Opposing, then complementary effects of Aerosol forced Atlantic and Pacific SST anomalies in 20th century Sahel precipitation

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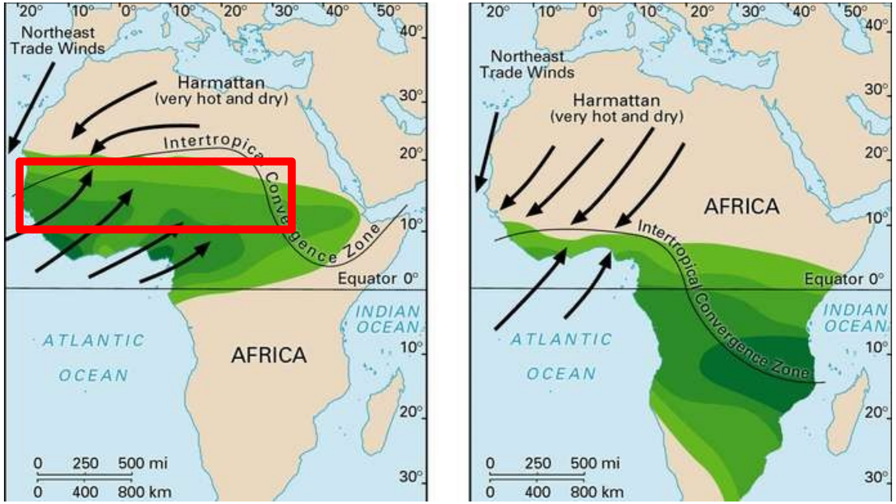
The Sahel in the 20th Century

- The Sahel is an arid region of North Africa
- Most rainfall occurs during the West African Monsoon, peaking in July-August-September (JAS)
- The Sahel experienced significant multidecadal precipitation variability during 20th century



Krishnamurti, T.N. , Smith, Phillip J. and Gentilli, Joseph. "West African monsoon". Encyclopedia Britannica, Invalid Date, https://www.britannica.com/science/West-African-monsoon. Accessed 16 February 2021.

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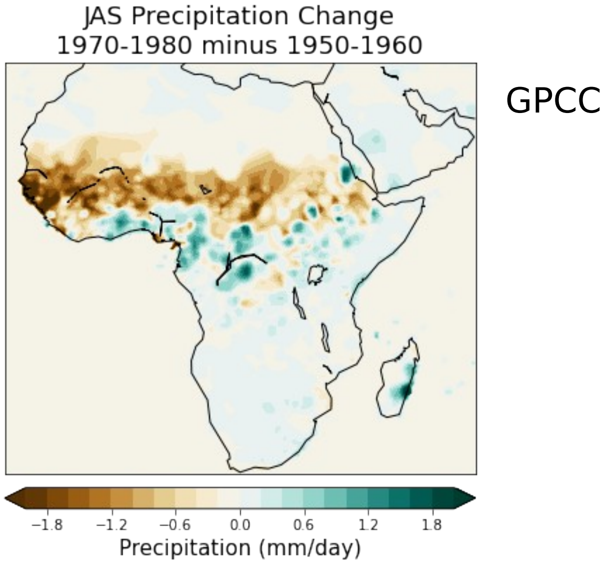
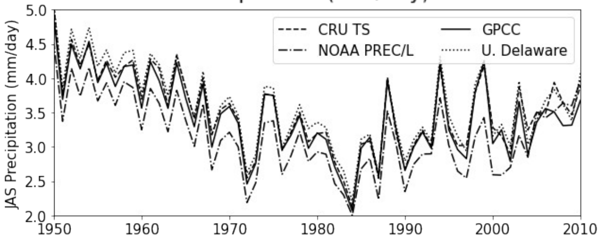
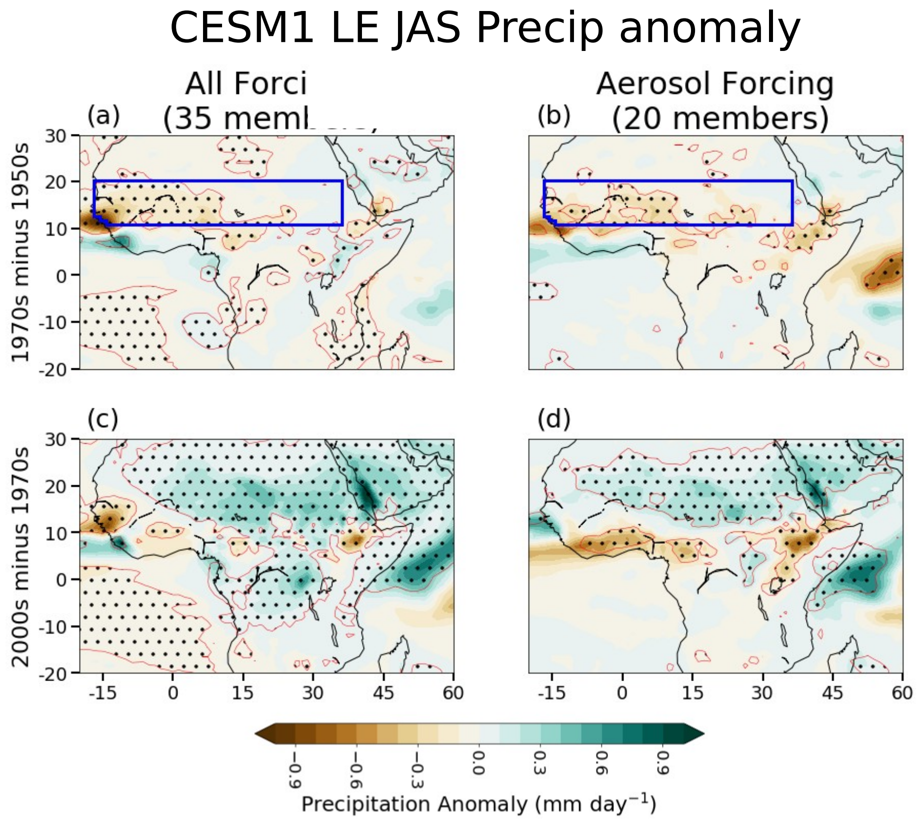




Aerosol Forcing Effect on the Sahel

- Historical aerosol forcing reduces rainfall in the Sahel region of Africa in coupled GCMs.
- This aerosol-forced drying is often interpreted as a response to hemispheric differences in SST cooling. [Ackerley et al., 2011]
- Sulphate forcing can cause drying even without SST change [Dong et al., 2014]



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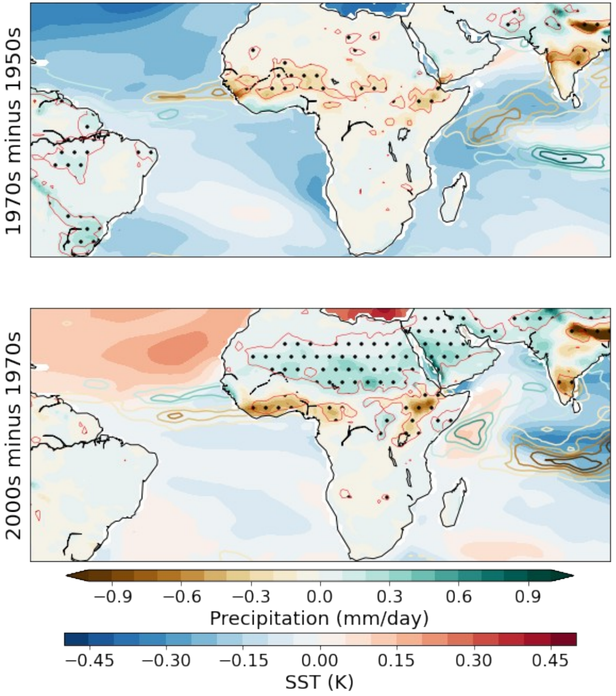
CESM1 ALL – XAER LE
JAS Precip anomaly + SST anomaly



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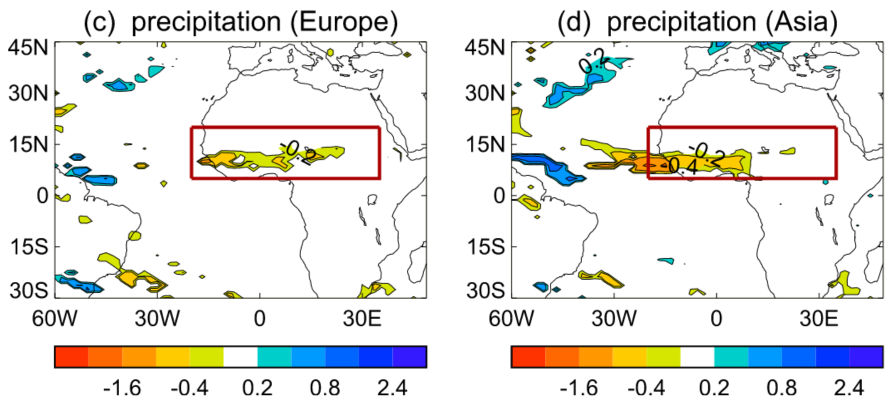


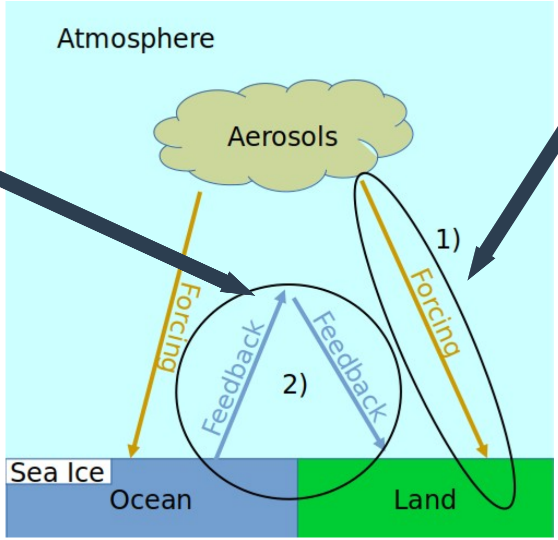
FIG. 4. The spatial patterns of changes in (a),(b) surface air temperature (°C) and (c),(d) precipitation (mm day^{-1}) in response to European and Asian sulfur dioxide emissions in JJA. Only changes that are statistically significant at the 90% confidence level using a two-tailed Student's *t* test are shown. The blue and red boxes highlight North Africa and the Sahel.

Dong et al., 2014

Direct-Atmosphere vs. Ocean-Mediated Response

- We seek to clearly determine the effects of the:

- **Ocean-mediated** (slow) response to aerosol forced SST change without emission changes
  - e.g. effect interhemispheric SST gradient



- **Direct-Atmospheric** (fast) response to the aerosol emission changes without sea surface temperature (SST) change
  - e.g. rapid atmospheric response to European emissions
  - Radiation + cloud interactions, etc

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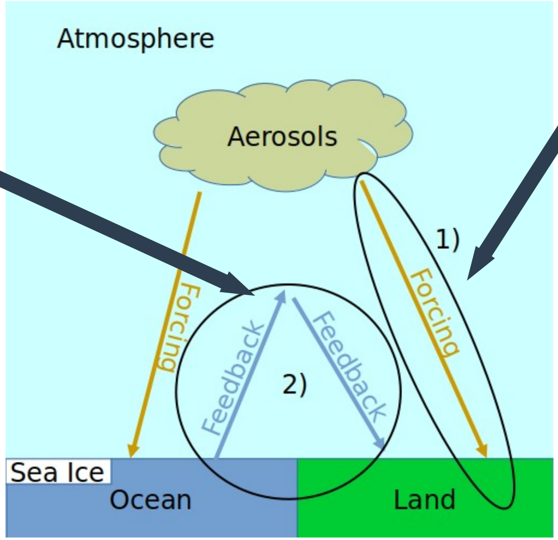

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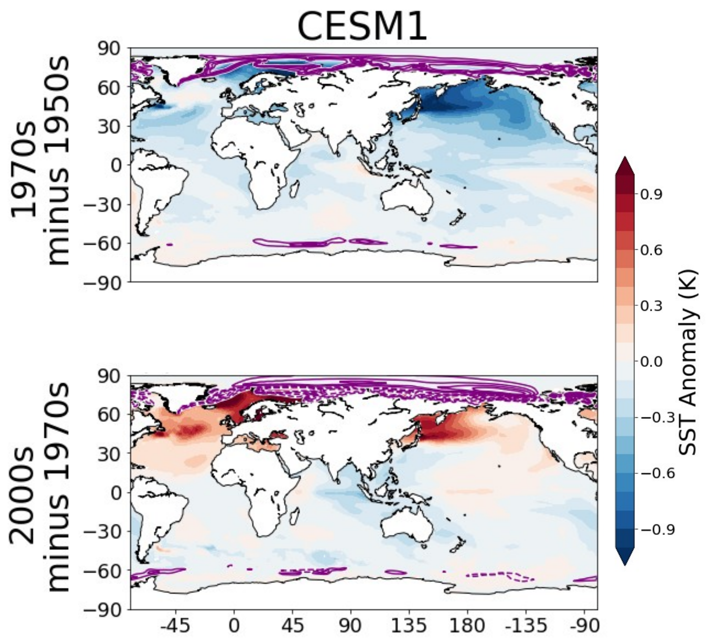
- We conduct **timeslice CAM5** simulations to separately test the roles of these components of the response for the 1950s to 1970s and 1970s to 2000s.

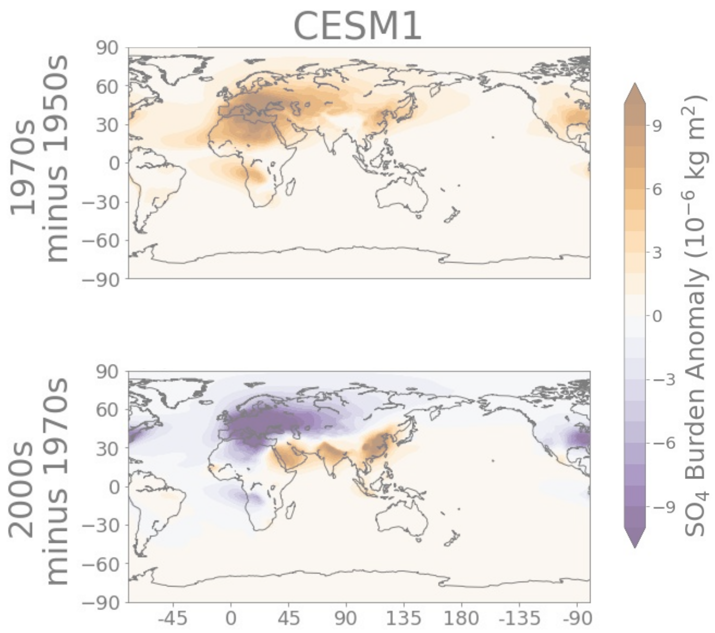
Timeslice Experiment Perturbations

Ocean-Mediated Response:
Aerosol-forced JAS SST anomalies



- SST and SIC anomalies obtained from CESM1 ALL – XAER simulation
- Looking at short period, so LE is important to filter internal variability

Direct-Atmospheric response:
JAS SO4 anomaly



Timeslice Experiment Perturbations

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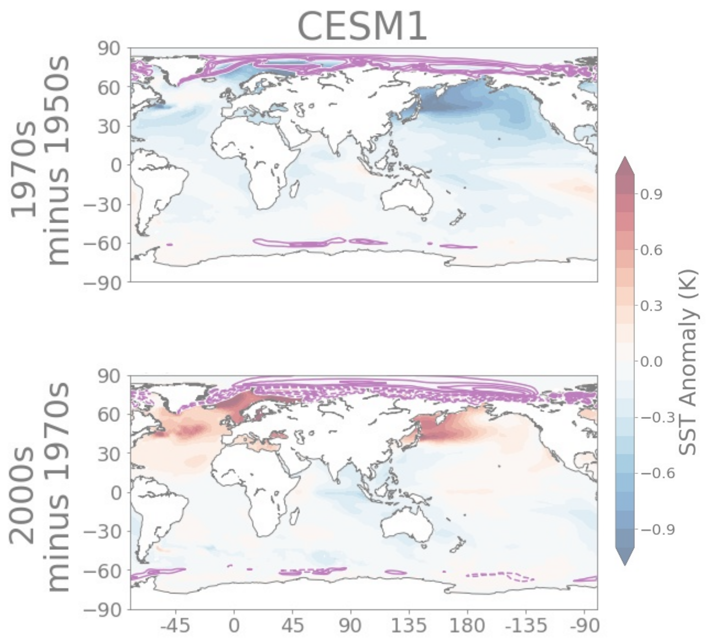
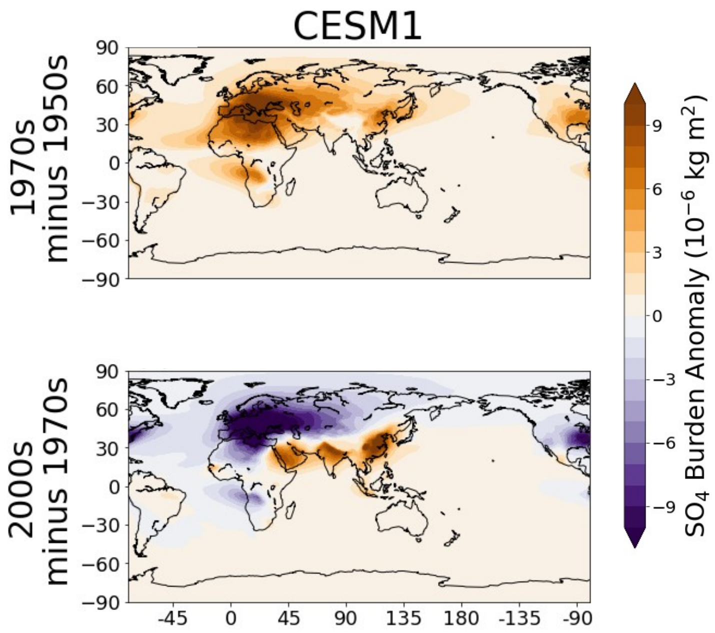
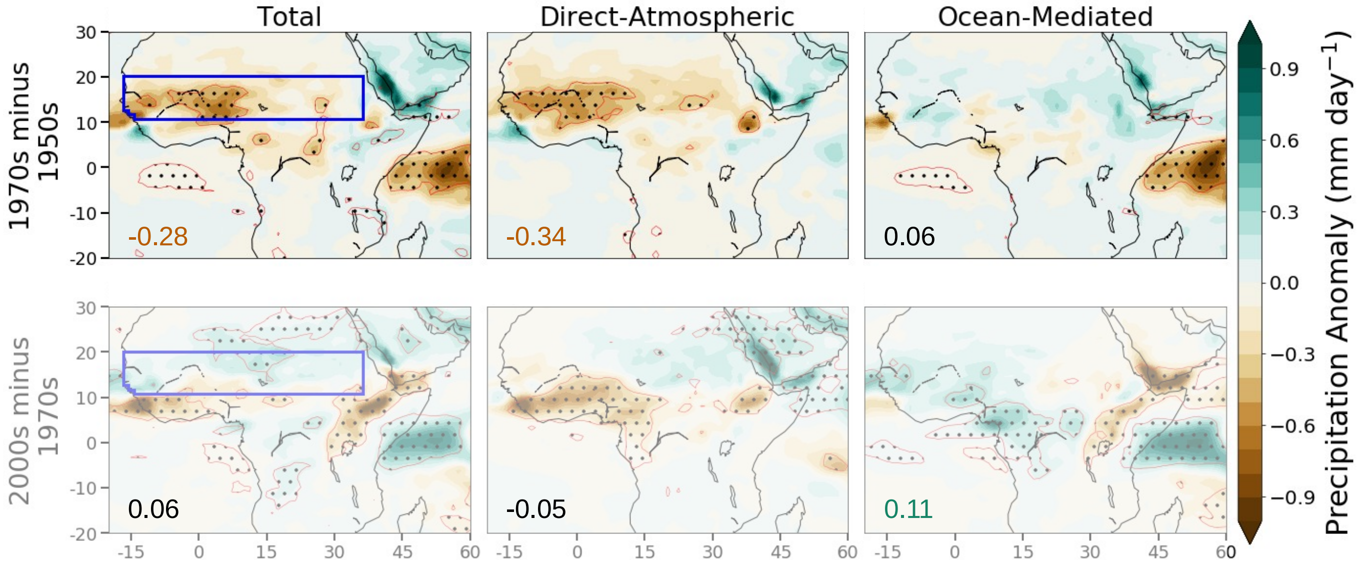


- All anthropogenic aerosol emissions are modified to target decade levels
- Includes sulphate and black carbon
- Omit fire emissions

Direct-Atmospheric response:
JAS SO4 anomaly



Direct Atmospheric Drying and Ocean-Mediated Recovery



- The 1970s-1950s drying is direct-atmospheric, with weak ocean-mediated effect
- The 2000s-1970s recovery is mainly ocean-mediated with some direct-atmospheric contribution

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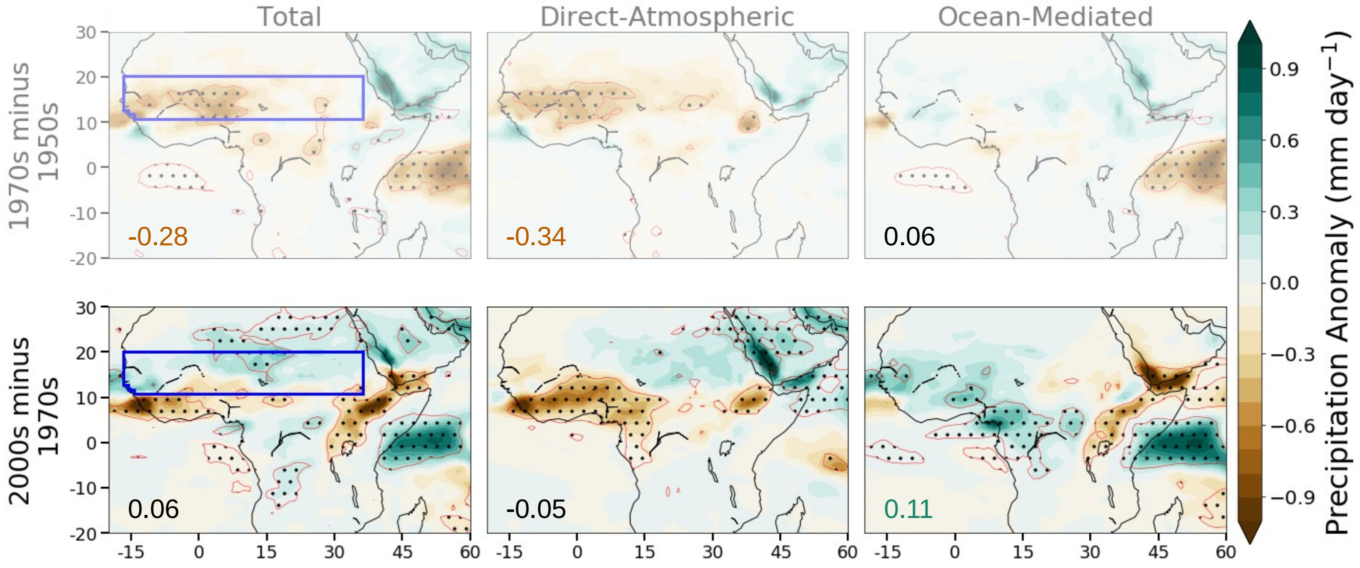

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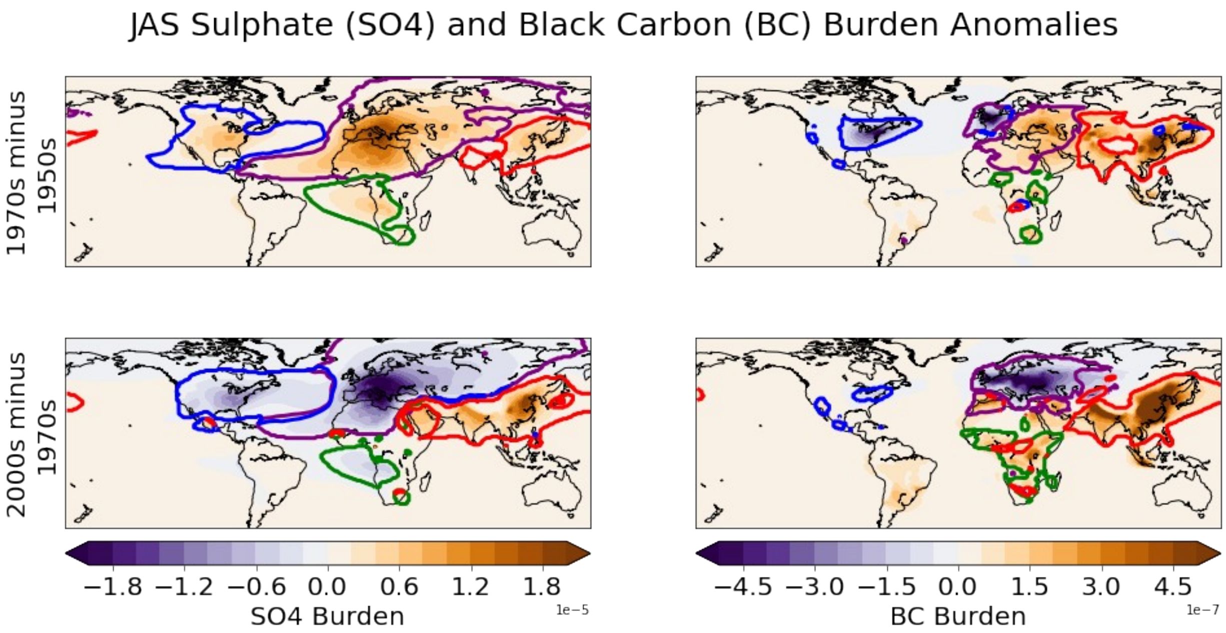
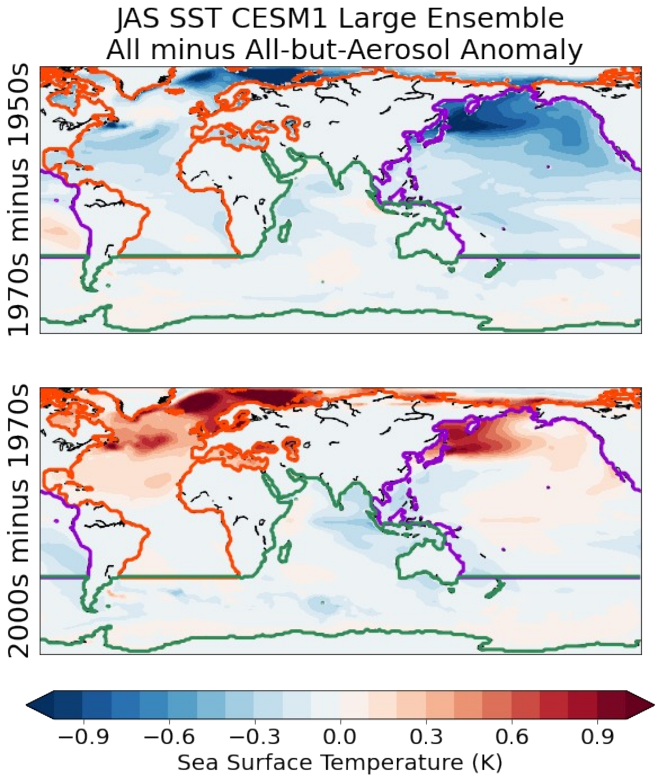
Breakdown of Direct-Atmospheric Response into Emission Regions



- We perform additional timeslice to separately test the effect of aerosol emissions from :
  - North America (Blue)
  - Europe (Purple)
  - Asia (Red)
  - Africa (Green)

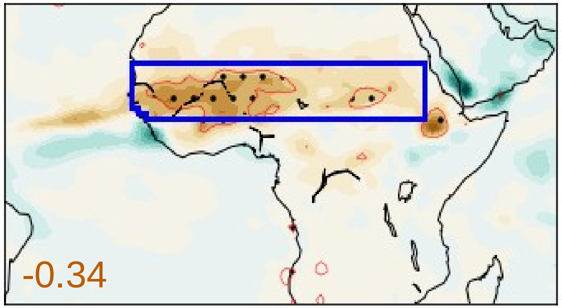
Breakdown of Ocean-Mediated Response into Ocean Basin Anomalies



- We perform additional timeslice to separately test the effect of aerosol-forced SST + SIC anomalies in the:
  - Atlantic + Arctic Oceans (Orange)
  - Indian + Southern Oceans (Green)
  - Pacific Ocean (Purple)
- Focusing on the 1970s-1950s
- Showing results from selected experiments

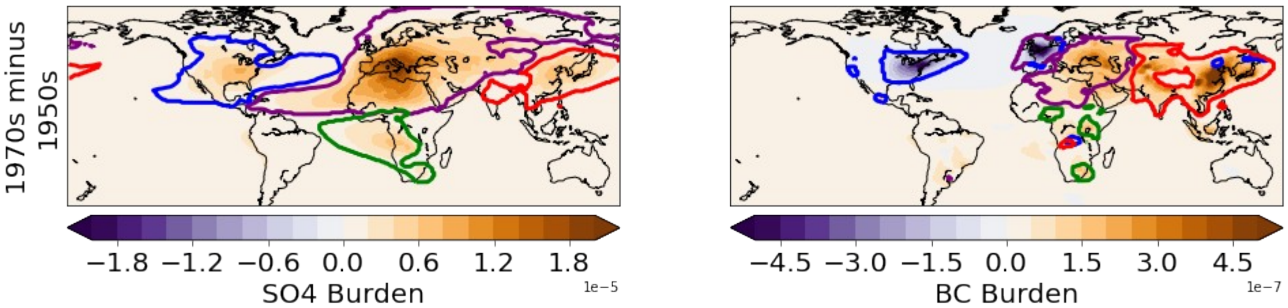
1970s - 1950s Direct Atmospheric Drying

Total Direct-Atmospheric



- 1970s-1950s emissions increase generally, with the strongest SO4 anomalies from Europe.
- BC declines in North America and West Europe, but increases in the rest of the world

JAS Sulphate (SO4) and Black Carbon (BC) Burden Anomalies



1970s - 1950s Drying is Due to North American Emissions

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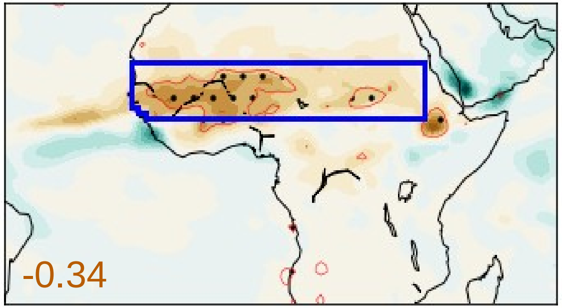
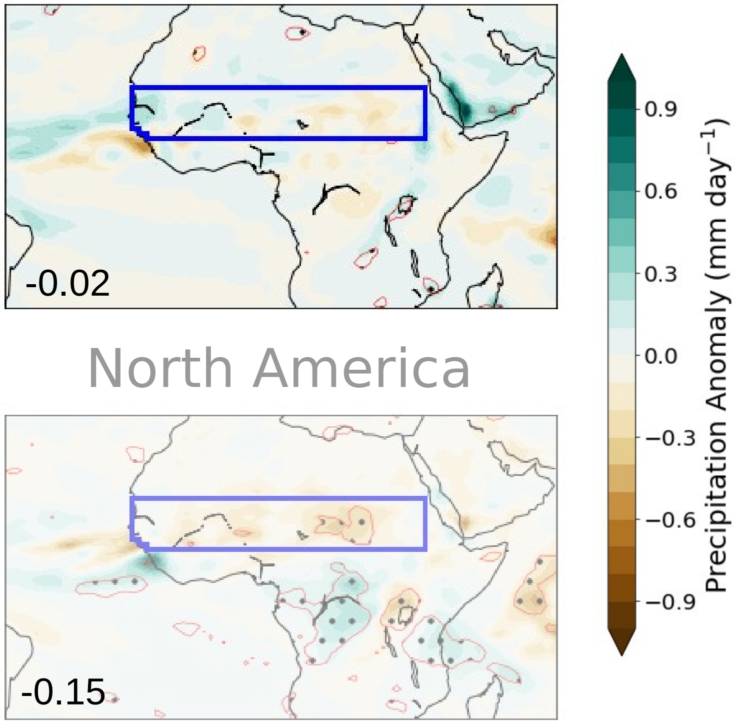


Europe

North America



- European emissions have little effect on precipitation, despite causing SO4 increases over N Africa
- Instead, North American emissions cause the most drying

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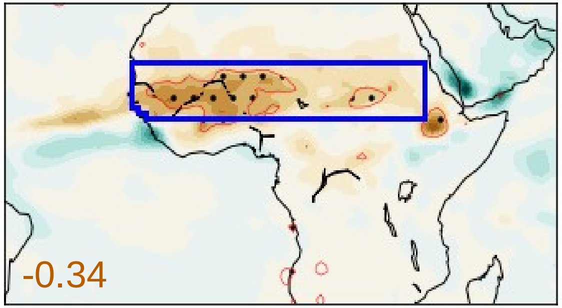

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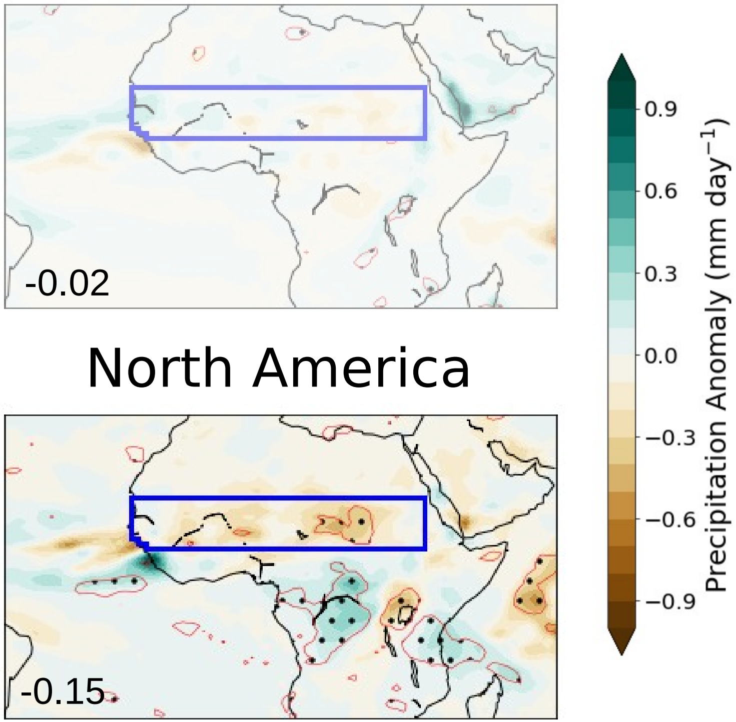

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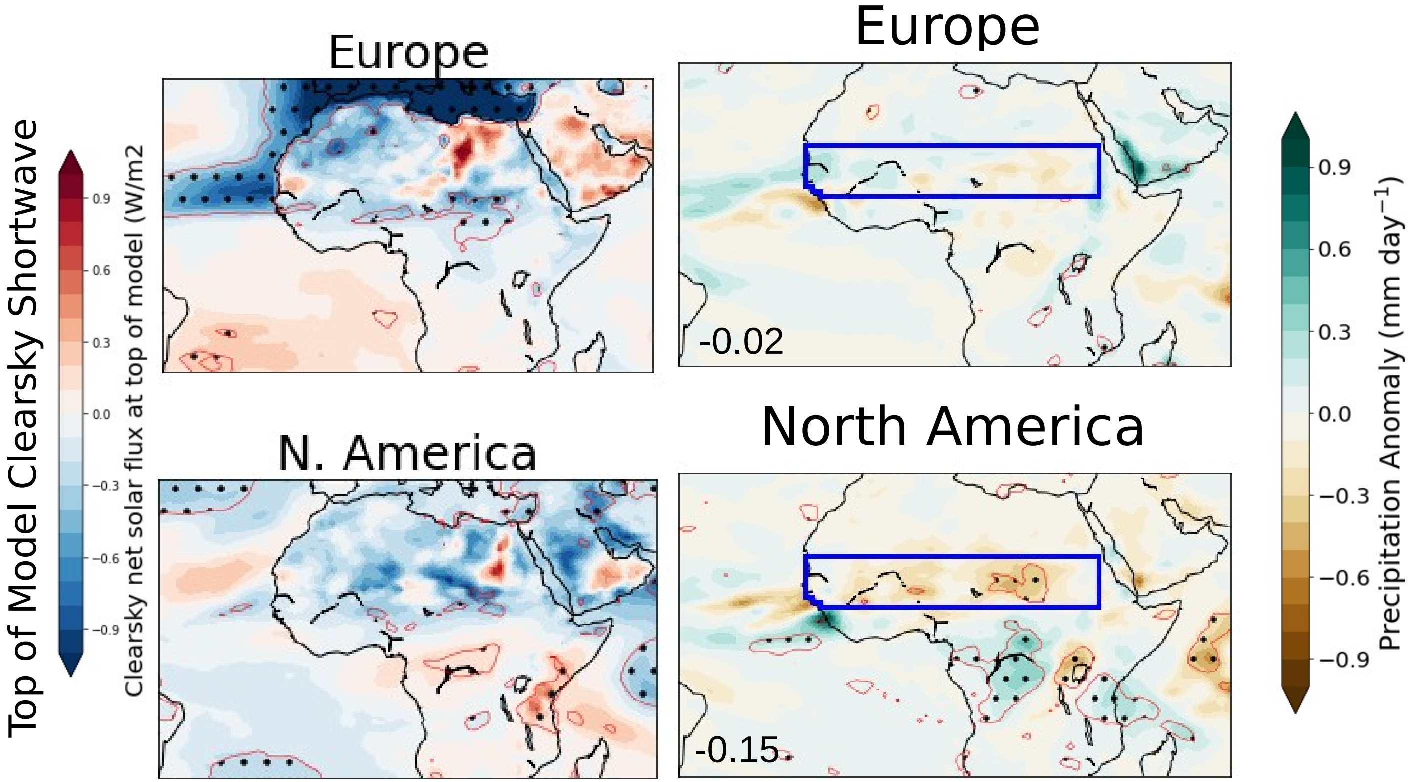
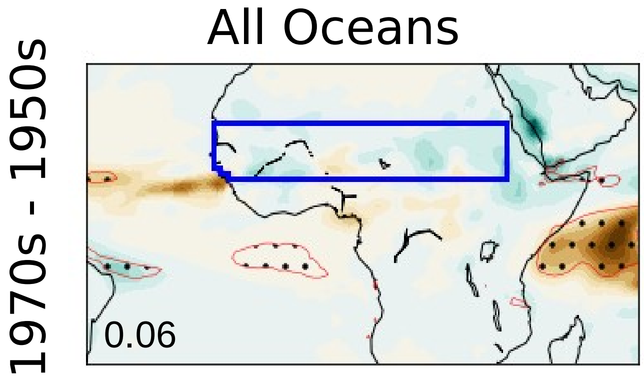
Weak Shortwave Effect over the Sahara?

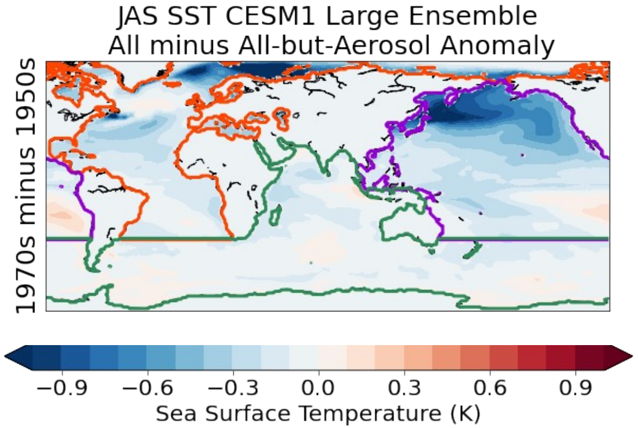
- European emissions have relatively weak impacts on clearsky SW radiation over the Sahara.



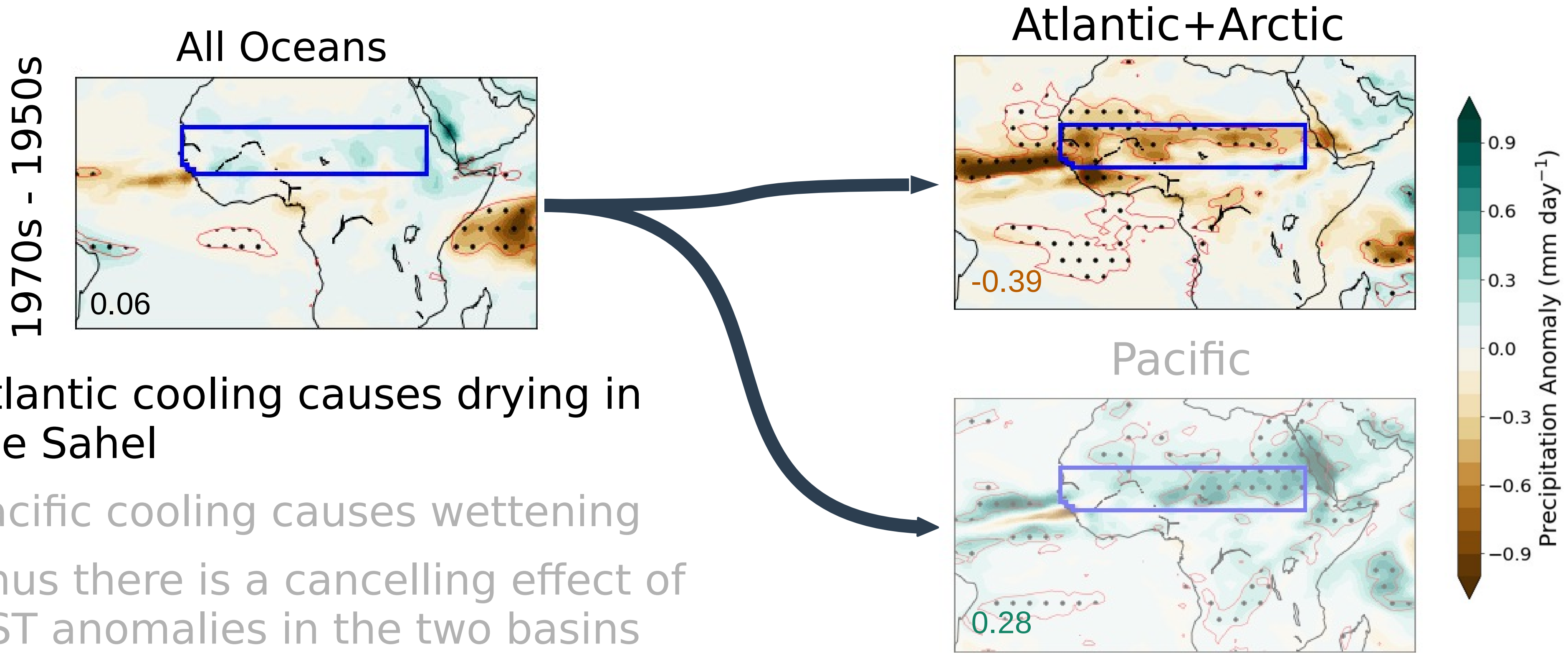
1970s – 1950s Weak Ocean Mediated Response



- General cooling due to SO4 forcing that is strongest in NH extratropics
- Strongest anomalies in Pacific ocean and weakest in Indian/Southern ocean.



Opposing influences of Atlantic and Pacific Cooling



- Atlantic cooling causes drying in the Sahel
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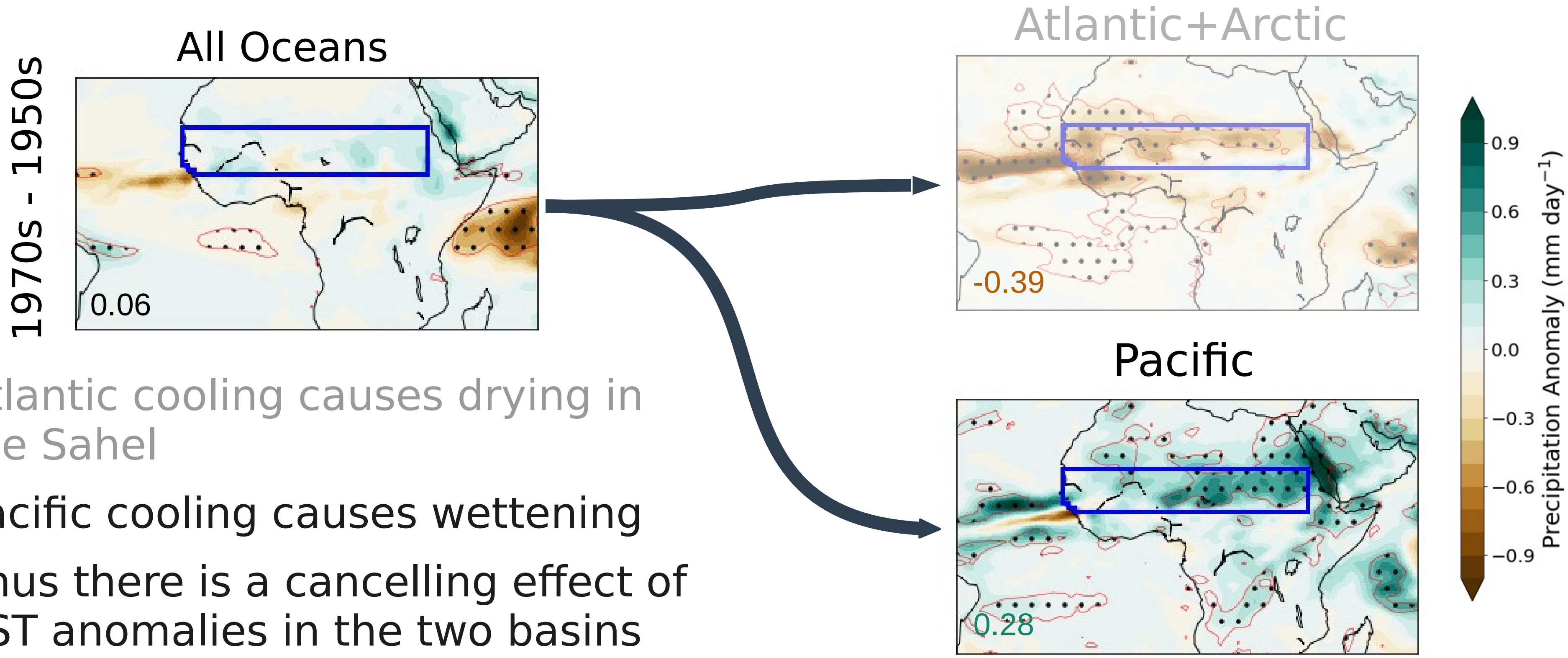

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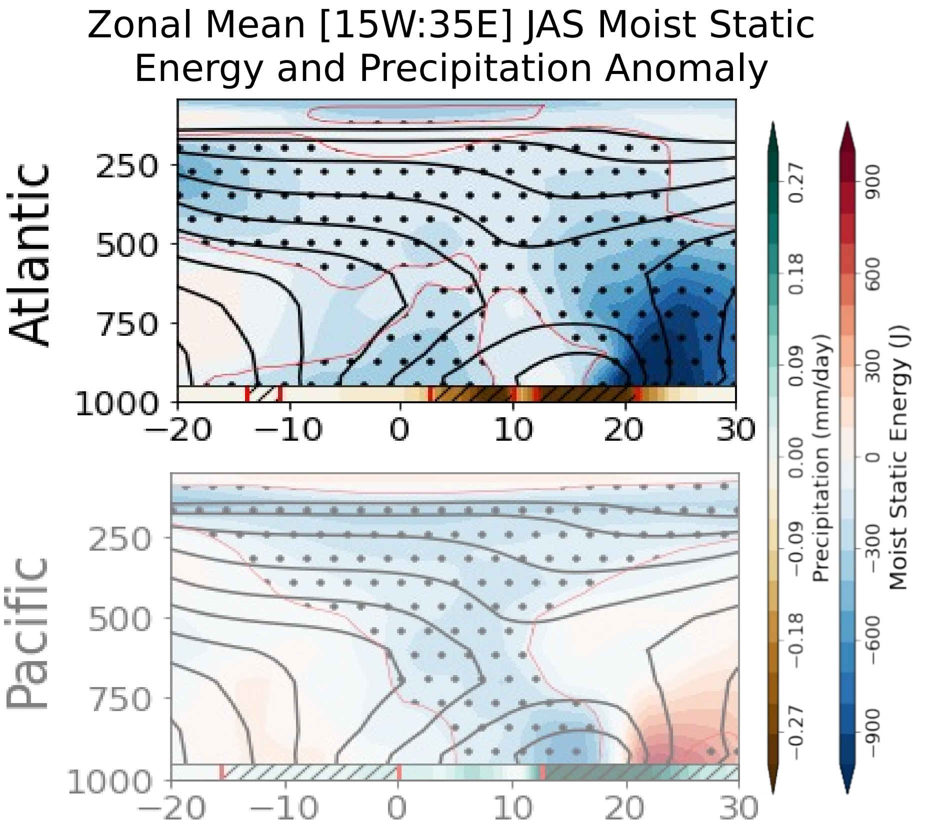
Why does Pacific Cooling Increase Sahel Precipitation?

- Atlantic cooling reduces humidity input into the monsoon, reducing precipitation
- Wetting driven by Pacific cooling suggests an "upped-ante" like mechanism [Giannini et al., 2013]
  - Tropical Pacific Cooling
  - Cooling of tropical upper troposphere
  - Reduced threshold for convection in Africa



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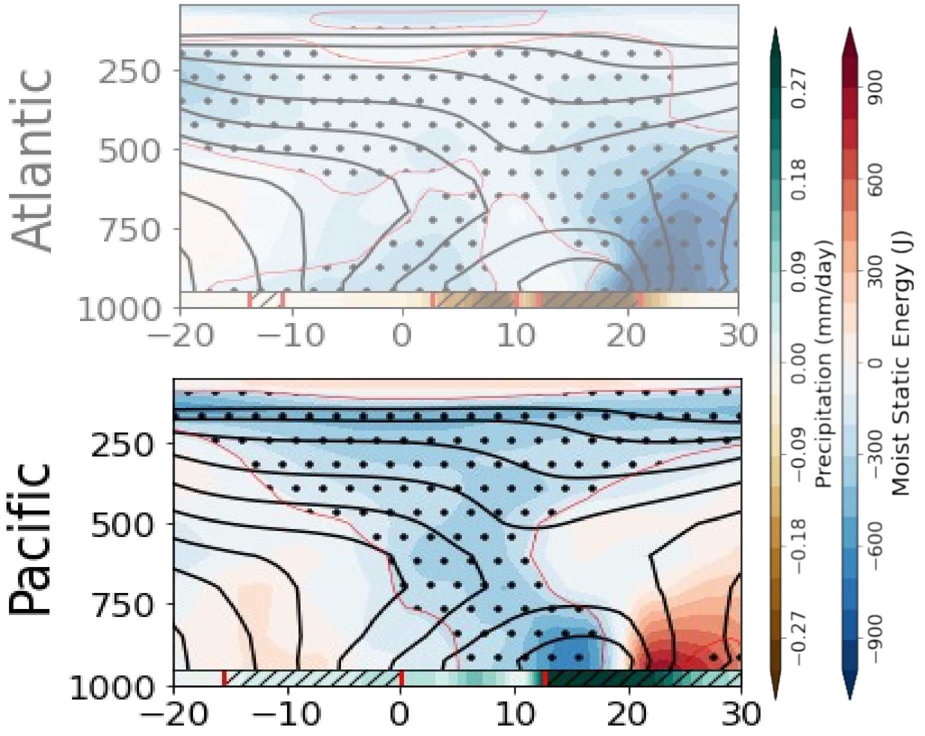
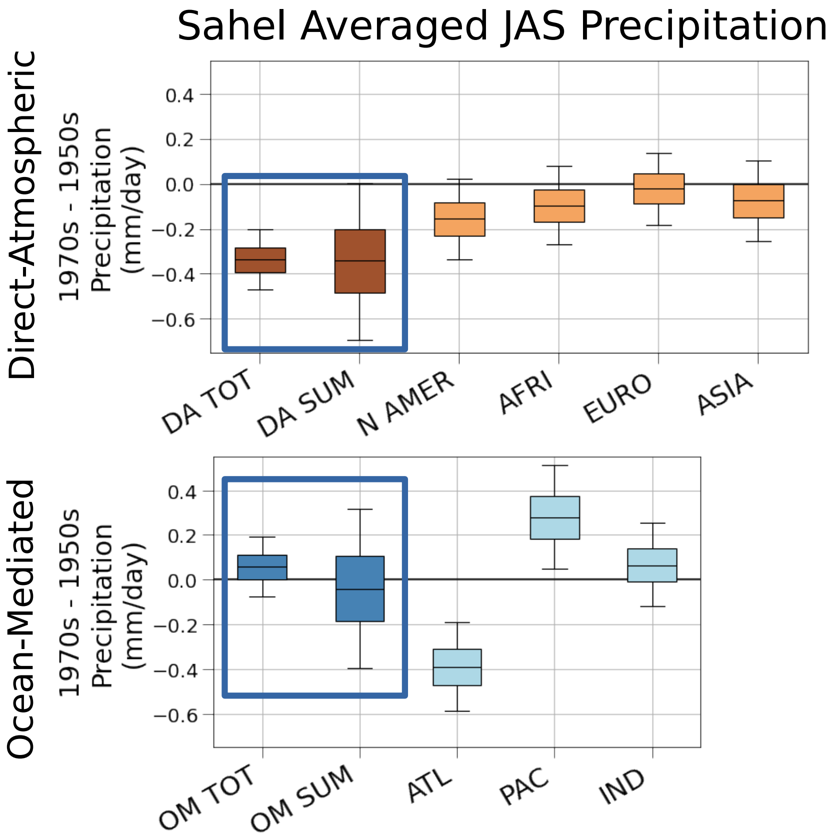
Zonal Mean [15W:35E] JAS Moist Static Energy and Precipitation Anomaly



Summary of 1970s – 1950s Sahel Precipitation Responses

- The sum of the Sahel averaged responses from the regional simulations is similar to the total simulation response.
- However, the sum is quite noisy.



Summary of 2000s-1970s Sahel Precipitation Responses

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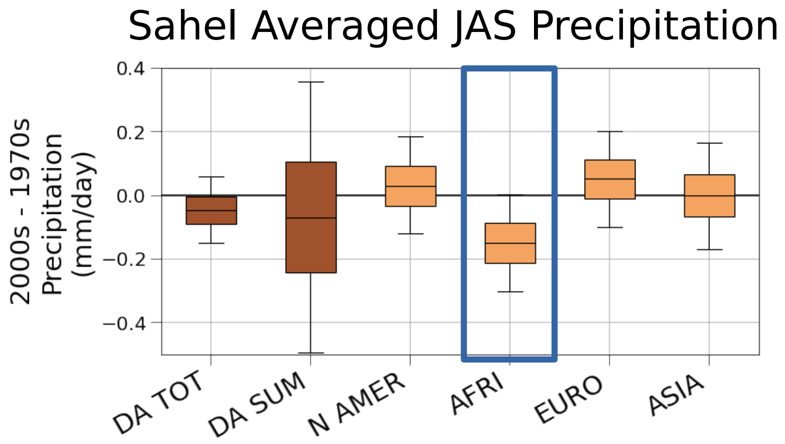
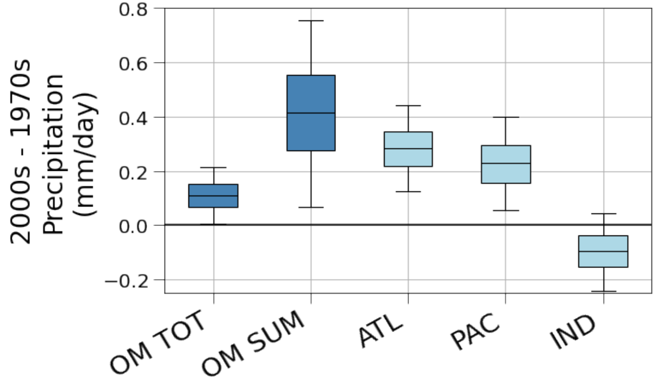
- Continued increases due to Pacific SST, perhaps due to cooling in the tropical west Pacific.





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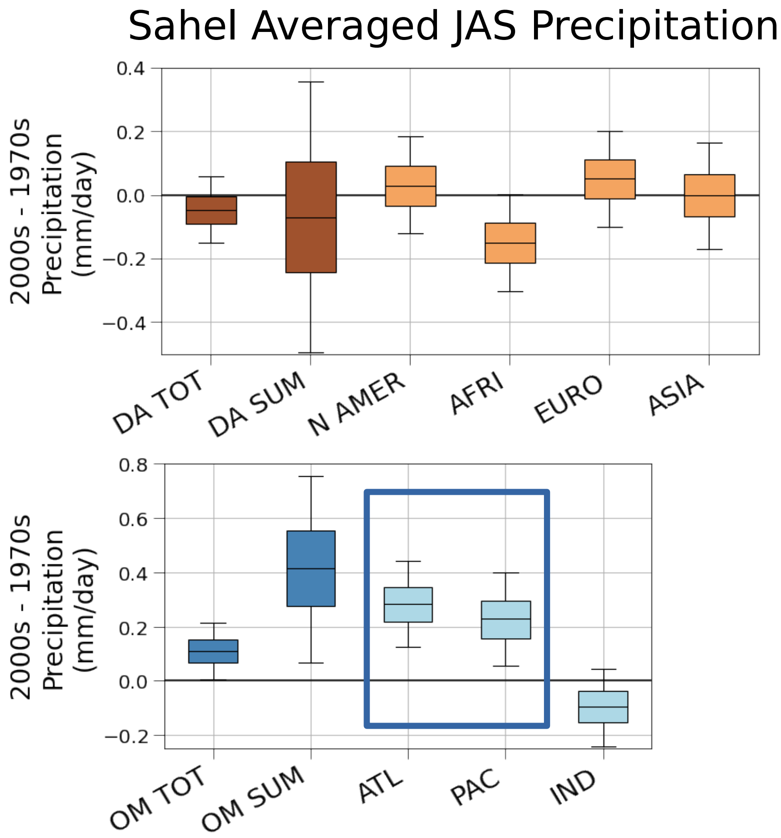
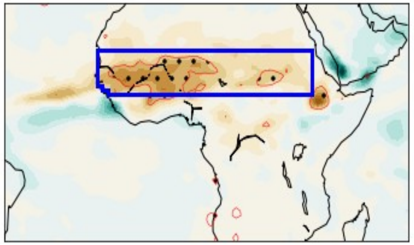


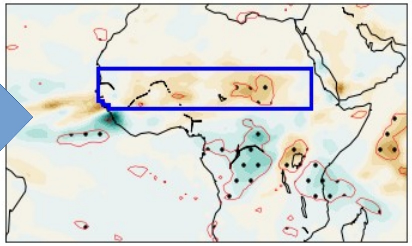
Summary

- Mechanisms of aerosol-forcing effect on Sahel precipitation change with time and spatial pattern.

All Emissions

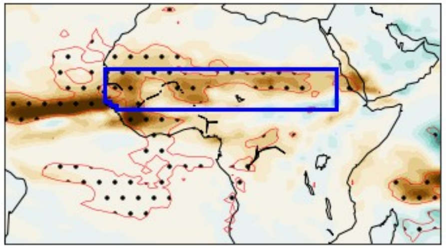


North American

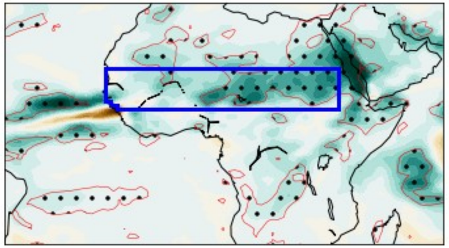


- 1970s - 1950s drying is direct-atmospheric and is mainly caused by remote North American emissions.

Atlantic + Arctic



Pacific

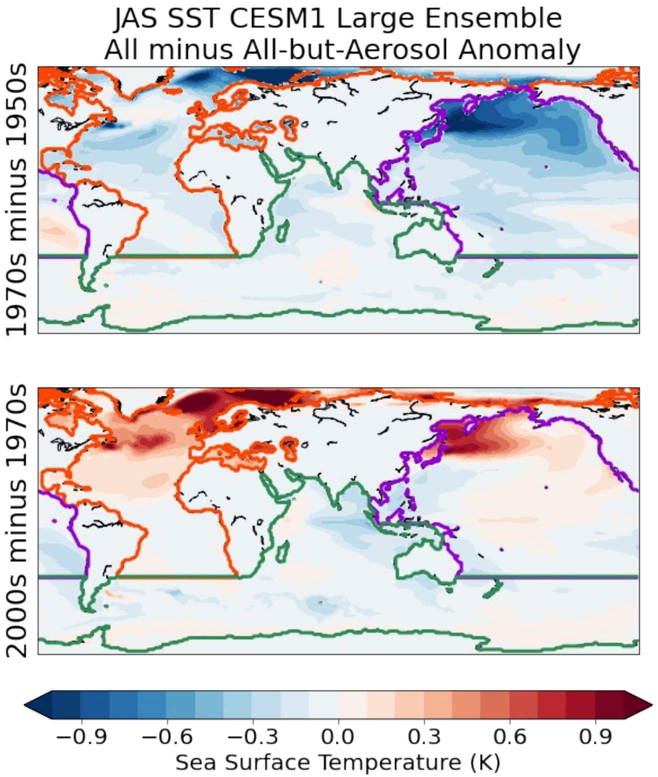


- Opposing effects of Atlantic and Pacific anomalies in the 1970s – 1950s
- Complementary effects from the basins in the 2000s-1970s.

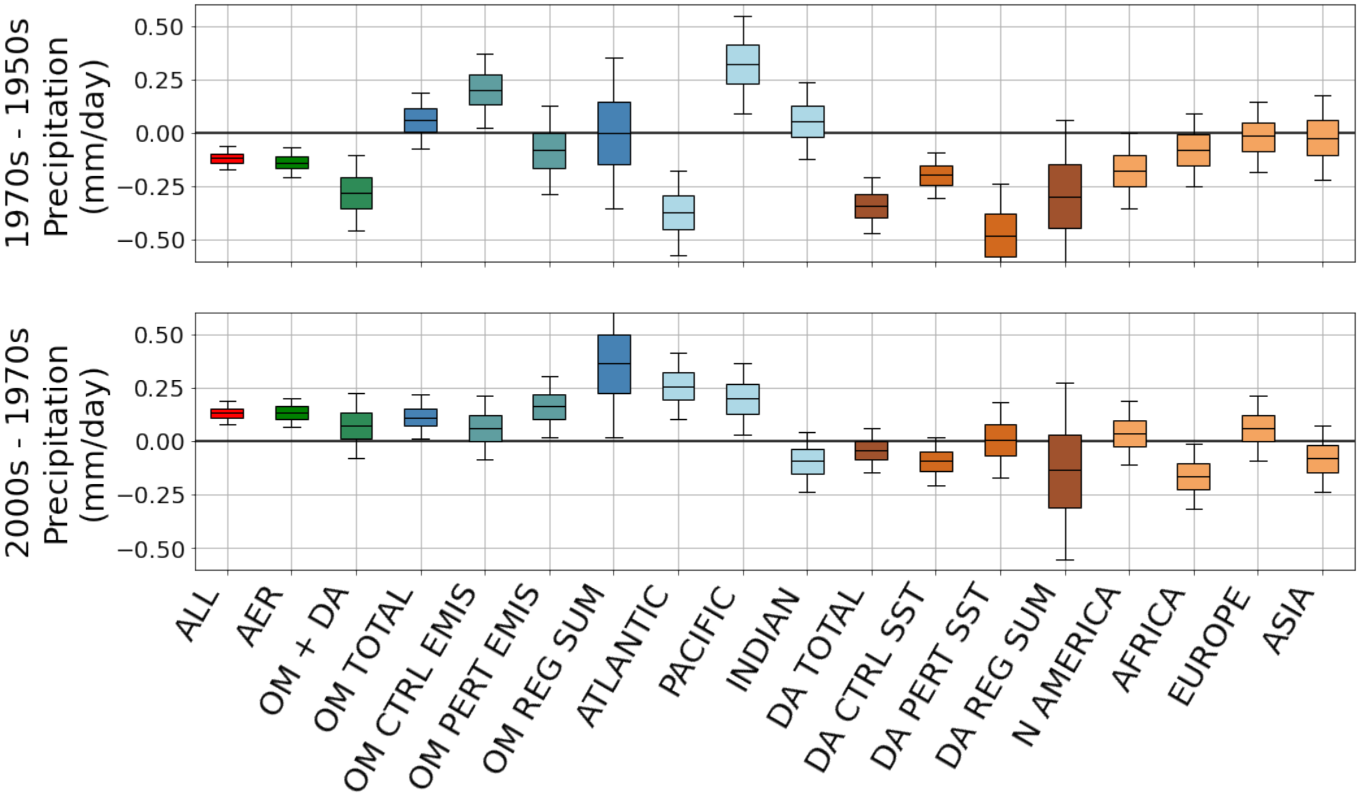
References

- Ackerley, D., B. B. B. Booth, S. H. E. Knight, E. J. Highwood, D. J. Frame, M. R. Allen, and D. P. Rowell, 2011: Sensitivity of Twentieth-Century Sahel rainfall to sulfate aerosol and CO2 forcing. J. Climate, 24, 4999–5014, https://doi.org/10.1175/JCLI-D-11-00019.1.
- Dong, B., R. T. Sutton, E. Highwood, and L. Wilcox, 2014: The impacts of European and Asian anthropogenic sulfur dioxide emissions on Sahel rainfall. J. Climate, 27, 7000–7017, https://doi.org/10.1175/JCLI-D-13-00769.1.
- Giannini, A., and A. Kaplan, 2019: The role of aerosols and greenhouse gases in Sahel drought and recovery. Climatic Change, 152, 449–466, https://doi.org/10.1007/s10584-018-2341-9.

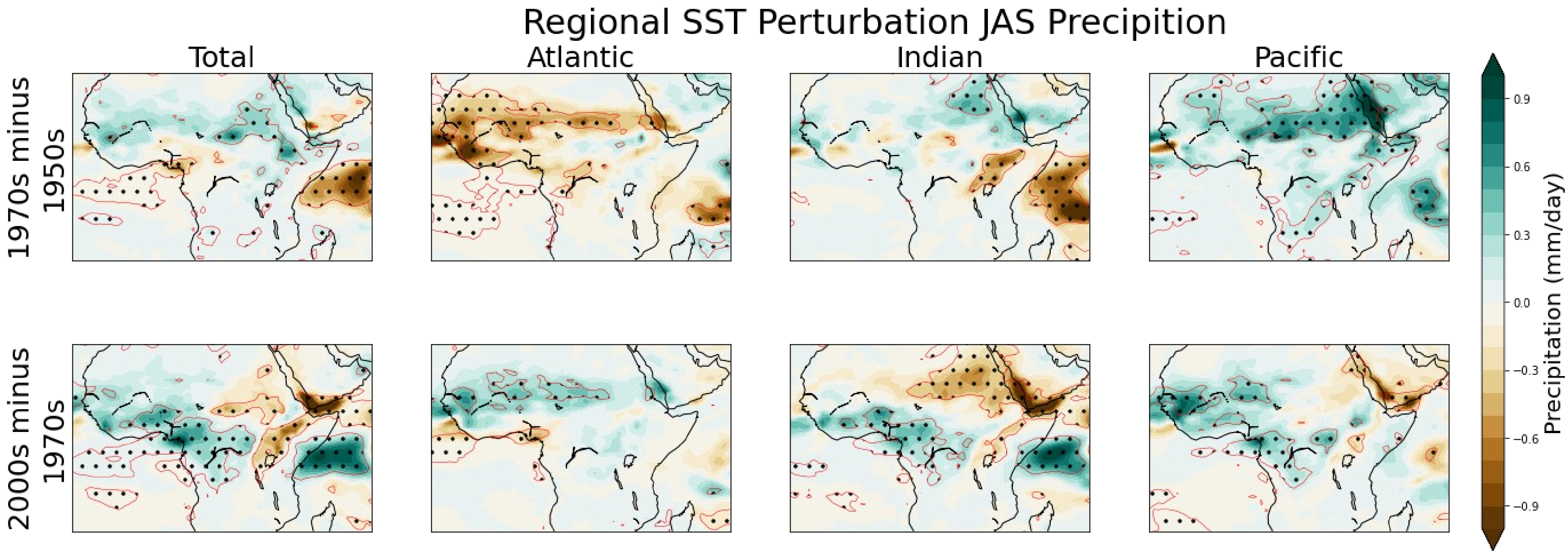
Supplementary : Definitions for ocean basin regions



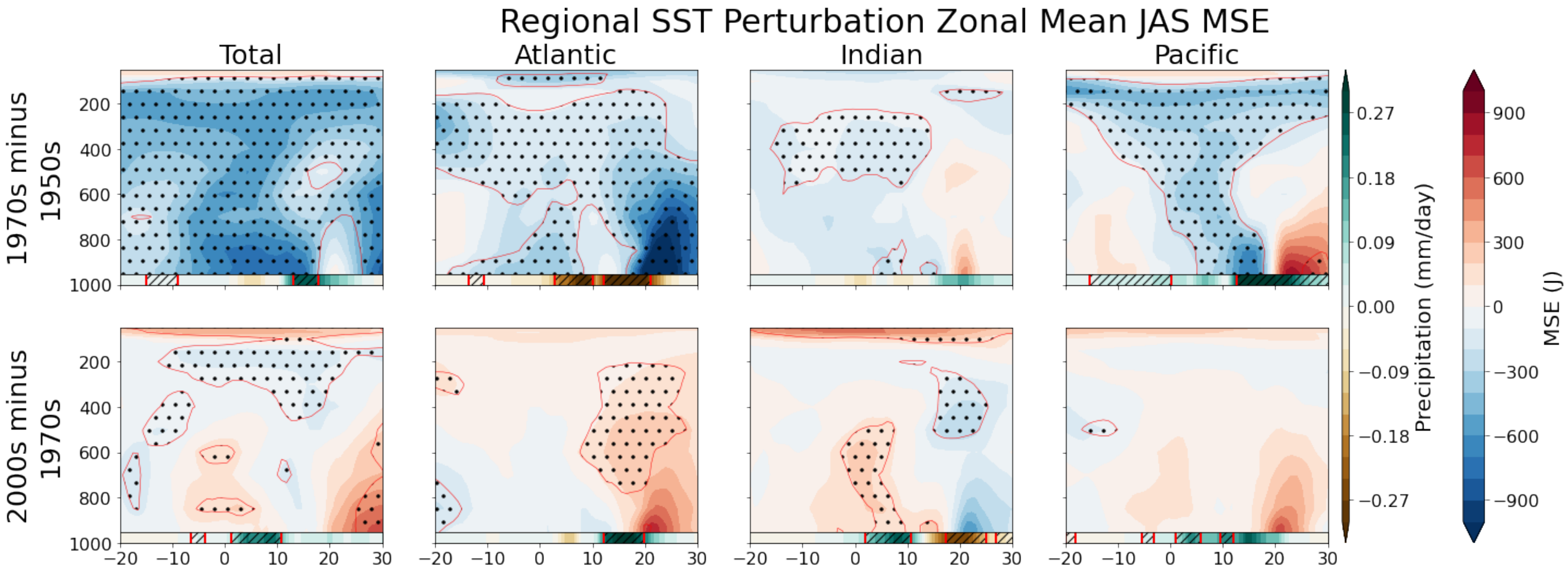
Sahel Averaged Anomalies



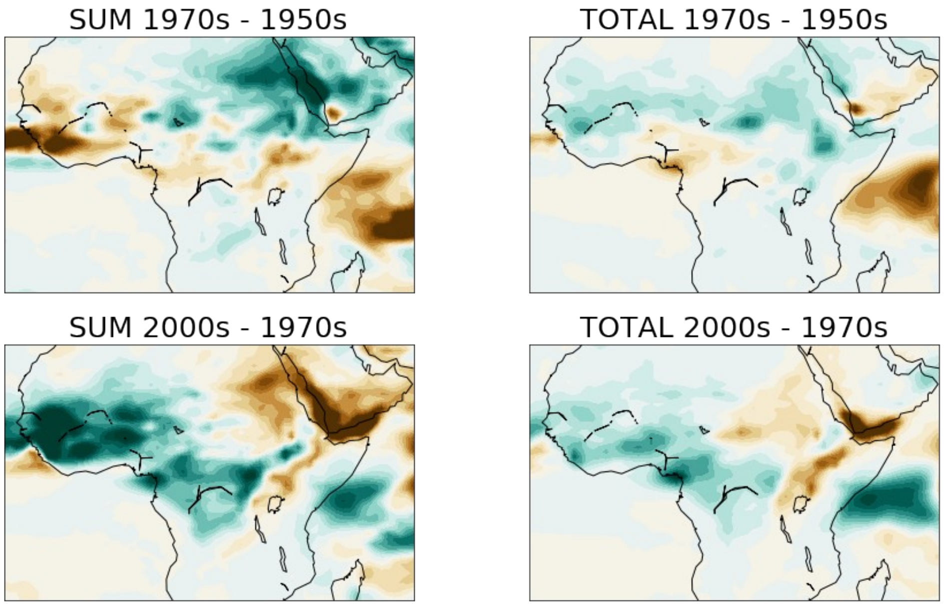
All Regional SST Perturbation Precipitation Responses



MSE for all basins

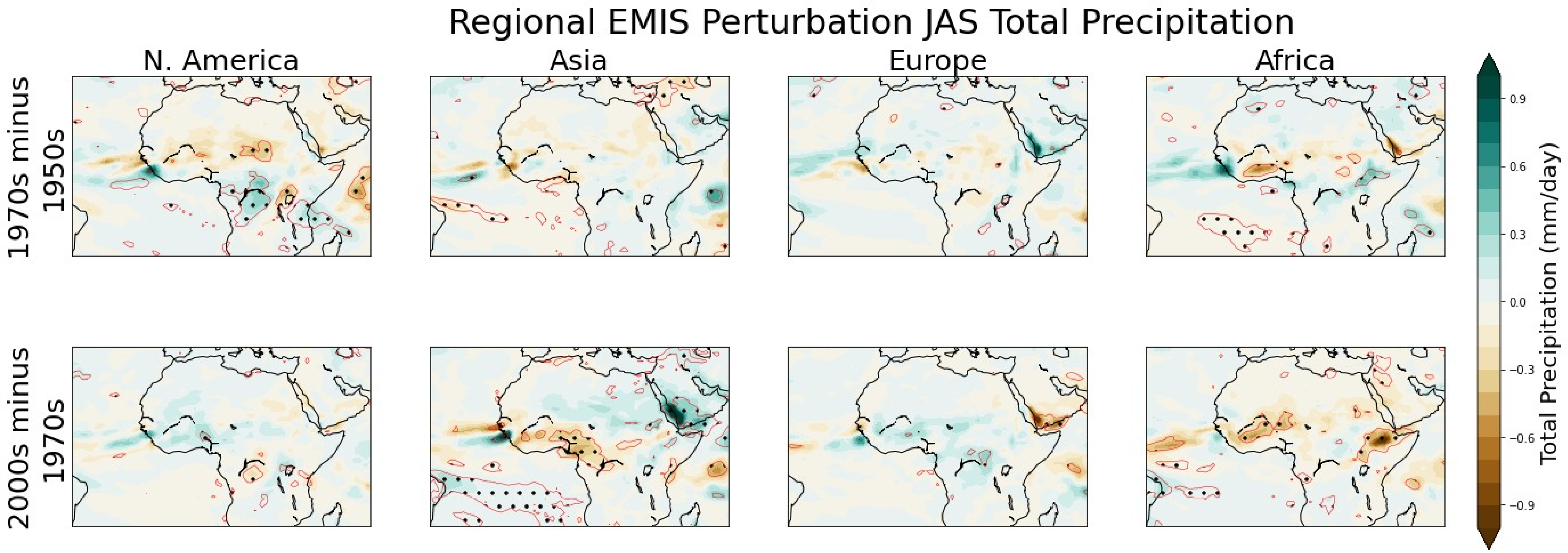


Regional SST Additivity

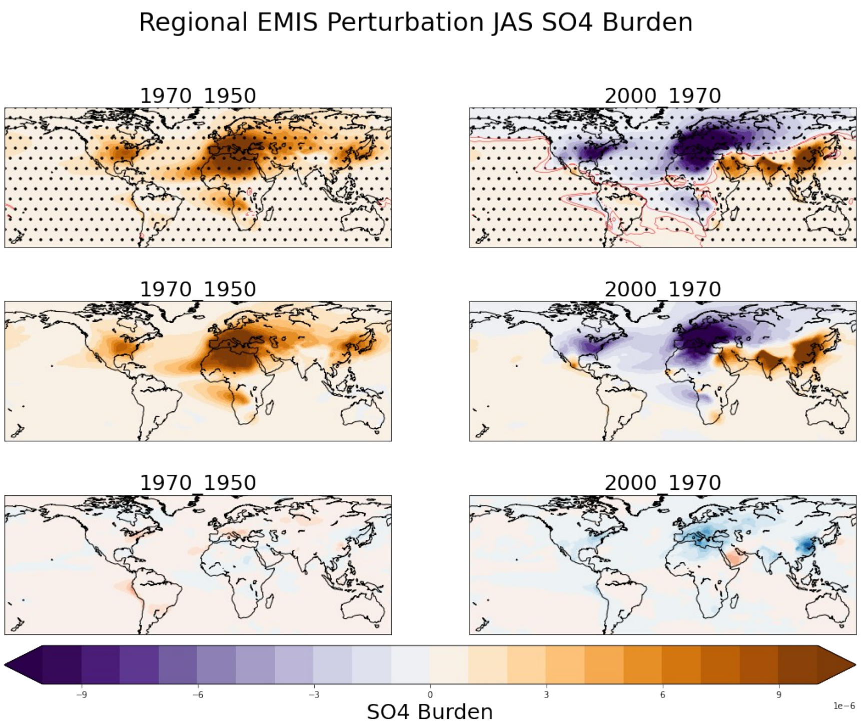


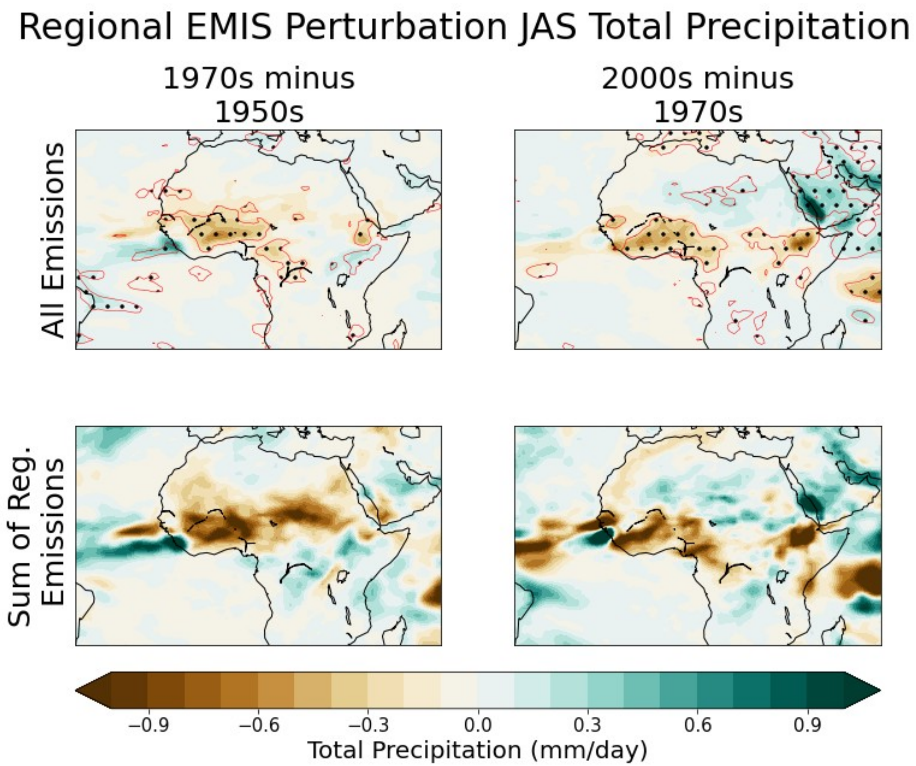
- Summing the response to different basins does not reproduce the overall response, but this may be due to internal variability

All emission regions

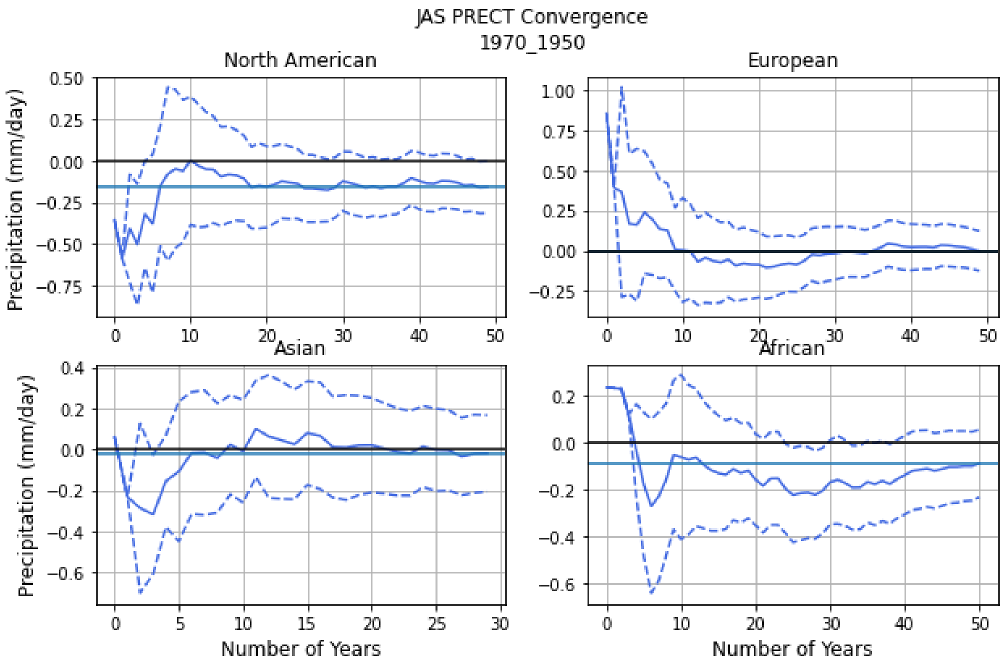


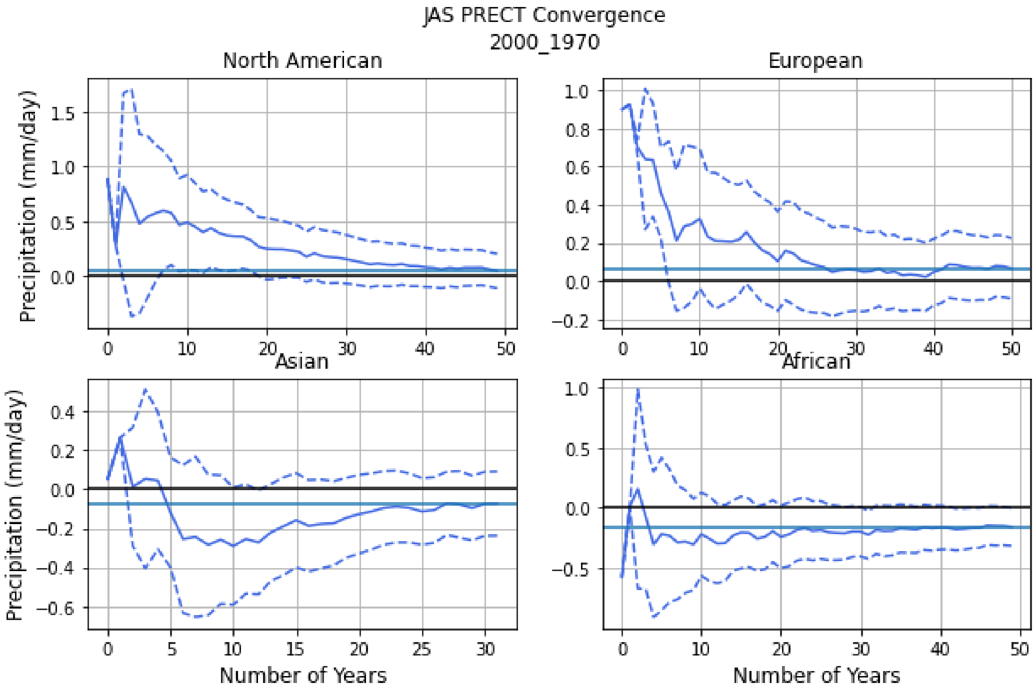
Regional Emission Additivity



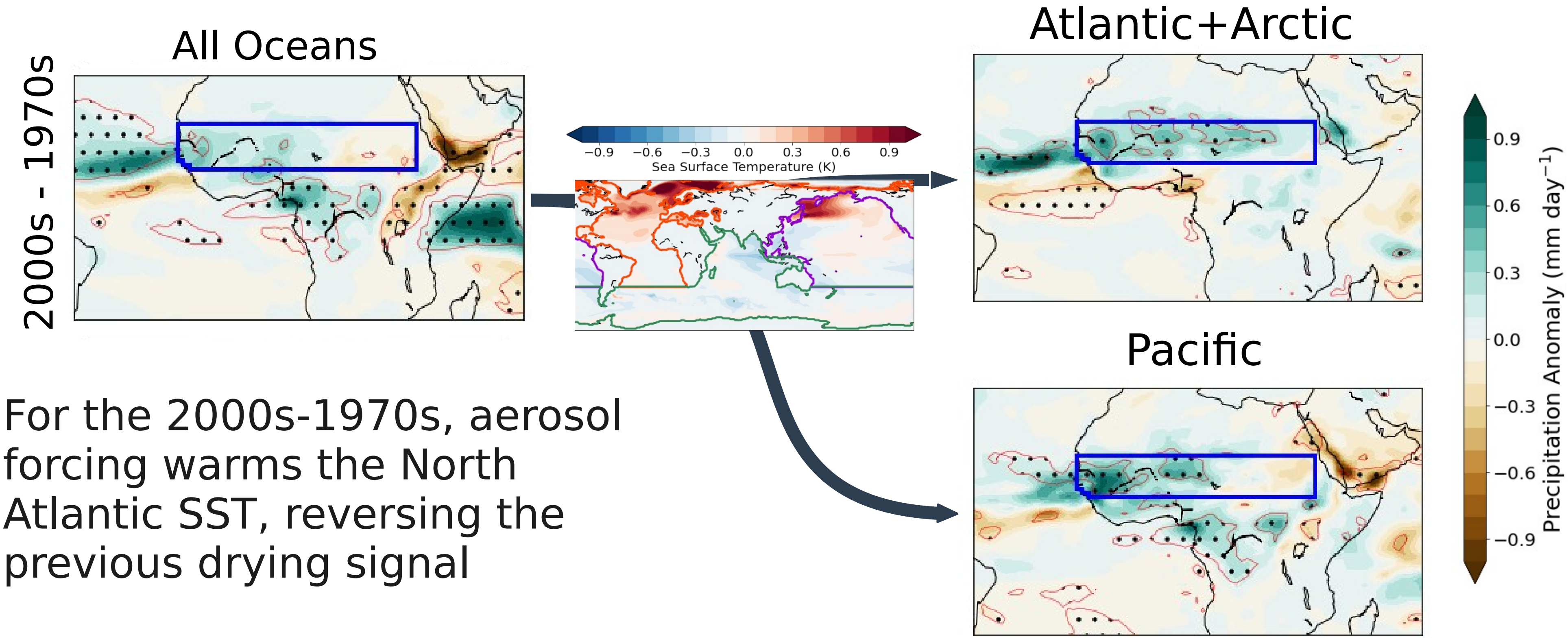


Effect of timeslice run length on Sahel regional average





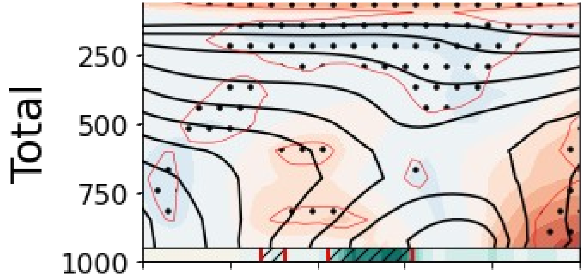
Changing Sign as Atlantic SSTs Warm

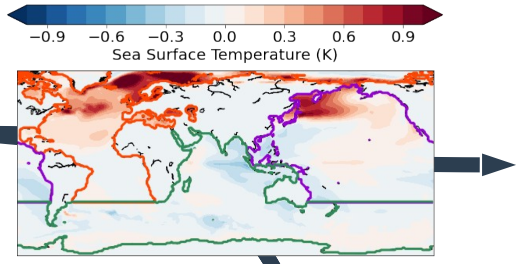


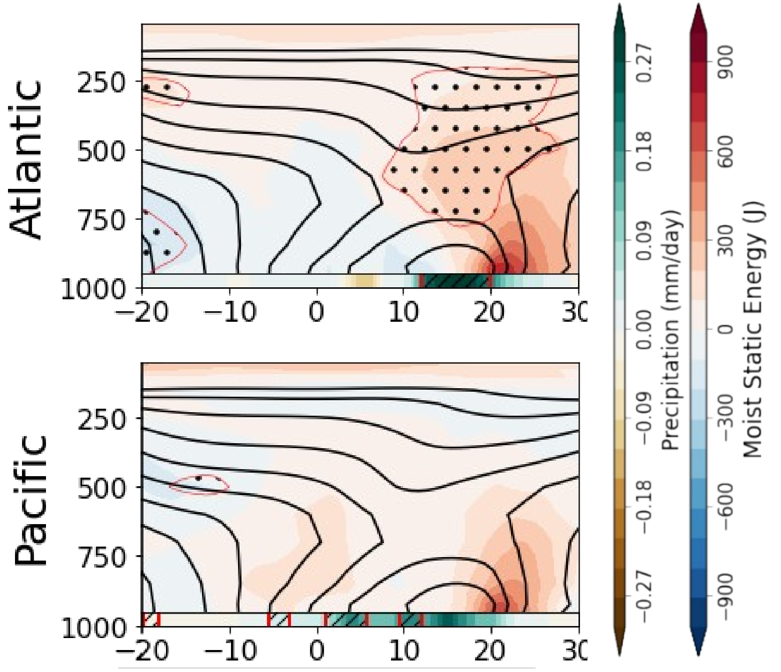
- For the 2000s-1970s, aerosol forcing warms the North Atlantic SST, reversing the previous drying signal

Why does Pacific Cooling Increase Sahel Precipitation?

2000s – 1970s Zonal Mean [15W:35E] JAS Moist Static Energy and Precipitation Anomaly

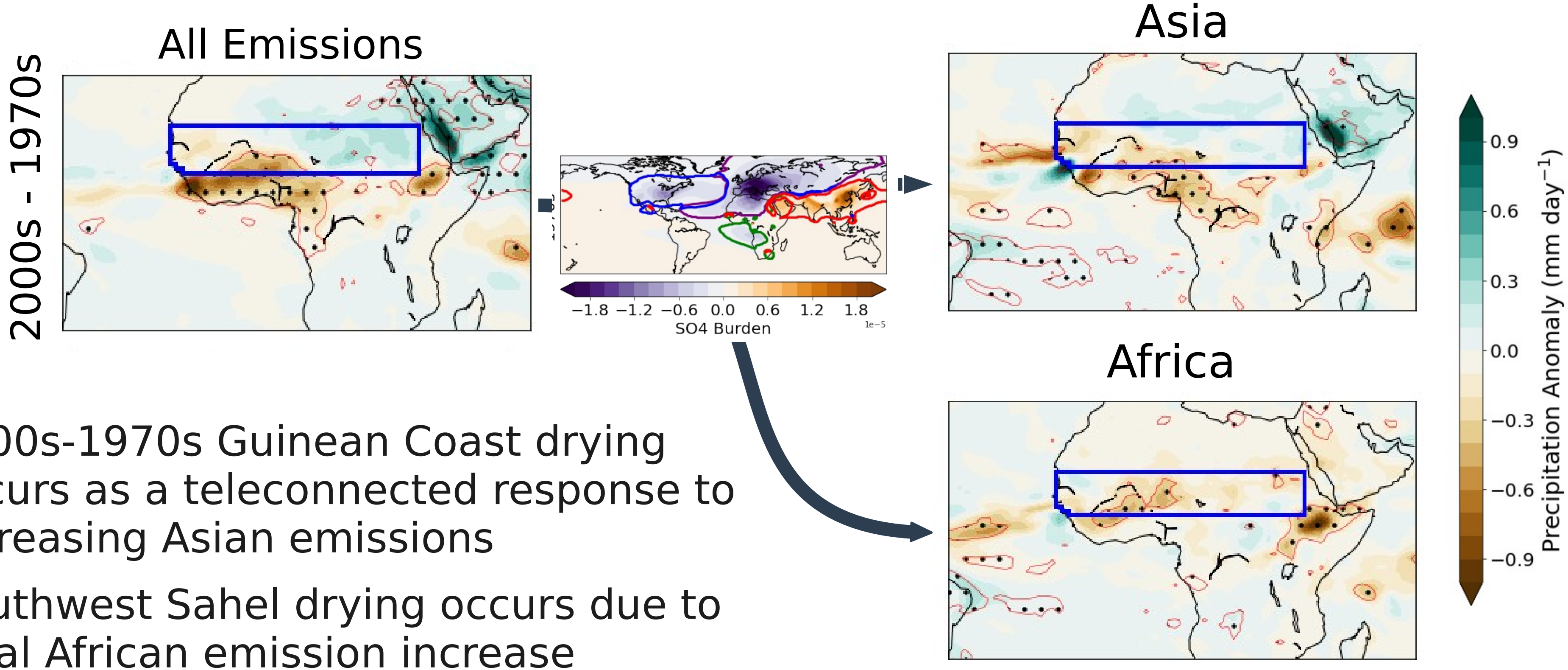






- In the 2000s-1970s, the warming North Atlantic results in greater moisture supply to the monsoon.
- The western tropical Pacific sees additional though weak cooling which may be driving more Sahel wetting.

2000s-1970s Influence of Remote Asian and Local African Emissions



- 2000s-1970s Guinean Coast drying occurs as a teleconnected response to increasing Asian emissions
- Southwest Sahel drying occurs due to local African emission increase