Disentangling warming and circulation influences on precipitation

Arianna M. Varuolo-Clarke, NOAA Climate & Global Change Postdoctoral Fellow
in collaboration with Jennifer E. Kay, Brian Medeiros, Nathan Lenssen, Kirsten Mayer, Will Chapman

05 February 2025
avclarke@ucar.edu | arianna.varuolo-clarke@colorado.edu

CPAESS Cooperative Programs for the Advancement of Earth System Science

Atmospheric and Oceanic Sciences UNIVERSITY OF COLORADO BOULDER

CIRES

Disentangling warming and circulation influences on precipitation using nudging experiments

Arianna M. Varuolo-Clarke, NOAA Climate & Global Change Postdoctoral Fellow
in collaboration with Jennifer E. Kay, Brian Medeiros, Nathan Lenssen, Kirsten Mayer, Will Chapman

05 February 2025

avclarke@ucar.edu | arianna.varuolo-clarke@colorado.edu

CPAESS
Cooperative Programs for the Advancement of Earth System Science
Atmospheric and Oceanic Sciences
UNIVERSITY OF COLORADO BOULDER
CIRES

Challenges of quantifying drivers of precipitation change

- While there is **high confidence** that anthropogenic forcing has contributed to mean multi-decadal precipitation changes across several regions (i.e., western Africa and southeastern South America)…
- …it is challenging to robustly assess the magnitude of relative contributions of greenhouse gas forcing (including stratospheric ozone depletion) and different species of aerosols because of:
    1. The large role of internal variability
    2. Observational uncertainty
    3. Model uncertainty
    4. Forcing uncertainty

IPCC Chapter 10; Doblas-Reyes et al. (2021); 10.1017/9781009157896.012

Challenges of quantifying drivers of precipitation change

- While there is **high confidence** that anthropogenic forcing has contributed to mean multi-decadal precipitation changes across several regions (i.e., western Africa and southeastern South America)…
- …it is challenging to robustly assess the magnitude of relative contributions of greenhouse gas forcing (including stratospheric ozone depletion) and different species of aerosols because of:
  1. **The large role of internal variability**
  2. Observational uncertainty
  3. Model uncertainty
  4. Forcing uncertainty

IPCC Chapter 10; Doblas-Reyes et al. (2021); 10.1017/9781009157896.012

Two mechanisms contribute to precipitation change under global warming

Thermodynamic

- These changes follow Clausius-Clapeyron suggesting that a warmer atmosphere can hold more water vapor
  - "wet get wetter and dry get drier"

Dynamic

- Result from shifts in atmospheric circulation which affect the horizontal and vertical transports of water vapor
- Modeling studies indicate that increasing greenhouse gas concentrations leads to:
  - An expansion of the tropical Hadley cell and subtropical dry zones
  - A poleward shift in storm tracks

Marvel and Bonfils 2013 *PNAS*; Allen and Ingram 2002, *Nature*; Held and Soden 2006, *J Clim*; Seidel et al. 2007, *Nat Geosci*; Shindell and Schmidt 2004, *GRL*

Driving research questions

1. Can we better understand the role of internal variability on precipitation change by quantifying the relative contributions of **dynamic** vs. **thermodynamic** changes in the CESM2 Large Ensemble?

2. Using idealized experiments, **what is the influence of warming alone on precipitation change?**

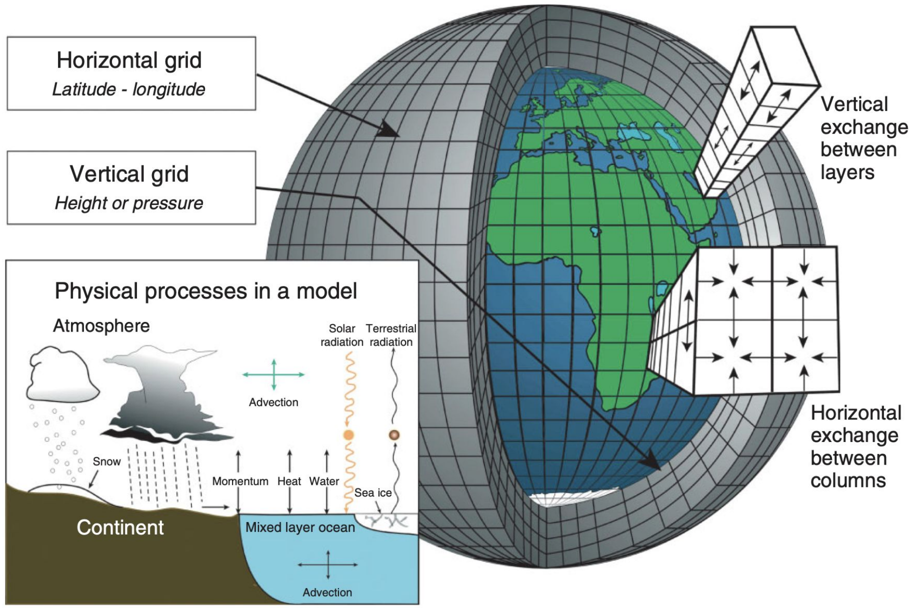
Driving research questions

1. Can we better understand the role of internal variability on precipitation change by quantifying the relative contributions of **dynamic** vs. **thermodynamic** changes in the CESM2 Large Ensemble?

2. Using idealized experiments, **what is the influence of warming alone on precipitation change?**

Quantifying dynamic vs. thermodynamic contributions to precipitation change

- Using CESM2 Large Ensemble:
  - Daily 500 hPa vertical velocity (ω)
  - Daily precipitation
  - Consider the mid-latitudes (broadly; 20°-70°)
  - Compare two periods:
    - Historical → 1981-2000
    - Future → 2081-2100
  - NH winter (DJF)
  - Fully coupled ocean-atmosphere model
  - 50 members with CMIP6 forcing
  - SSP3-7.0



Danabasoglu et al. 2019 JAMES; Edwards 2010 *WIREs Climate Change*

Quantifying dynamic vs. thermodynamic contributions to precipitation change

1. Obtain the PDF of ω (PDF_{ω}) for a historical and future period
2. Composite daily precipitation for each ω bin for both periods (P_{ω})

Example for all NH mid-latitudes

Bony et al. 2004, *Clim. Dyn.;* Emori and Brown 2005, *GRL*

Quantifying dynamic vs. thermodynamic contributions to precipitation change

1. Obtain the PDF of ω (PDF_{ω}) for a historical and future period
2. Composite daily precipitation for each ω bin for both periods (P_{ω})
3. 'Dynamic change' is the change in mean precipitation due to the change in PDF_{ω}:

$$P_{\omega[historical]} (PDF_{\omega[future]} - PDF_{\omega[historical]})$$

4. 'Thermodynamic change' is the change in the expected precipitation for a given ω:

$$PDF_{\omega[historical]} (P_{\omega[future]} - P_{\omega[historical]})$$

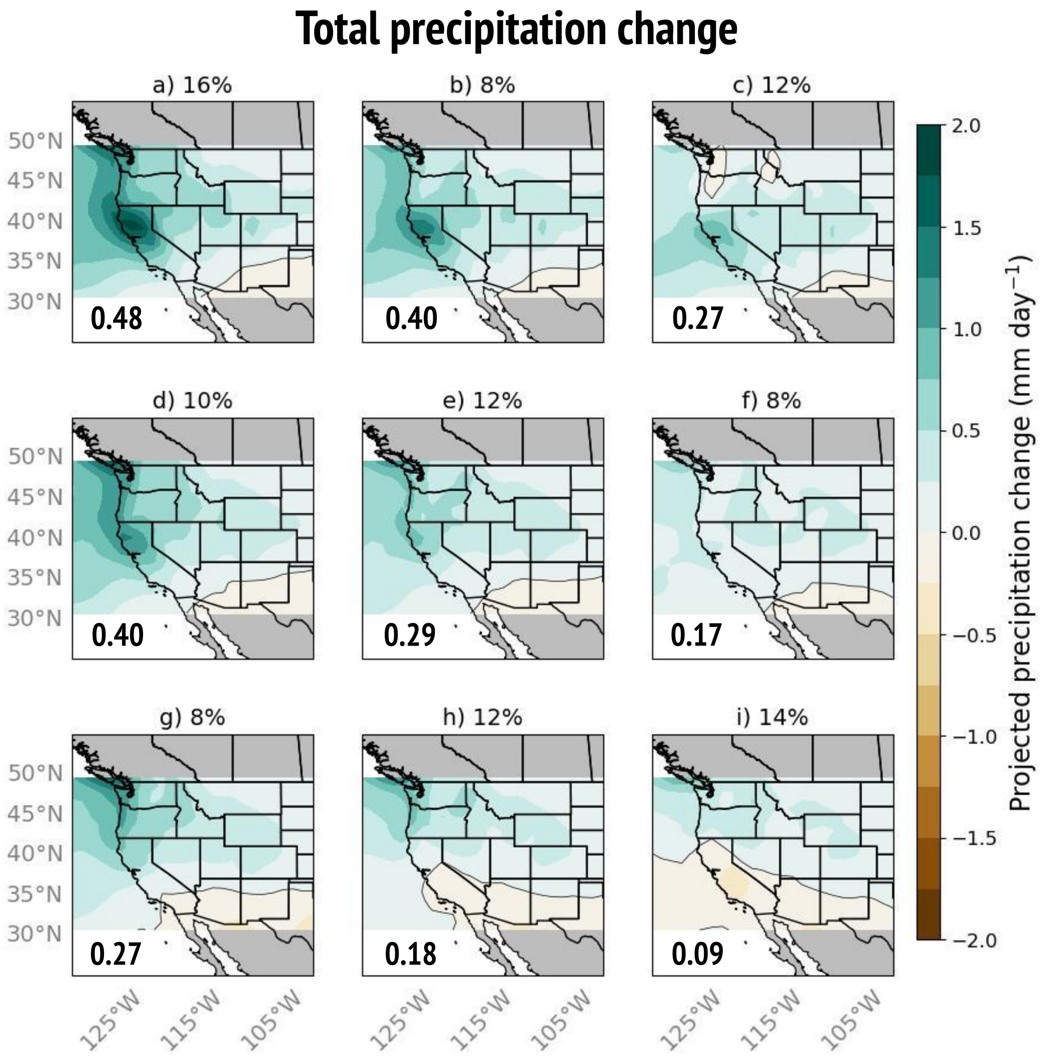
Bony et al. 2004, *Clim. Dyn.;* Emori and Brown 2005, *GRL*

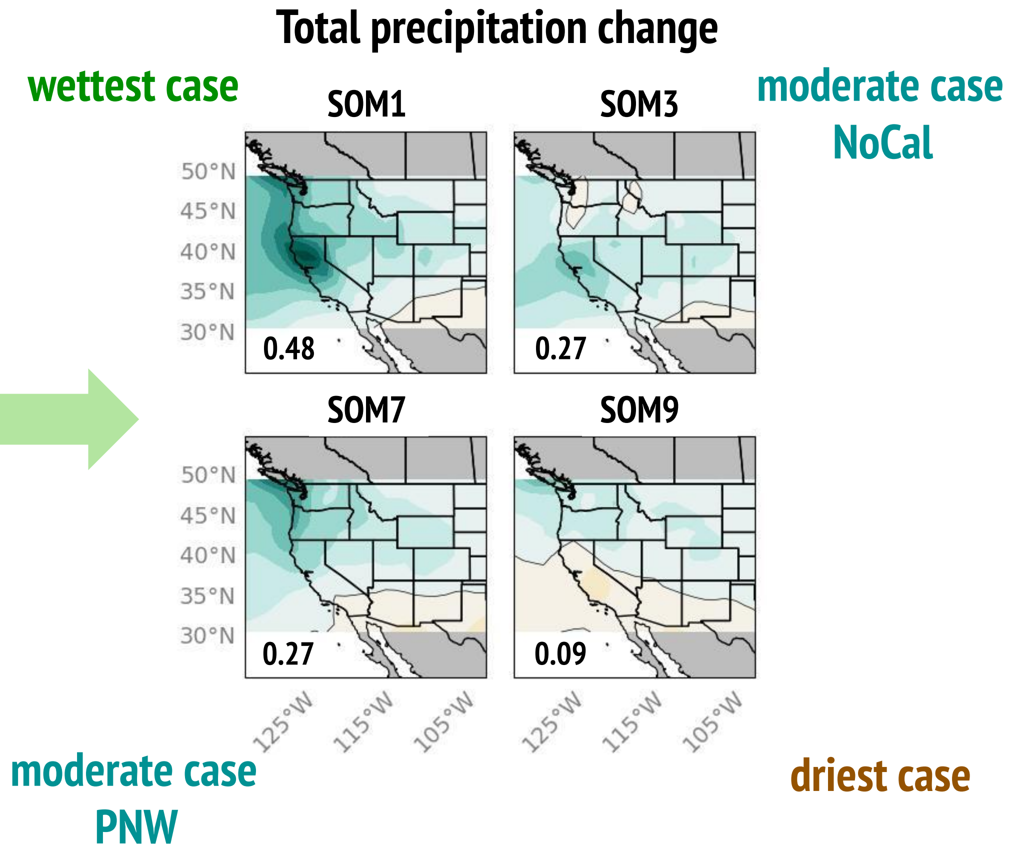
Ensemble mean NH winter precipitation changes

Key changes:
- P↑ over land
- P↓ over Mediterranean regions
- P↓ equatorward of storm tracks
- P↑ poleward of storm tracks

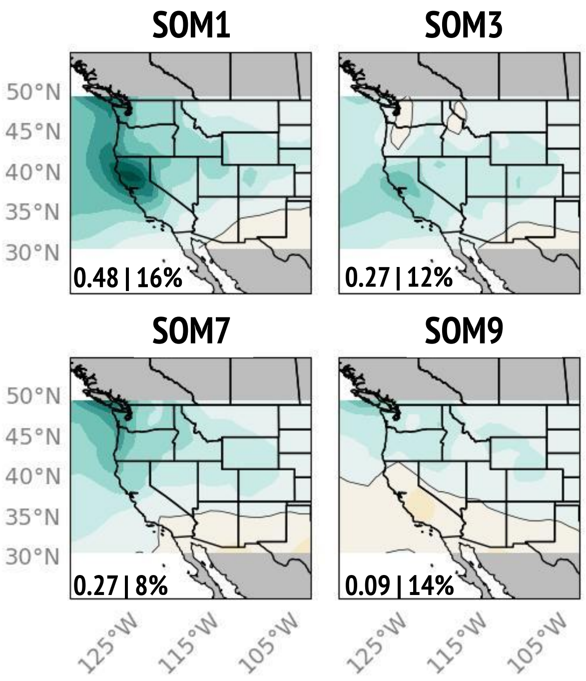
What spatial patterns lead to the variability in projected precipitation change?

What spatial patterns lead to the variability in projected precipitation change?





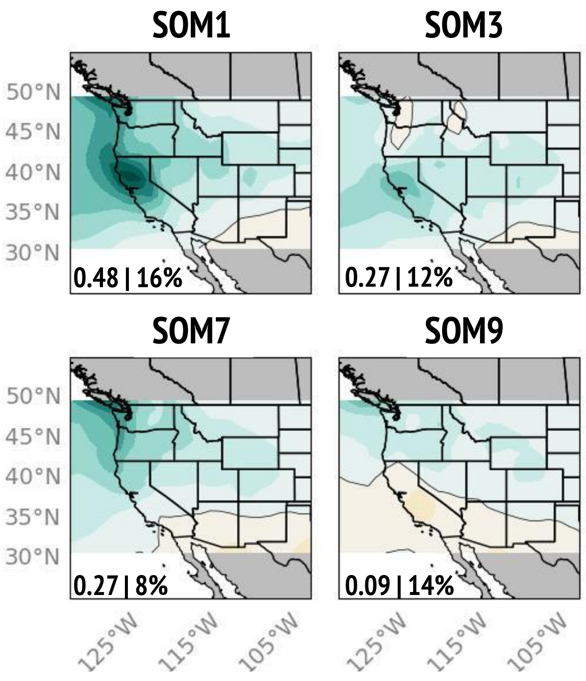
What spatial patterns lead to the variability in projected precipitation change?



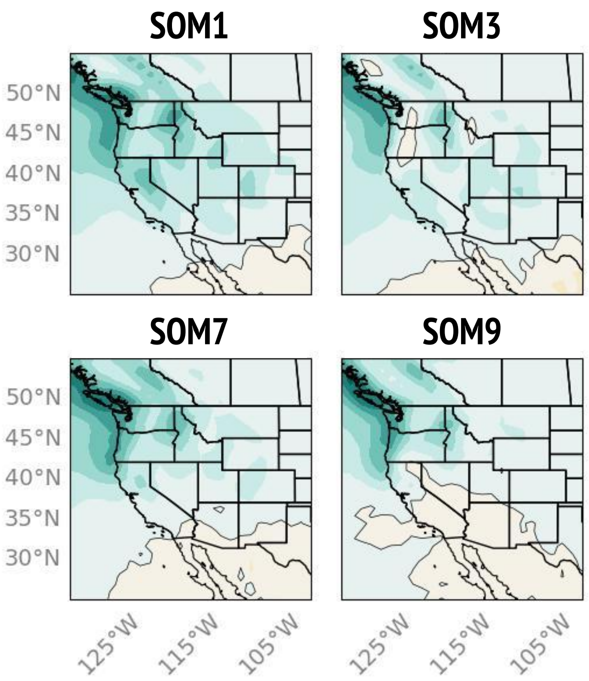
Total precipitation change

What spatial patterns lead to the variability in projected precipitation change?

Total precipitation change

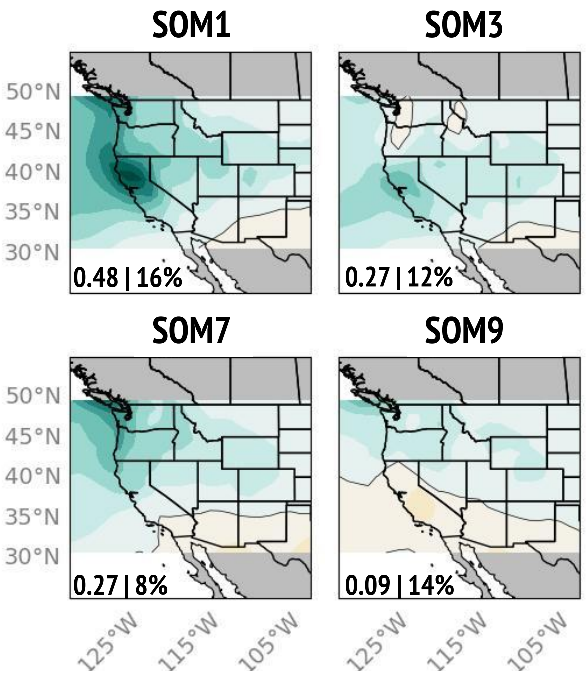


Thermodynamic change

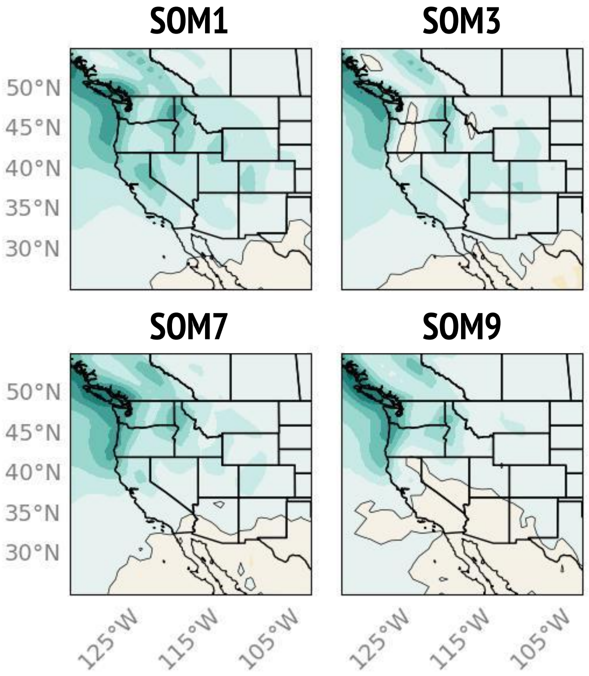


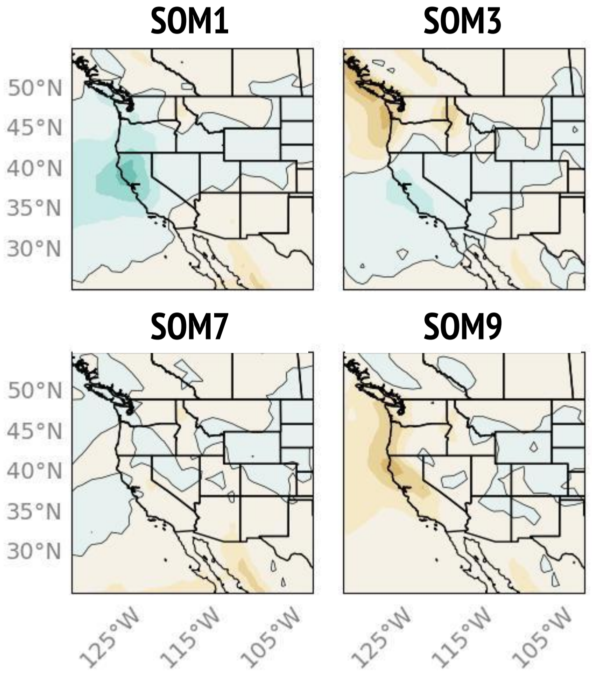
What spatial patterns lead to the variability in projected precipitation change?

Total precipitation change



Thermodynamic change

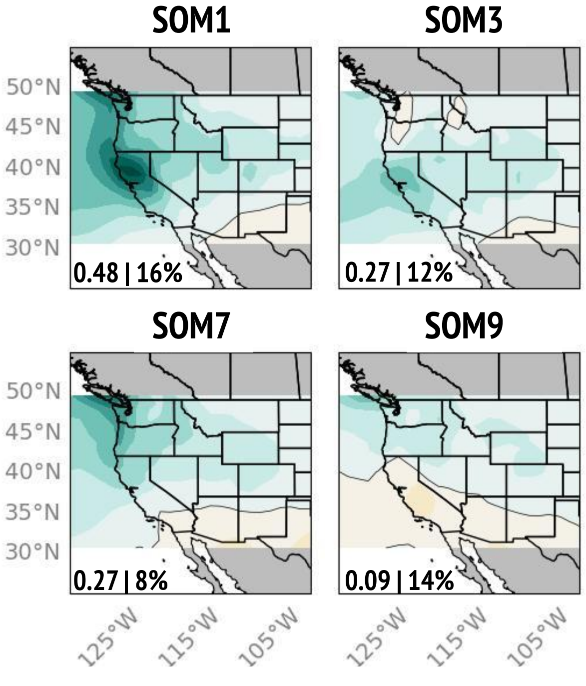




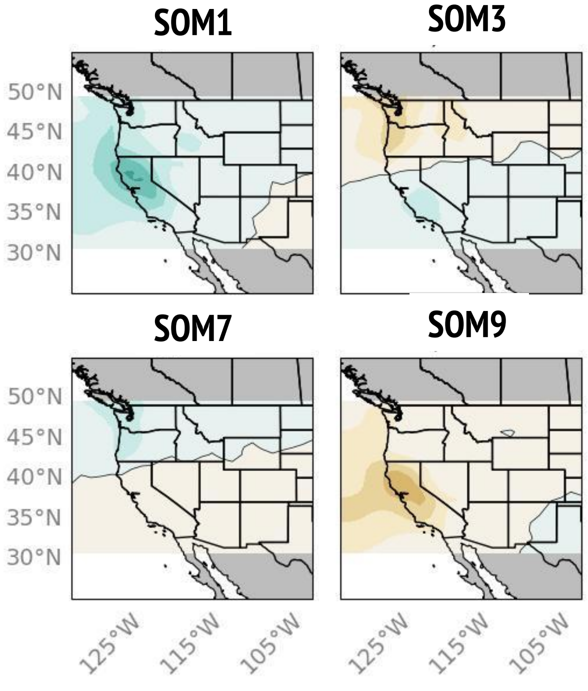
Dynamic change

What spatial patterns lead to the variability in projected precipitation change?

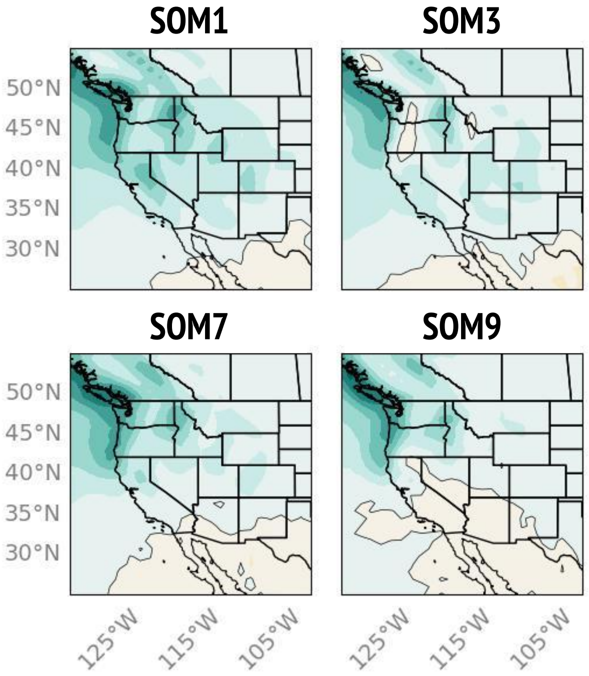
Total precipitation change



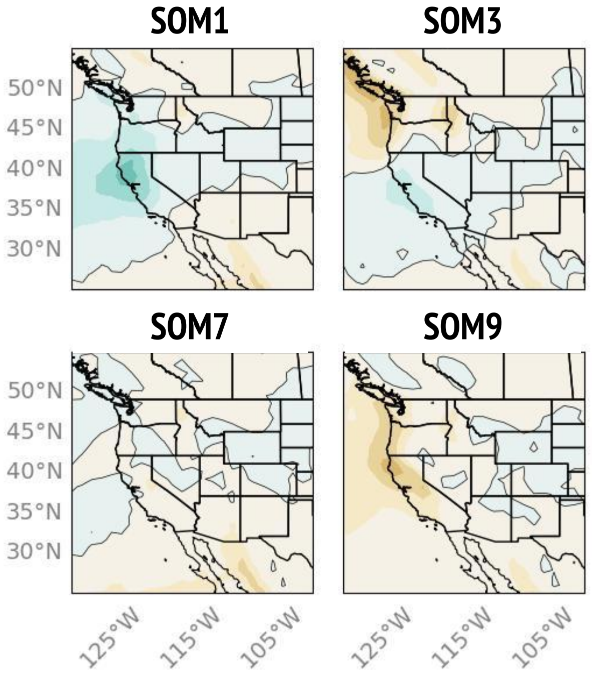
Total precipitation change, ensemble mean removed



Thermodynamic change

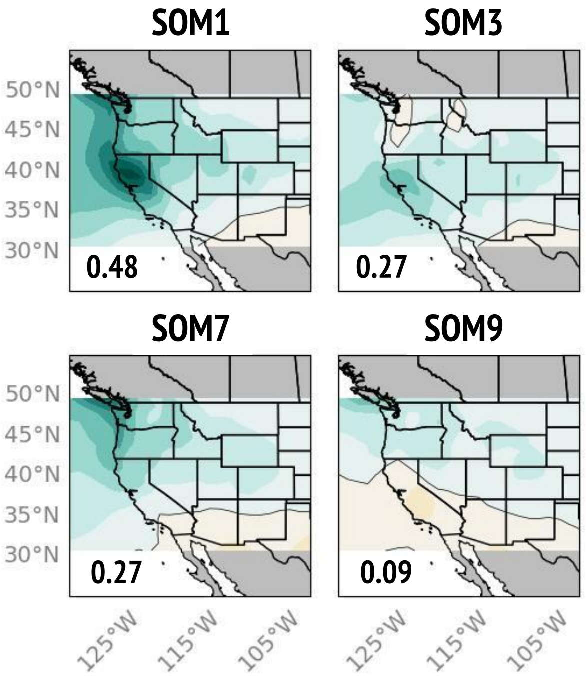


Dynamic change

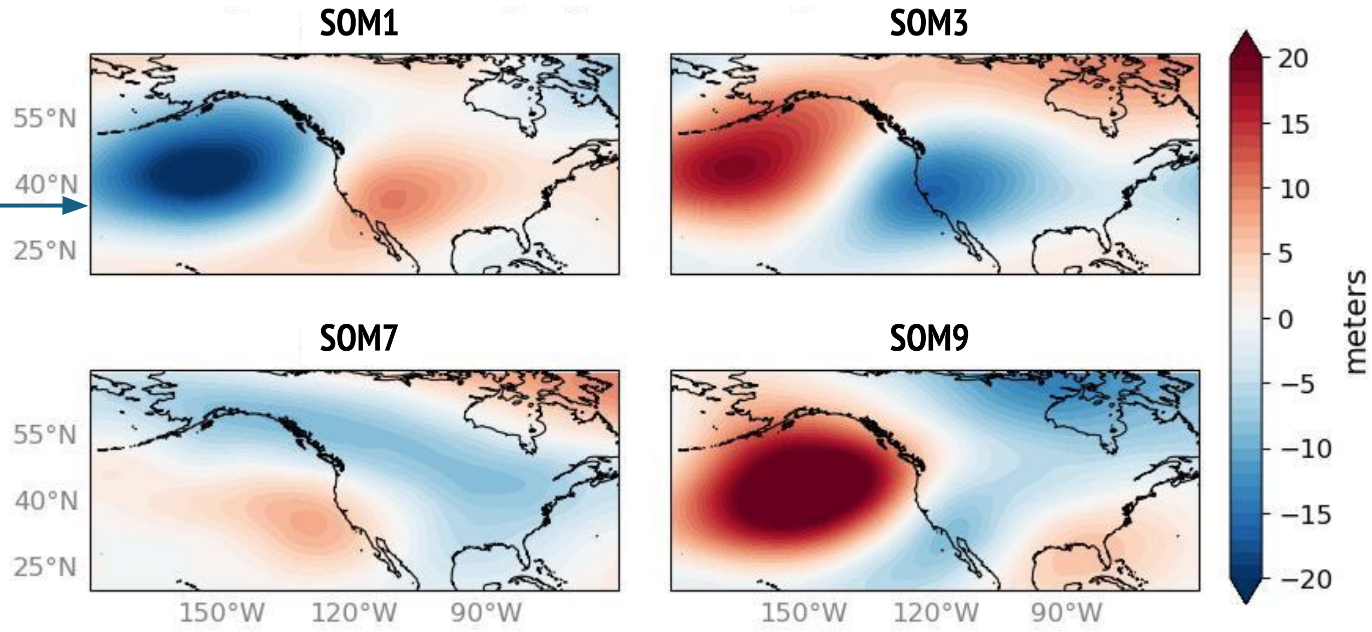


What are the large-scale atmospheric circulation changes across these SOMs?

Total precipitation change



500 hPa geopotential heights (zonal mean removed) change, ensemble mean removed

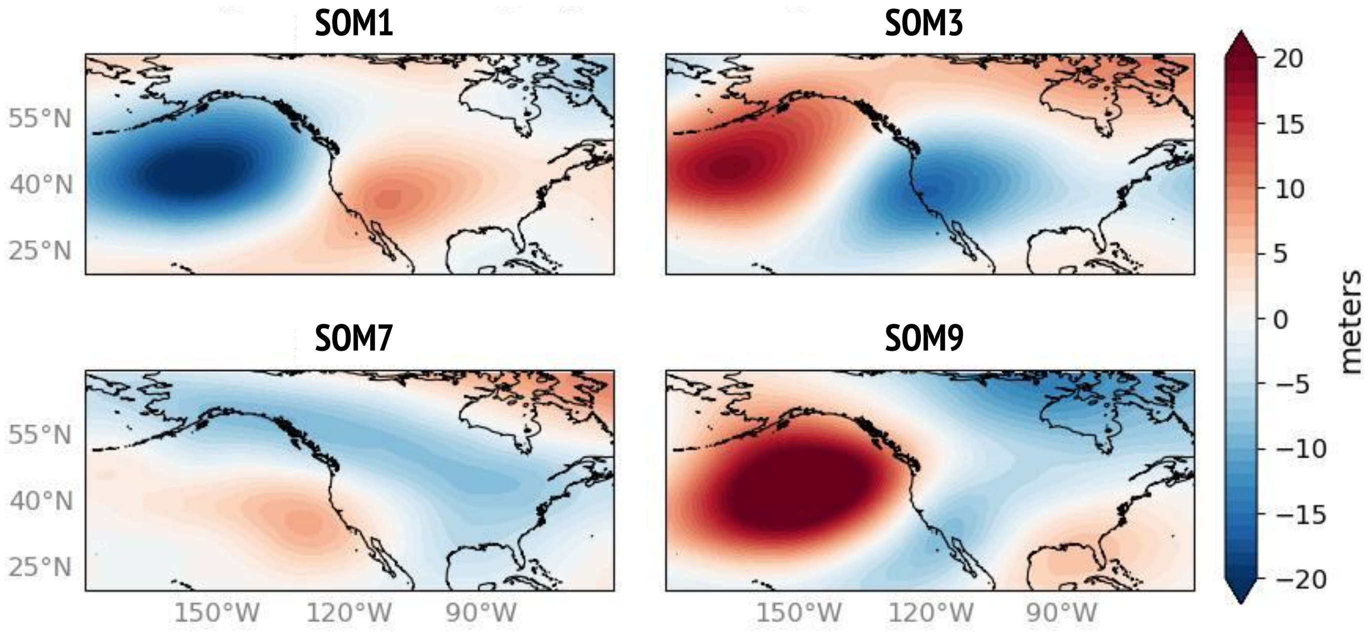


SOM1 has a strong negative trend that allows the eastward extension and strengthening of the subtropical jet

Question 1: **Can we better understand the role of internal variability on precipitation change by quantifying the relative contributions of dynamic vs. thermodynamic changes in the CESM2 Large Ensemble?**

- Why do some ensemble members see an expansion and strengthening of the jet while others do not?
- Can this help us rule out some of the scenarios in CESM2?
  - Similar to questions posed by Grise (2022; *GRL*)

500 hPa geopotential heights (zonal mean removed) change, ensemble mean removed



Driving research questions

1. Can we better understand the role of internal variability on precipitation change by quantifying the relative contributions of **dynamic** vs. **thermodynamic** changes in the CESM2 Large Ensemble?

2. Using idealized experiments, **what is the influence of warming alone on precipitation change?**

CAM6 experimental design

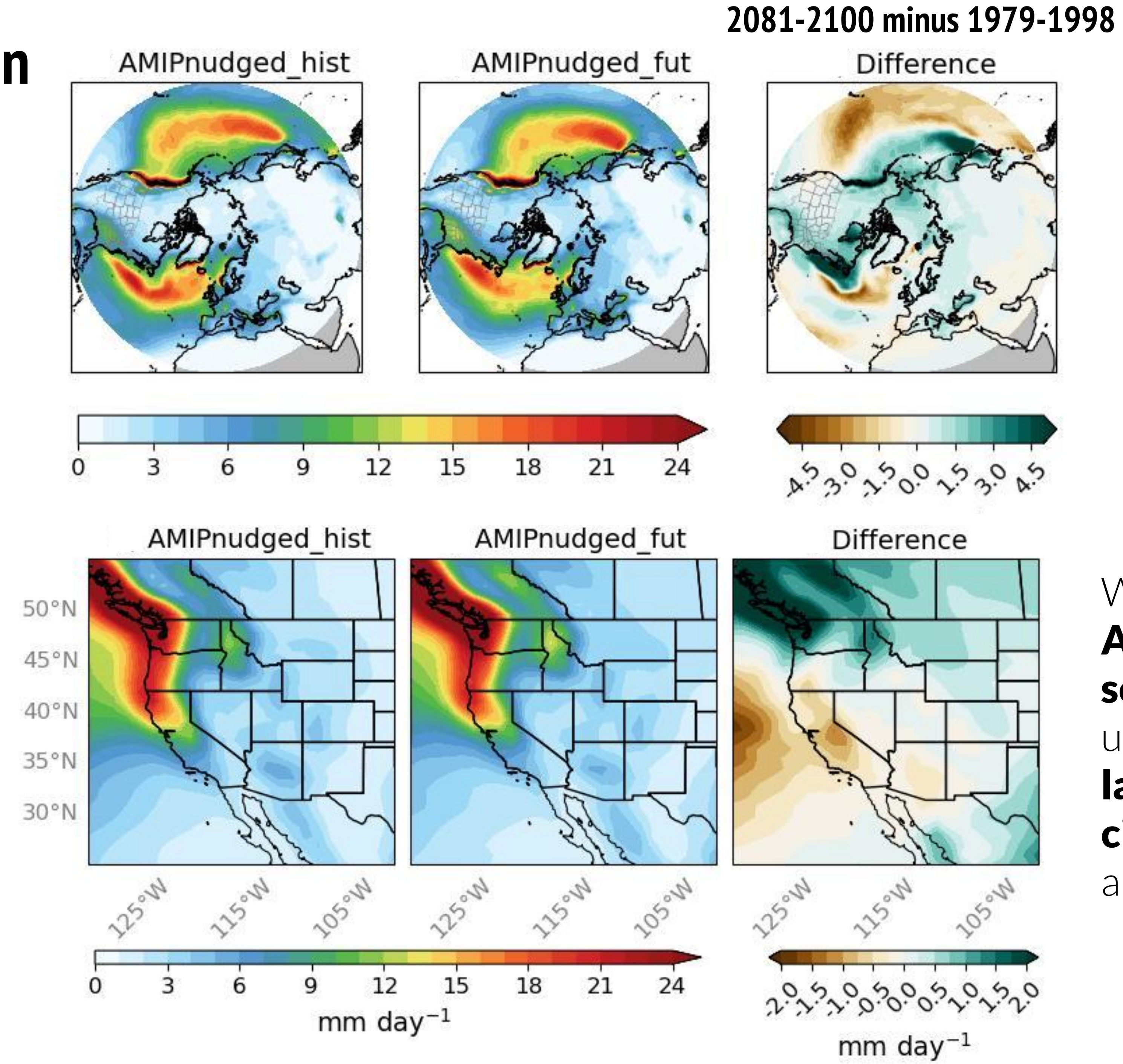
AMIPnudged_hist

- Winds nudged to ERA5 reanalysis every 6 hours from 850 hPa to the top of the atmosphere
- 1979-2014
- Prescribed historical SSTs and sea ice extent

AMIPnudged_fut

- Winds nudged to ERA5 reanalysis every 6 hours from 850 hPa to the top of the atmosphere
- 1979-1998
- Prescribed SSTs and sea ice extent taken from the CESM2-LE mean from 2081-2100

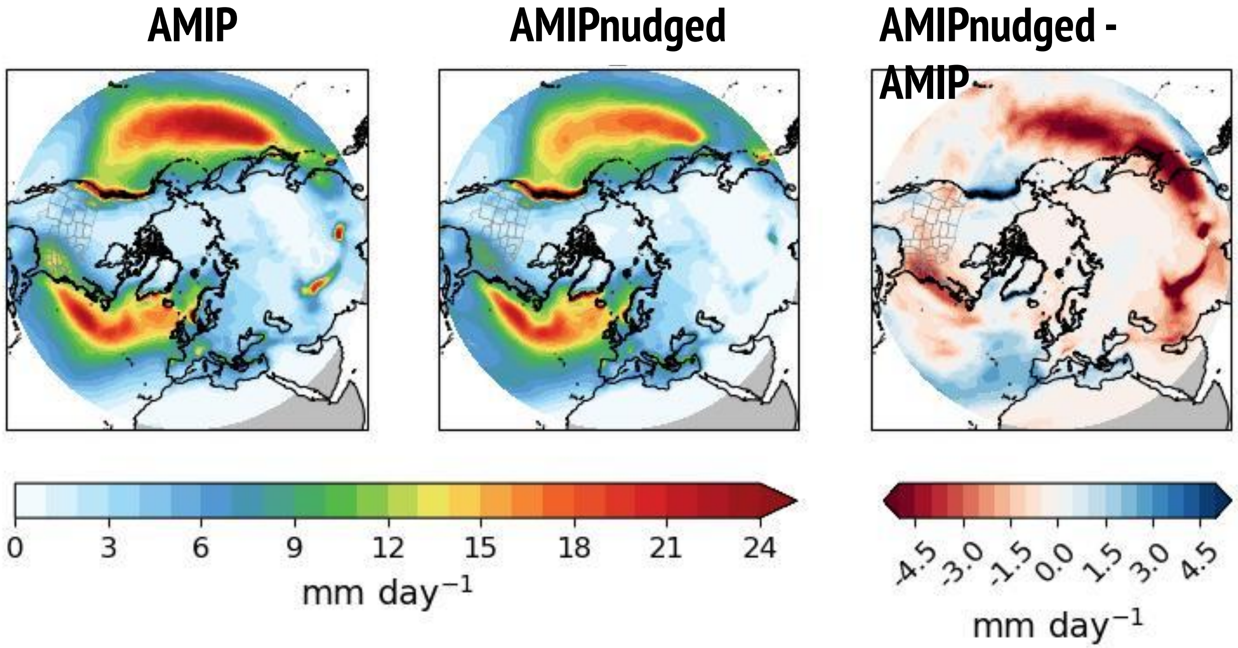
Total precipitation



Why would the **North American southwest get drier** under **historical large-scale circulation** patterns and a **warmer ocean** ?

Next steps

- What are the precipitation trends in each nudged run?
- What does the tropical Pacific look like for each nudged run?
- Can we use idealized simulations where we nudge horizontal winds to better understand hydroclimate trends?



References

Allen MR, Ingram WJ (2002) Constraints on future changes in climate and the hydrologic cycle. Nature 419(6903):224–232.

Bony, S., Dufresne, J. L., Le Treut, H., Morcrette, J. J., & Senior, C. (2004). On dynamic and thermodynamic components of cloud changes. *Climate dynamics*, *22*, 71-86.

Bony, S., Bellon, G., Klocke, D., Sherwood, S., Fermepin, S., & Denvil, S. (2013). Robust direct effect of carbon dioxide on tropical circulation and regional precipitation. *Nature Geoscience*, *6*(6), 447-451.

Doblas-Reyes, F.J., A.A. Sörensson, M. Almazroui, A. Dosio, W.J. Gutowski, R. Haarsma, R. Hamdi, B. Hewitson, W.-T. Kwon, B.L. Lamptey, D. Maraun, T.S. Stephenson, I. Takayabu, L. Terray, A. Turner, and Z. Zuo, 2021: Linking Global to Regional Climate Change. InClimate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1363–1512, doi: 10.1017/9781009157896.012.

Emori, S., and S. J. Brown (2005), Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate, *Geophys. Res. Lett.*, 32, L17706, doi:10.1029/2005GL023272.

Held, I.M., Soden, B.J. (2006) Robust responses of the hydrological cycle to global warming. J Clim 19:5686–5699.

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

Marvel, K., & Bonfils, C. (2013). Identifying external influences on global precipitation. Proceedings of the National Academy of Sciences, 110(48), 19301-19306.

Seidel, D.J., Fu, Q., Randel, W.J., Reichler, T.J. (2007) Widening of the tropical belt in a changing climate. Nat Geosci 1:21–24.

Shindell, D.T., Schmidt, G.A. (2004) Southern hemisphere climate response to ozone changes and greenhouse gas increases. Geophys Res Lett 31:L18209.