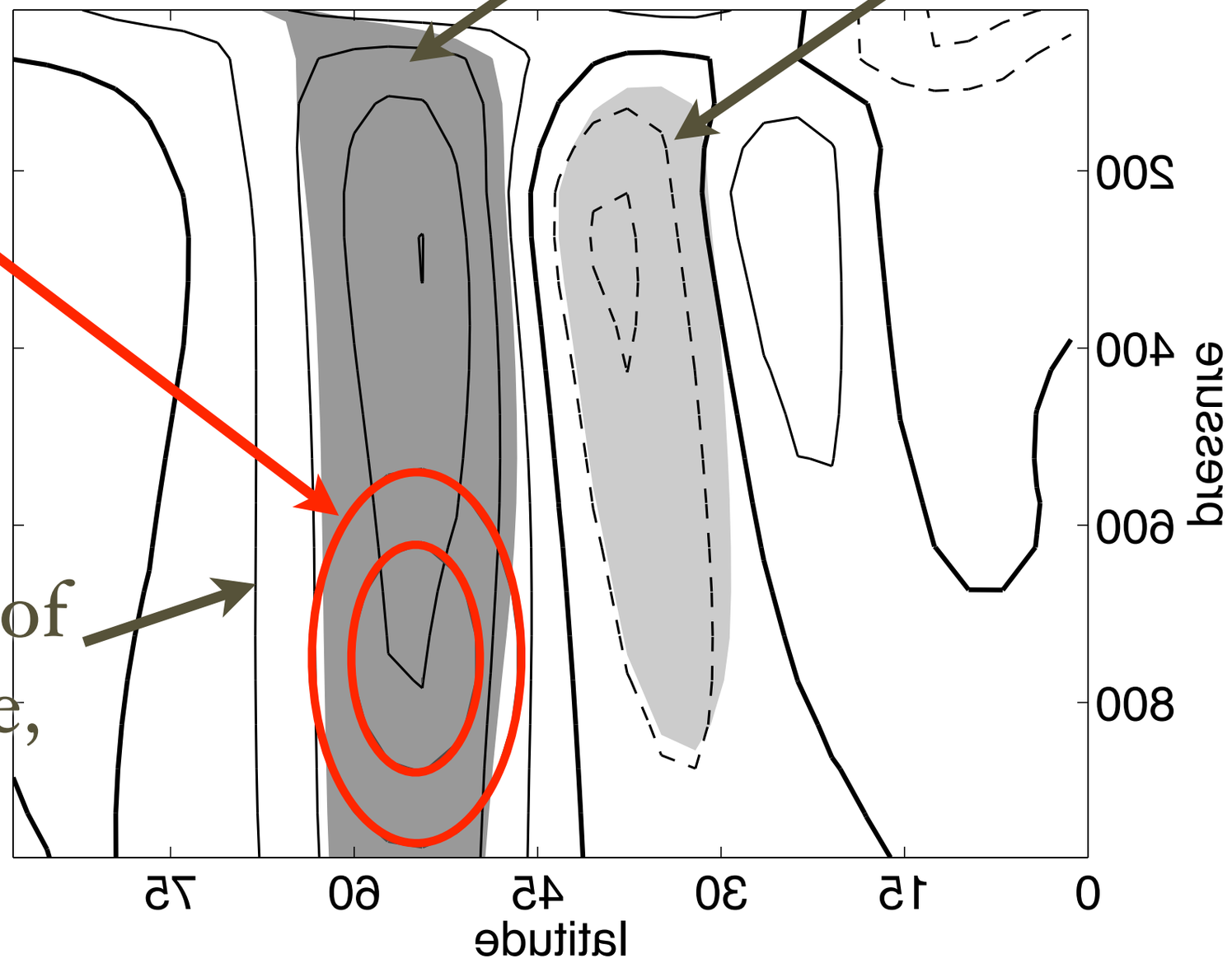
shading: annular mode positive and negative

torque

contours: response of model to the torque,

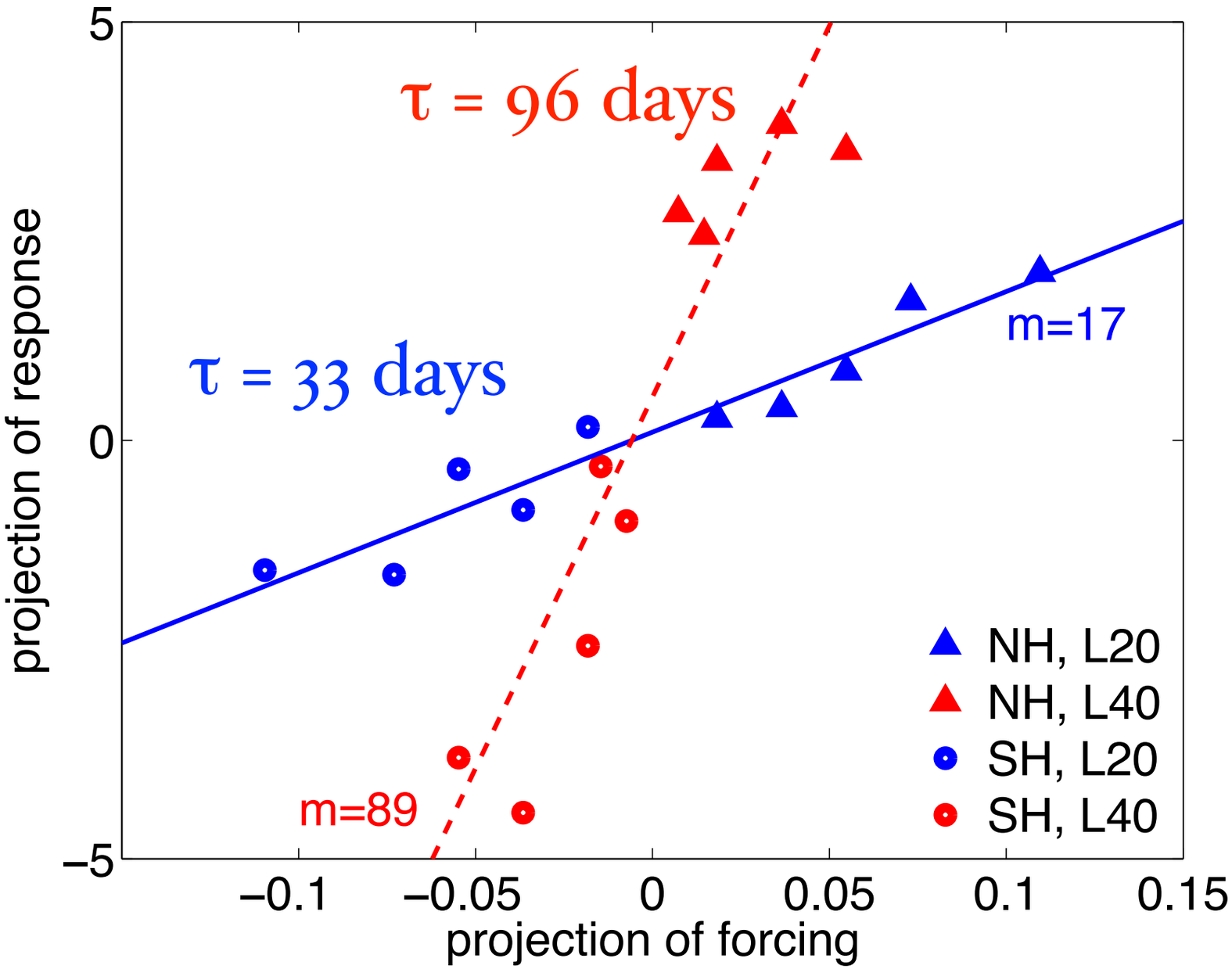
$\bar{u}_{forced} - \bar{u}_{control}$

(negative dashed)



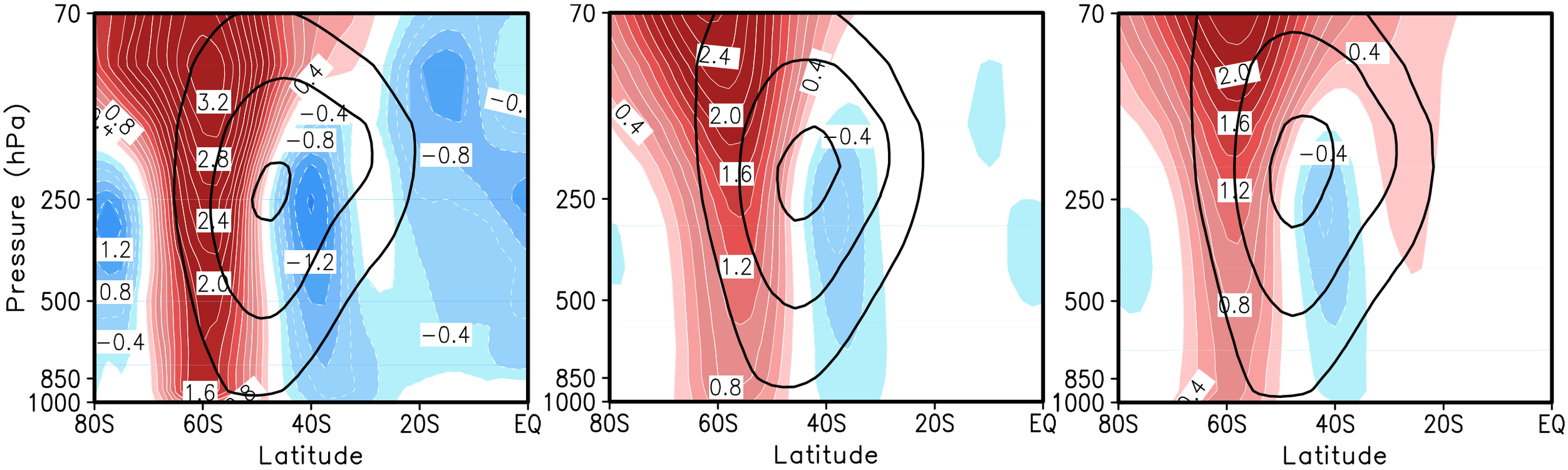
[after Ring and Plumb 2008]

Fluctuation-Dissipation Theory: Model with greater persistence more sensitive to external forcing



[Gerber, Voronin, and Polvani 2008]

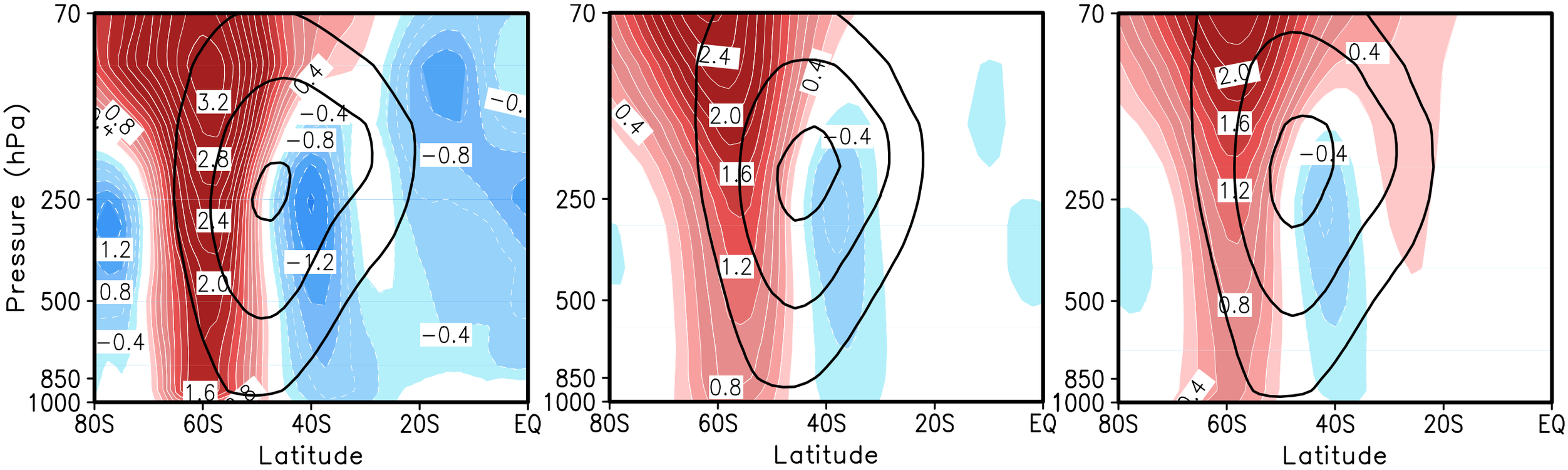
1979-1999 DJF Trends in zonal mean zonal wind



ECMWF CCMVal2 CMIP3 w/ O^3

[Son et al. 2008; Gerber et al. 2011]

1979-1999 DJF Trends in zonal mean zonal wind



ECMWF CCMVal2 CMIP3 w/ O^3

A Paradox: Models *overestimate* AM time scales, but their 20th century circulation response is *too weak*!

[Son et al. 2008; Gerber et al. 2011]

Conclusions

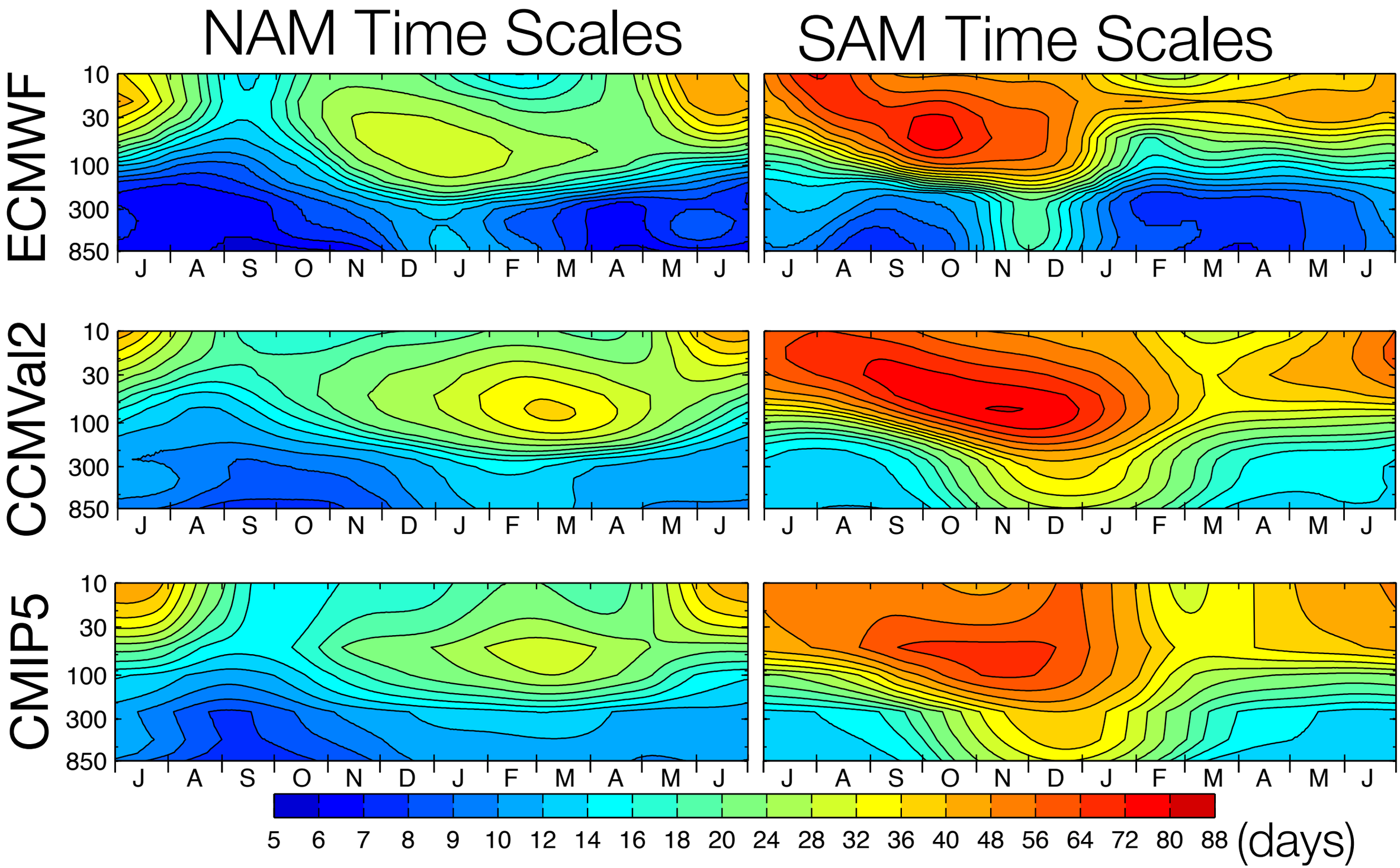
- The Southern Hemisphere jet stream is *pushed* poleward by GHG induced tropical warming and *pulled* poleward by ozone induce cooling. Too date, ozone has dominated DJF signal.

- Uncertainty stems from differences in the *thermal response* to anthropogenic forcing and the *dynamical sensitivity* to temperature changes

- A models circulation response is related to it's ability to simulate the observed climate: models with an *equatorward bias* in the jet and *overly persistent natural variability* are more sensitive to external forcing

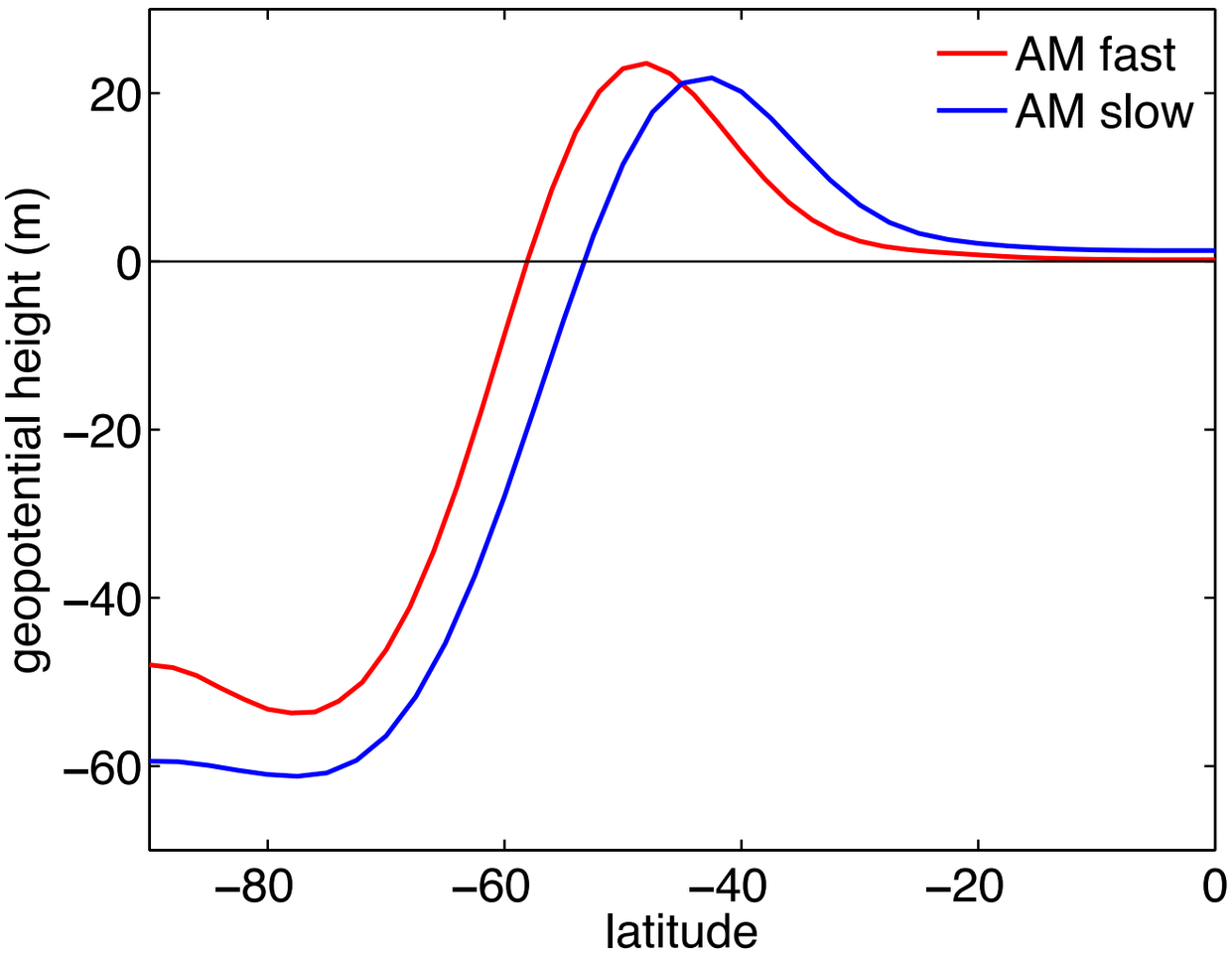
- Eddy-mean flow interactions make the austral jet stream in summer very difficult to simulate: *there are still open questions in large scale dynamics*

Epilogue ... Preliminary calculations suggest that (some) CMIP5 model's have similar biases!



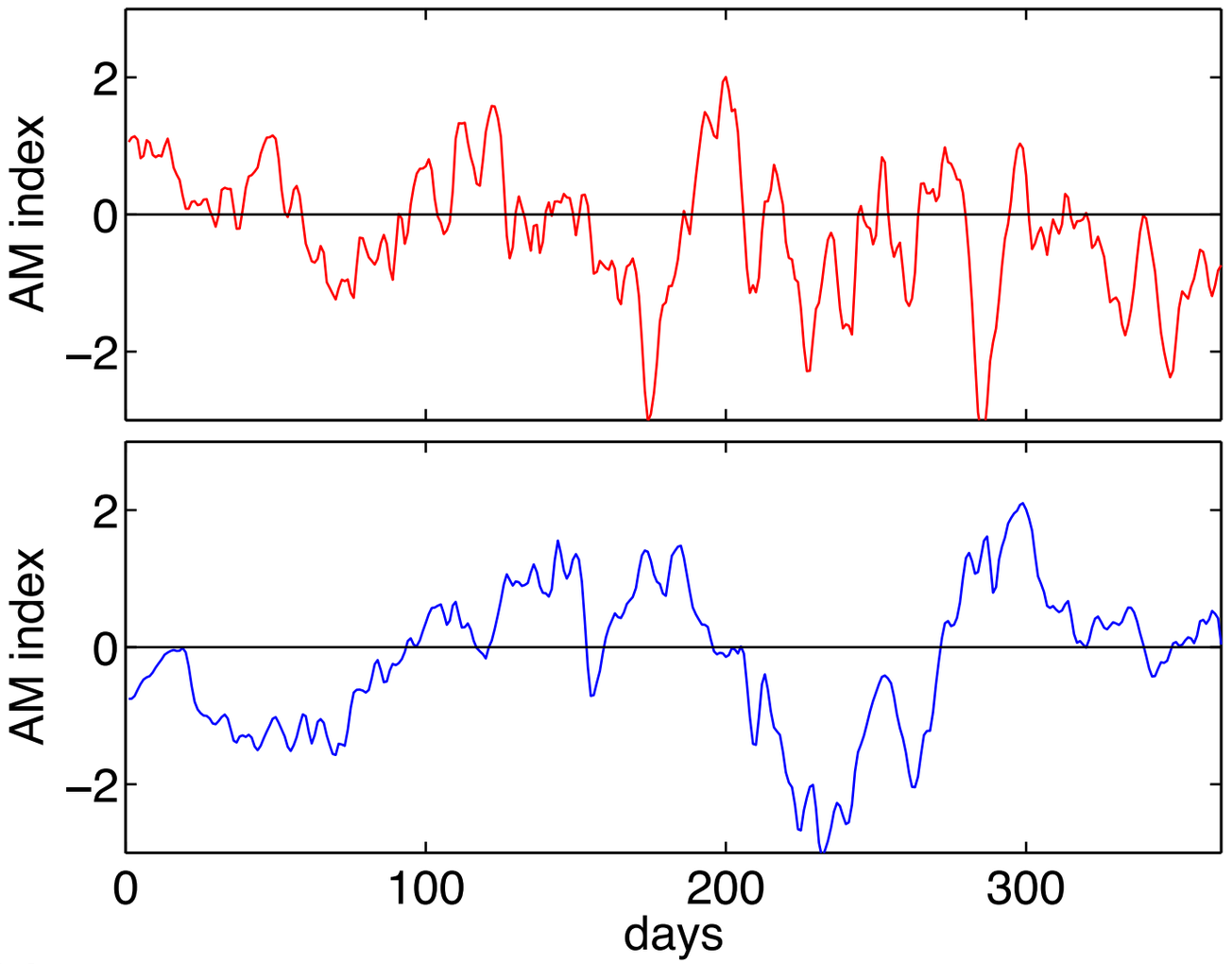
The annular mode “time scale”

Annular Mode Patterns



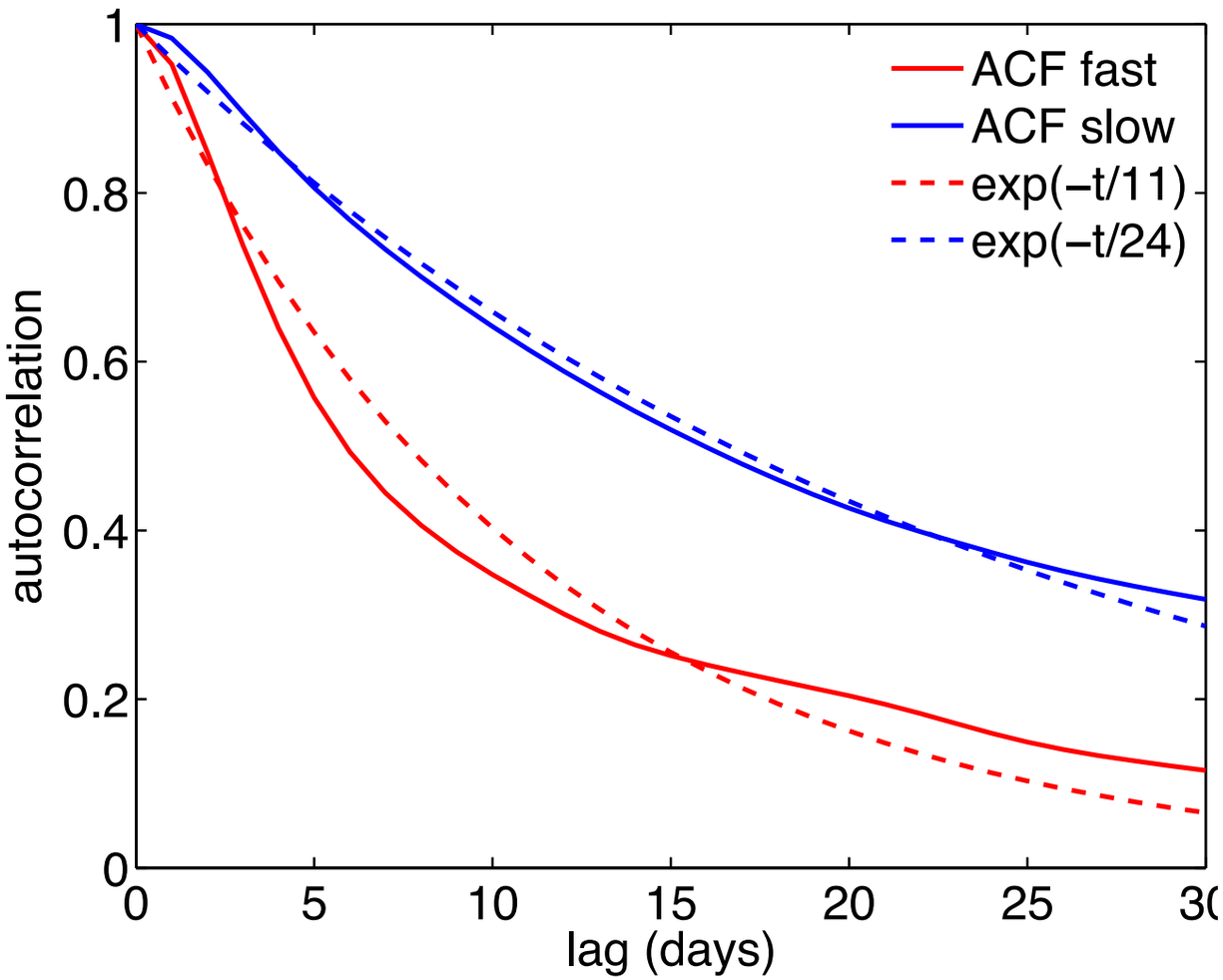
(first EOFs of zonal mean $\bar{Z}$)

Annular Mode Indices



The annular mode “time scale”

Autocorrelation Functions



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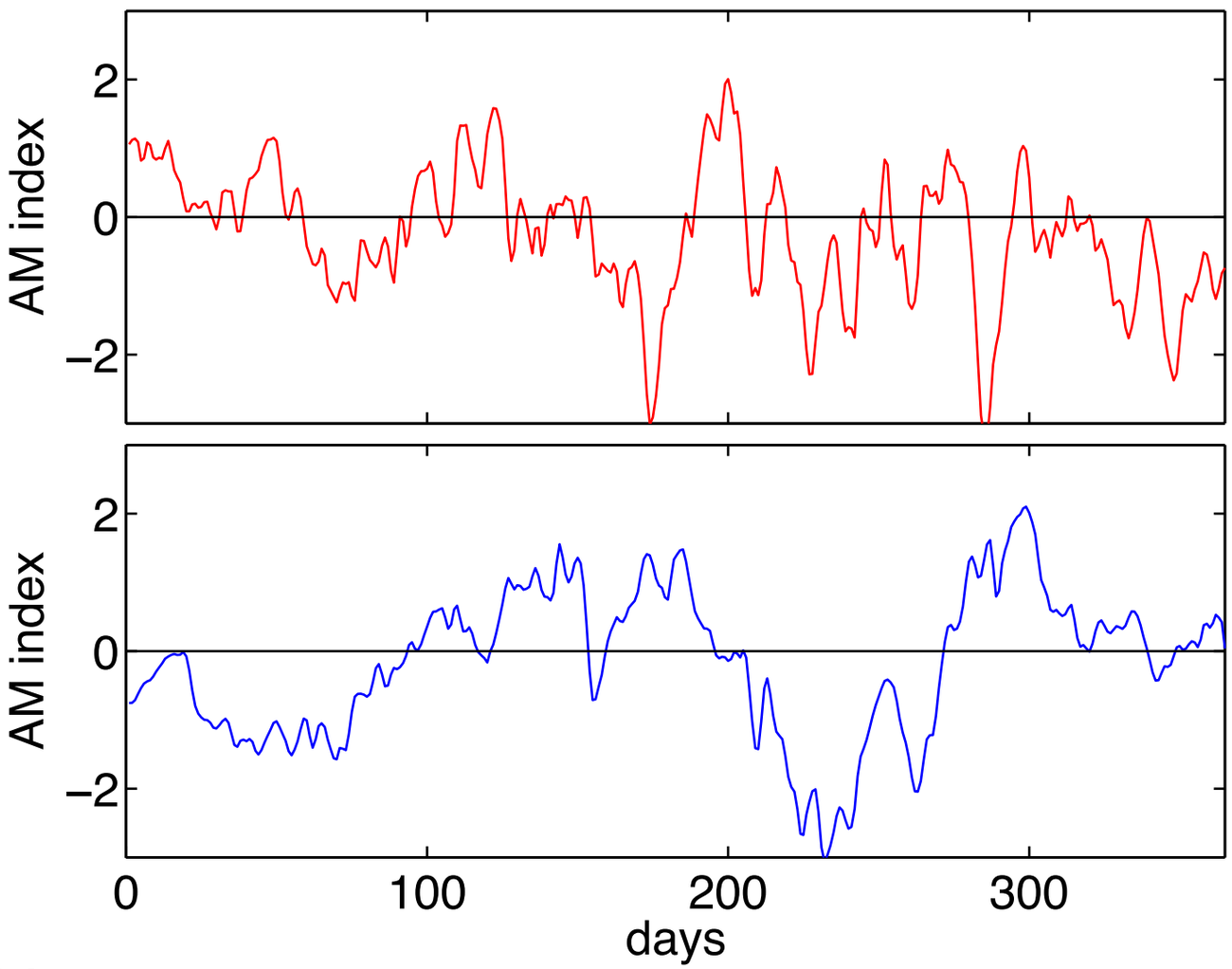
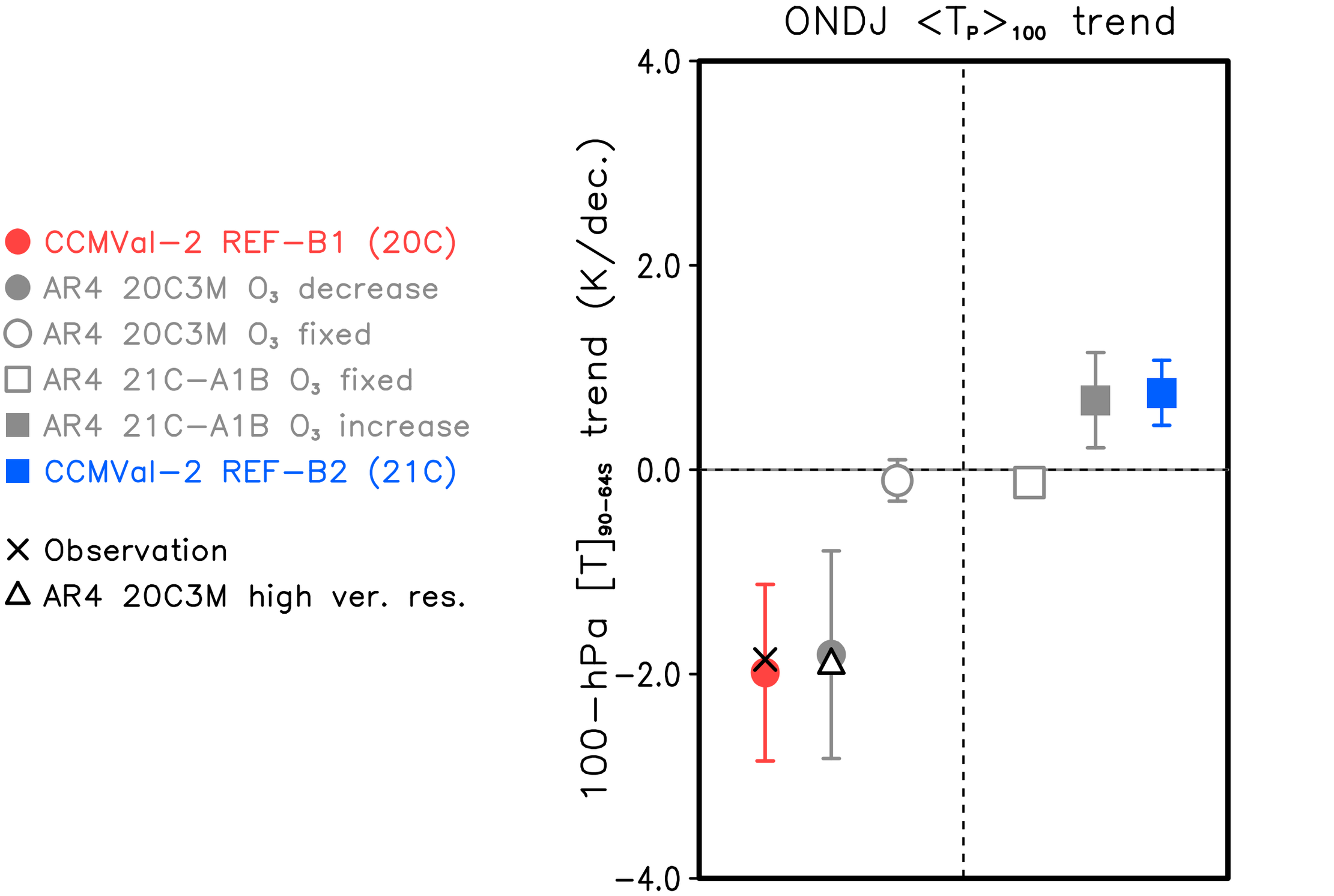
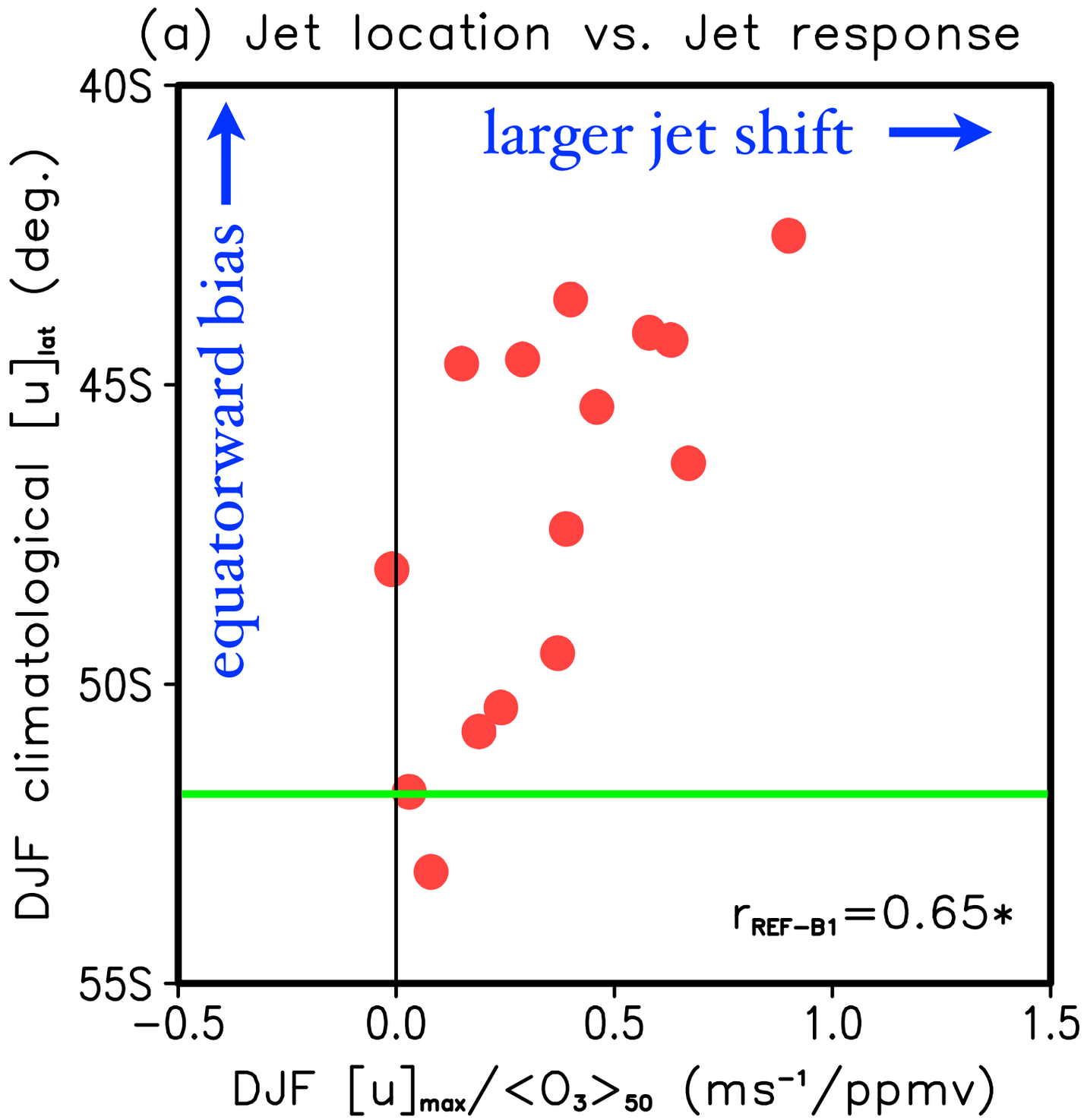
Annular Mode Indices



Polar Cap Temperature Trends

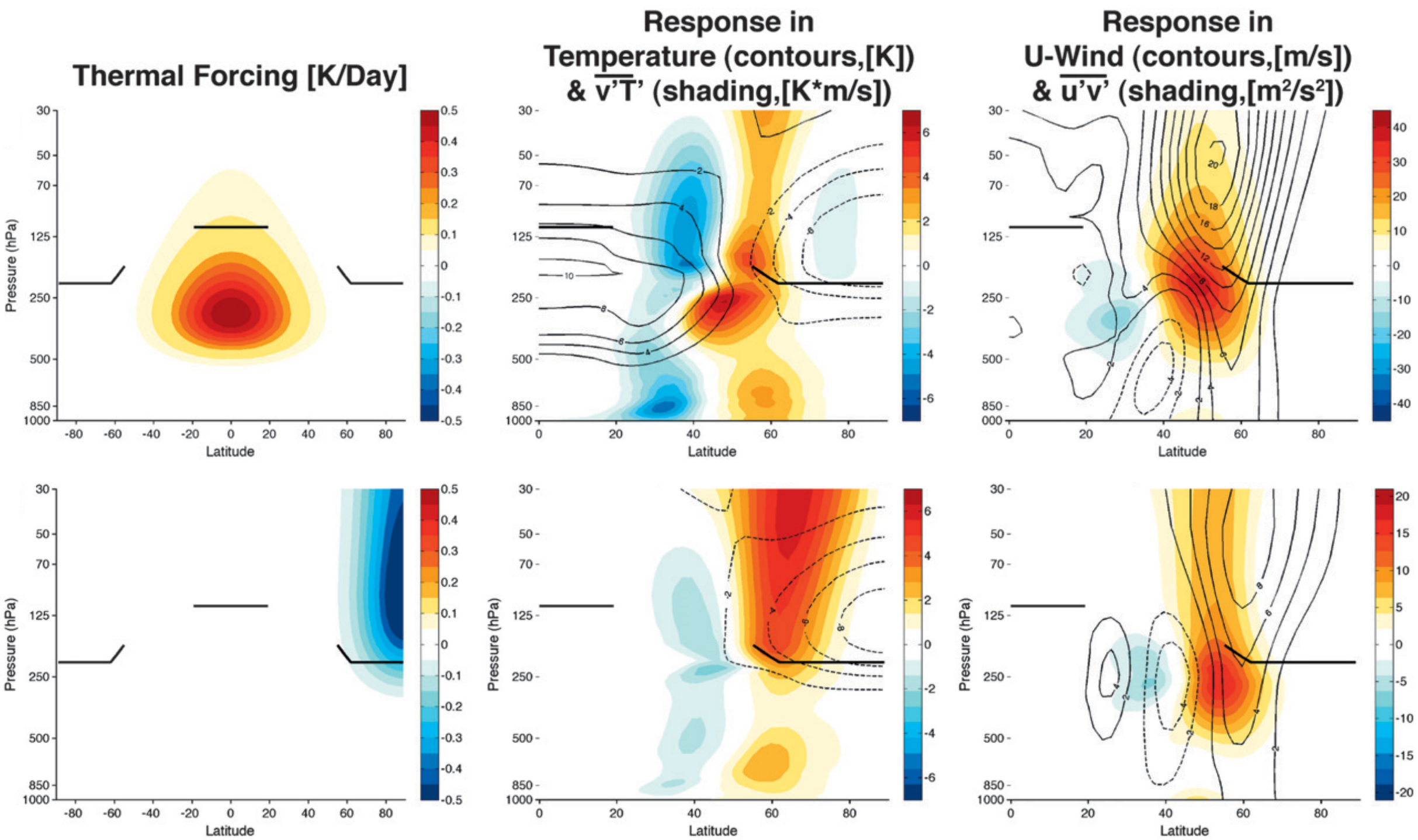


Linking differences in dynamical sensitivity



GHG warming pushes jet ...

... ozone pulls it



Butler et al. 2010

A Simple Model of the Jet Response

jet shift = ozone pull + GHG push

$$\Delta U_{lat} = r_{O_3} \cdot \Delta T_{0_3} + r_{GHG} \cdot \Delta T_{GHG}$$

two unknowns

two equations:

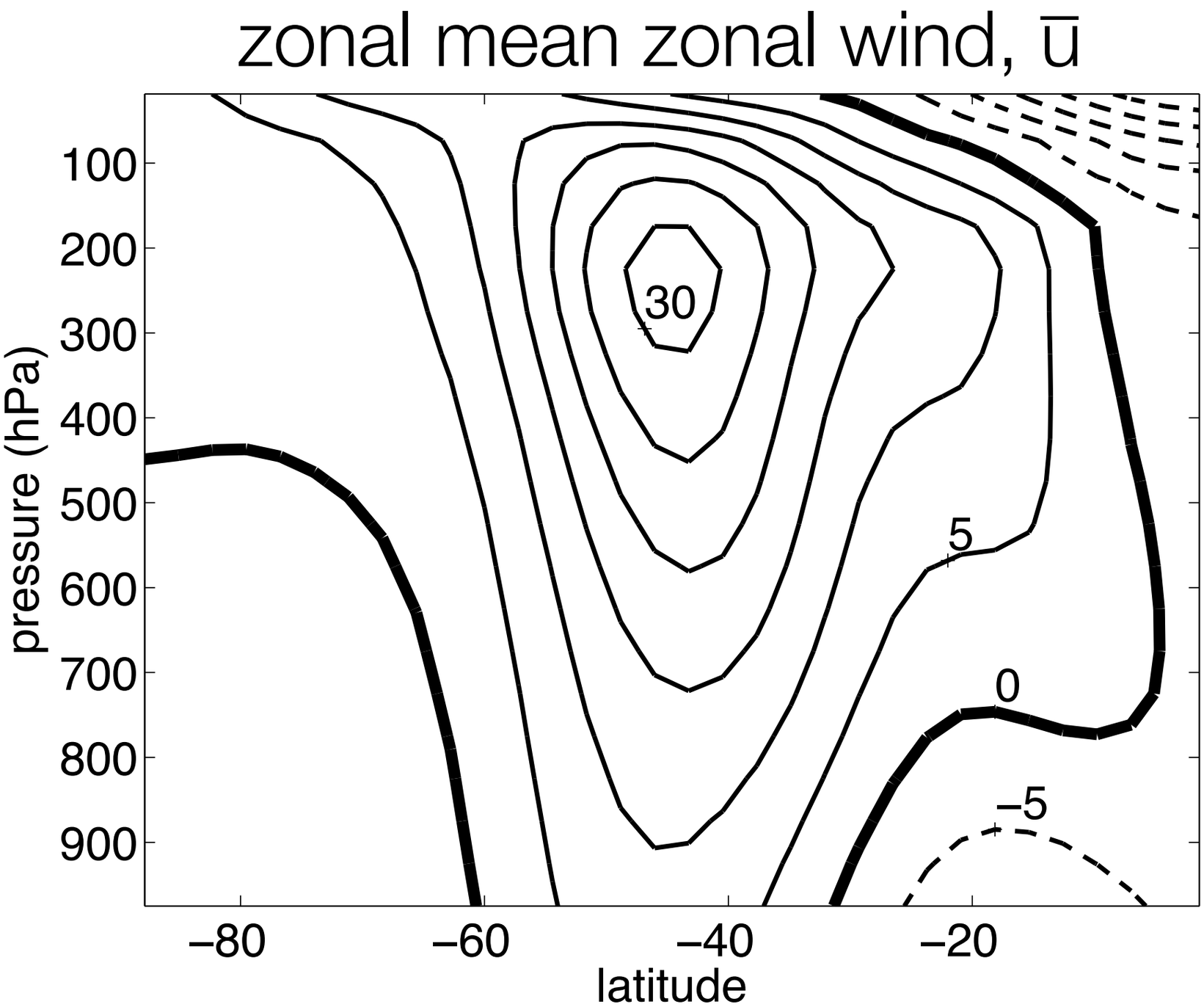
20th Century (1960-99) Model Changes

$$\Delta U_{lat}(20C) = r_{O_3} \cdot \Delta T_{0_3}(20C) + r_{GHG} \cdot \Delta T_{GHG}(20C)$$

21st Century (2000-79) Model Changes

$$\Delta U_{lat}(21C) = r_{O_3} \cdot \Delta T_{0_3}(21C) + r_{GHG} \cdot \Delta T_{GHG}(21C)$$

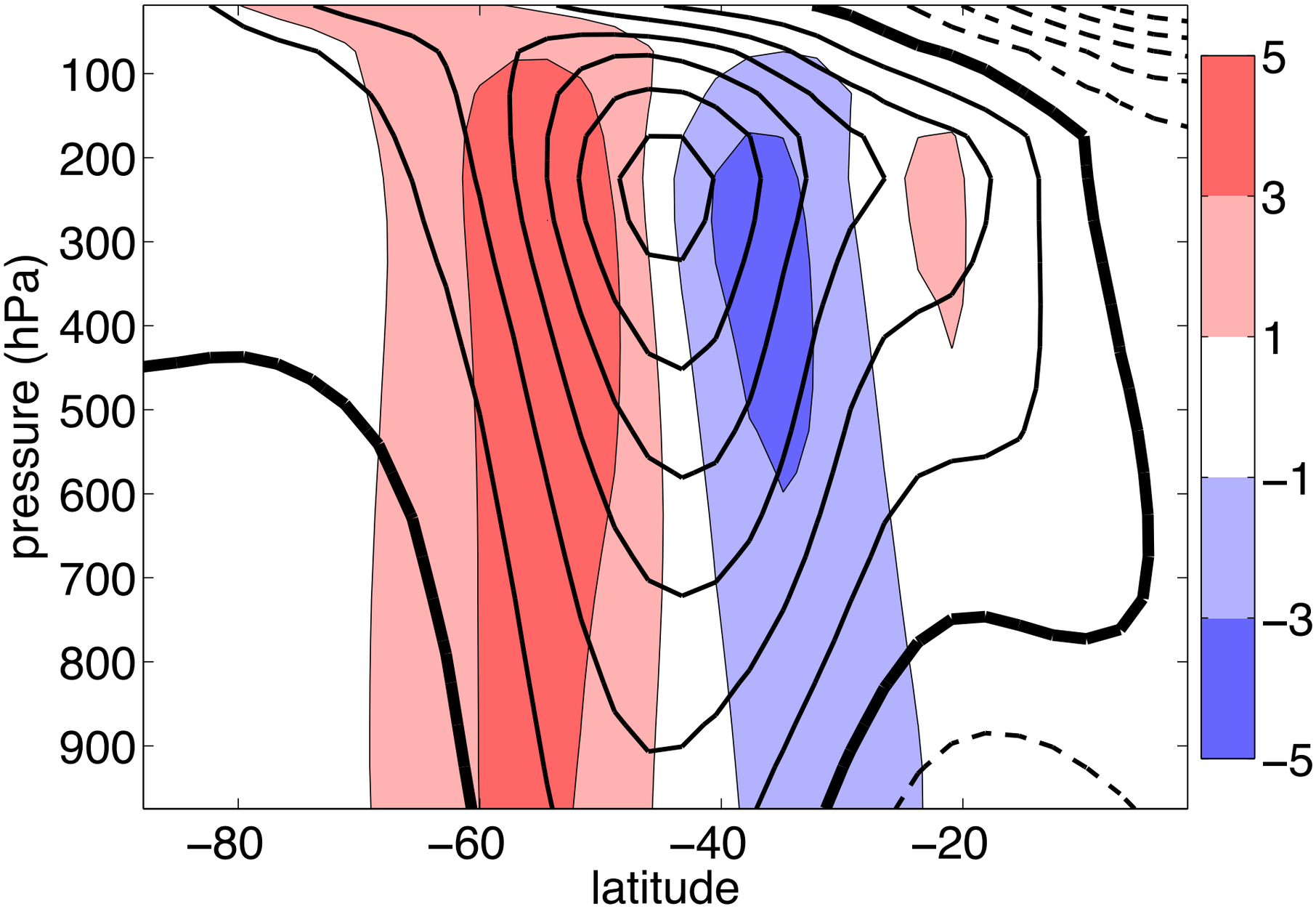
Idealized GCM Experiments



[Vallis et al. 2004]

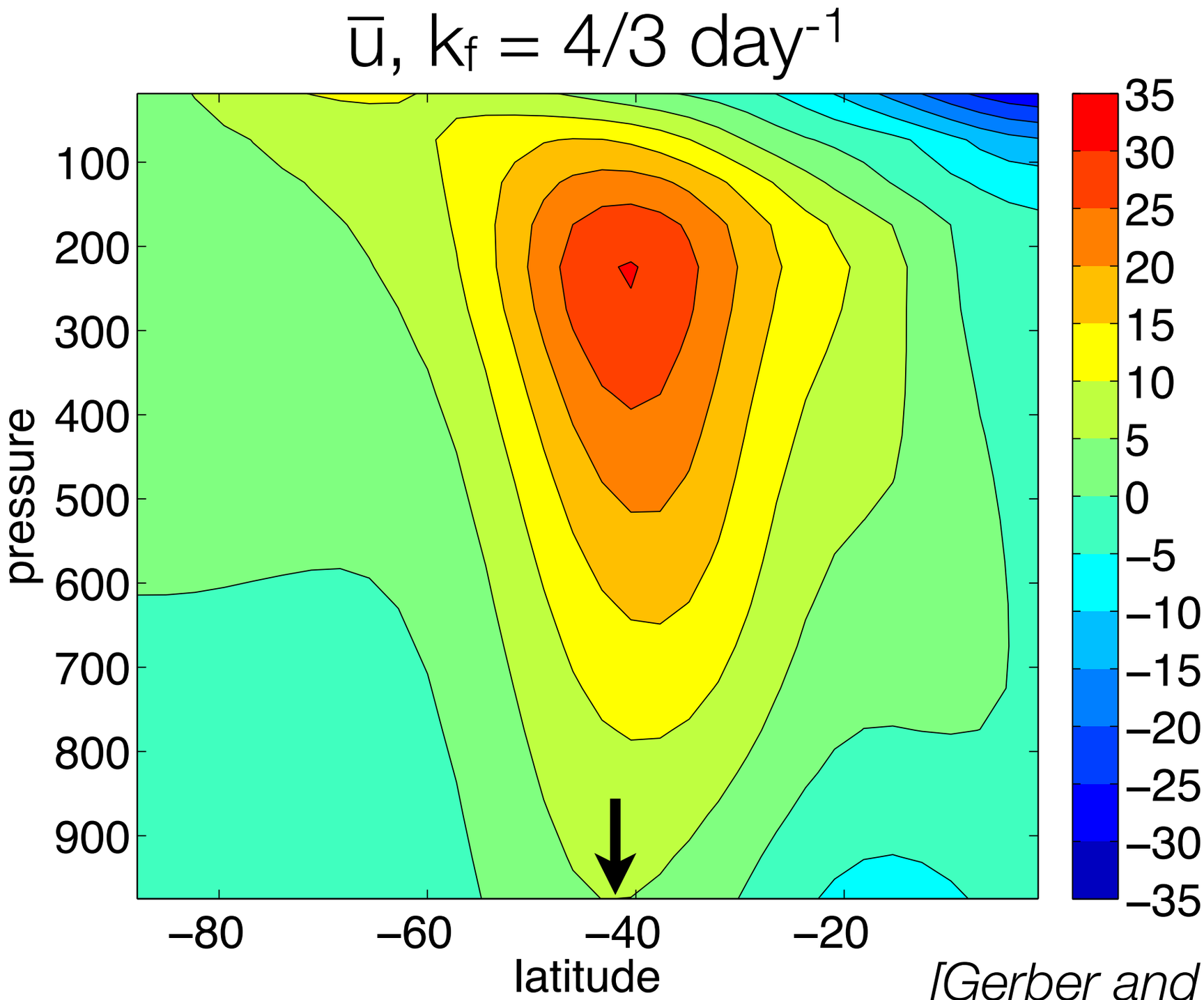
Dynamical core experiments: interaction between the “stirring” and the flow

$\bar{u}$ and the annular mode



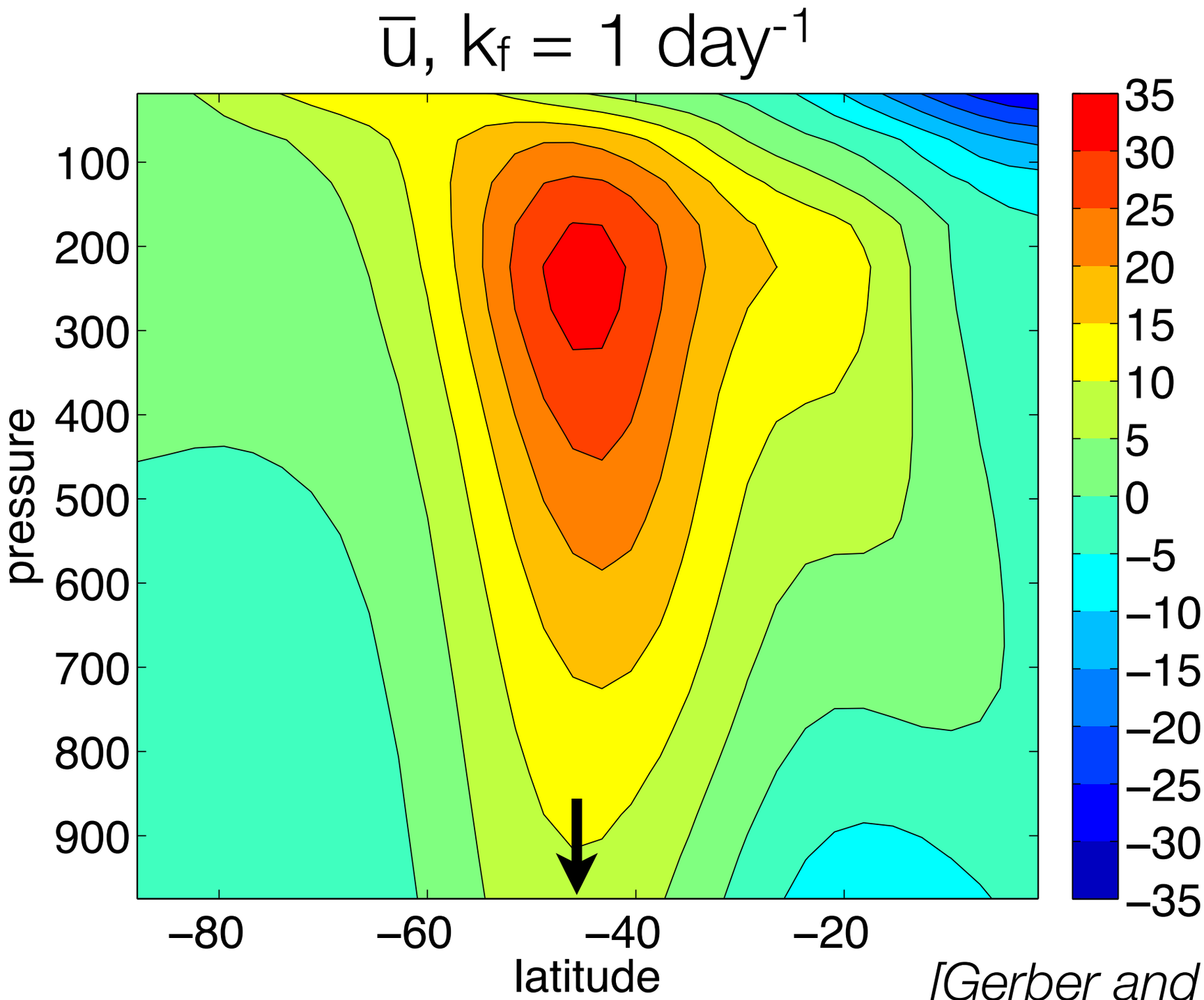
[Vallis et al. 2004]

Experiment #1: Vary surface friction



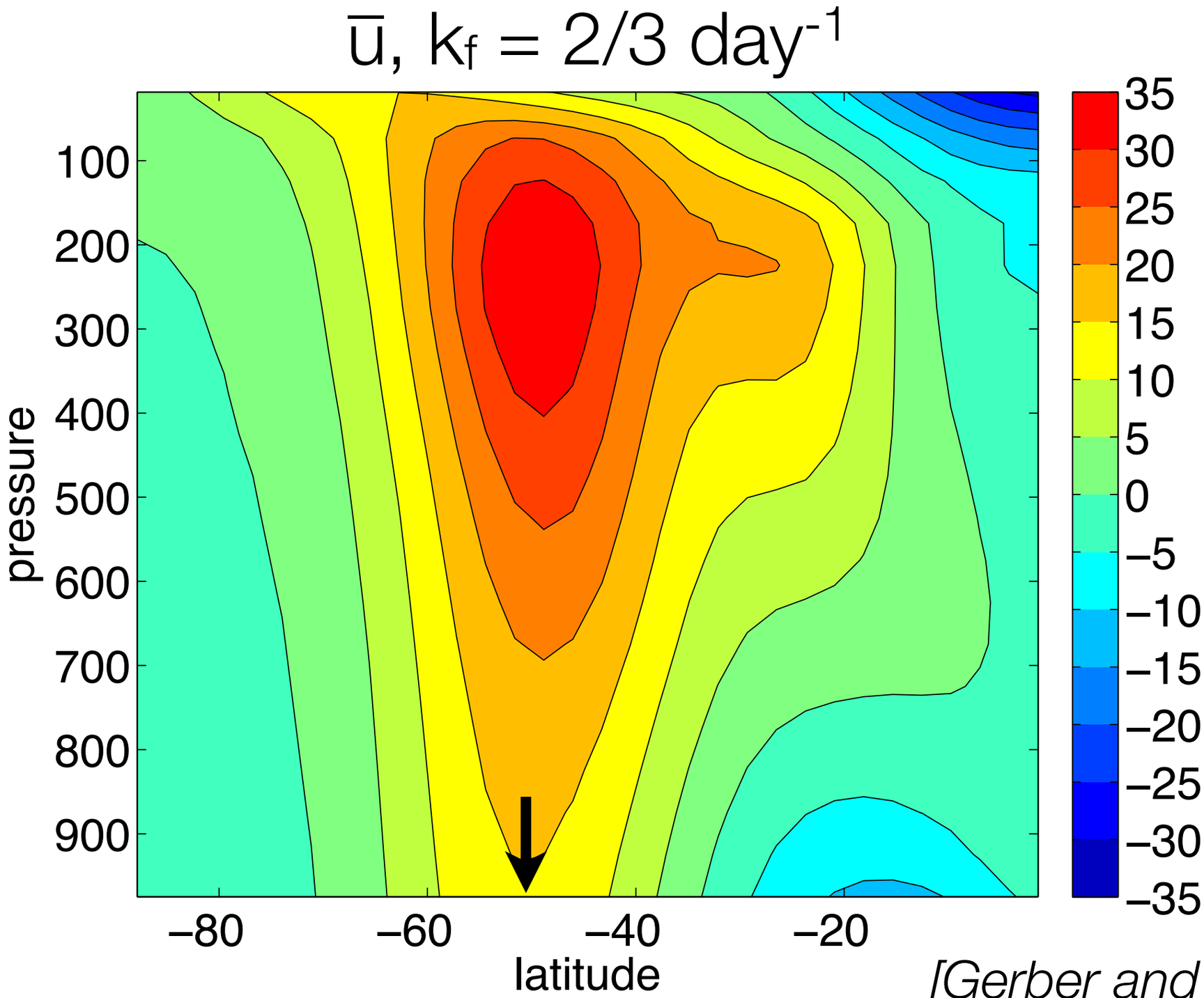
[Gerber and Vallis 2007]

Experiment #1: Vary surface friction



[Gerber and Vallis 2007]

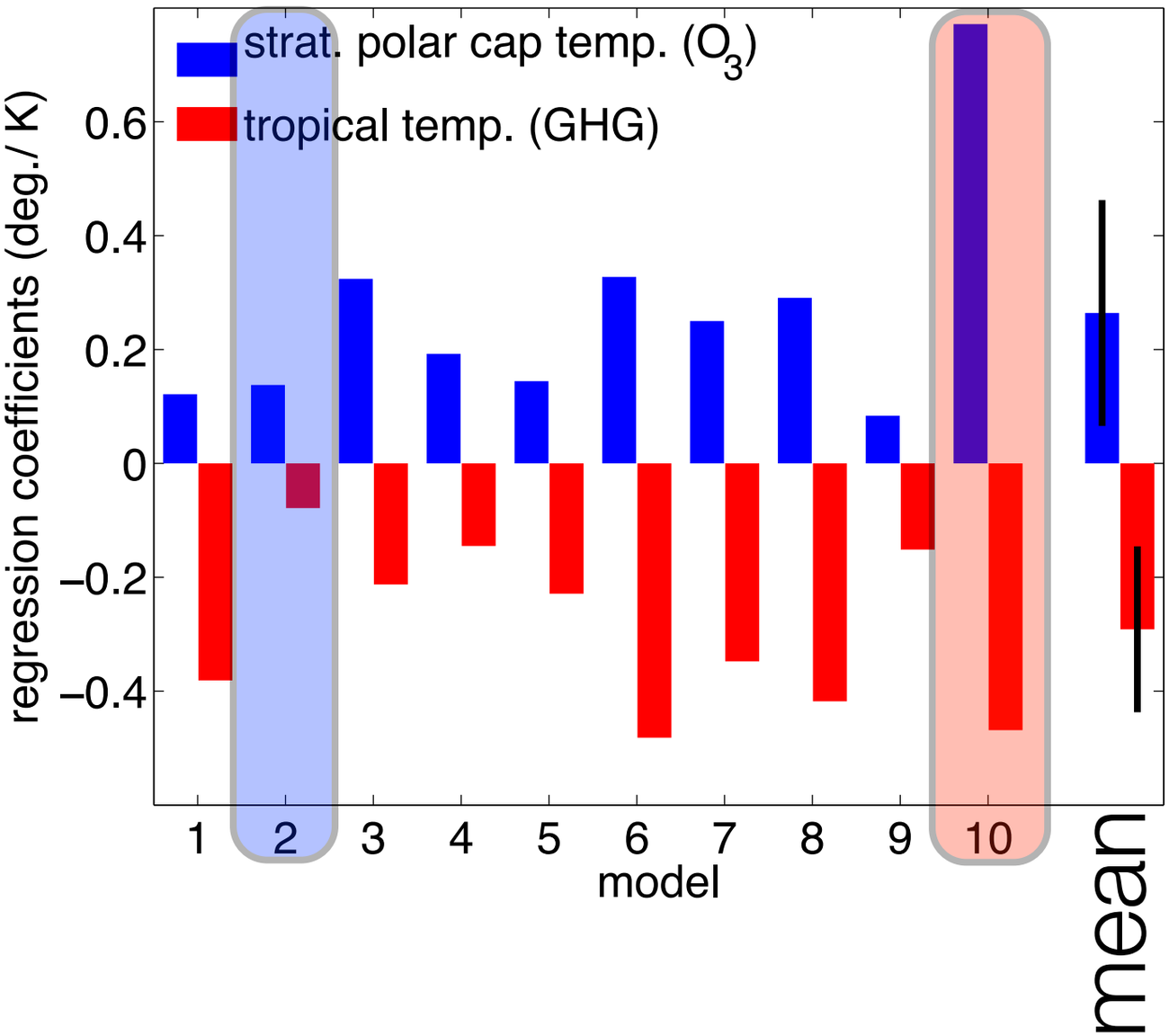
Experiment #1: Vary surface friction



[Gerber and Vallis 2007]

Regression Coefficients: Estimate of Sensitivity

CCMVal2 Models

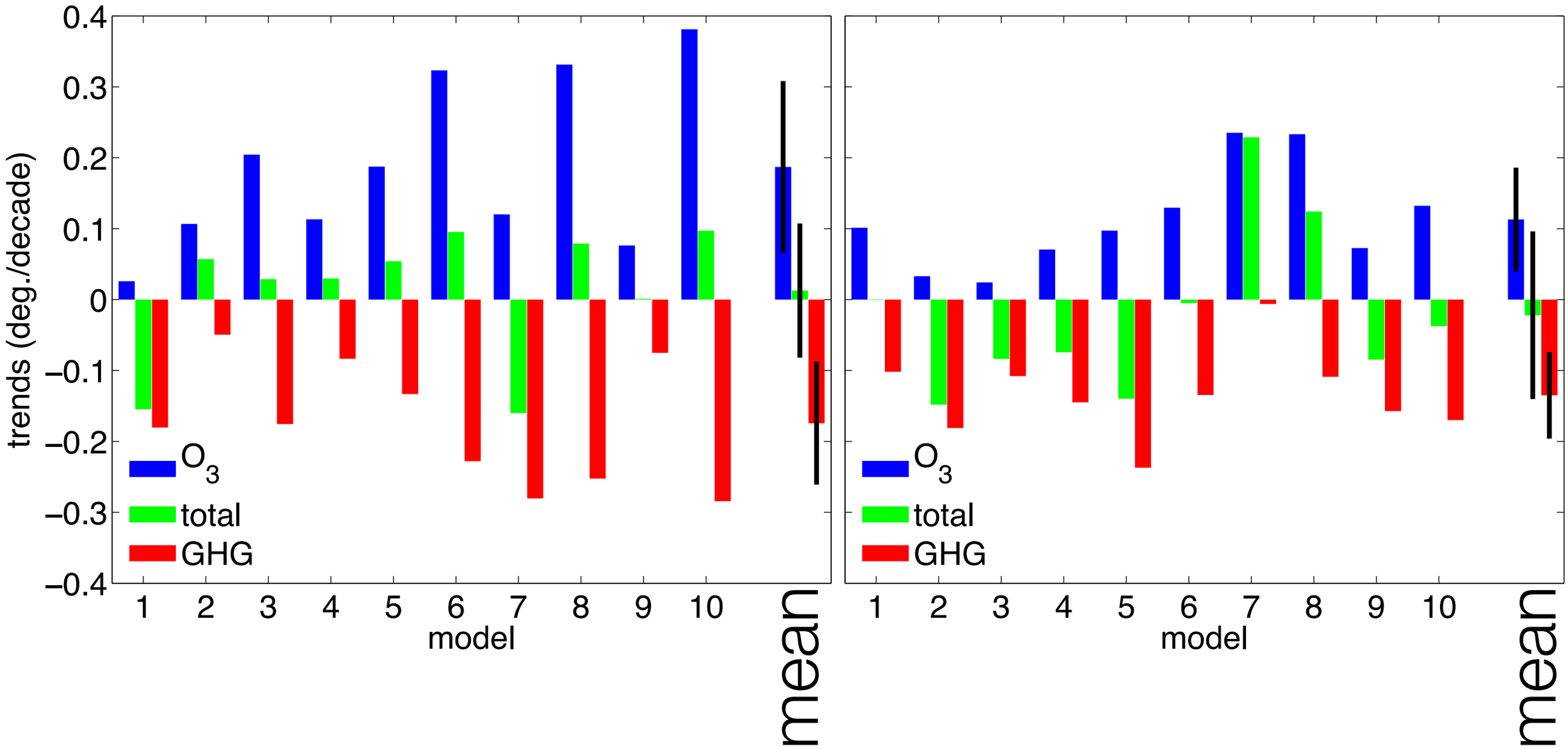


$$\Delta U_{lat} = r_{O_3} \cdot \Delta T_{0_3} + r_{GHG} \cdot \Delta T_{GHG}$$

Attribution of 21st Century Climate Trends

CCMVal2 Models

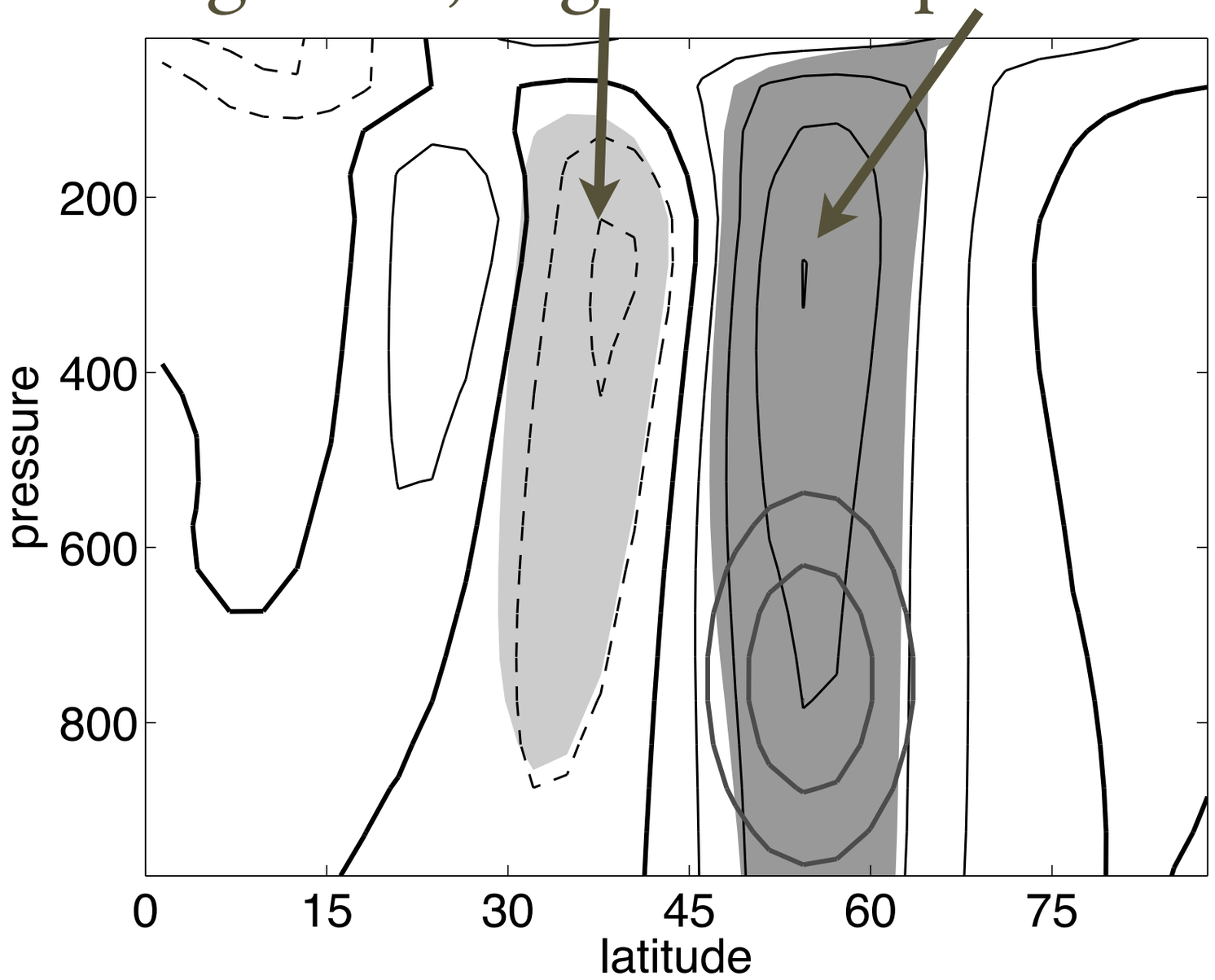
CMIP3 Models



$$\Delta U_{lat} = r_{O_3} \cdot \Delta T_{0_3} + r_{GHG} \cdot \Delta T_{GHG}$$

Fluctuation-Dissipation Theory
Impact of longer time scale on response to forcing

shading: first EOF of u from control integration, negative and positive

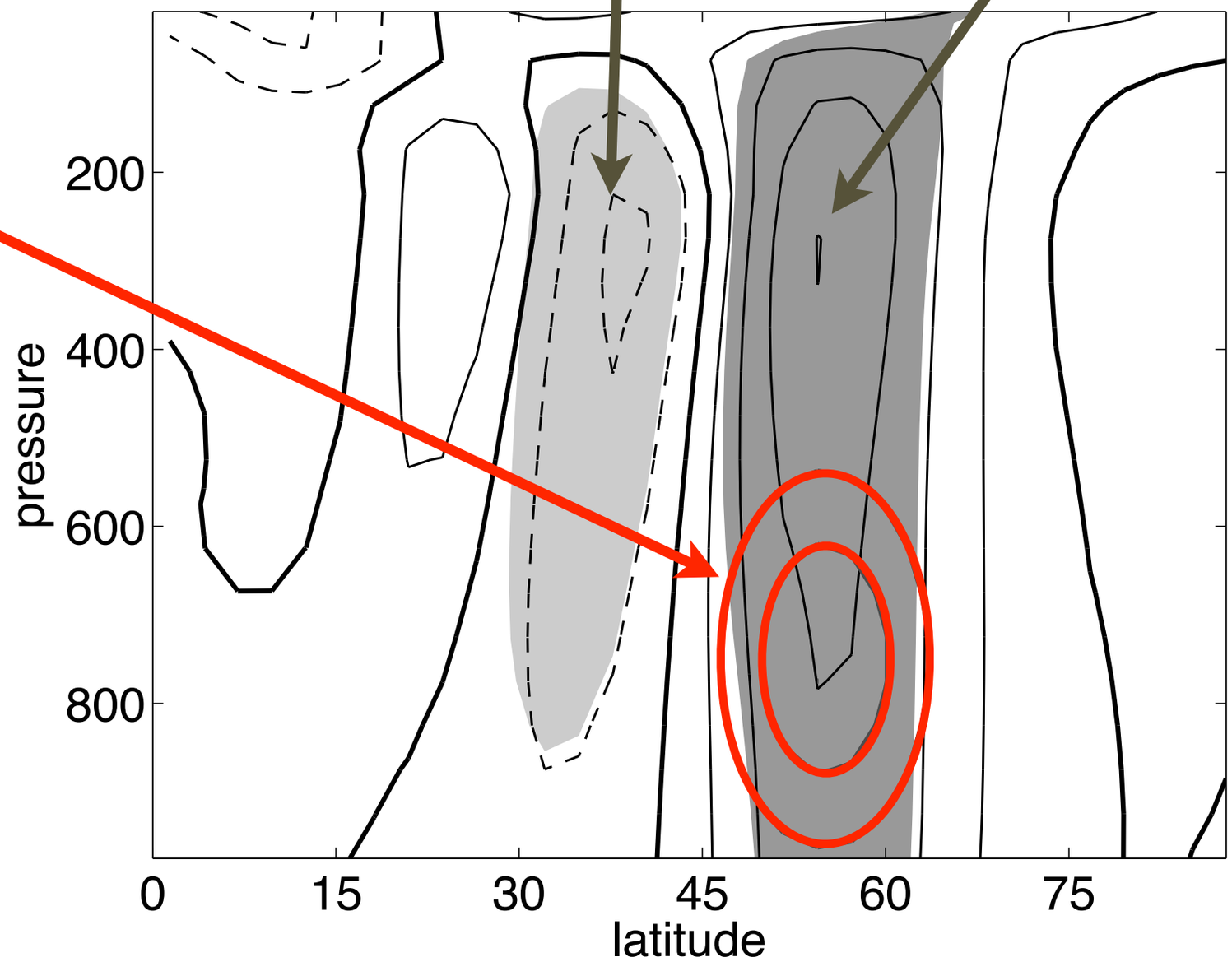


[After Ring and Plumb 2008]

Fluctuation-Dissipation Theory
Impact of longer time scale on response to forcing

shading: first EOF of u from control integration, negative and positive

apply a torque that projects onto the EOF



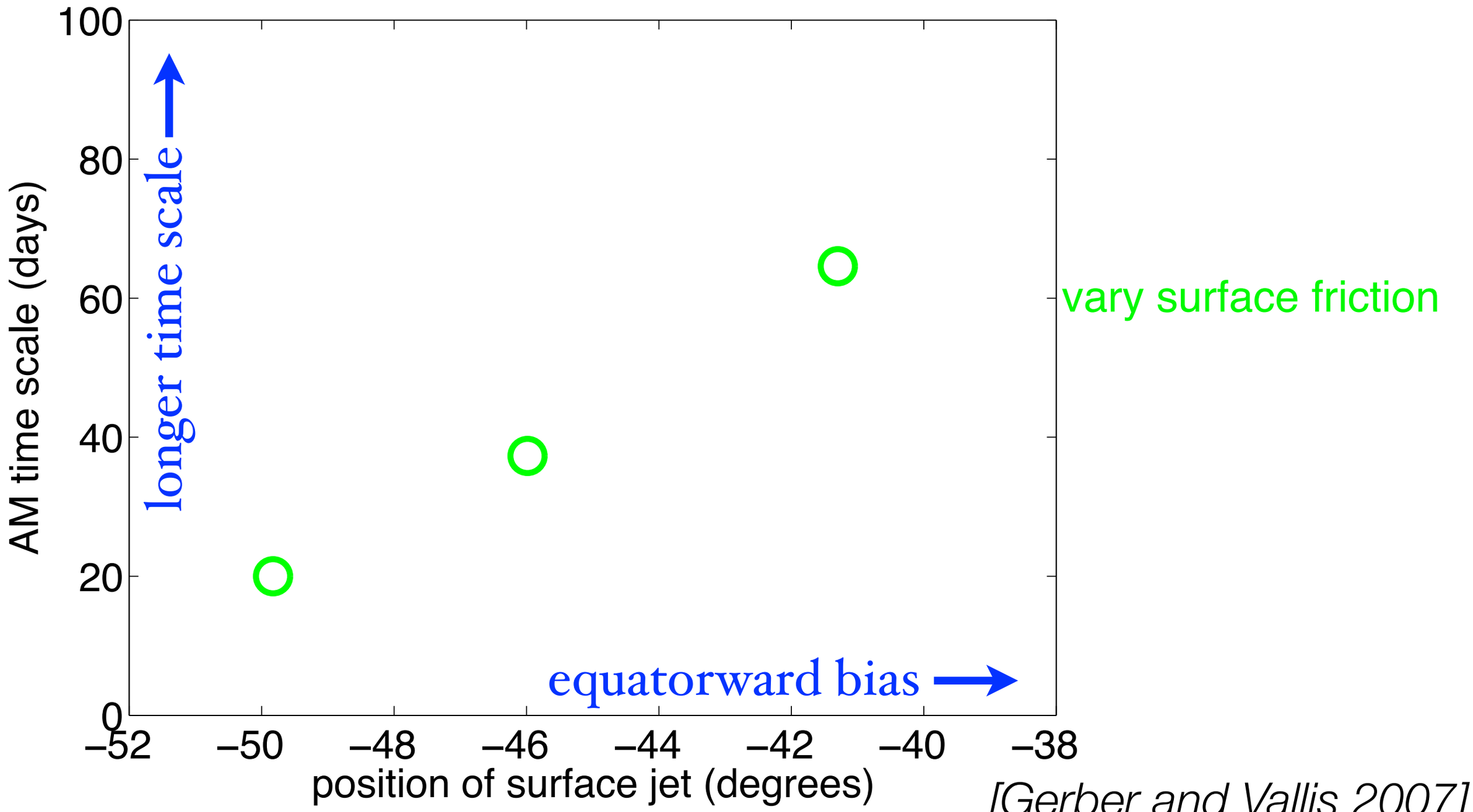
[After Ring and Plumb 2008]

Idealized GCM Experiments

- Held and Suarez (1994) Physics

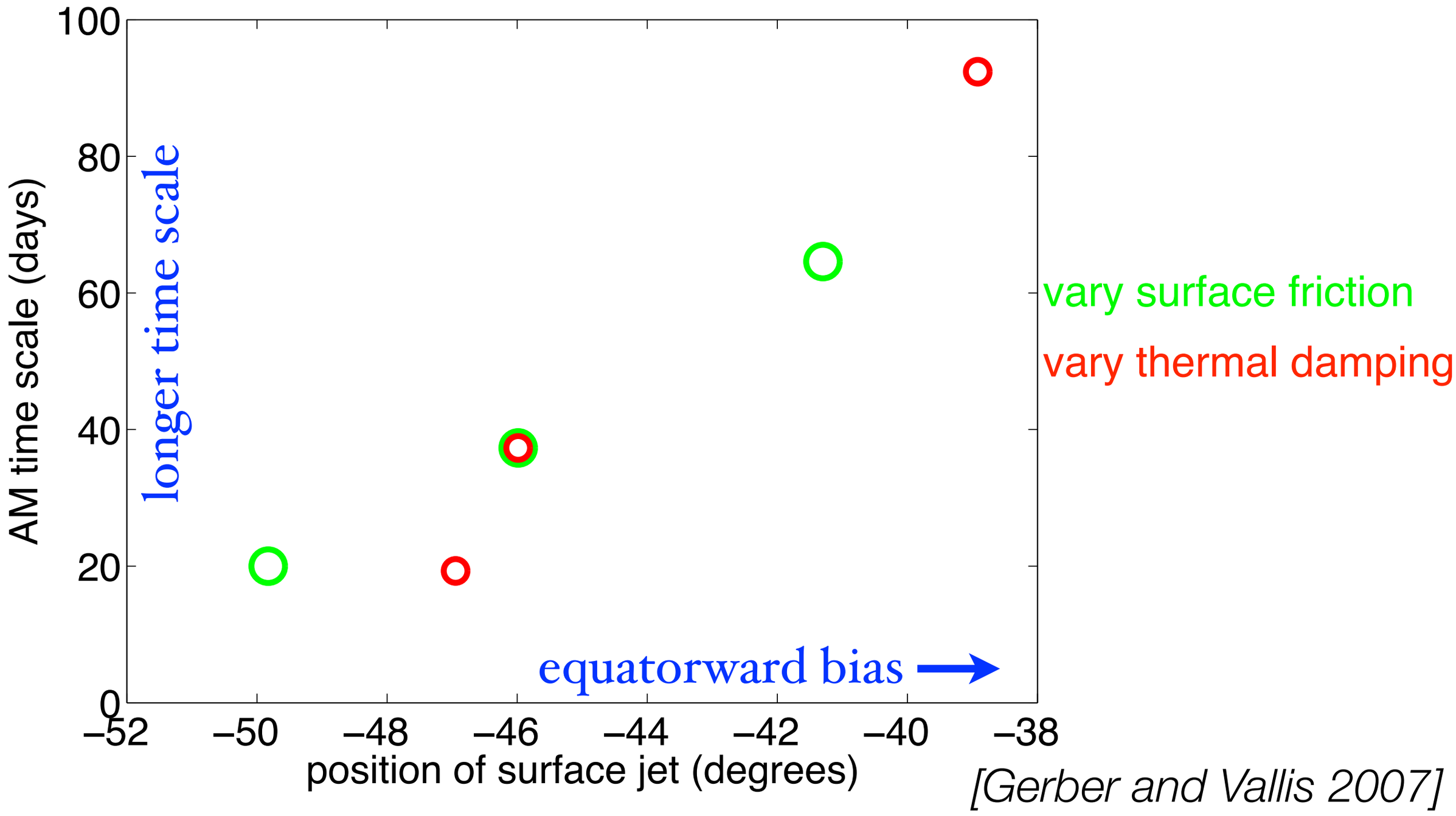
- Allow us to focus on the role of large scale dynamics in shaping the climate

Experiment #1: Vary surface friction
Jet Latitude - Time Scale Connection



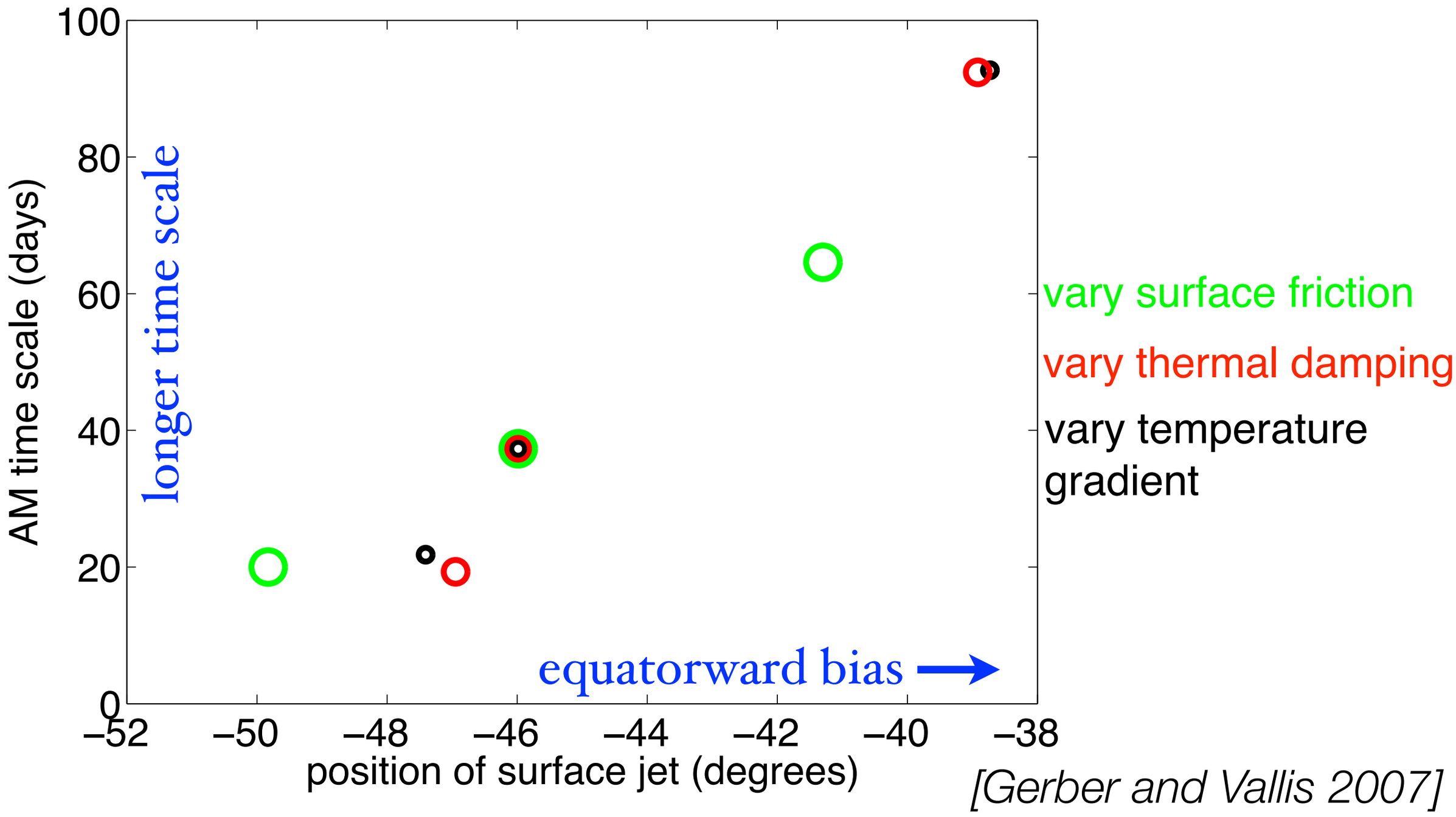
[Gerber and Vallis 2007]

Experiment #2: Vary thermal damping time scale
Jet Latitude - Time Scale Connection



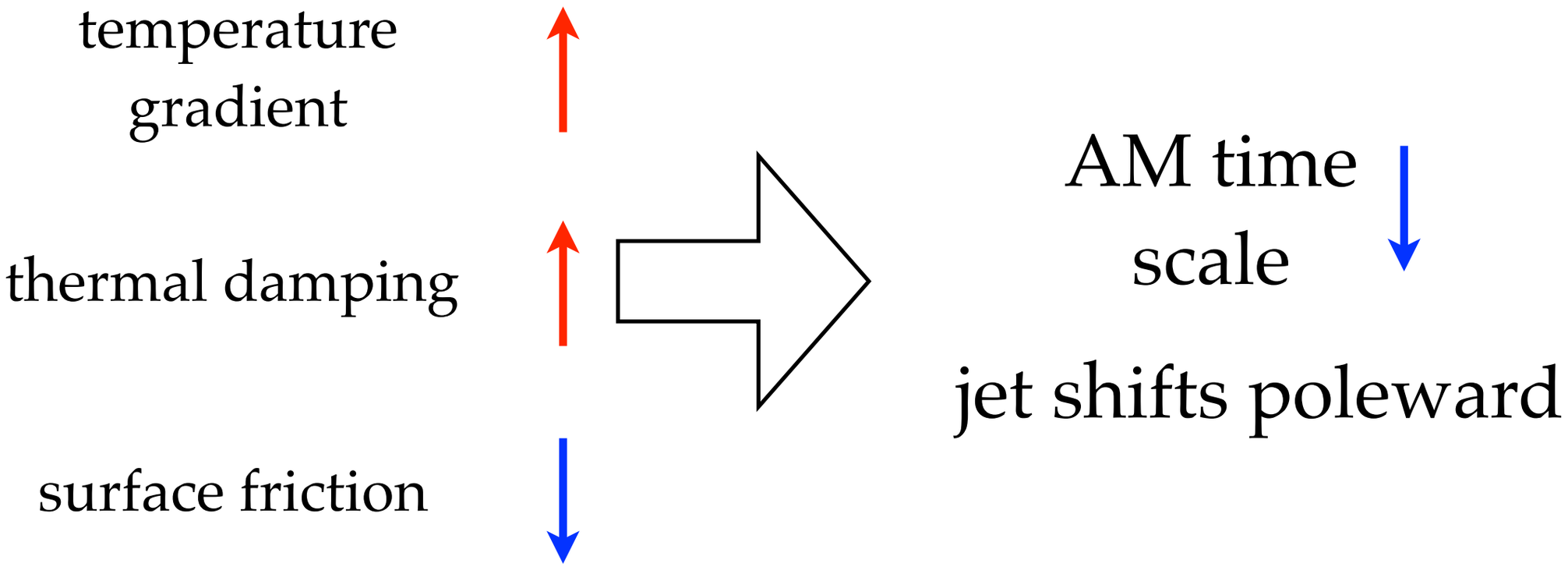
[Gerber and Vallis 2007]

Experiment #3: Vary temperature gradient
Jet Latitude - Time Scale Connection

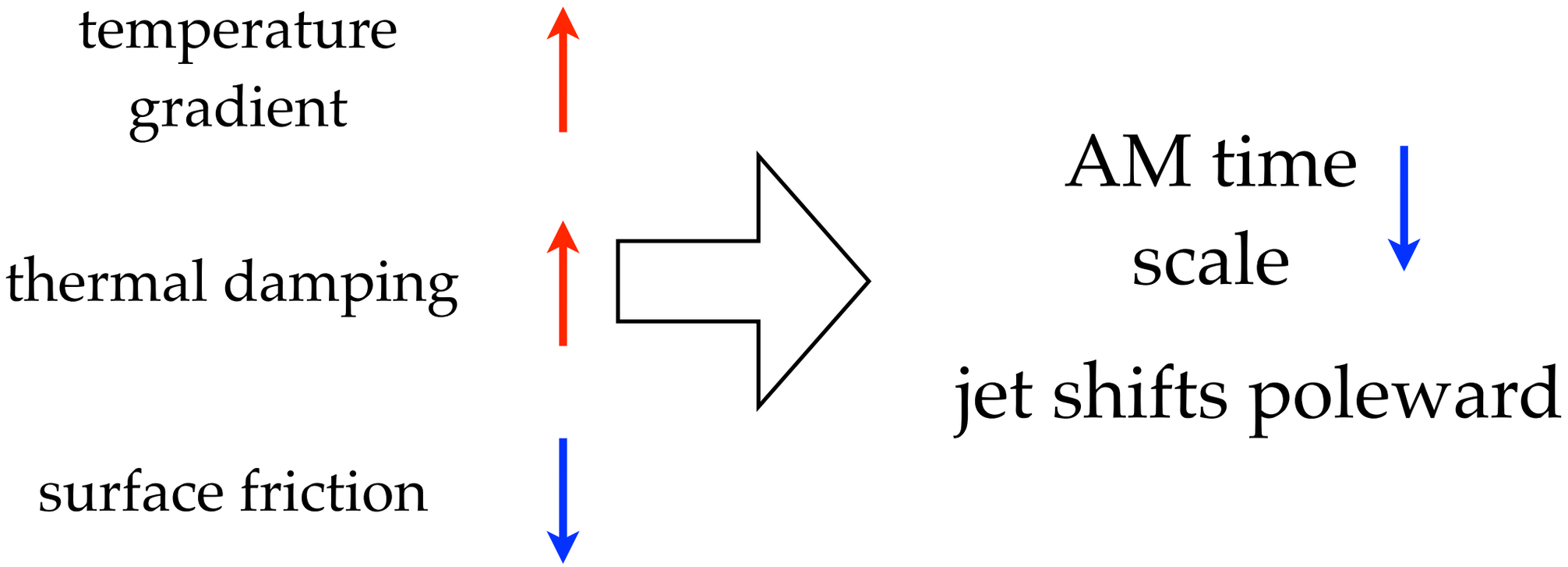


[Gerber and Vallis 2007]

Summary of GCM Experiments



Summary of GCM Experiments



Implications:

1) AM time scale is distinct from the imposed time scales, rather a product of eddy-mean flow interactions
2) processes that set jet location also set AM time scale