Fast and Slow Response of West African Precipitation to Aerosol Forcing

Haruki Hirasawa (**project lead**) and Paul Kushner (**presenting**)
Department of Physics, University of Toronto

Michael Sigmond and John Fyfe, *Environment and Climate Change Canada*
Clara Deser, *NCAR*
Thomas Oudar, *CNRM, Toulouse*

Overview

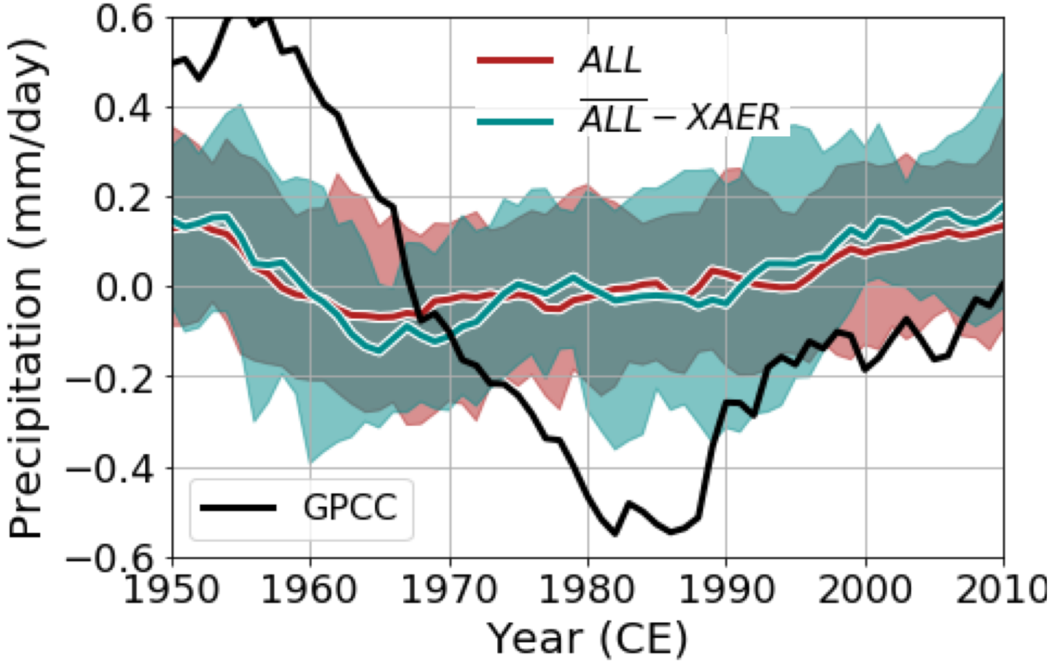
Overview

- Large initial-condition ensembles of Earth System Models isolate global SST and sea ice responses to aerosol forcing.
- They show a strong aerosol-dominated and transient signal in West African precipitation, consistent with a lot of prior work.
- Using the large ensemble SST and sea ice boundary conditions allows us to separate *fast* (aerosol-driven) and *slow* (ocean mediated) drivers of precipitation signals.
- The approach is relevant to North Atlantic themes of this workshop.

Aerosols Dominate Modeled Sahel Precipitation Changes

July-August-September (JAS) Sahel Precipitation Anomalies in Large Initial Condition Ensembles

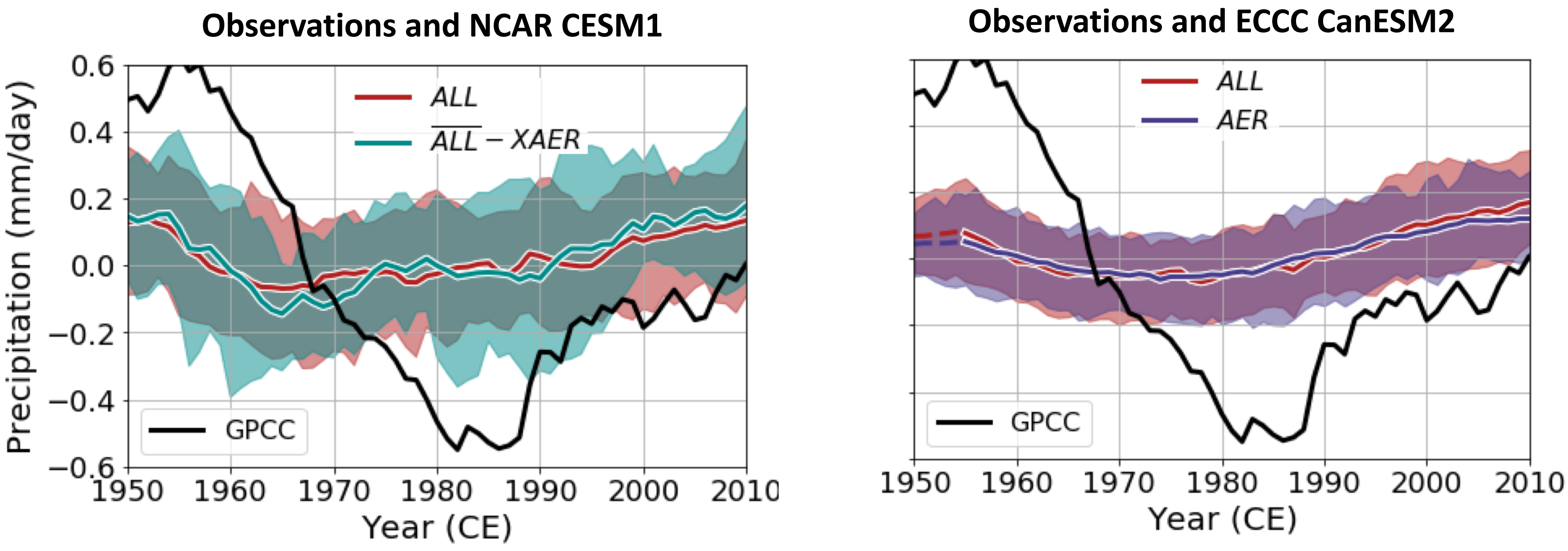
Observations and NCAR CESM1



10 year running mean of land areas for 10N-20N, 20W-35E. 5-95% range shown for models.

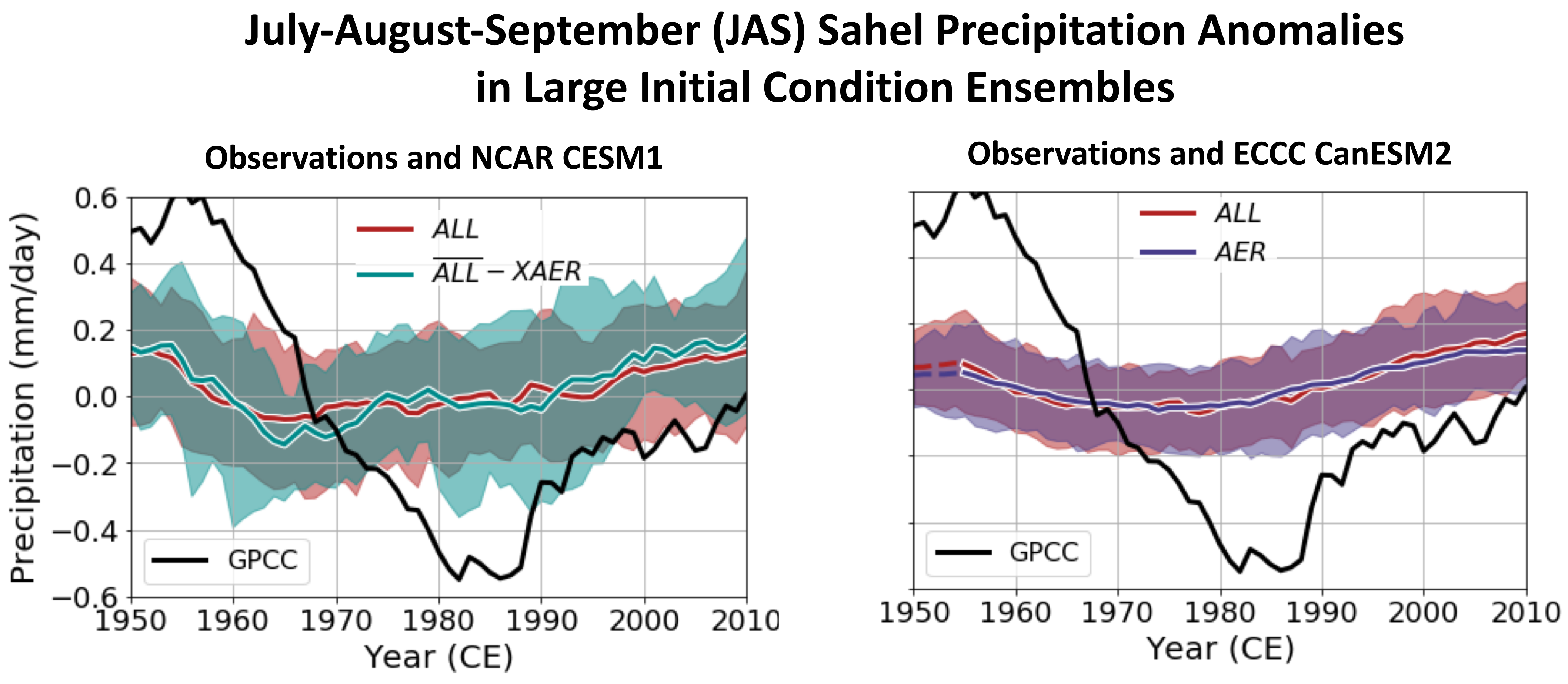
Aerosols Dominate Modeled Sahel Precipitation Changes

July-August-September (JAS) Sahel Precipitation Anomalies in Large Initial Condition Ensembles



10 year running mean of land areas for 10N-20N, 20W-35E. 5-95% range shown for models.

Aerosols Dominate Modeled Sahel Precipitation Changes



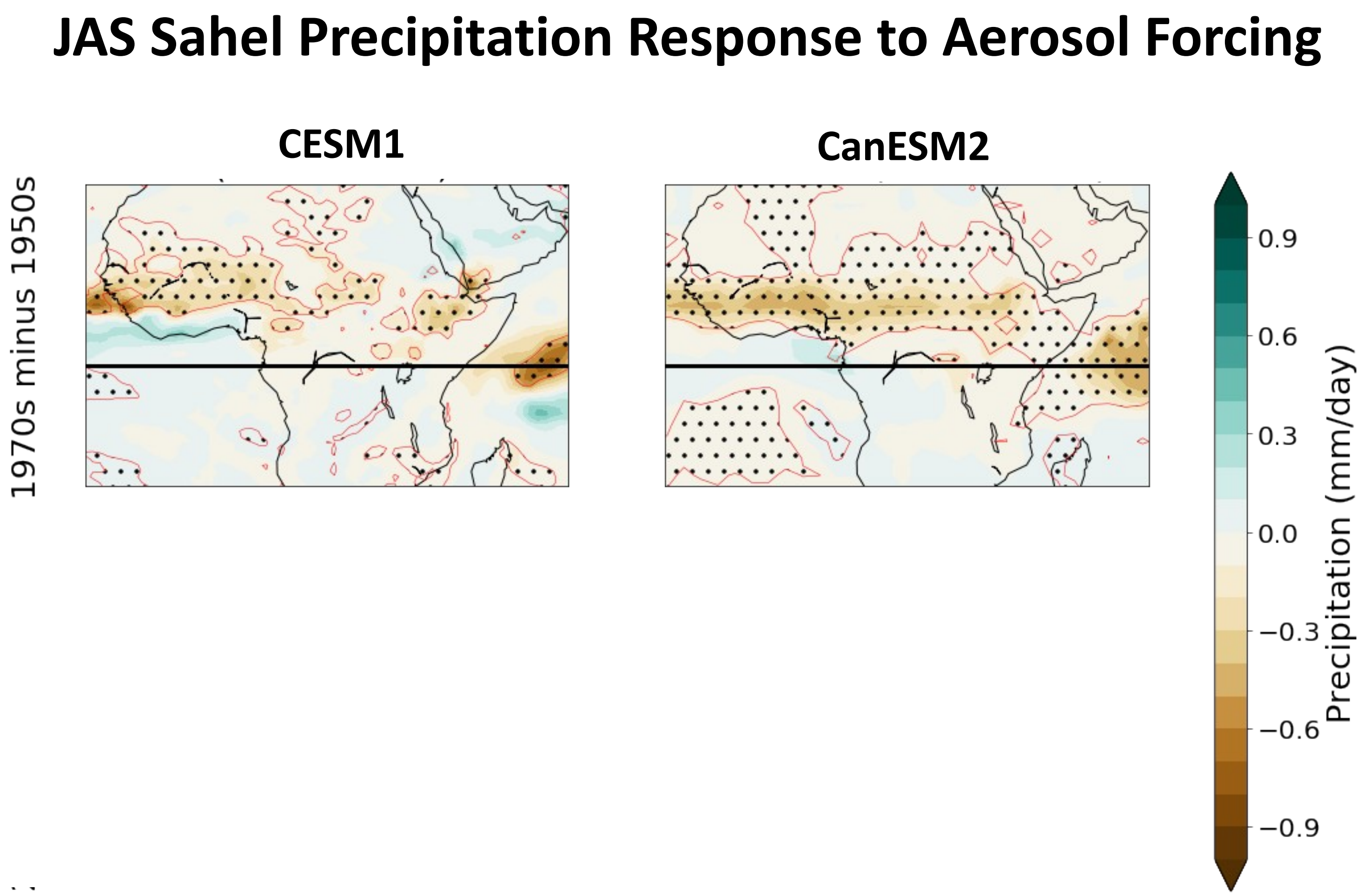
10 year running mean of land areas for 10N-20N, 20W-35E. 5-95% range shown for models.

- Many realizations sampled to extract a robust temporal signal to anthropogenic aerosol forcing.
- Regional warming is dominated by greenhouse gases (extra slides)

The Patterns of Drying and Moistening Are Robust

CESM1 and CanESM2 similar despite distinctive aerosol schemes.

Again, many realizations required to estimate this signal.

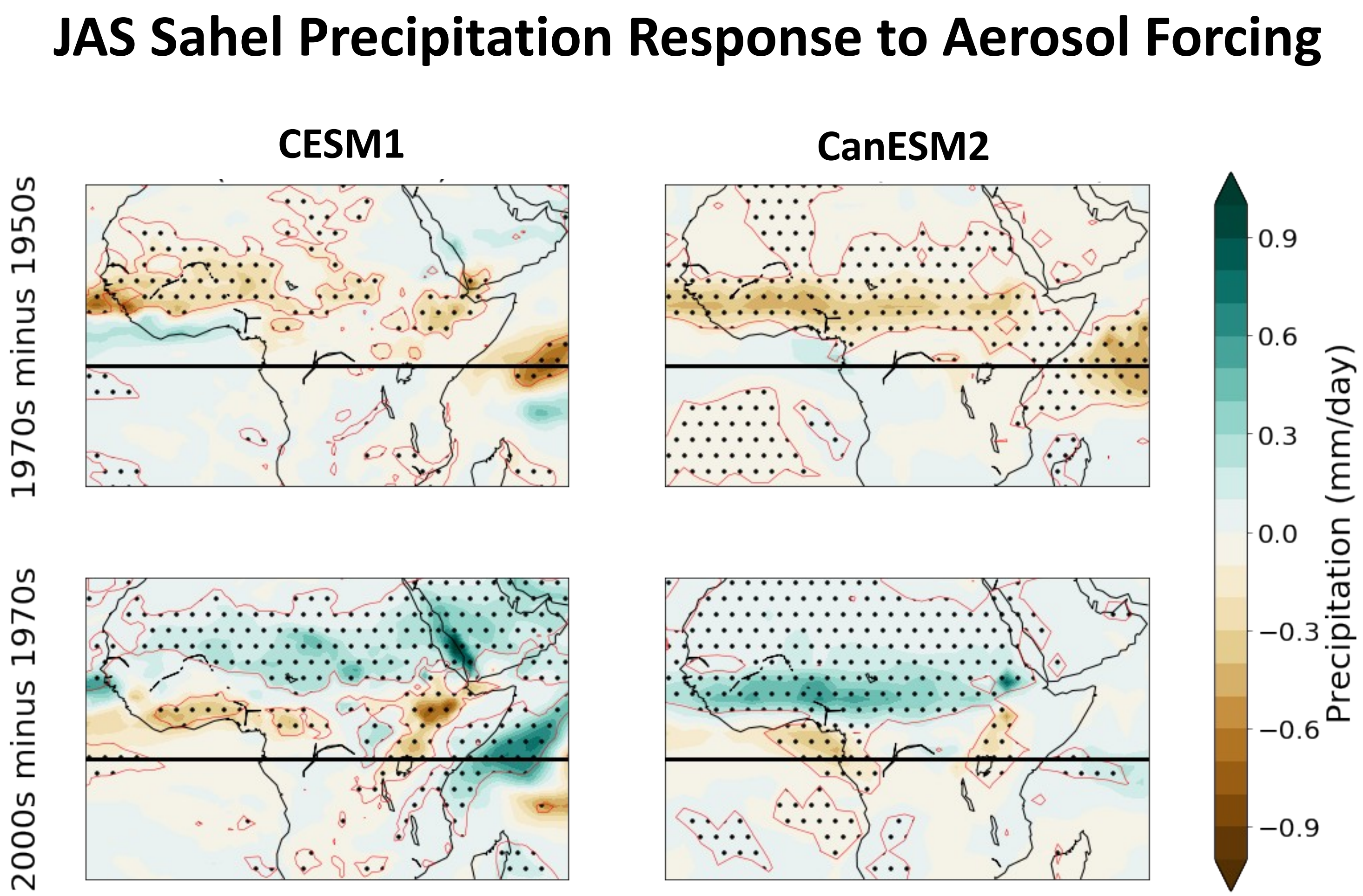


The Patterns of Drying and Moistening Are Robust

CESM1 and CanESM2 similar despite distinctive aerosol schemes.

Again, many realizations required to estimate this signal.

Aerosol driven drying through the 1970's, and aerosol driven recovery through the 2000's.

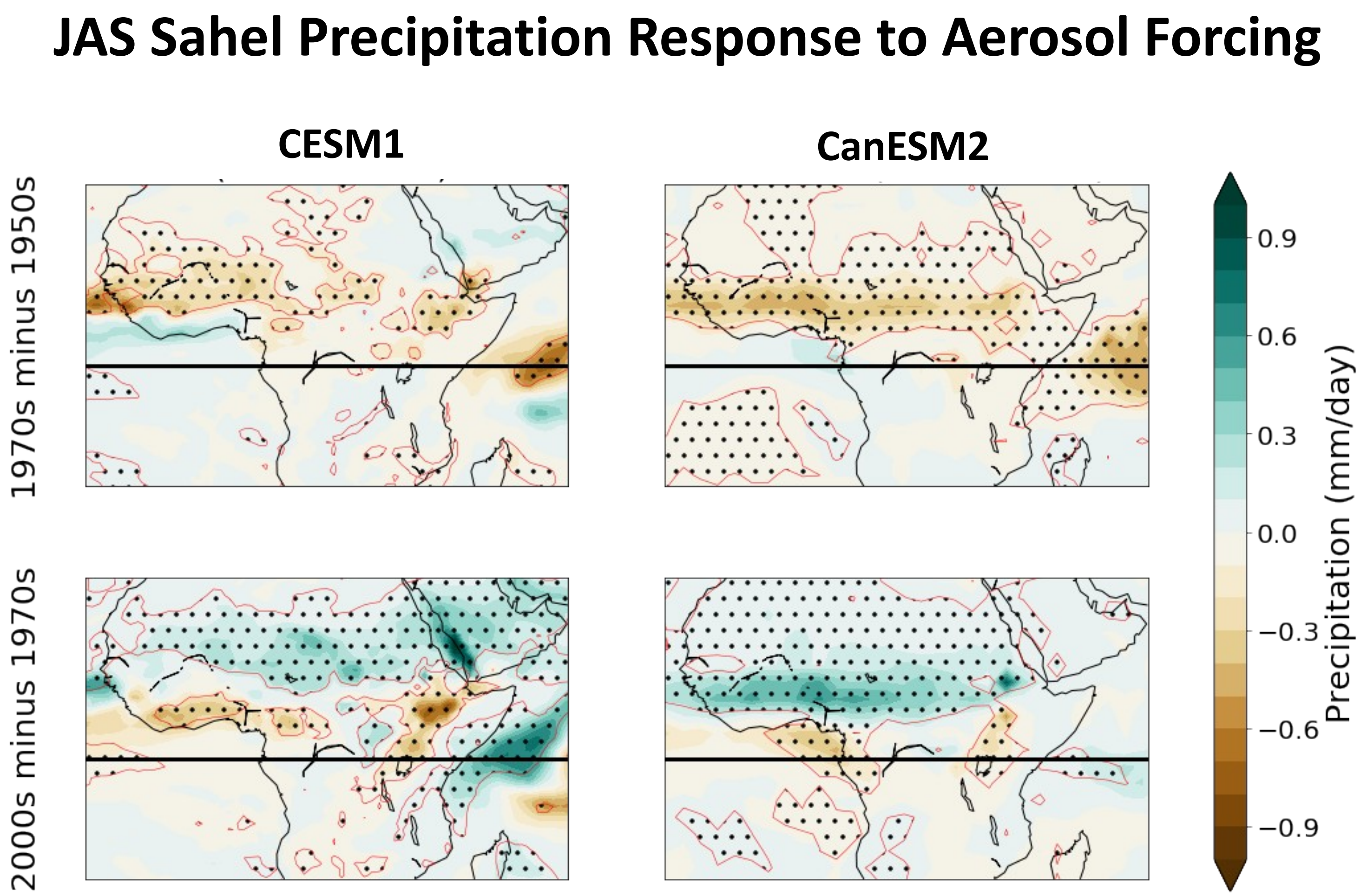


The Patterns of Drying and Moistening Are Robust

CESM1 and CanESM2 similar despite distinctive aerosol schemes.

Again, many realizations required to estimate this signal.

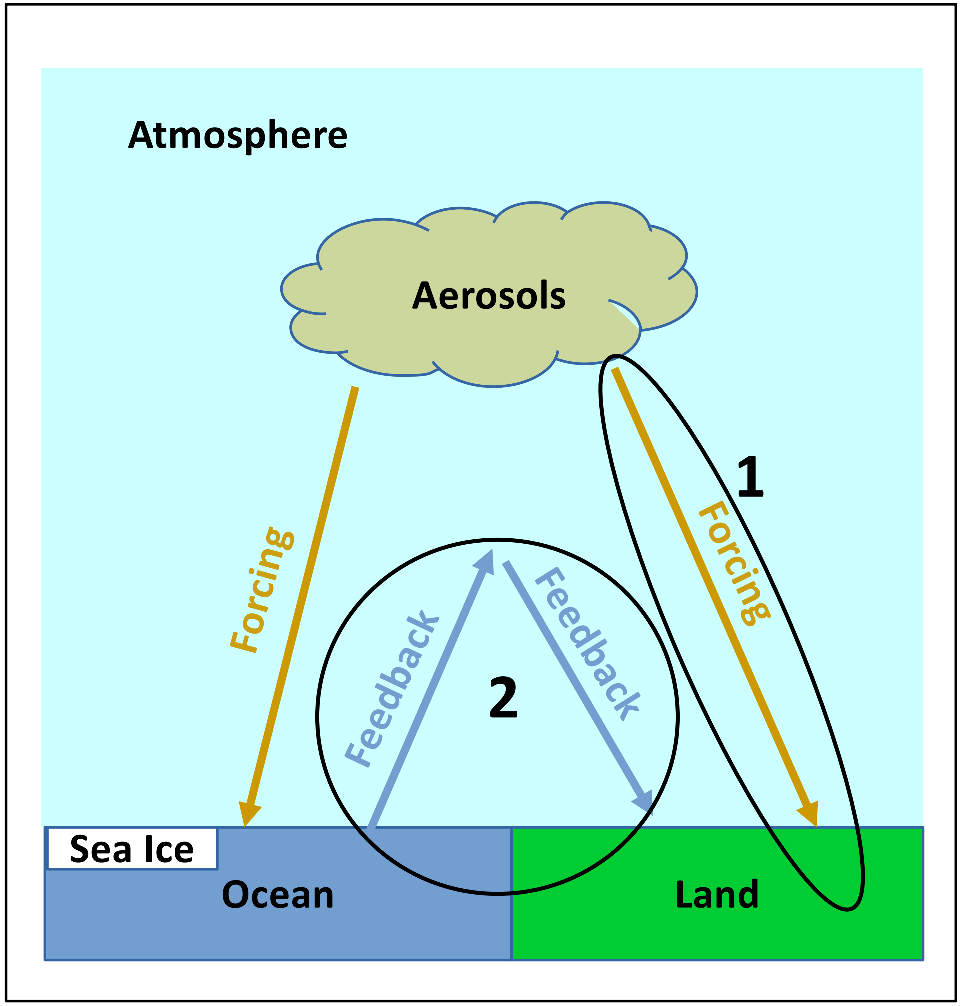
Aerosol driven drying through the 1970’s, and aerosol driven recovery through the 2000’s.



What is the dynamics of this response?

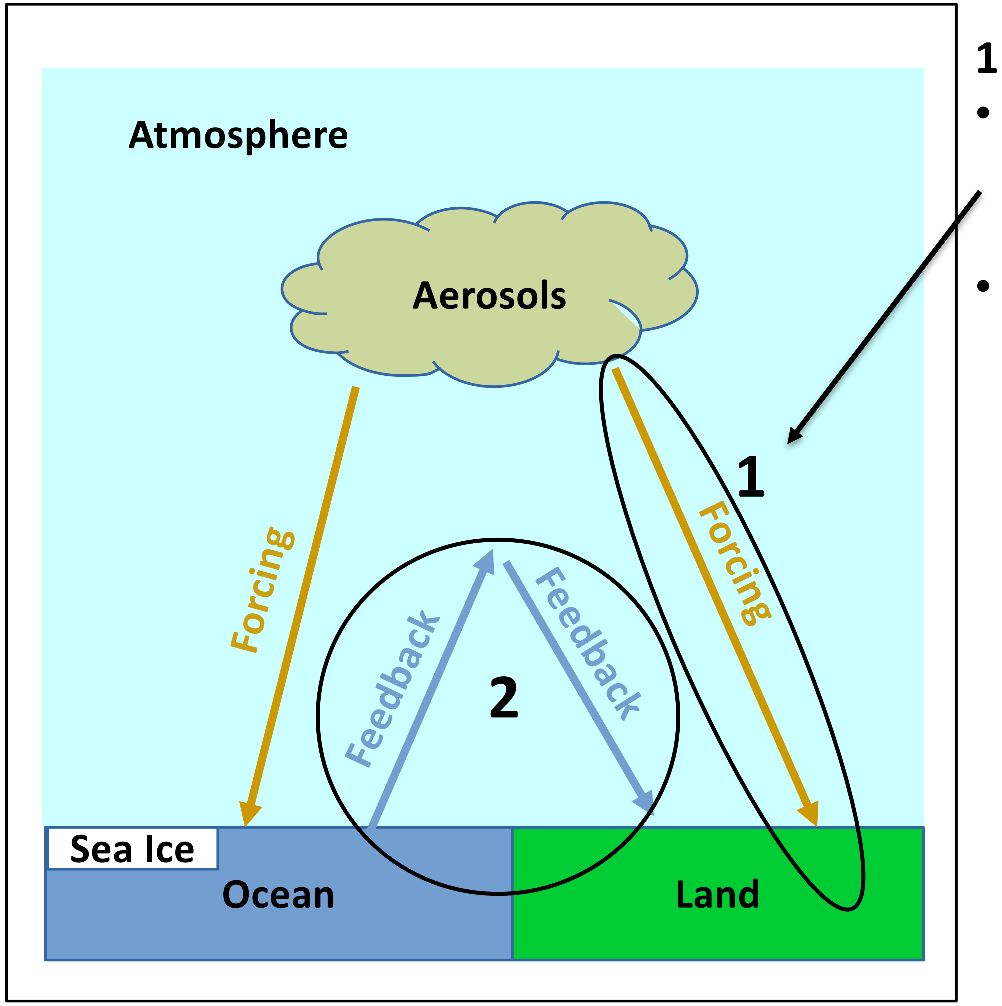
Framework: Fast and Slow Drivers

We use AGCM simulations to separate fast radiative/cloud and slow SST/sea-ice drivers.



Framework: Fast and Slow Drivers

We use AGCM simulations to separate fast radiative/cloud and slow SST/sea-ice drivers.



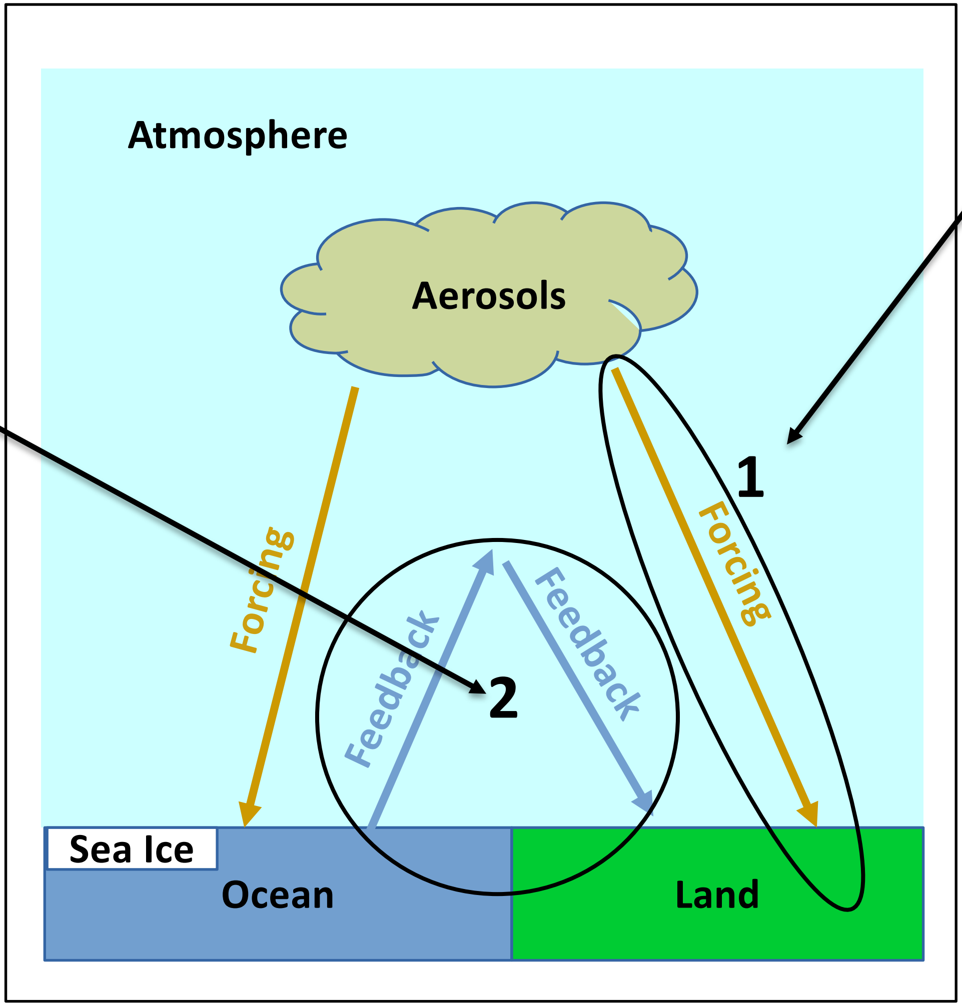
1. Fast (radiative/cloud) response:

- The atmosphere/land response that is directly due to the radiative forcing.
- E.g. Li et al. 2018 study of East Asian Monsoon.

Framework: Fast and Slow Drivers

We use AGCM simulations to separate fast radiative/cloud and slow SST/sea-ice drivers.

2. Slow (SST/sea ice) response:
- The atmospheric response that is mediated by changes to SST and sea ice.
- E.g. Wang et al. 2016 study of tropical trade wind response to aerosol-forced SST changes.

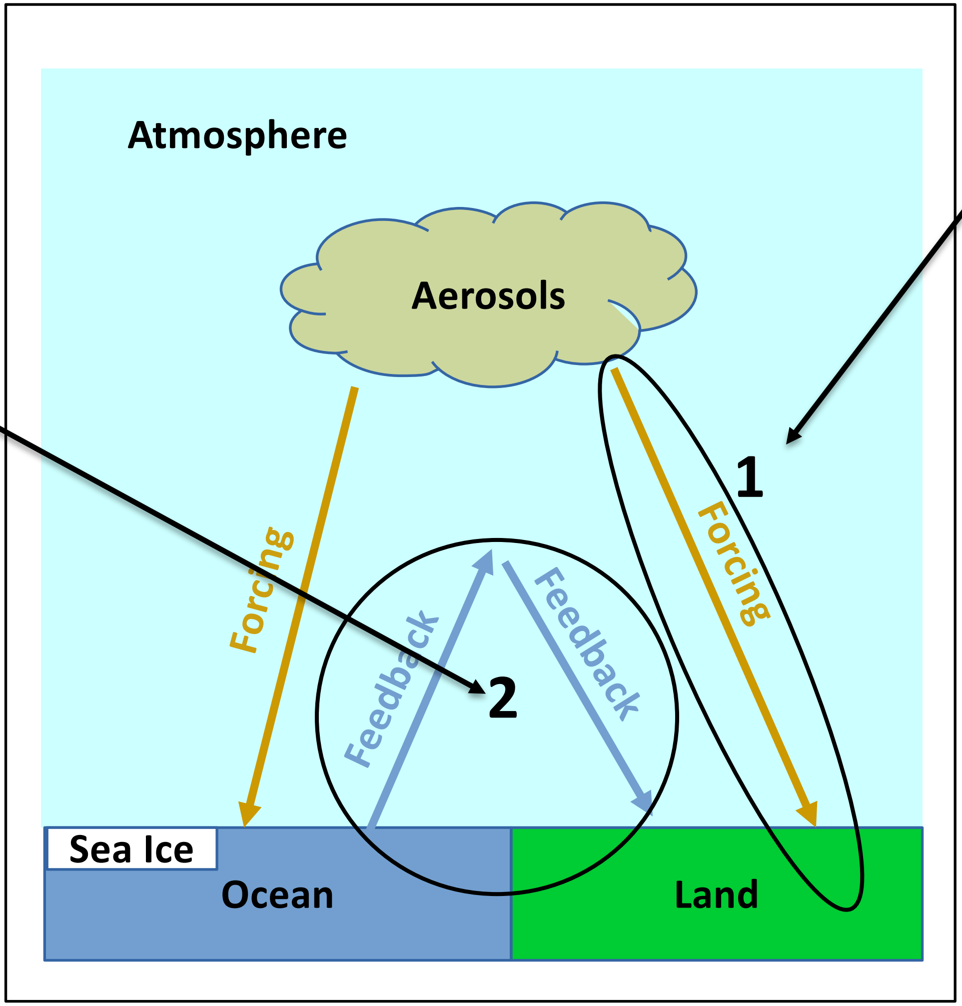


1. Fast (radiative/cloud) response:
- The atmosphere/land response that is directly due to the radiative forcing.
- E.g. Li et al. 2018 study of East Asian Monsoon.

Framework: Fast and Slow Drivers

We use AGCM simulations to separate fast radiative/cloud and slow SST/sea-ice drivers.

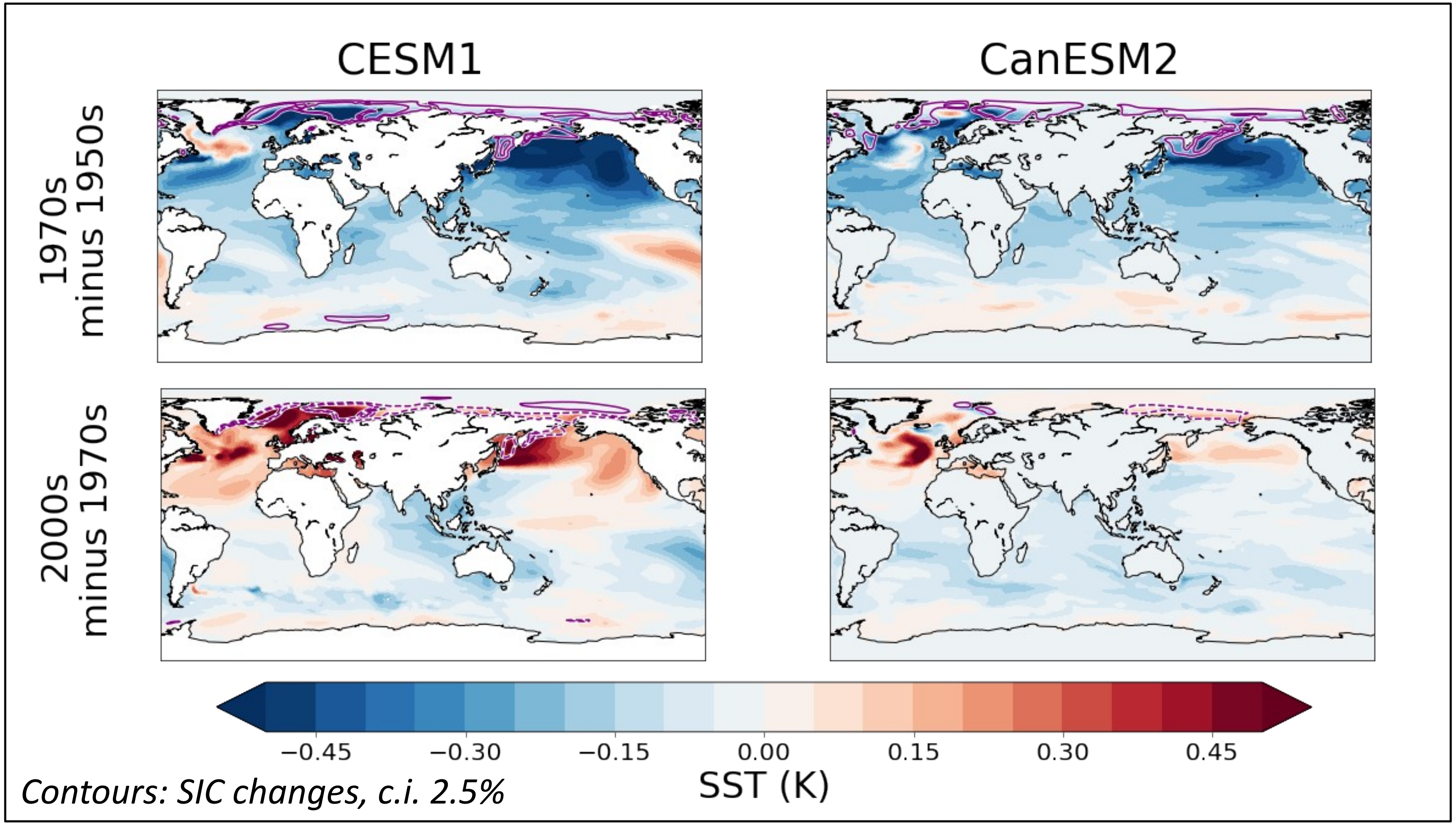
2. Slow (SST/sea ice) response:
- The atmospheric response that is mediated by changes to SST and sea ice.
- E.g. Wang et al. 2016 study of tropical trade wind response to aerosol-forced SST changes.



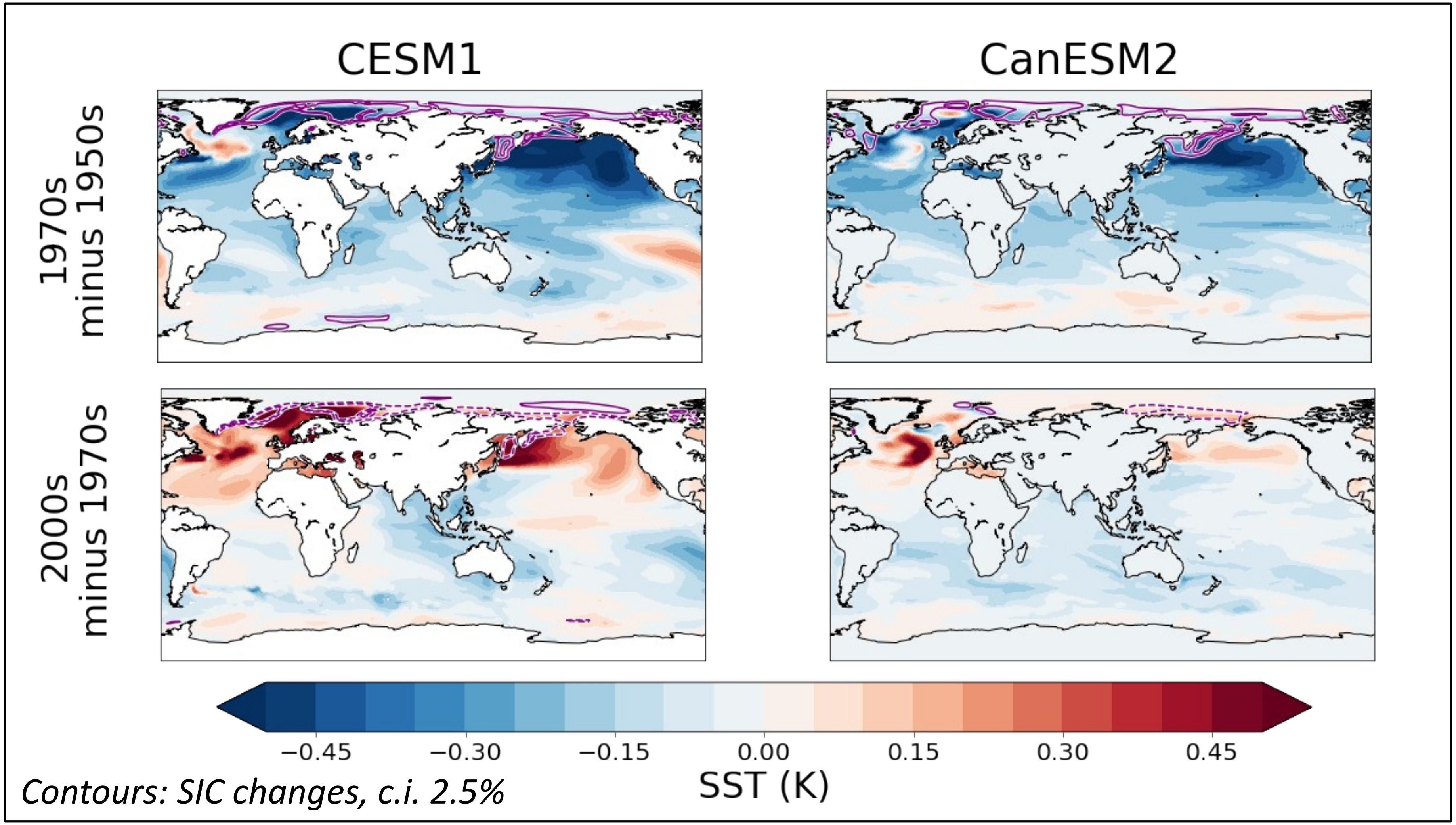
1. Fast (radiative/cloud) response:
- The atmosphere/land response that is directly due to the radiative forcing.
- E.g. Li et al. 2018 study of East Asian Monsoon.

Setup:
- 100 Year time slice simulations
- Carried out for epochs of 1950’s, 1970’s, 2000’s
- Limited testing of additivity (see discussion)
- Carried out using NCAR CAM5 and ECCC CanESM2

Slow Forcing: SST and Sea Ice Responses from the Large Ensembles

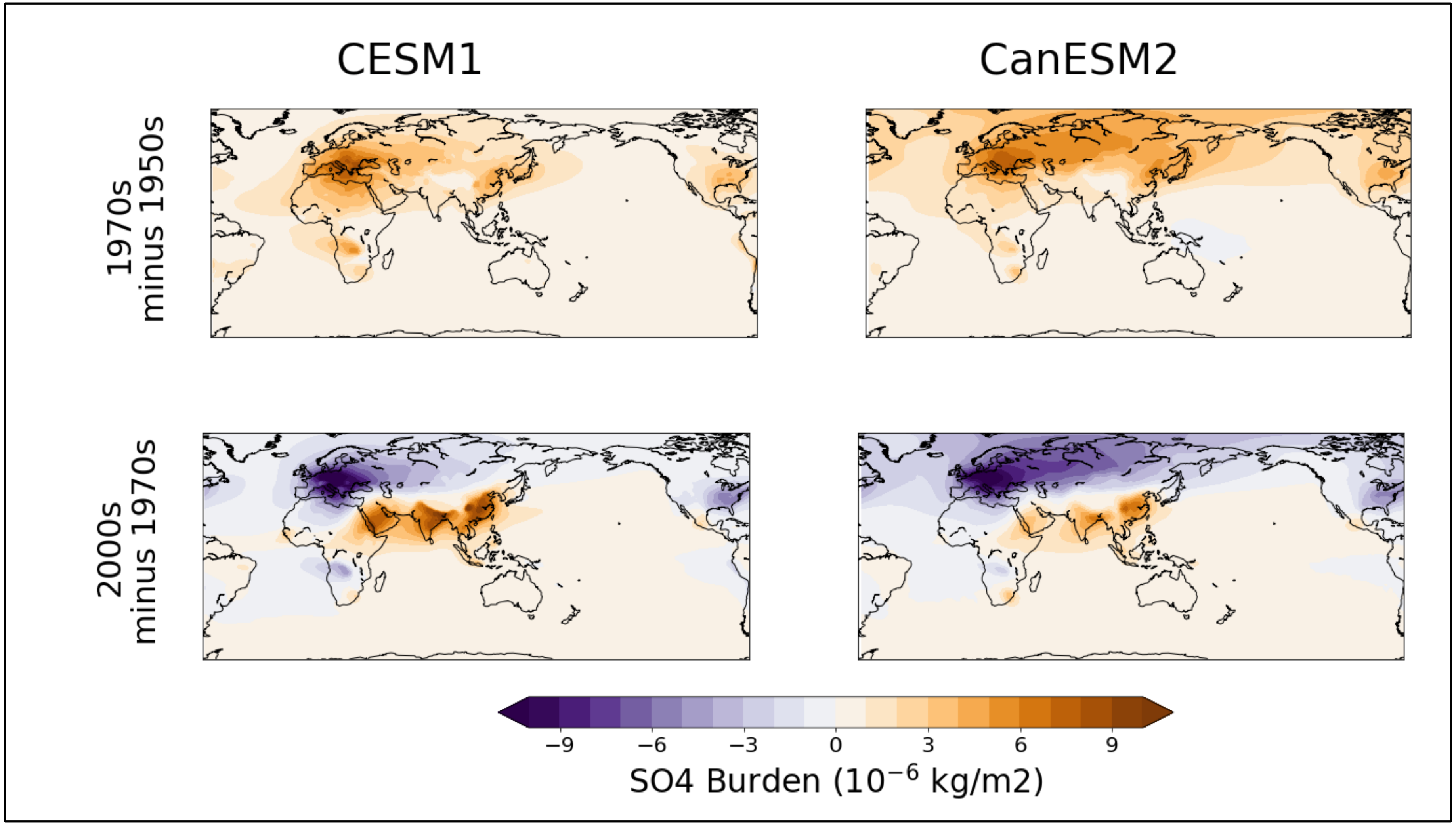


Slow Forcing: SST and Sea Ice Responses from the Large Ensembles

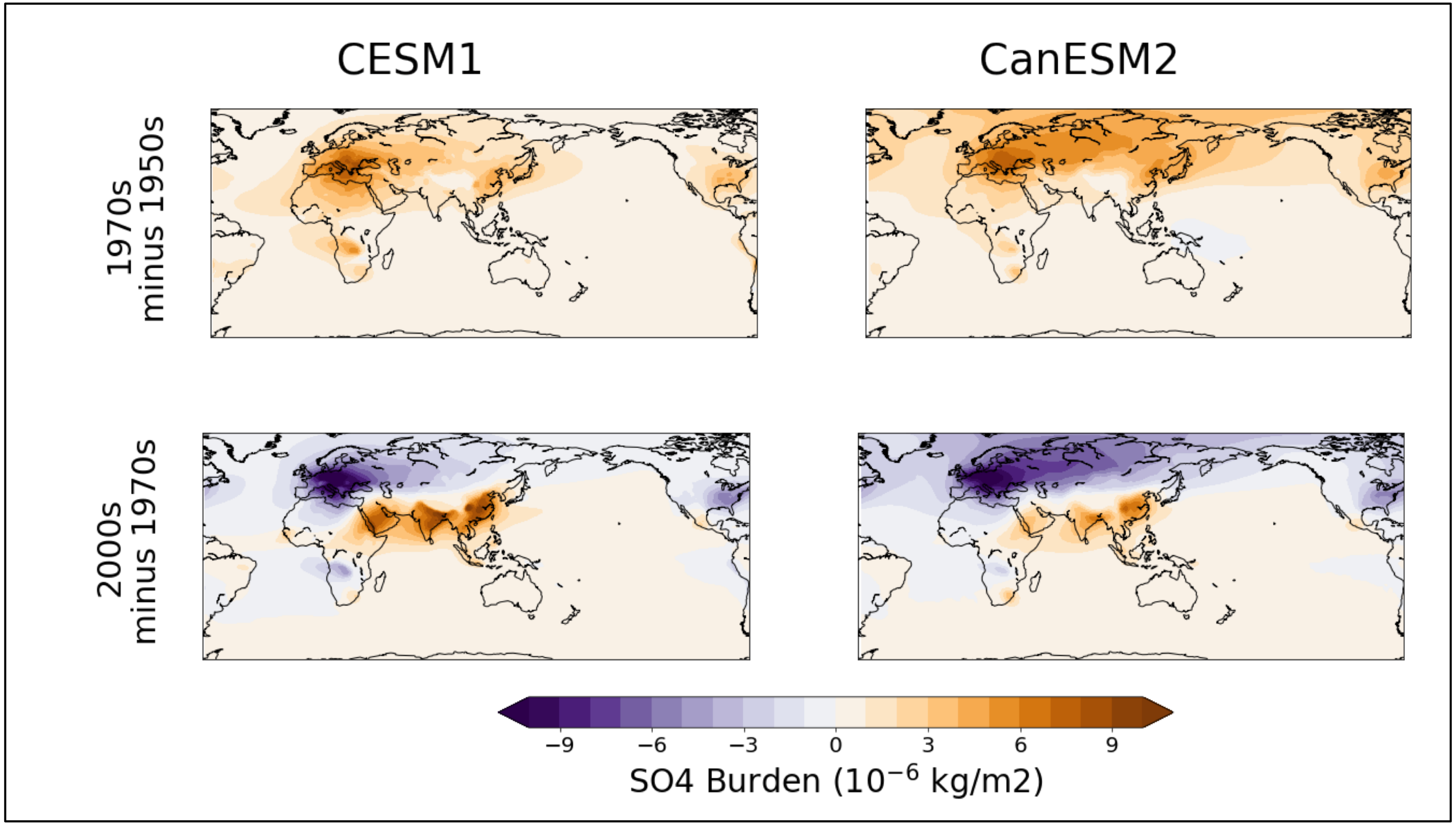


- CESM1 cooling and warming stronger than CanESM2.
- [What drives the North Atlantic cooling hole/enhanced warming? Direct aerosol forcing? AMOC adjustment?]

Fast Forcing: Aerosol Responses

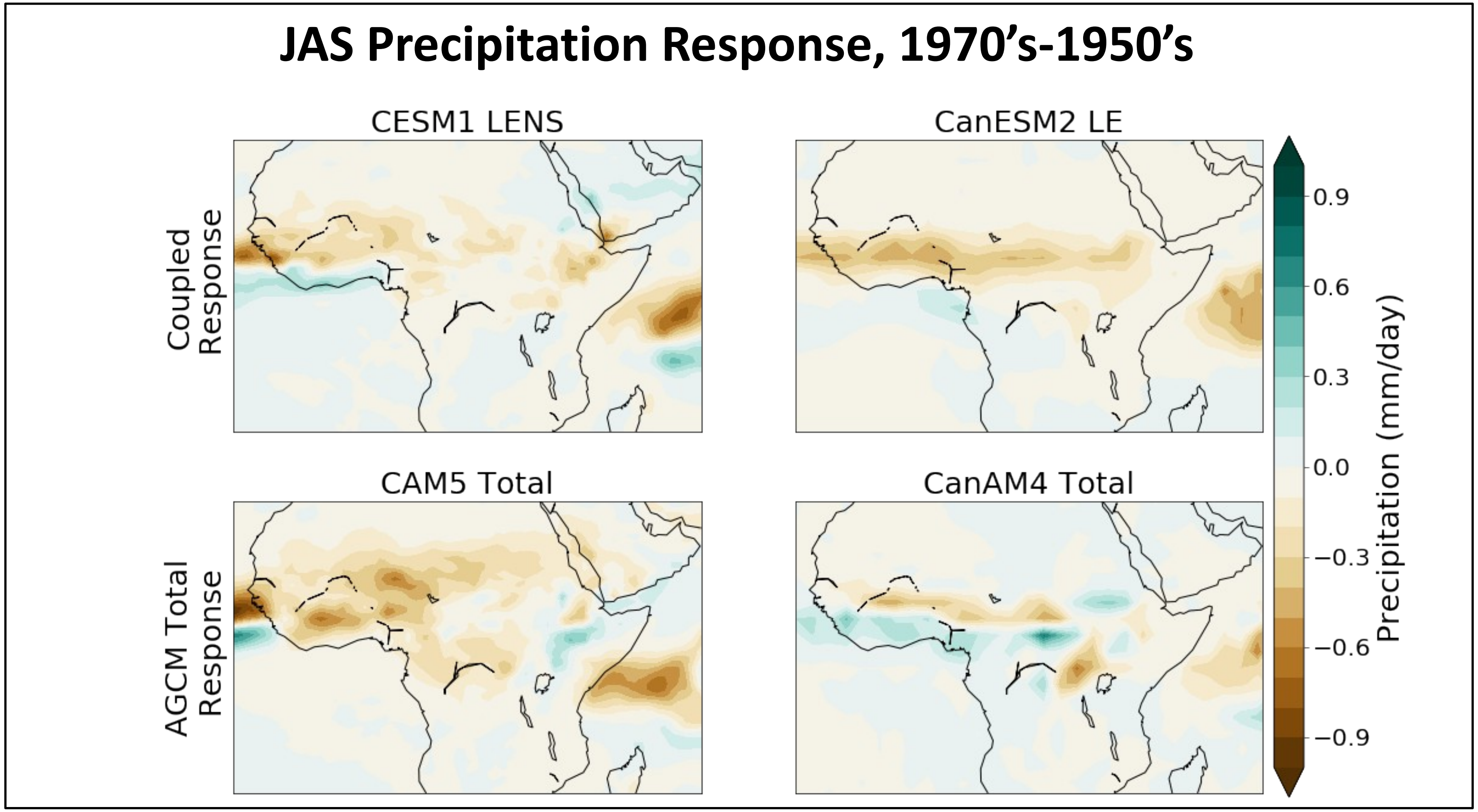


Fast Forcing: Aerosol Responses

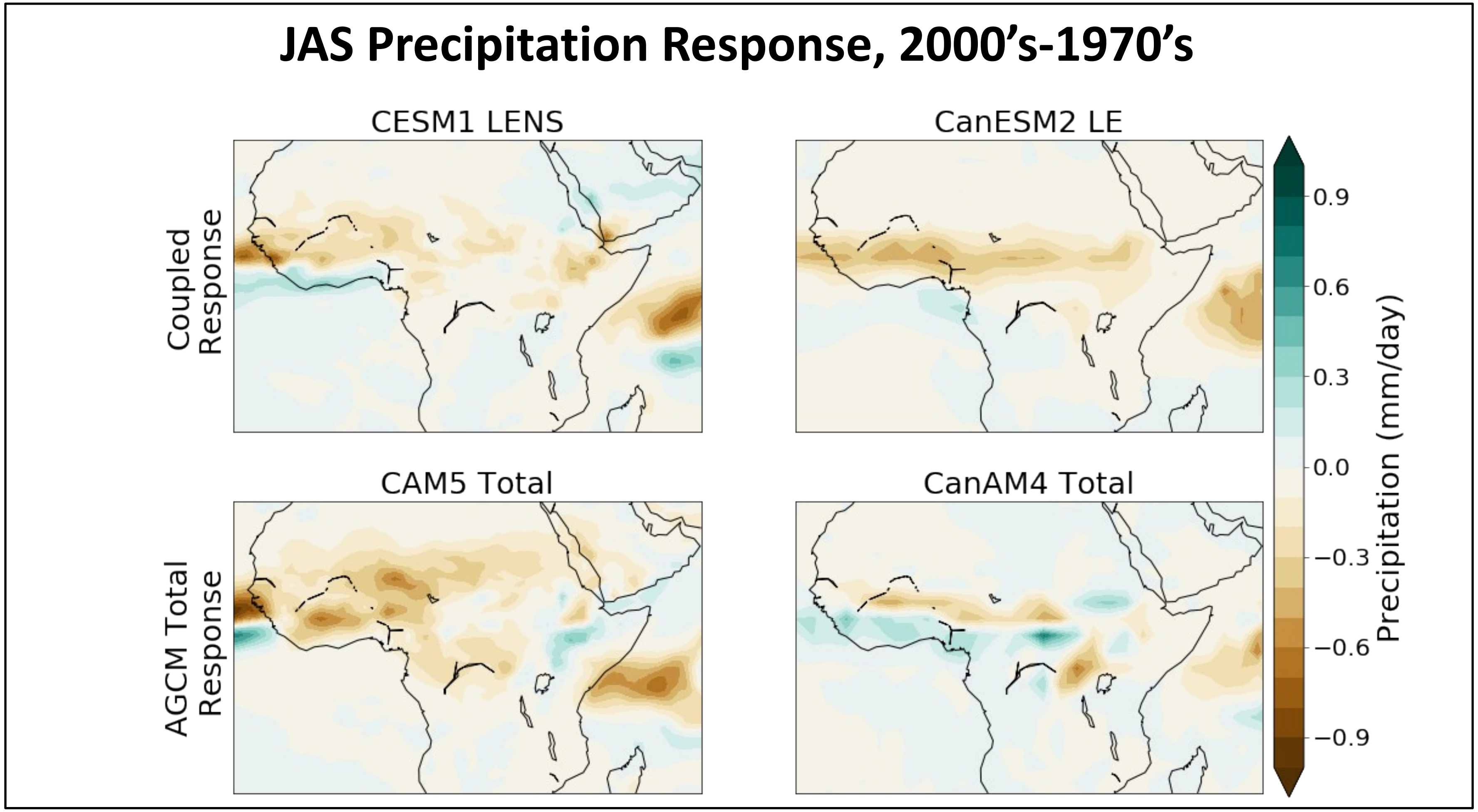


- Note complicated structure of late 20th century aerosol forcing.
- Radiative/cloud responses are stronger in CESM1 (not shown).

How Do Our AGCM Experiments Capture the Coupled Model Response?

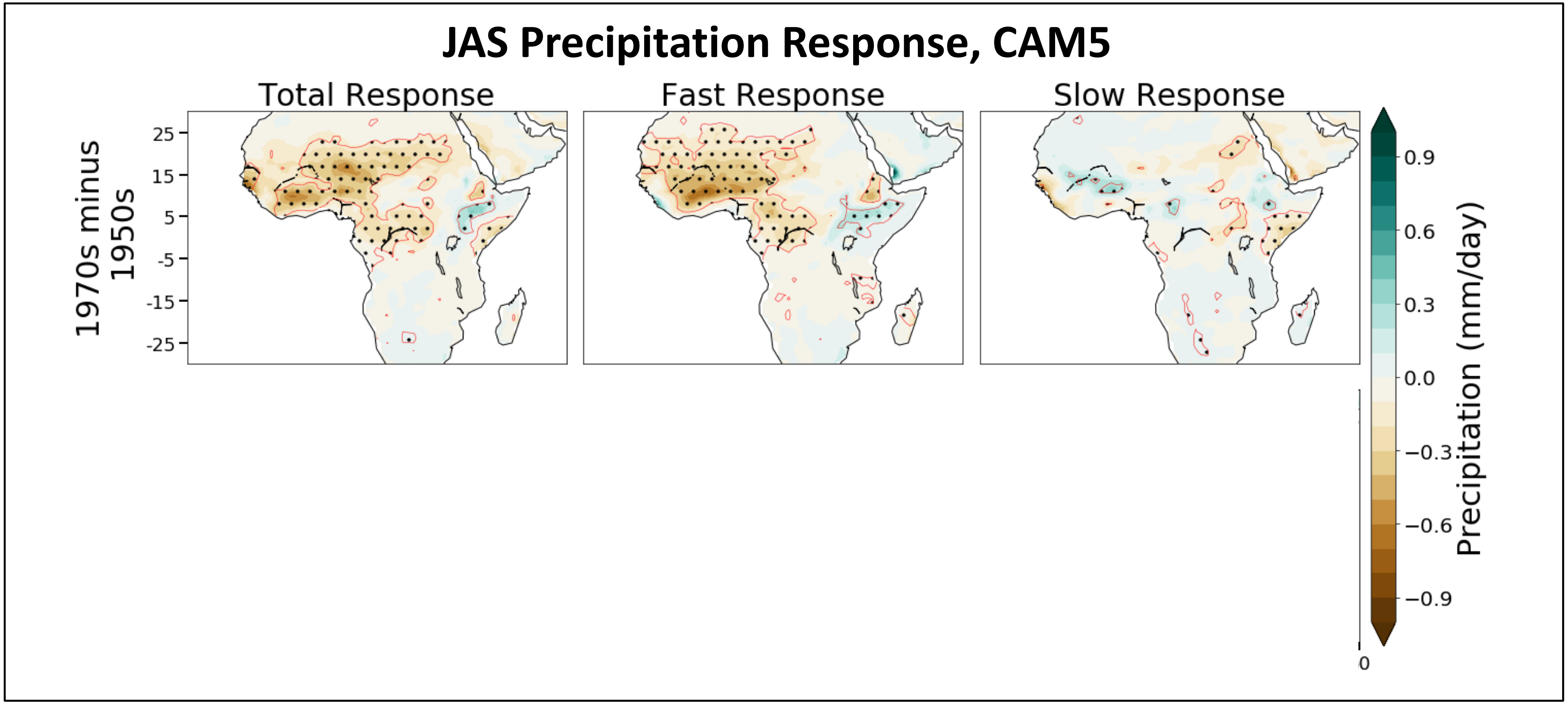


How Do Our AGCM Experiments Capture the Coupled Model Response?

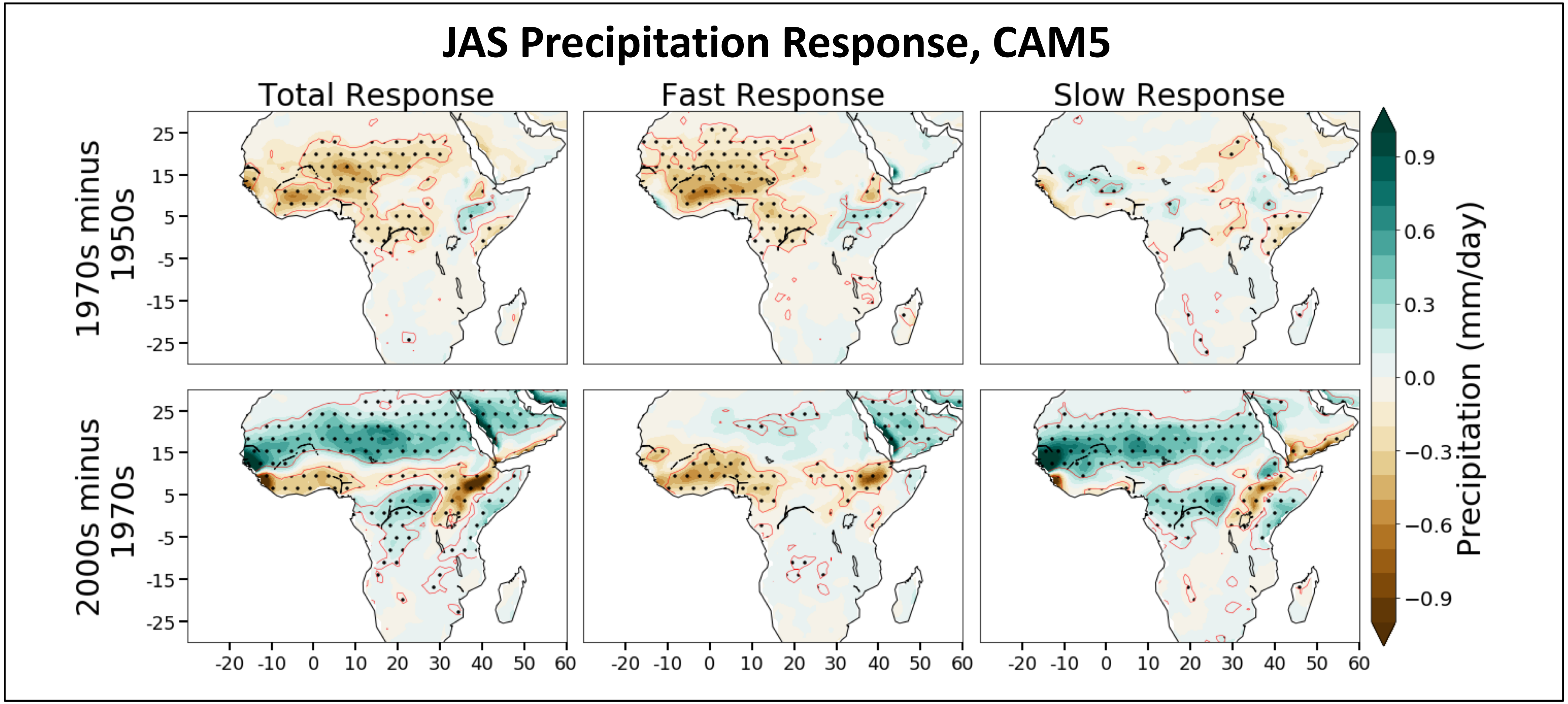


- The precipitation response patterns are broadly consistent across the globe (extra slides).
- Regional details differ, of course: AMIP versus coupled, time slice versus transient.

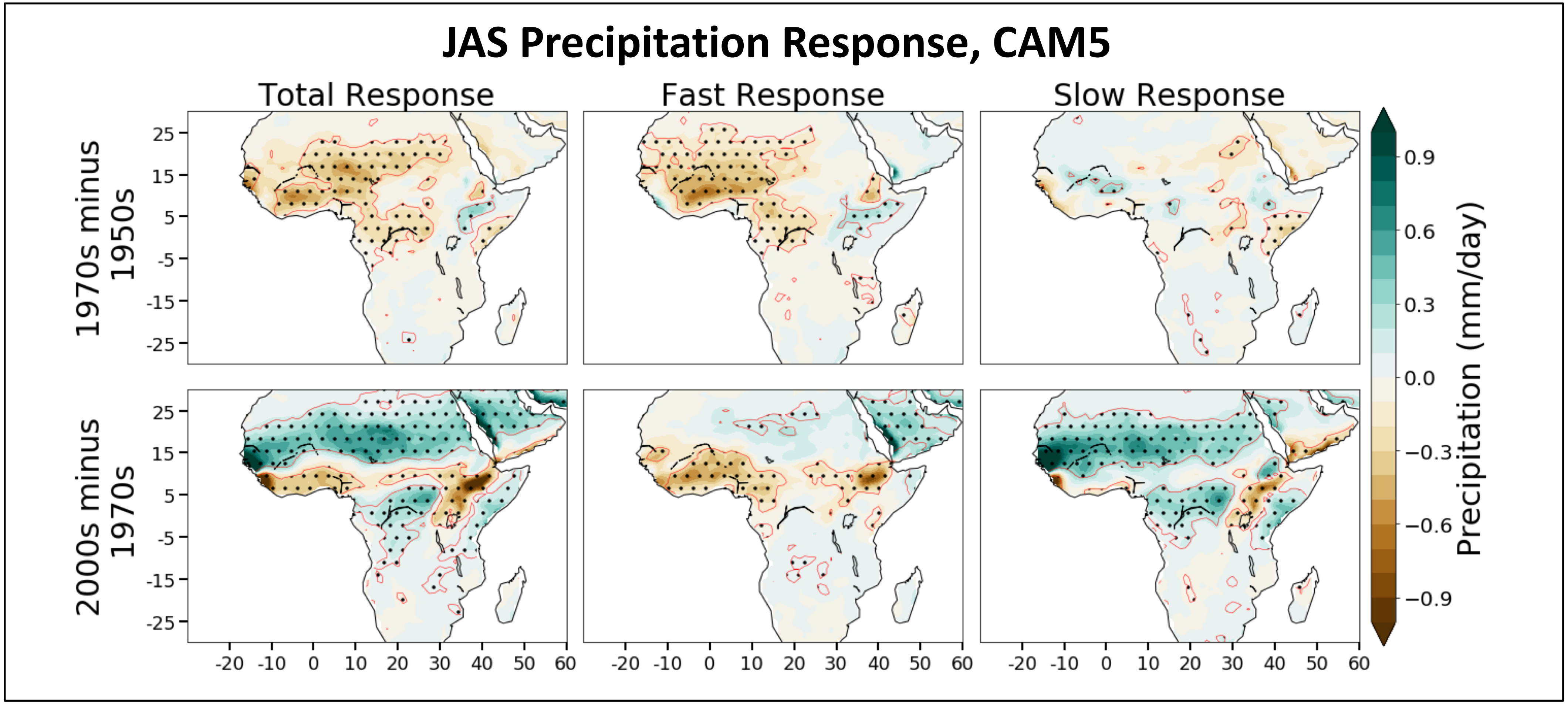
CAM5 Results: Slow Driving Controls Decadal Variability



CAM5 Results: Slow Driving Controls Decadal Variability

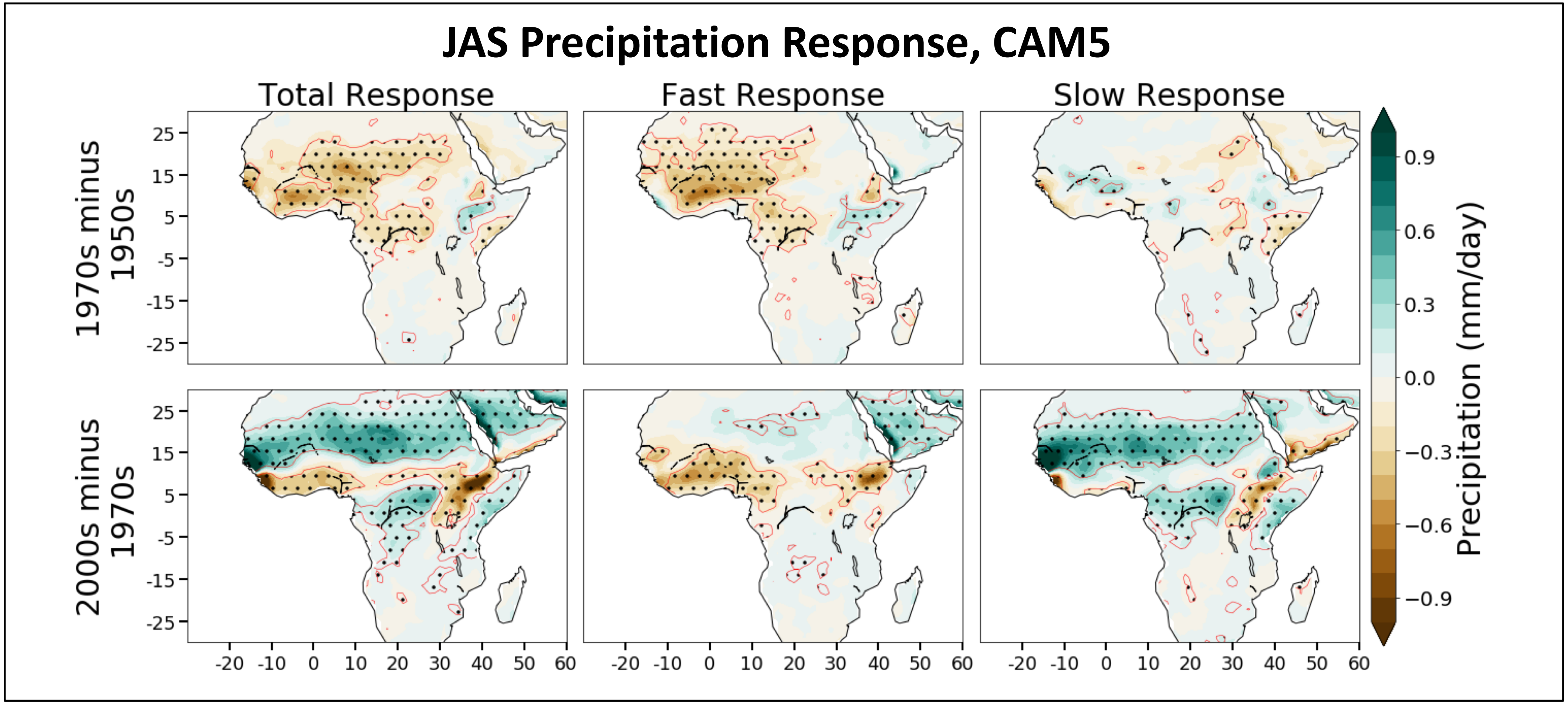


CAM5 Results: Slow Driving Controls Decadal Variability



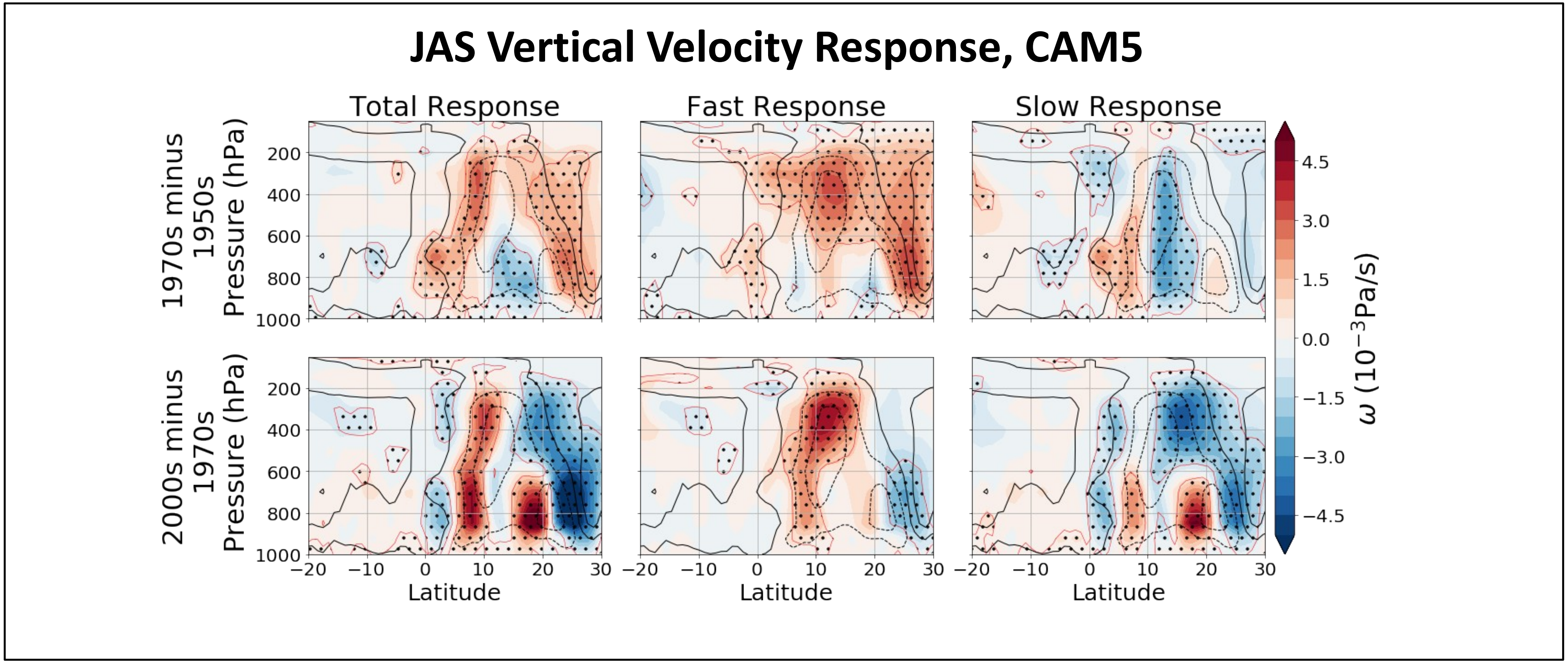
- Fast aerosol driving dries throughout the period.
- SST driving moistens starting in 1970’s.

CAM5 Results: Slow Driving Controls Decadal Variability

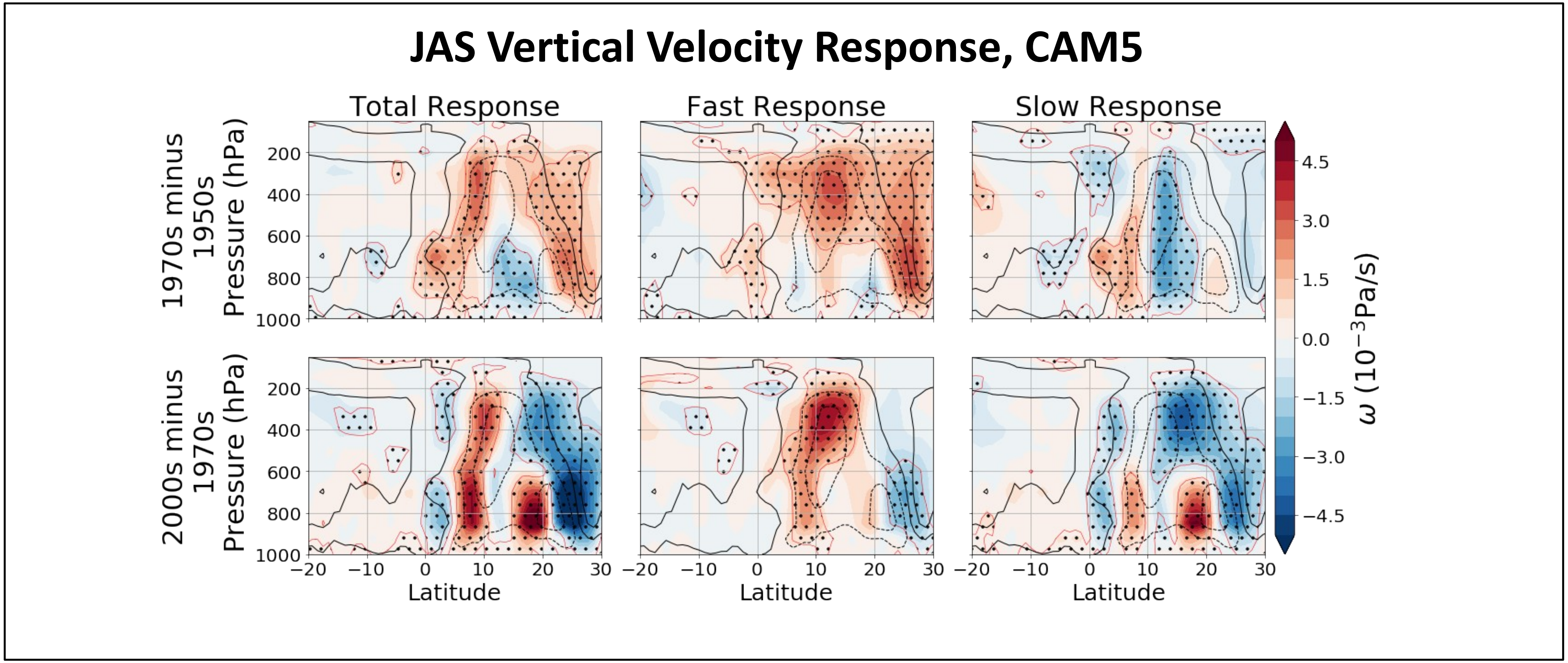


- Fast aerosol driving dries throughout the period.
- SST driving moistens starting in 1970’s.
- 1970’s to 2000’s northward shift over West Africa combines aerosol drying and SST moistening.

CAM5 Results: Slow Driving Controls Decadal Variability

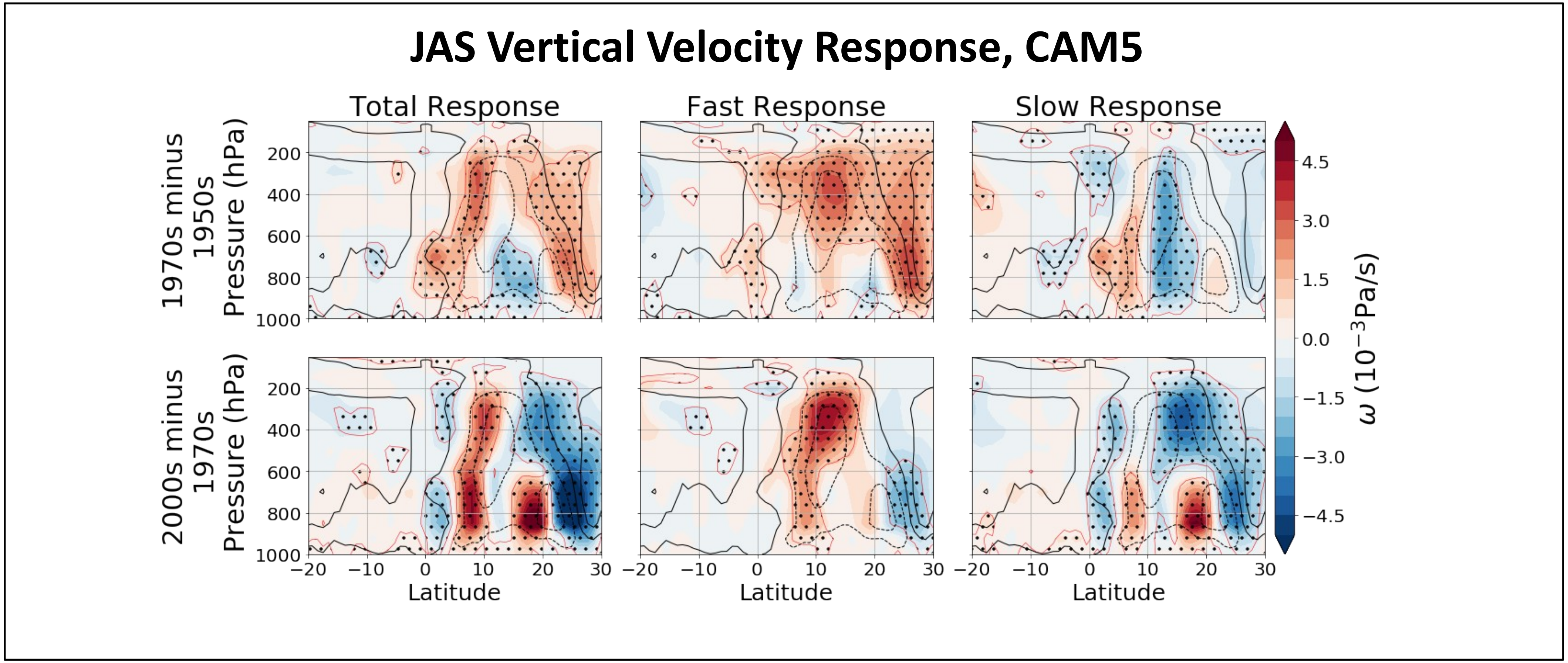


CAM5 Results: Slow Driving Controls Decadal Variability



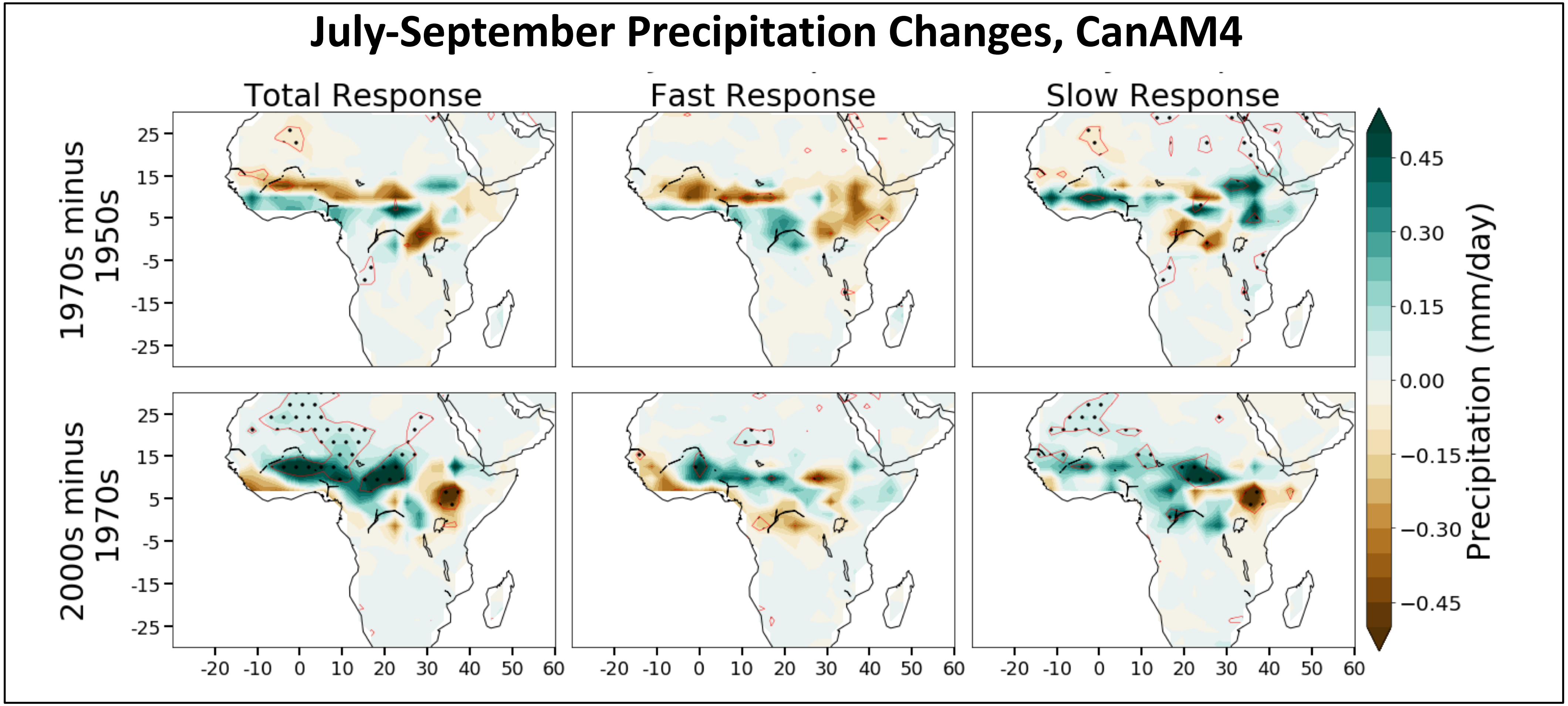
- Aerosol drying associated with enhanced subsidence in both periods.

CAM5 Results: Slow Driving Controls Decadal Variability

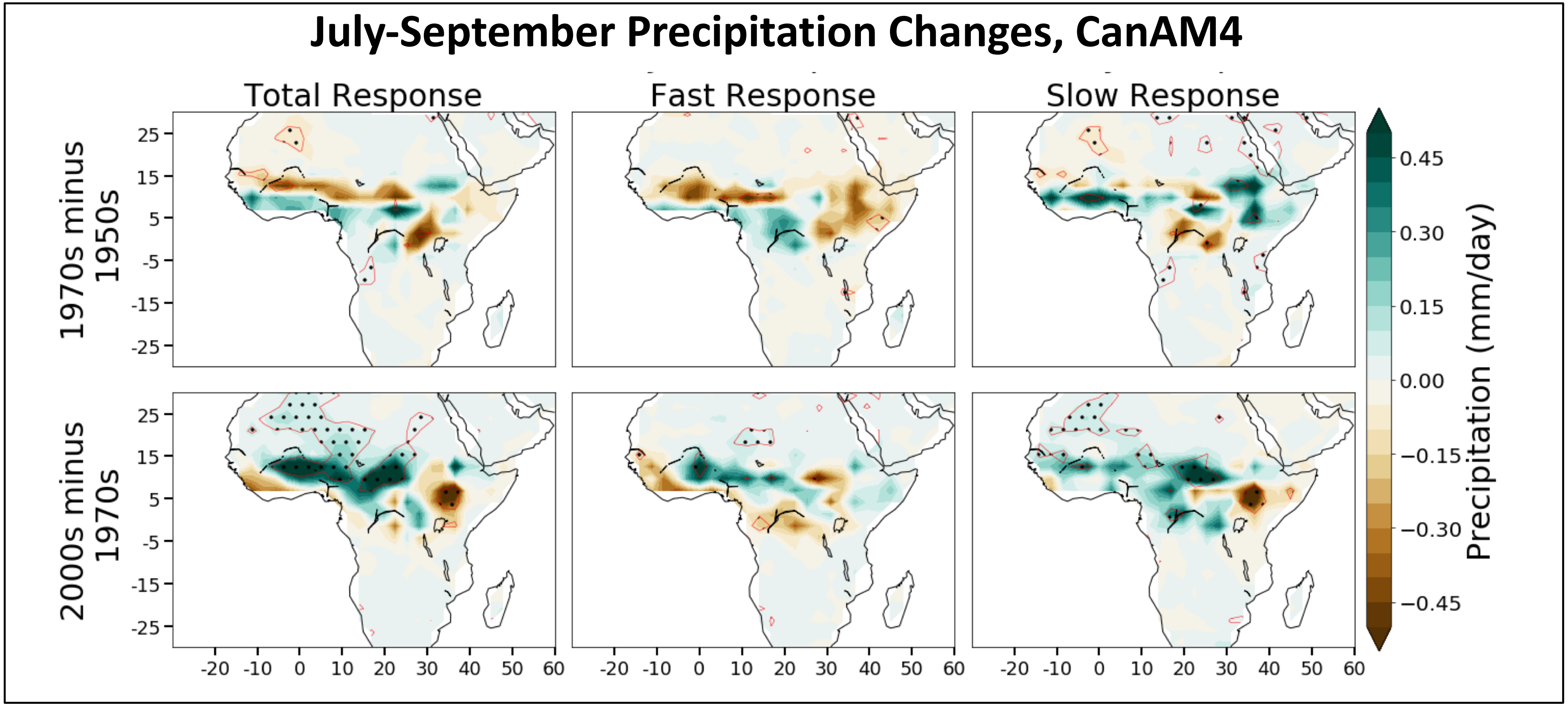


- Aerosol drying associated with enhanced subsidence in both periods.
- SST moistening associated with enhanced upwelling in both periods

CanAM4 Results: Signal Is Weak and Controlled by Fast Driving

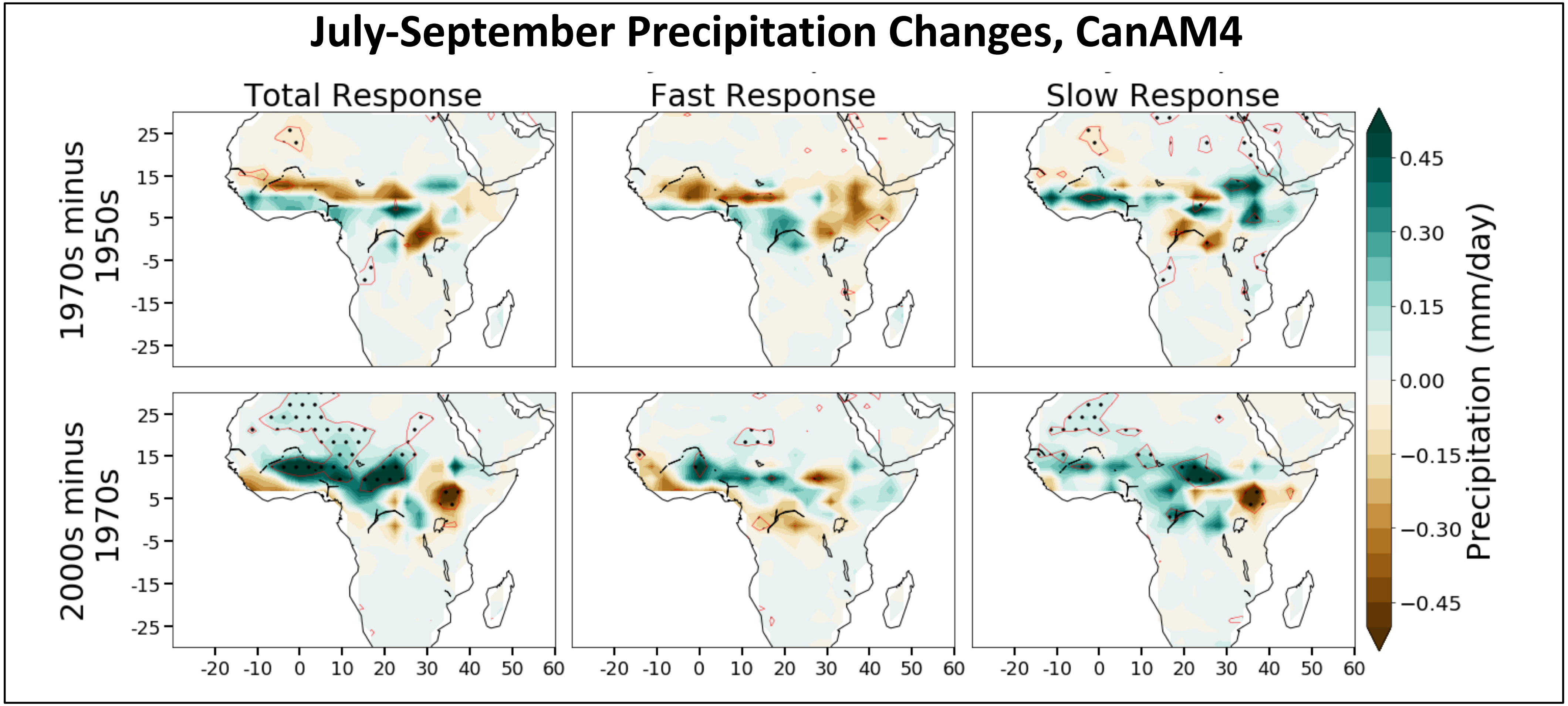


CanAM4 Results: Signal Is Weak and Controlled by Fast Driving



- Signals are highly structured and marginally significant
- Aerosol driving changes through two periods.

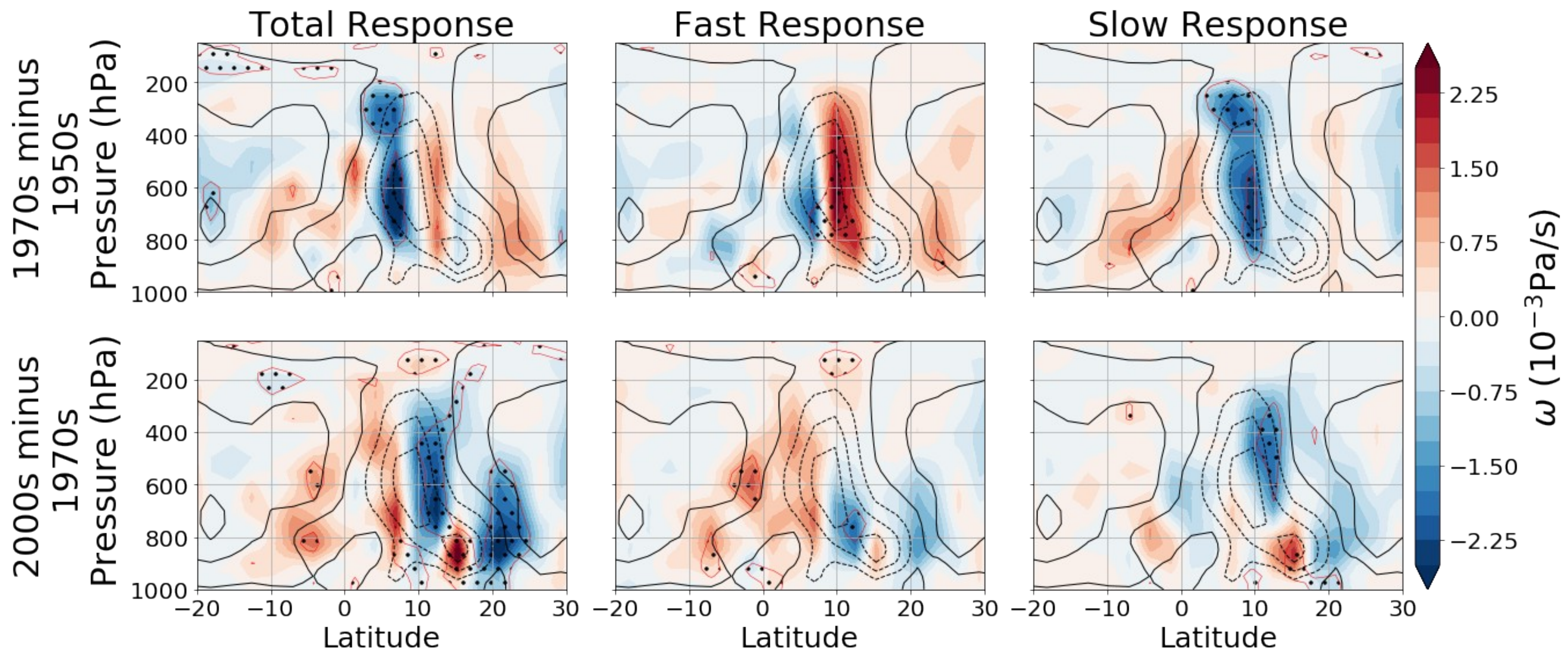
CanAM4 Results: Signal Is Weak and Controlled by Fast Driving



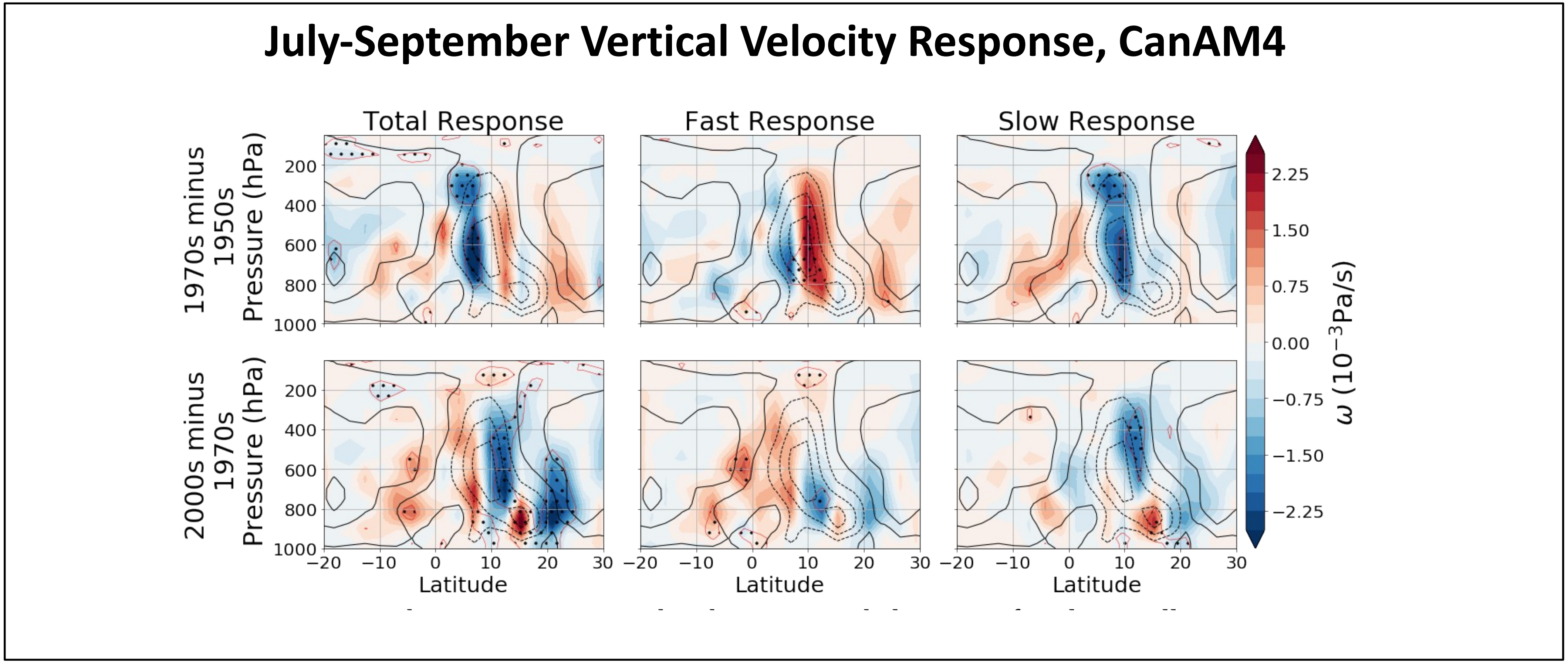
- Signals are highly structured and marginally significant
- Aerosol driving changes through two periods.
- Slow driving more consistent through two periods.

CanAM4 Results: Fast Driving of (Weak) Decadal Variabiltiy

July-September Vertical Velocity Response, CanAM4

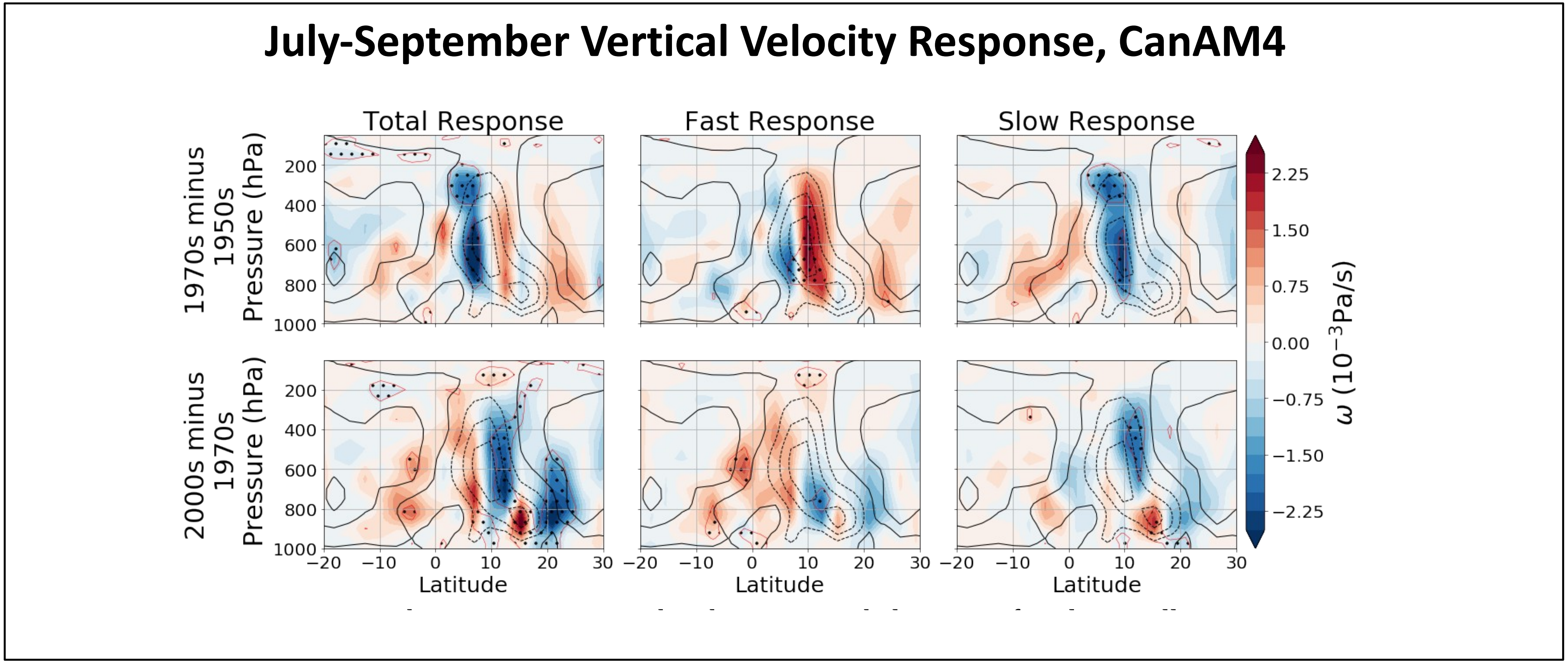


CanAM4 Results: Fast Driving of (Weak) Decadal Variabiltiy



- Overall, sign of response is similar in CAM5 and CanAM4.

CanAM4 Results: Fast Driving of (Weak) Decadal Variabiltiy



- Overall, sign of response is similar in CAM5 and CanAM4.
- Balance of slow and fast responses that determines the overall climatological impact.

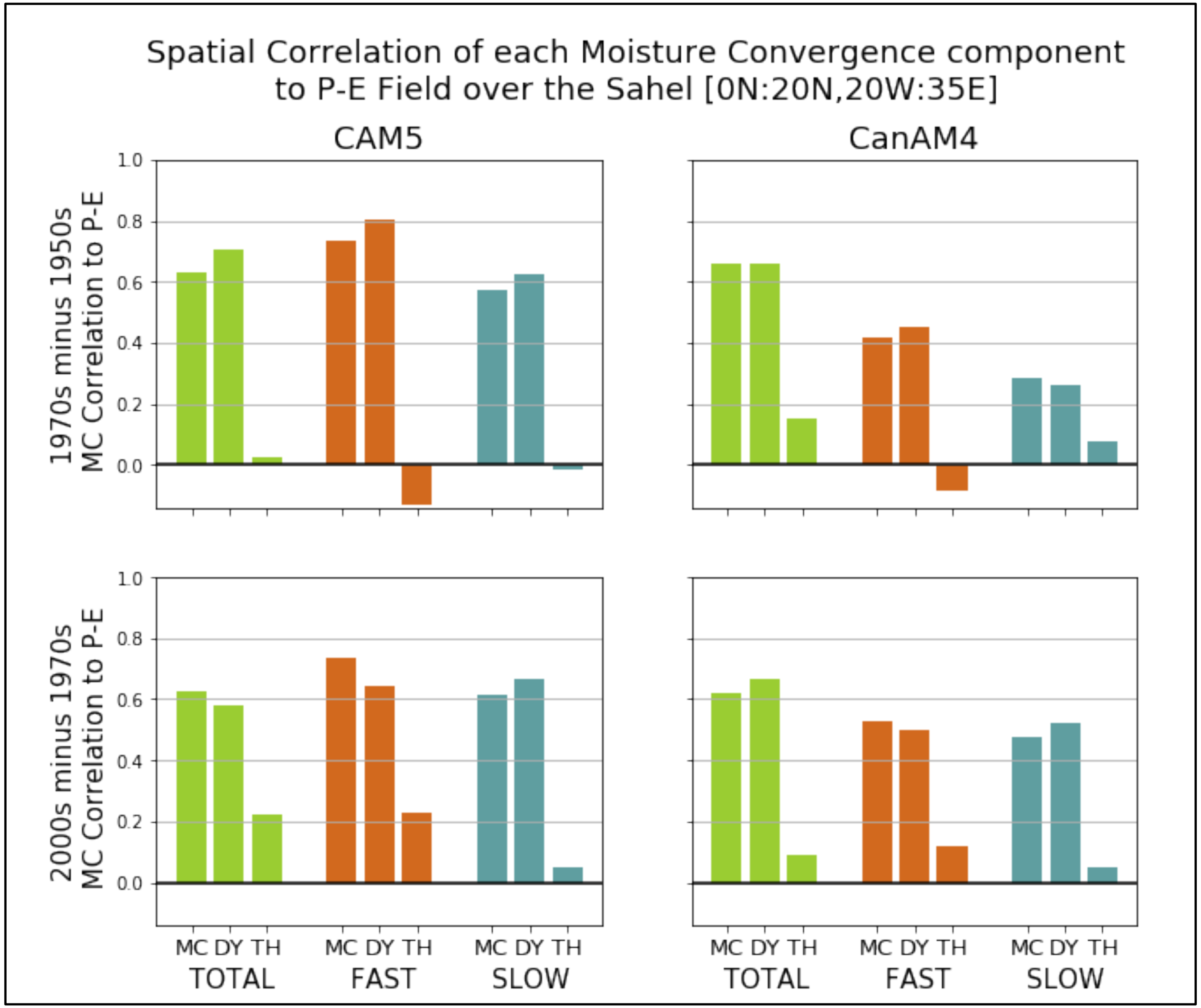
Dominance of the Dynamical Response

The proximity of the bars to unity indicates how well moist convergence from monthly data explain changes to P-E.

For all experiments, it is the dynamical contribution of the response that is most important.

Altered monsoonal circulations are the main drivers of the different responses, as opposed to thermodynamic changes.

To explore: connection to 'tug-of-war' in monsoonal circulation between slow and fast responses for greenhouse warming (Shaw and Voigt 2015).



Key Points

Key Points

- Coupled ocean-atmosphere large ensembles isolate global SST and sea ice response to aerosol forcing.
- These simulations confirm that West African precipitation response is dominated by aerosol forcing.
- *Fast* (aerosol-driven) drying is in a tug-of-war with *slow* (ocean mediated) moistening.
- Fast and slow responses are fairly robust and reflect circulation changes, but their timing and relative contributions are model dependent.

Discussion

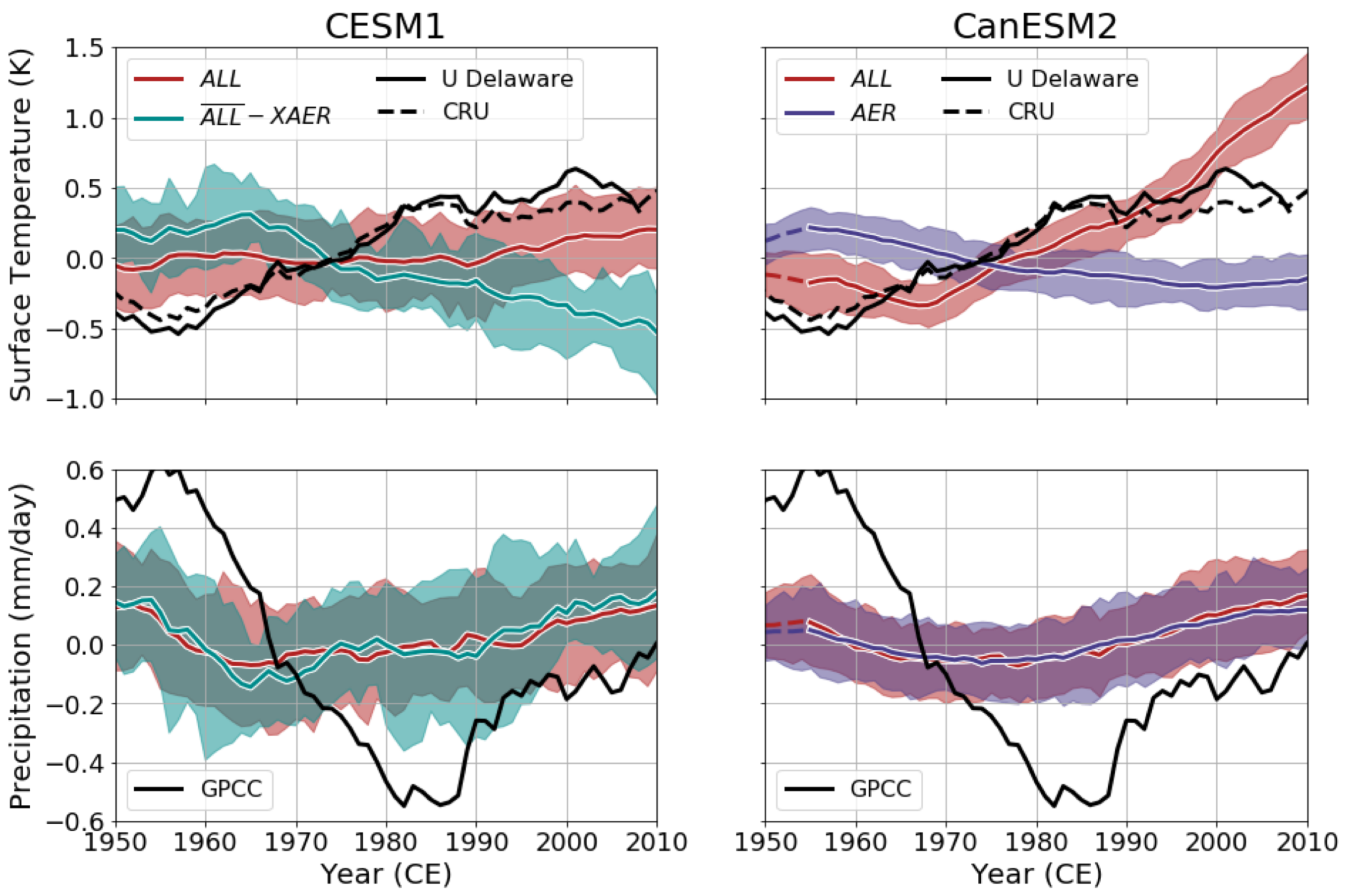
Discussion

- Over the 1970’s-2000’s period, CanAM4 fast response is weak and is not a simple drying, but is more structured.
- There are distinctive roles for transport of pollutants and for black carbon forcing that need to be sorted out in these two models.
- A tug-of-war effect is also seen in East Asian monsoon response to greenhouse gas forcing. How are these results related?
- We have diagnosed nonlinear interactions between greenhouse forcing and aerosol forcing (extra slides). How should this be dealt with?

Extra Slides

Aerosol Forcing Drives Precipitation Changes in West Africa

July-August-September Sahel Surface Temperature and Precipitation Anomalies w.r.t. 1950-1909

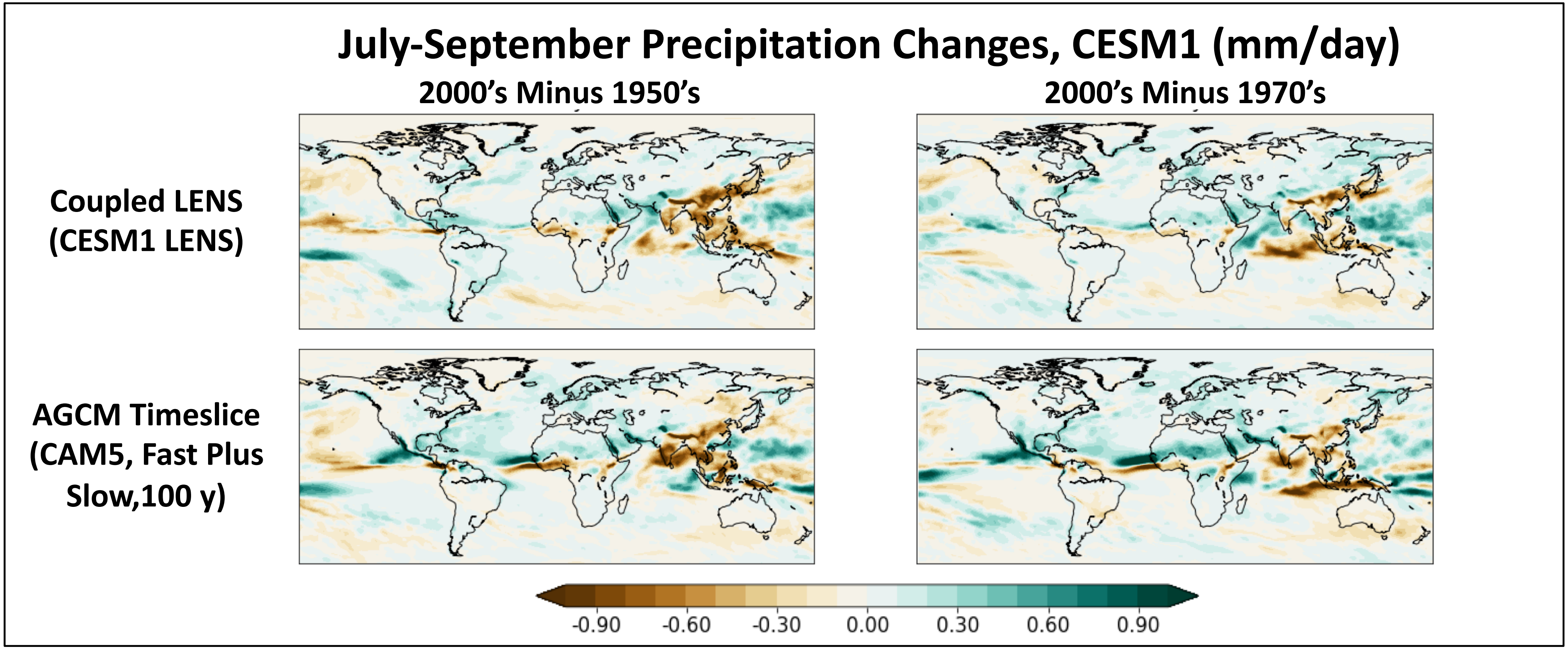


10 year running mean

Averaging box: land areas for 10N-20N, 20W-35E

5-95% range shown for models.

Are AGCMs a Good Testbed for Understanding Precipitation Responses?

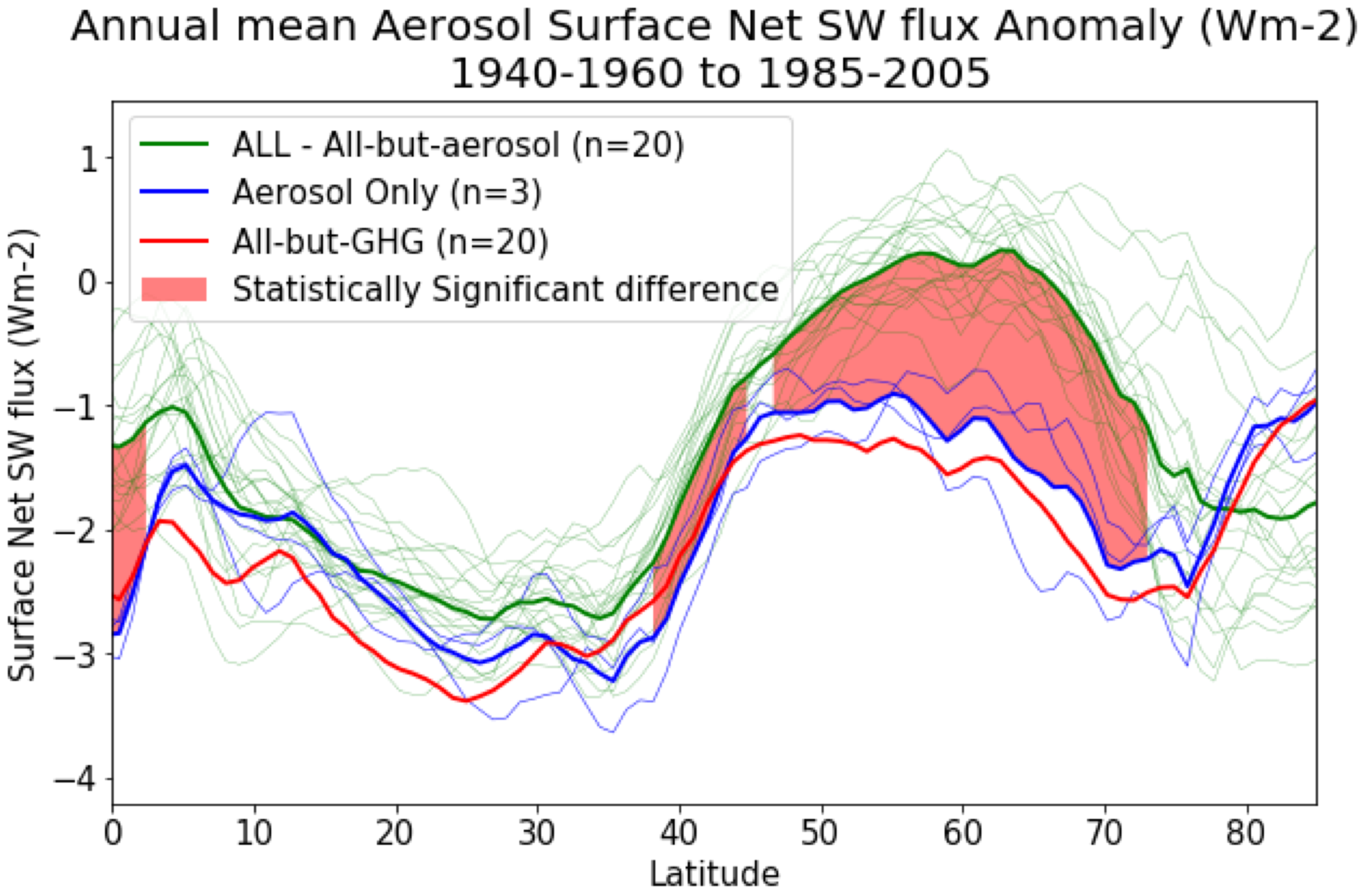


- AGCM experiments captures global pattern of precipitation changes over land from coupled models
- Over tropical ocean and coastal regions, some AGCM responses appear unrealistically amplified.

Nonlinear Interactions between Greenhouse and Aerosol Forcing?

- CESM1 20-member large ensemble uses All-but-Aerosol forcing.
- CESM1 also has a 3-member Aerosol-Only ensemble (with differences in tropical emissions).
- Aerosol-Only response in SW is weaker than Aerosol-Only.
- Note that CanESM2 large ensemble uses Aerosol-Only.

• If greenhouse warming response significantly modulates aerosol forcing, a cleaner coupled model intercomparison might be required.



Coupled and AGCM Experiments

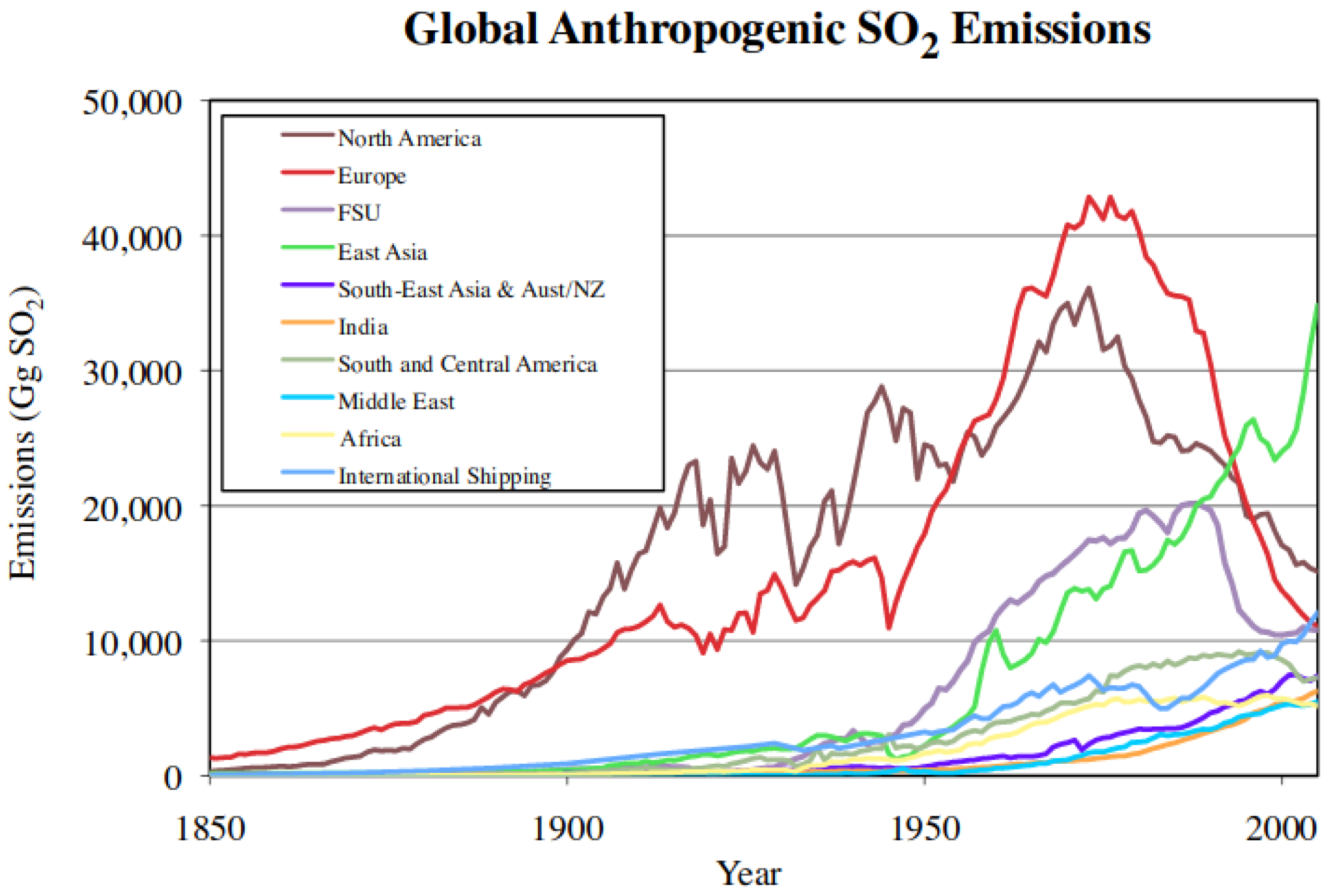
AGCM

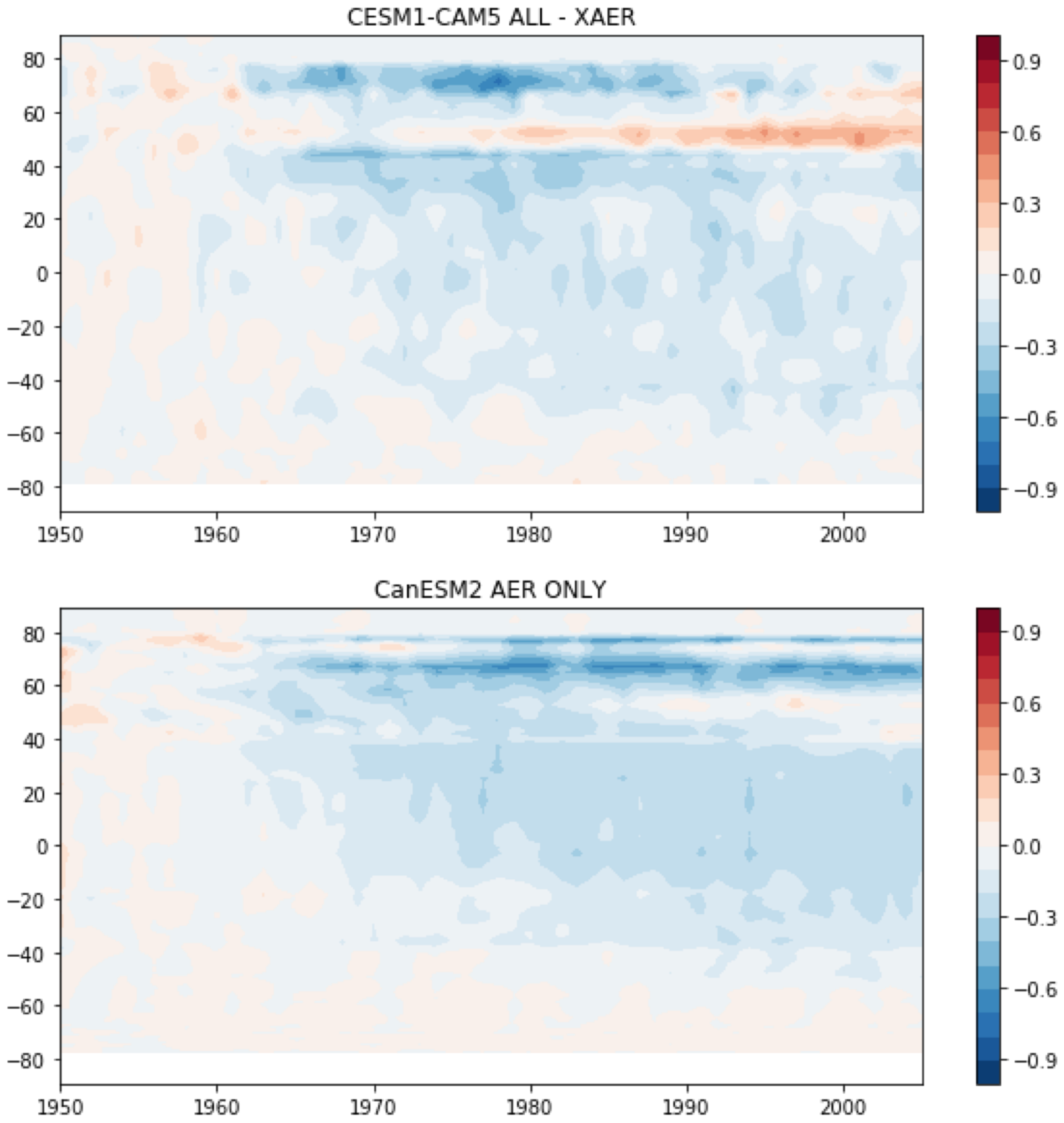
Model	Simulation Nickname	Aerosol Emissions	SST/SI	Simulation Years
CAM5	$S_{CTRL}A_{2000}$	2000-2009	HadISST 2000's	>100
CAM5	$S_{CTRL}A_{1950}$	1950-1959	HadISST 2000's	>100
CAM5	$S_{PERT1950}A_{2000}$	2000-2009	HadISST 2000's minus (2000's – 1950's) CESM1 Aerosol Anomaly	>100
CAM5	$S_{PERT1950}A_{1950}$	1950-1959	HadISST 2000's minus (2000's – 1950's) CESM1 Aerosol Anomaly	>100
CAM5	$S_{CTRL}A_{1970}$	1970-1979	HadISST 2000's	>100
CAM5	$S_{PERT1970}A_{1970}$	1970-1979	HadISST 2000's minus (2000's – 1970's) CESM1 Aerosol Anomaly	>100
CanAM4	$S_{CTRL}A_{2000}$	2000-2009	HadISST 2000's	>100
CanAM4	$S_{CTRL}A_{1950}$	1950-1959	HadISST 2000's	>100
CanAM4	$S_{PERT1950}A_{2000}$	2000-2009	HadISST 2000's minus (2000's – 1950's) CanESM2 Aerosol Anomaly	>100
CanAM4	$S_{PERT1950}A_{1950}$	1950-1959	HadISST 2000's minus (2000's – 1950's) CanESM2 Aerosol Anomaly	>100
CanAM4	$S_{CTRL}A_{1970}$	1970-1979	HadISST 2000's	In Progress
CanAM4	$S_{PERT1970}A_{1970}$	1970-1979	HadISST 2000's minus (2000's – 1970's) CanESM2 Aerosol Anomaly	In Progress

Coupled

Model	Simulation Name	Anthropogenic Aerosols	GHG	Other	Ens. Size	Years
CESM1	Historical (ALL)	Historical	Historical	Historical	35	1920-2080
CESM1	Historical All-but-Aerosol (XAER)	Pre-industrial	Historical	Historical	20	1920-2080
CESM1	Historical All-but-GHG (XGHG)	Historical	Pre-industrial	Historical	20	1920-2080
CESM1	Historical Aerosol Only (AER)	Historical	Pre-industrial	Pre-industrial	3	1850-2005
CanESM2	Historical	Historical	Historical	Historical	50	1950-2020
CanESM2	Historical Aerosol Only	Historical	Pre-industrial	Pre-industrial	50	1950-2020

Decadal Variations of Anthropogenic Aerosol Forcing




CESM1-CAM5 ALL - XAER
80
60
40
20
0
−20
−40
−60
−80
1950
1960
1970
1980
1990
2000
0.9
0.6
0.3
0.0
−0.3
−0.6
−0.9
CanESM2 AER ONLY
80
60
40
20
0
−20
−40
−60
−80
1950
1960
1970
1980
1990
2000
0.9
0.6
0.3
0.0
−0.3
−0.6
−0.9

References