CESM Annual Workshop
ESPWG Session
June 11, 2024

From AMOC to Impacts:

The Resolution Sensitivity of Coupled Model Response to Persistent NAO Buoyancy Forcing

Steve Yeager[1], Jon Robson[2], Who Kim[1], Nan Rosenbloom[1]

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- Decadal Atlantic Ocean memory associated with persistent NAO buoyancy forcing is hypothesized to be a key source of decadal prediction skill.

NAO drives NADW formation.

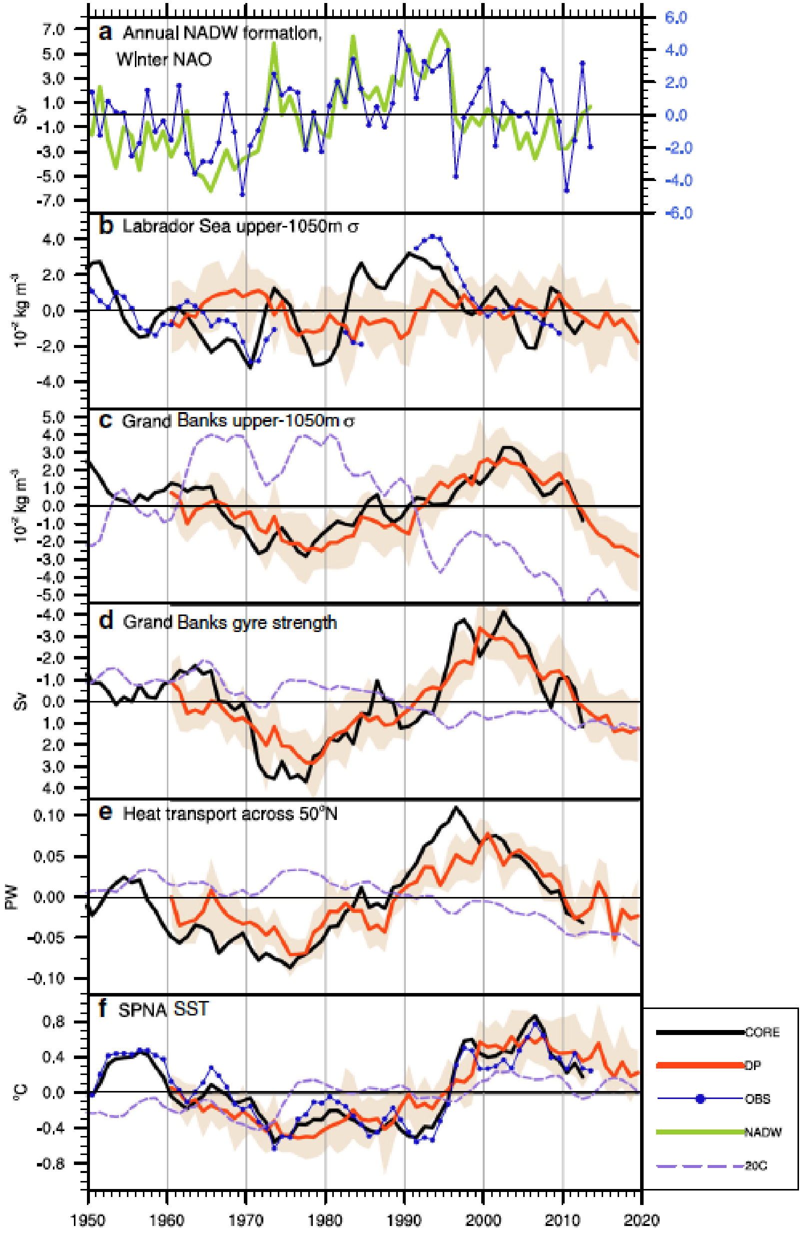
Corresponding Lab Sea density changes are present in DP initial conditions, but they are not well predicted.

However, southeastward export of initialized NADW signals <u>is</u> well predicted.

This yields high predictability for decadal variations in THC strength,

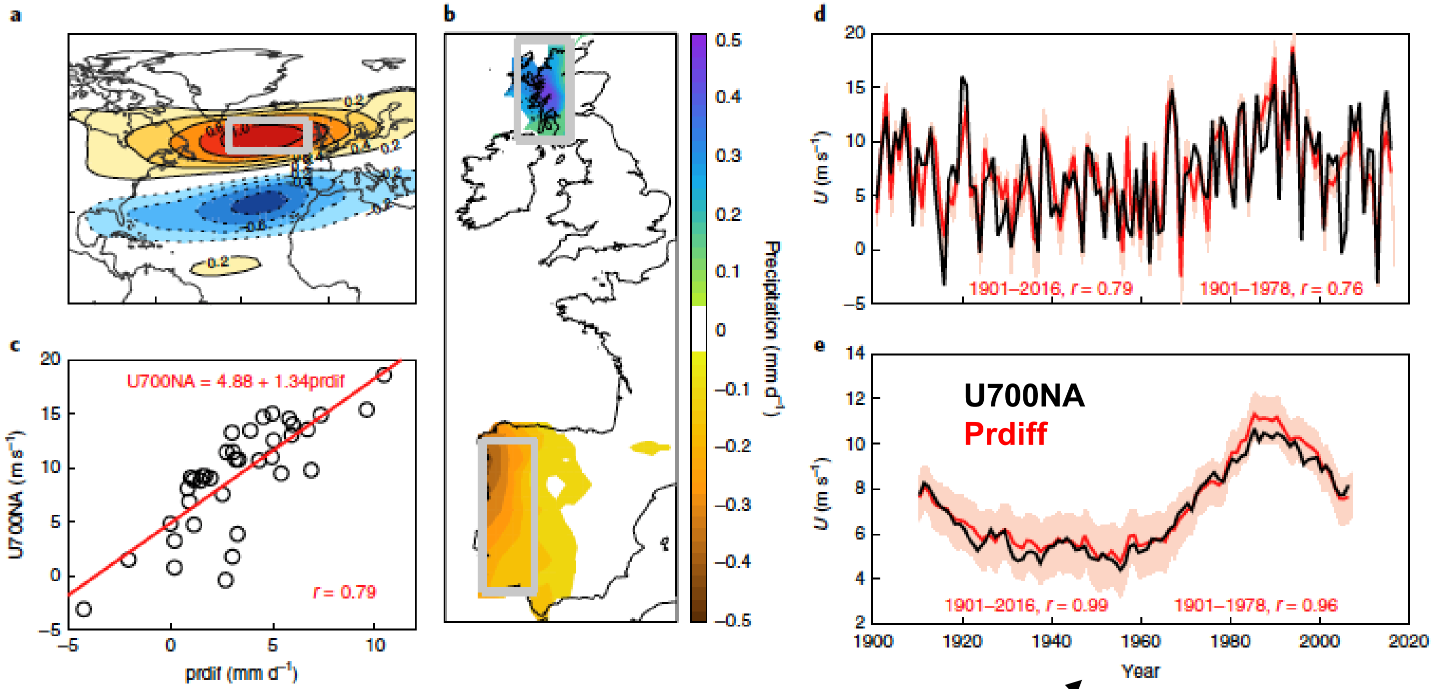
meridional ocean heat transport,

& subpolar Atlantic heat content and SST.



Yeager & Robson (2017, *Curr Clim Change Rep*)

Covariability between N. Atlantic Jet and W. European precipitation (**March**):

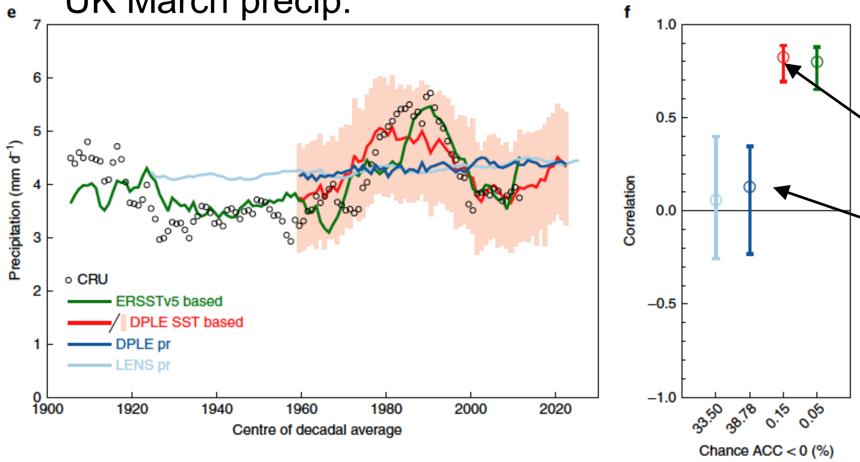


- Decadal skill for impacts over land is much lower than for SPNA SST

- The observed connection between low-frequency N. Atlantic SST, jet latitude, and European winter precipitation is too weak in CESM1-DPLE, necessitating a combined dynamical/statistical prediction approach

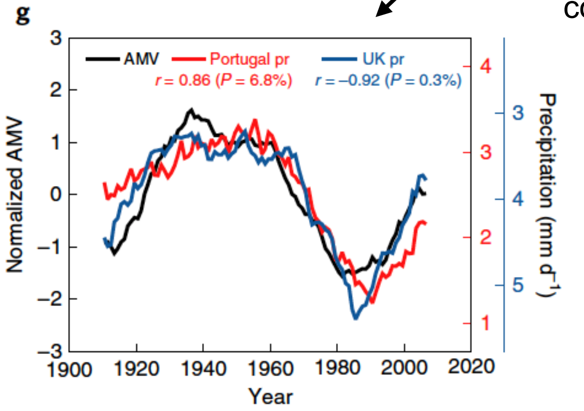
Simpson et al. (2019, *Nat Geosci*)

UK March precip:



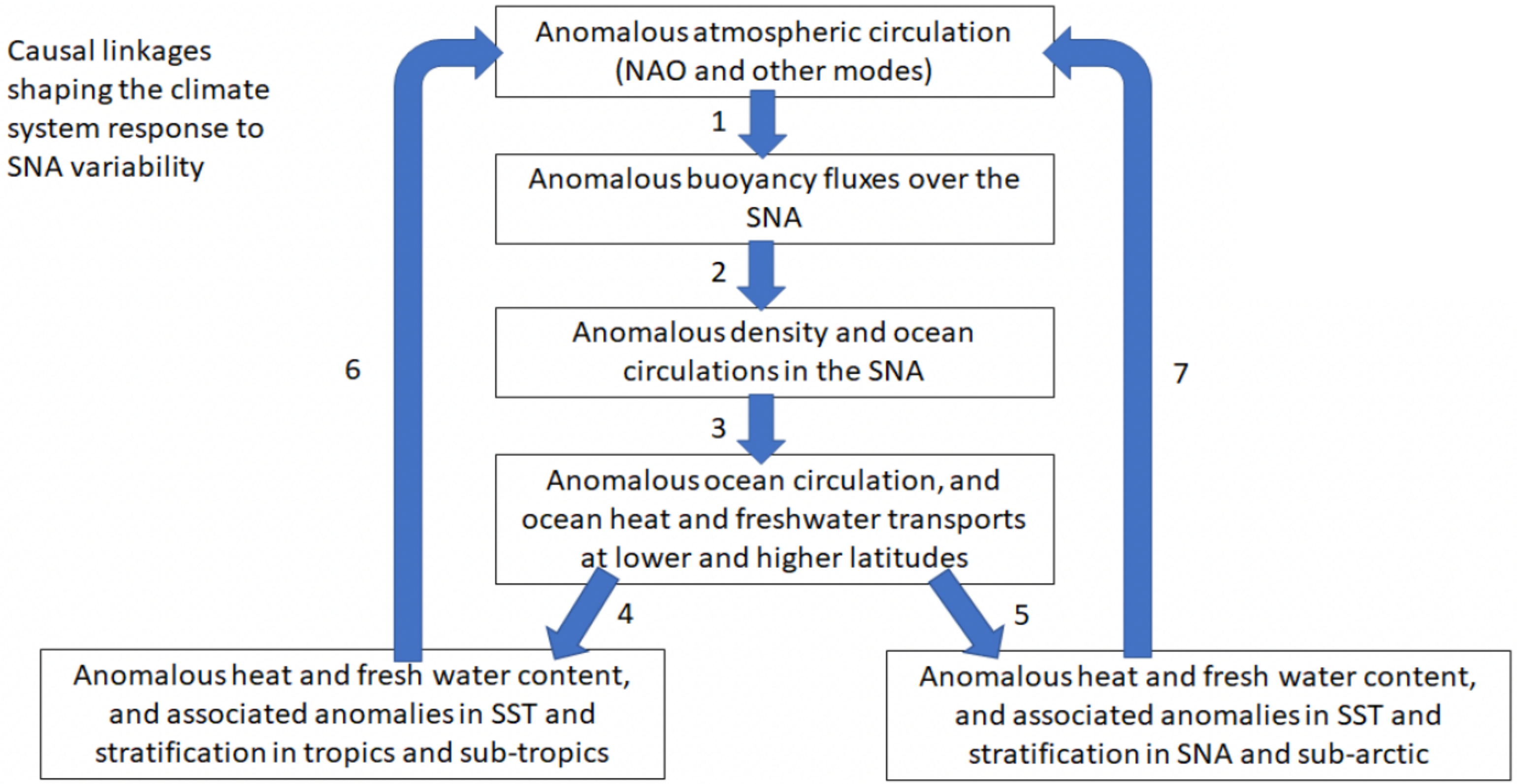
using DPLE SST

raw DPLE



High observed correlation with AMV

- Wider impacts of Subpolar North Atlantic decadal variability on the ocean and atmosphere (WISHBONE)

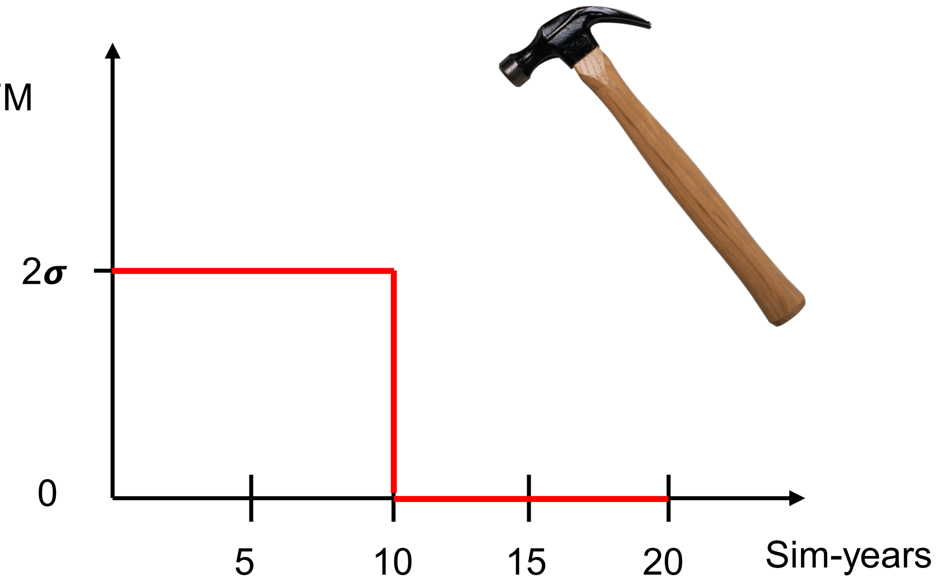


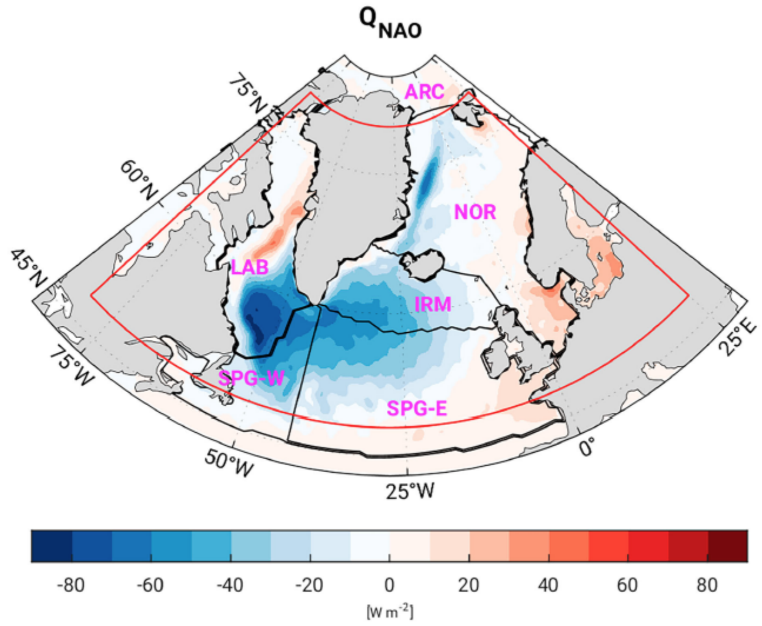
NSF Award 2040020

Experiment Design

Aim: Isolate the ocean & coupled ocean/atmosphere response to buoyancy-driven AMOC change.

- WISHBONE fully-coupled "BSPNA" experiment (inspired by Delworth et al. 2016, 2017)
  - forcing in SPNA region = observed 2σ DJFM NAO net heat flux (ERA5)
  - NAO+ forcing for 10 consecutive winters followed by 10 (to 20) unforced years
  - multiple ensemble members to separate "forced" vs. "internal" variability





Kim et al. (2024, *J Clim*)

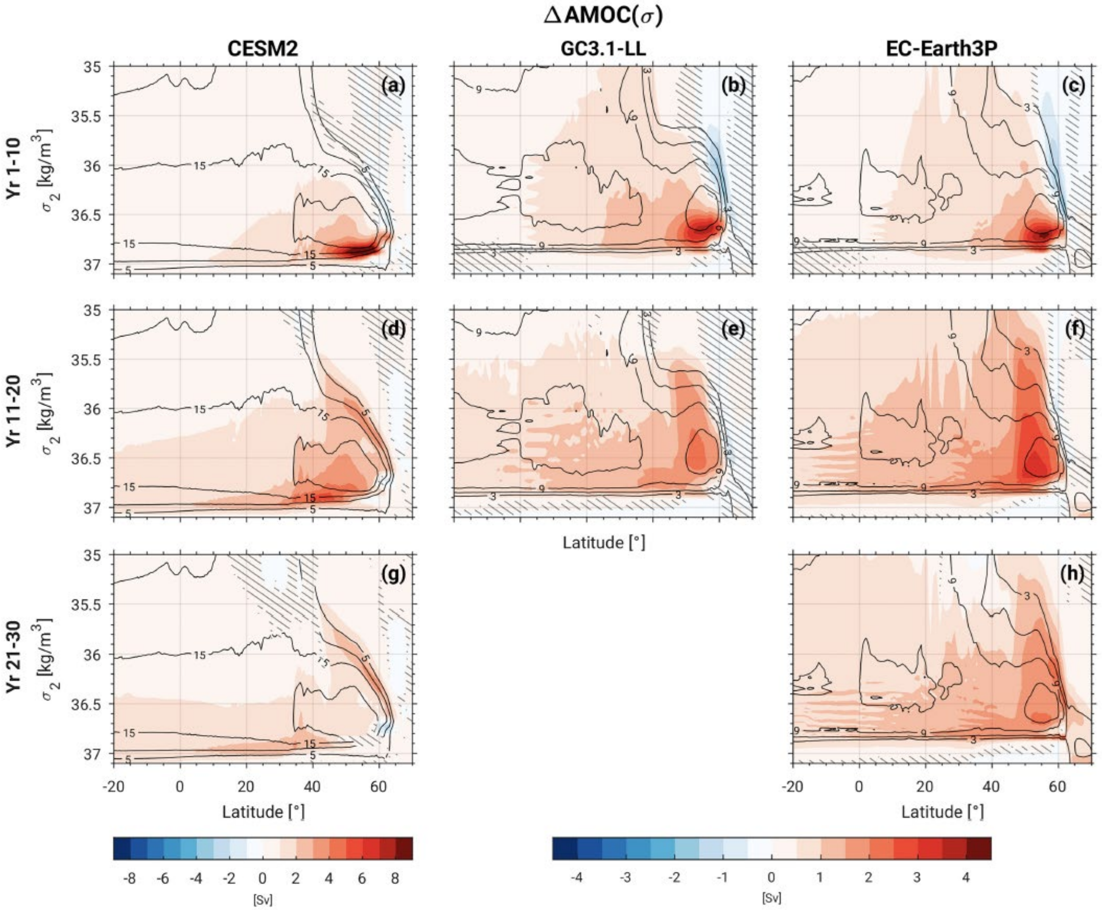
North Atlantic Response to Observed North Atlantic Oscillation Surface Heat Flux in Three Climate Models

Who M. Kim,[a] Yohan Ruprich-Robert,[b] Alcide Zhao,[c] Stephen Yeager,[a] and Jon Robson[c]

Kim et al. (2024, *J Clim*)

Forcing Period

No Forcing Period

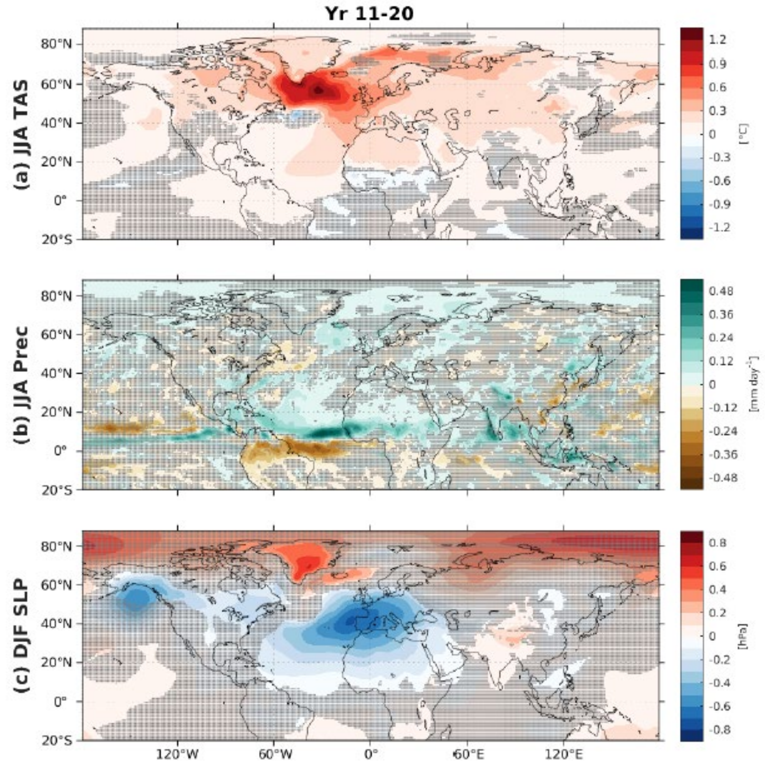


Broadly consistent ocean response:

- initial densification of AMOC lower limb
- persistent SPNA AMOC signal associated with dense LSW thickness anomalies & steric zonal SSH gradient
- anomalous WMT in SPNA-West dominates

Amplitude of AMOC response set by density outcrop area.

Evidence of AMV-like impacts:



NEW: Extend to HR

Aim: Isolate the ocean & coupled ocean/atmosphere response to buoyancy-driven AMOC change.

- WISHBONE fully-coupled “BSPNA” experiment (inspired by Delworth et al. 2016, 2017)
  - perturbed heat flux in SPNA region = 2σ DJFM NAO
  - NAO+ forcing for 10 consecutive winters followed by 10 unforced years
  - multiple ensemble members to separate “forced” vs. “internal” variability

- **LR**:
  - CESM2 (~1° ocean, ~1° atmosphere)
  - 20-member ensemble of 30-year NAO+ simulations (Kim et al. 2024)
  - initialized at 20 year intervals from CESM2 long PI-control simulation

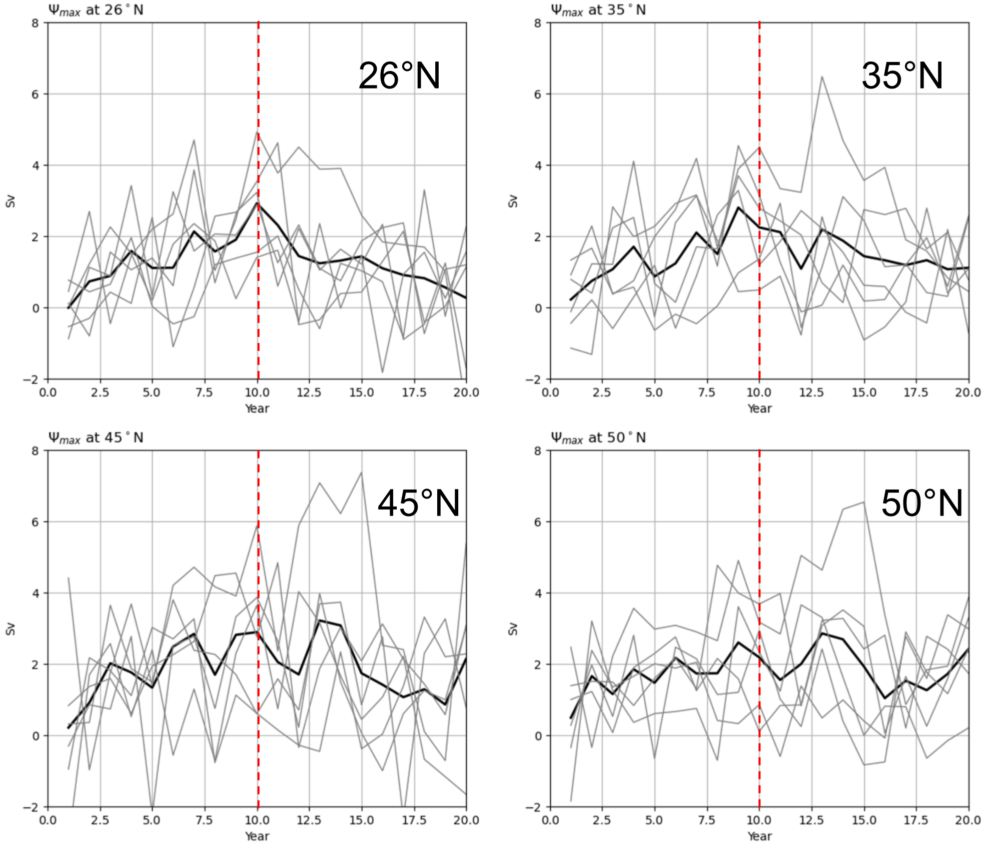
- **HR**:
  - CESM1 (~0.1° ocean, ~0.25° atmosphere)
  - 7-member ensemble of 20-year NAO+ simulations
  - initialized at 3-10 year intervals from HighResMIP (~100-year) 1950 control simulation

Methods

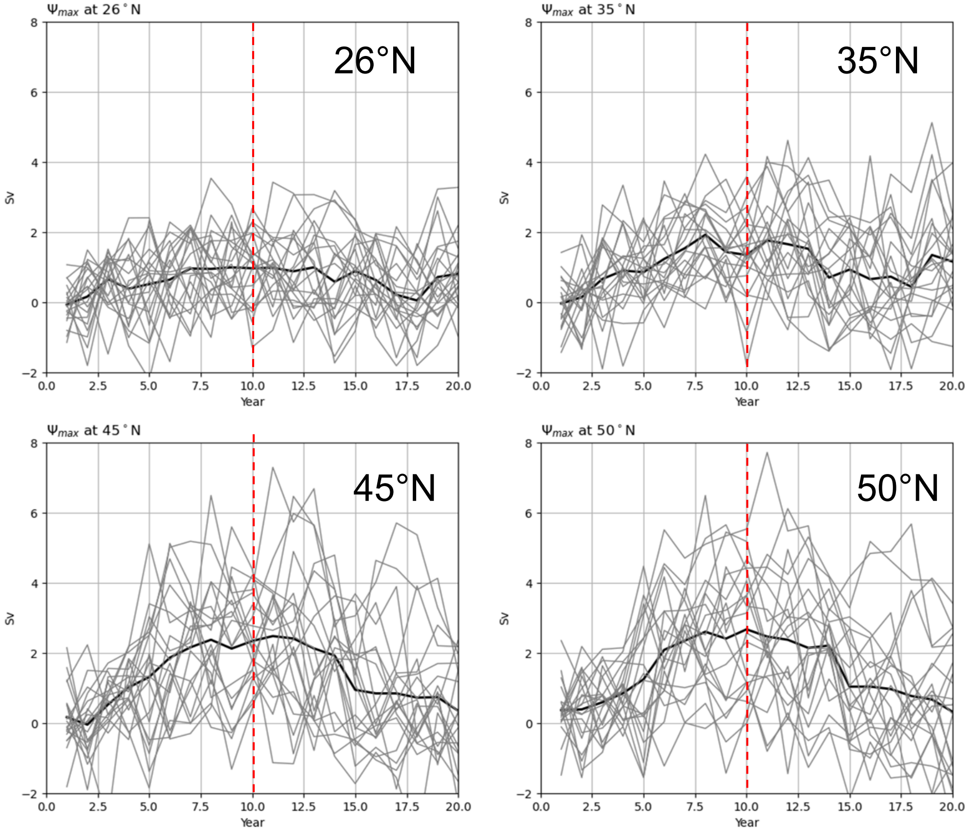
- Consider positive forcing experiment only (NAO+)
- **S**: Signal(t) = [NAO^+(i, t) – CONTROL(t)].mean(‘i’), where ‘i’ is member
- N: Noise(t) = [NAO^+(i, t) – CONTROL(t)].std(‘i’)
- **S2N** = Signal(t)/Noise(t)
  - in units of **σ**
  - S2N>1 : 84% confidence in sign of response
- Focus on pentadal/decadal average response to forcing

Annual AMOC(σ)$_{max}$

HR (6)



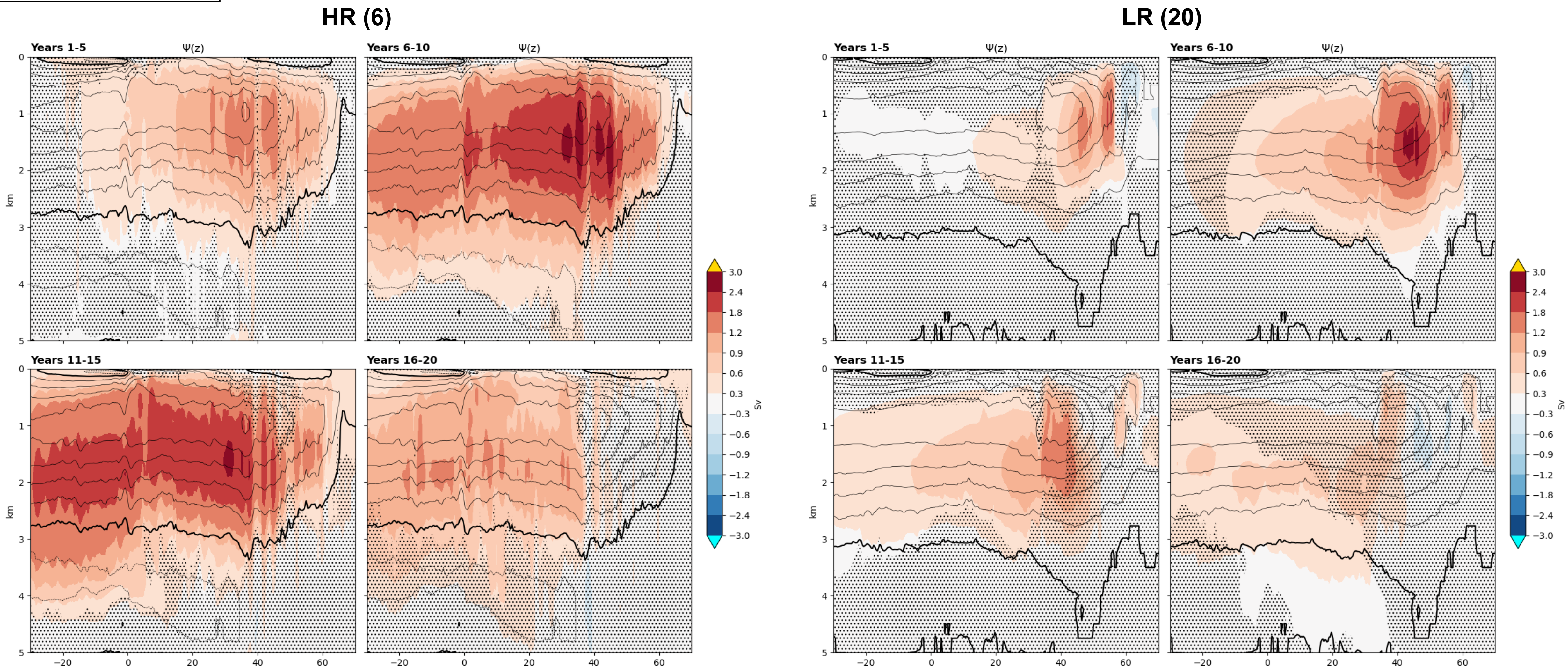
LR (20)



- Similar magnitude signals north of ~35°N that grow/persist well past end of forcing
- Stronger subtropical signal in HR

Annual AMOC(z)

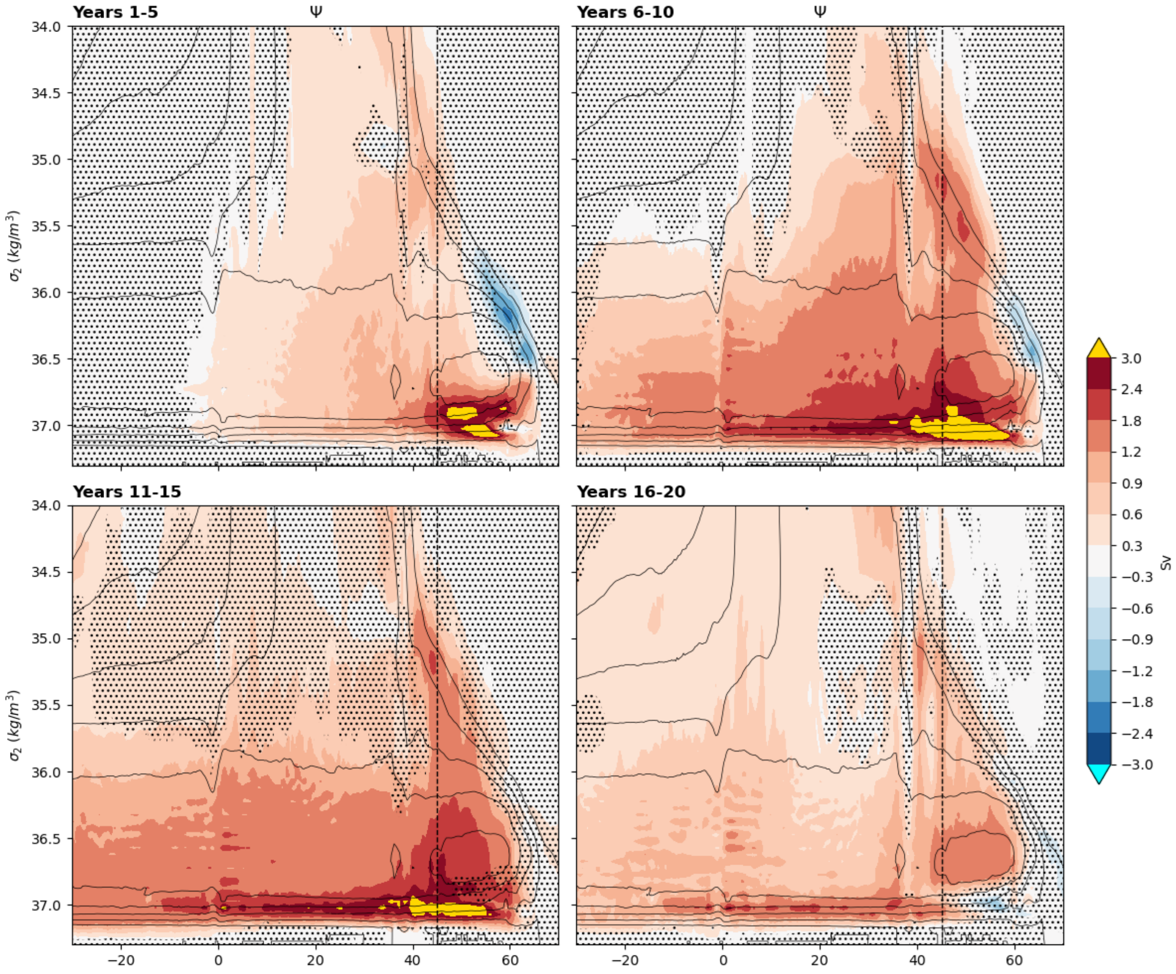
(stippled where S2N<1)



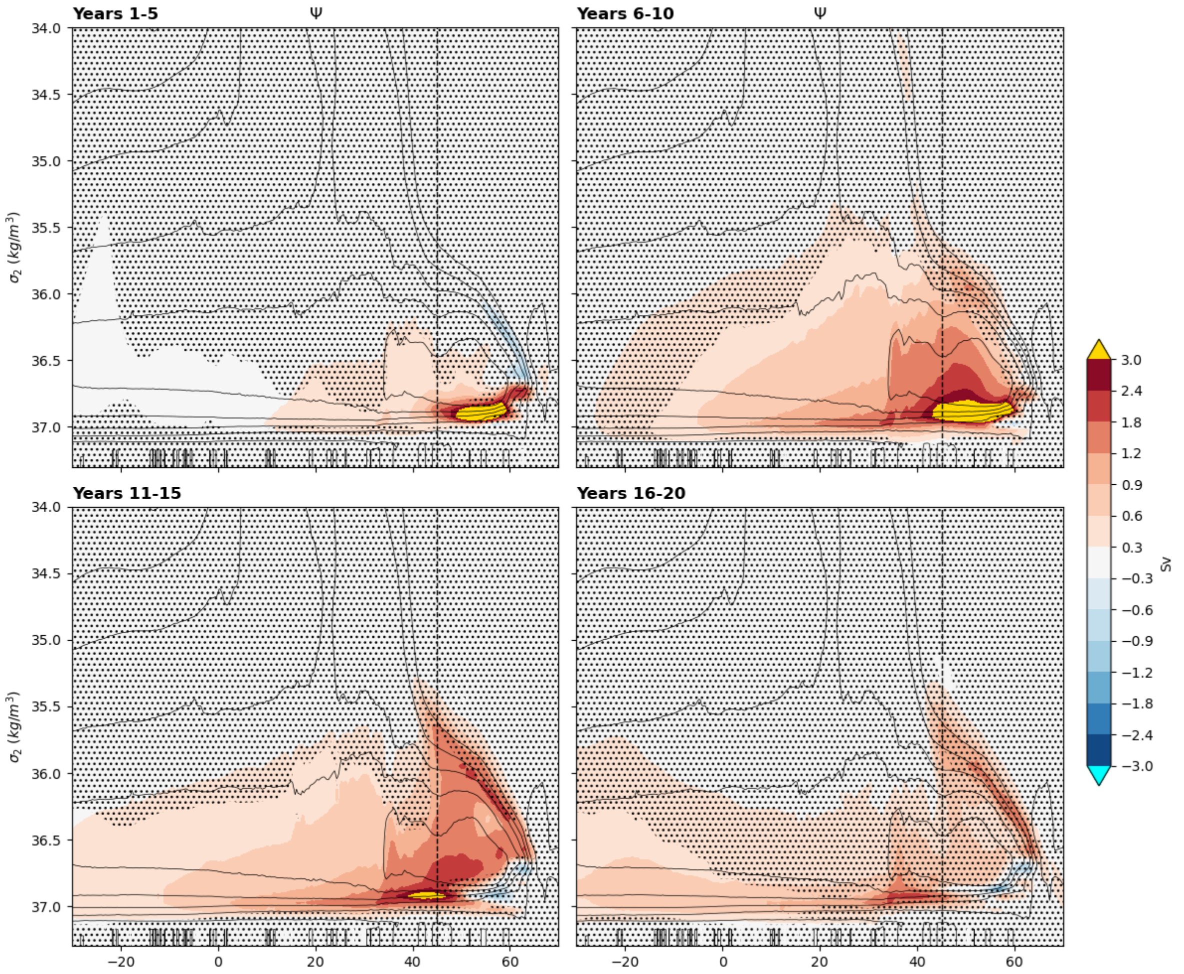
- Stronger, more persistent, more coherent AMOC signal in HR (with higher S2N)
- Signal is most prominent in lower limb (deeper, denser flow)

Annual AMOC(σ)

HR (6)

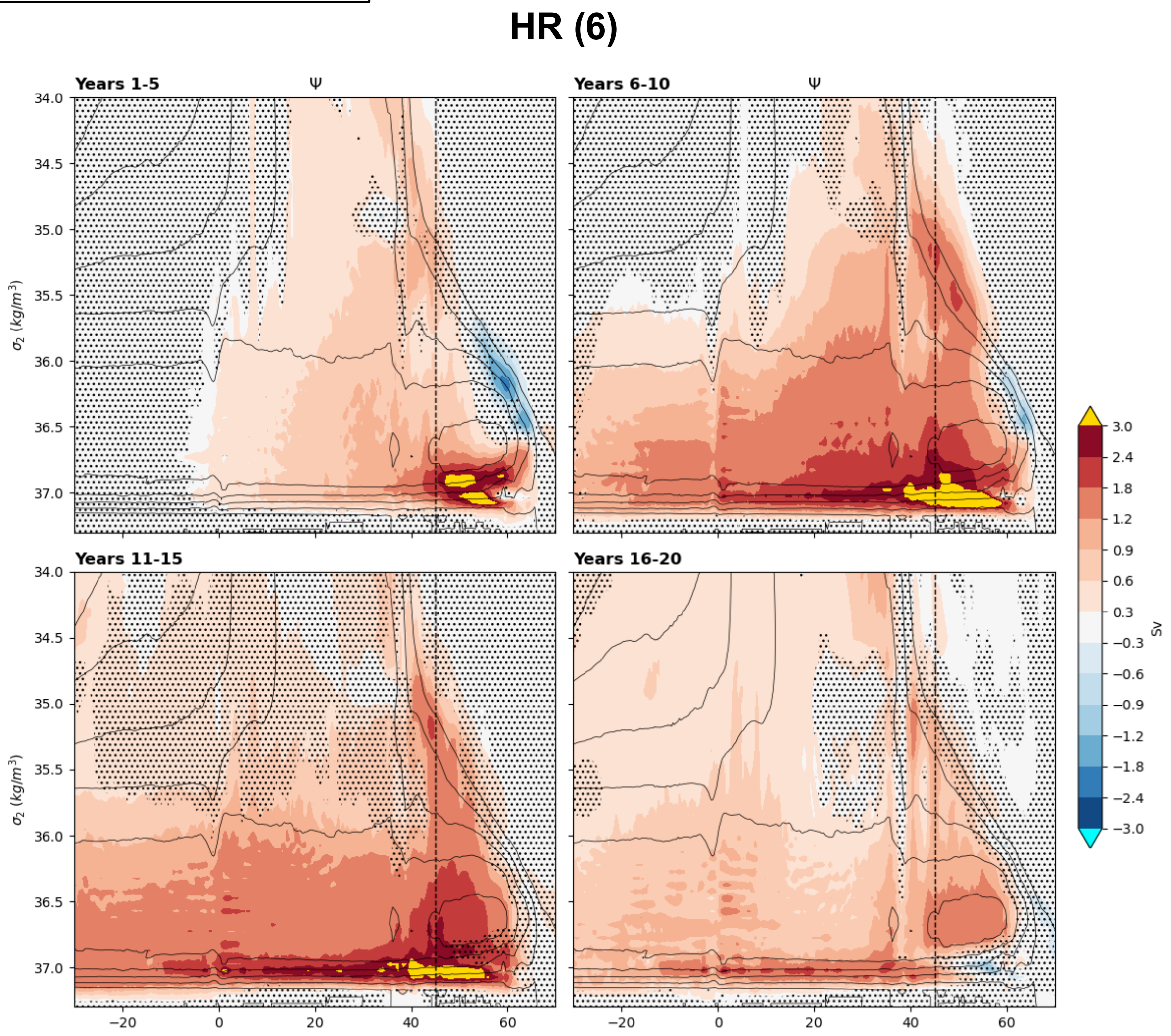


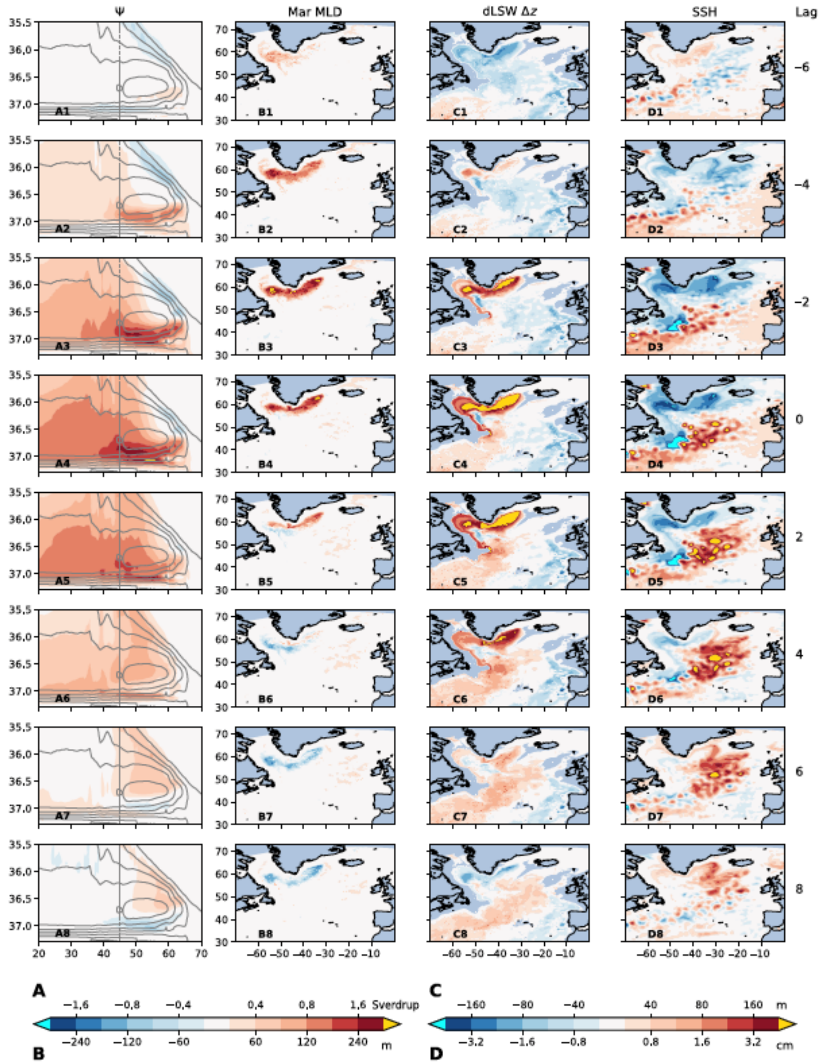
LR (20)



- Immediate effect of forcing is to **densify** (not strengthen) SPNA overturning
- Delayed response: strengthened overturning & lighter NAC

Annual AMOC(σ)



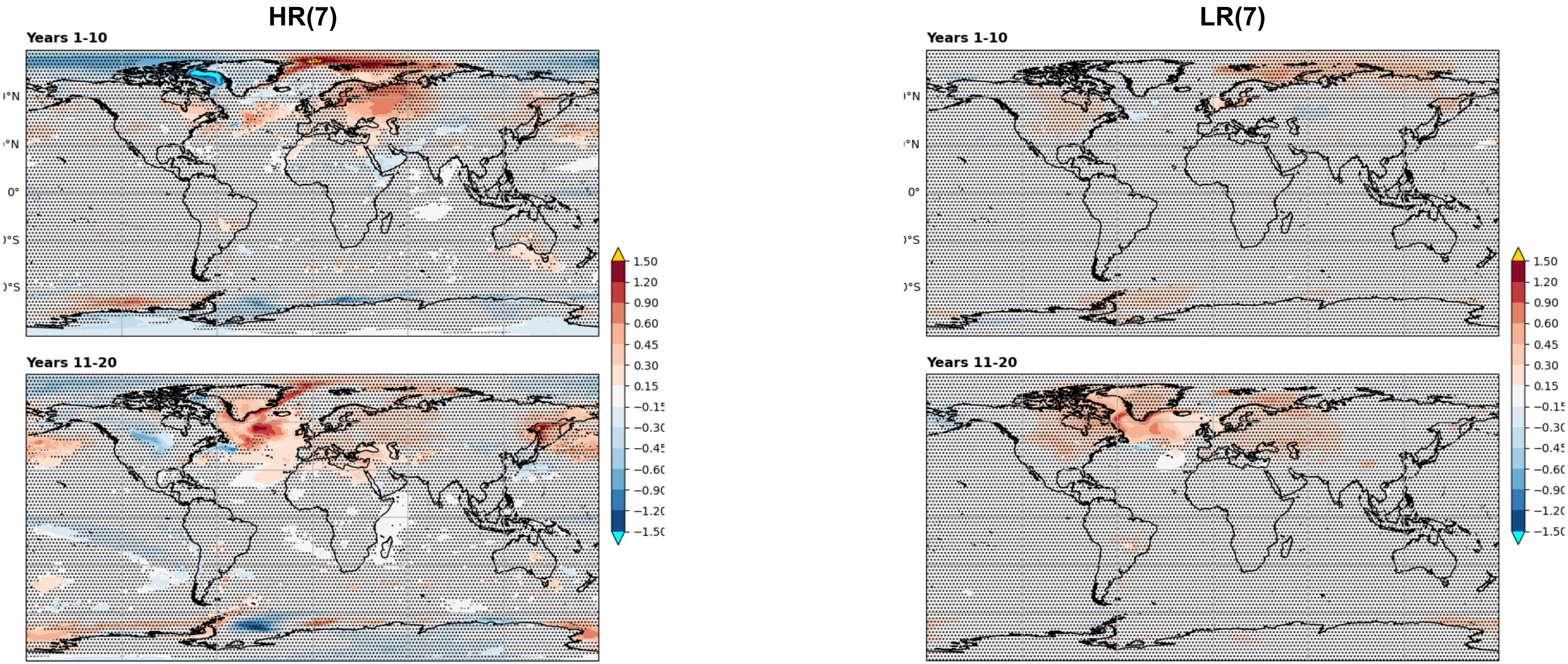


- AMOC($\boldsymbol{\sigma}$) evolution resembles that seen in long HR PI-control (Yeager et al. 2021)

- Immediate effect of forcing is to **densify** (not strengthen) SPNA overturning
- Delayed response: strengthened overturning & lighter NAC

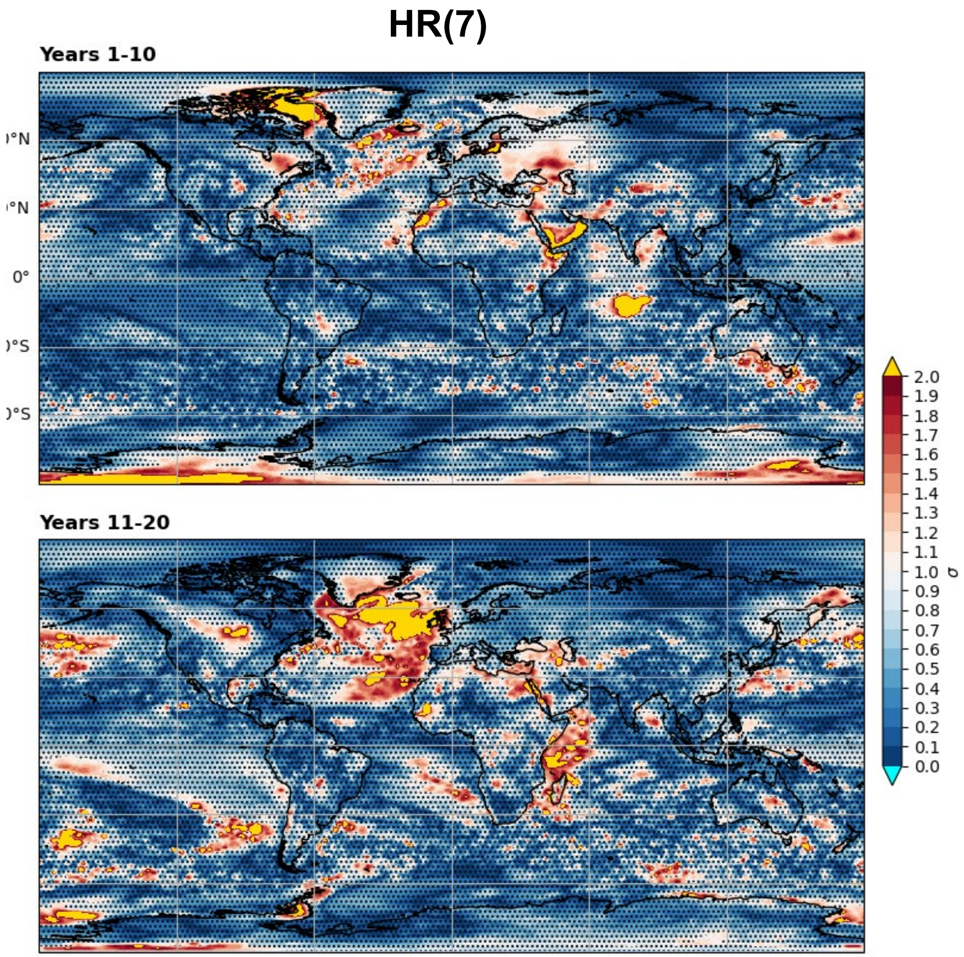
Annual Surface Temp

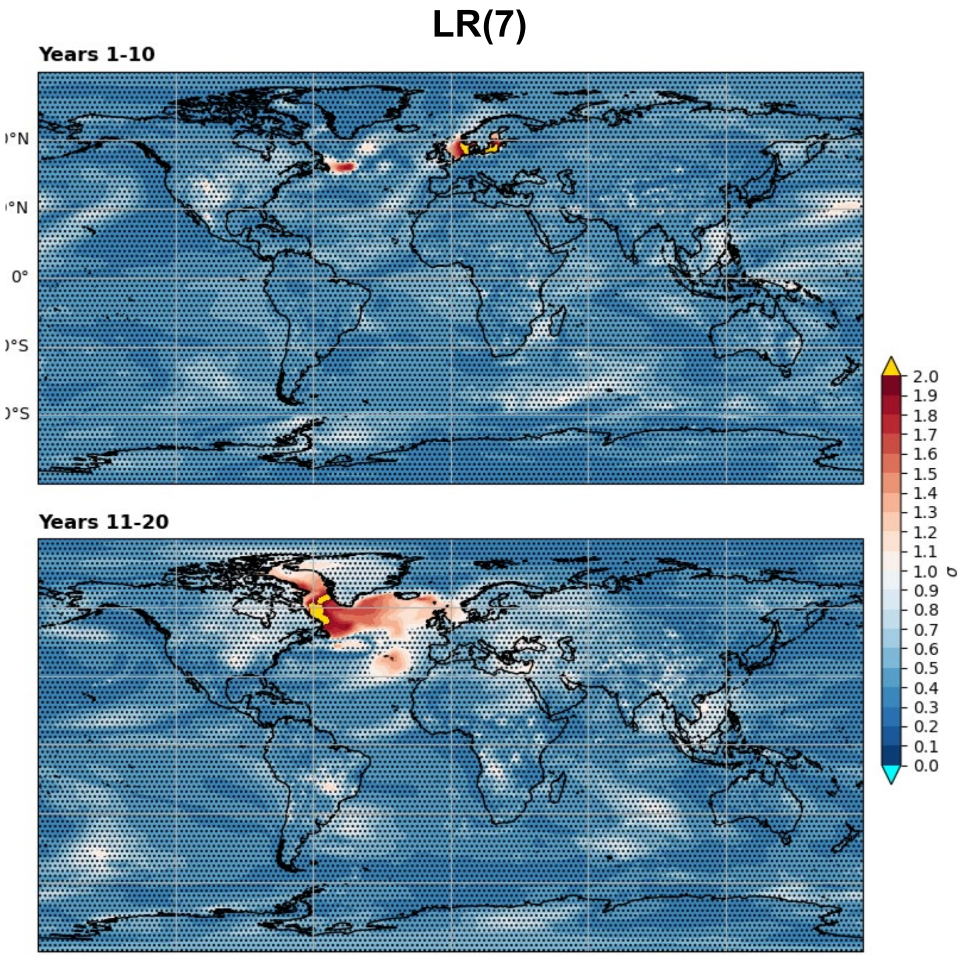
- Much stronger SAT signal in HR
  - greater ocean heat transport efficiency in HR (Chang et al. 2020)?
  - stronger coupled feedbacks?
- Pacific response limited to northern high latitudes
  - perhaps not fully developed?



Annual Surface Temp S2N

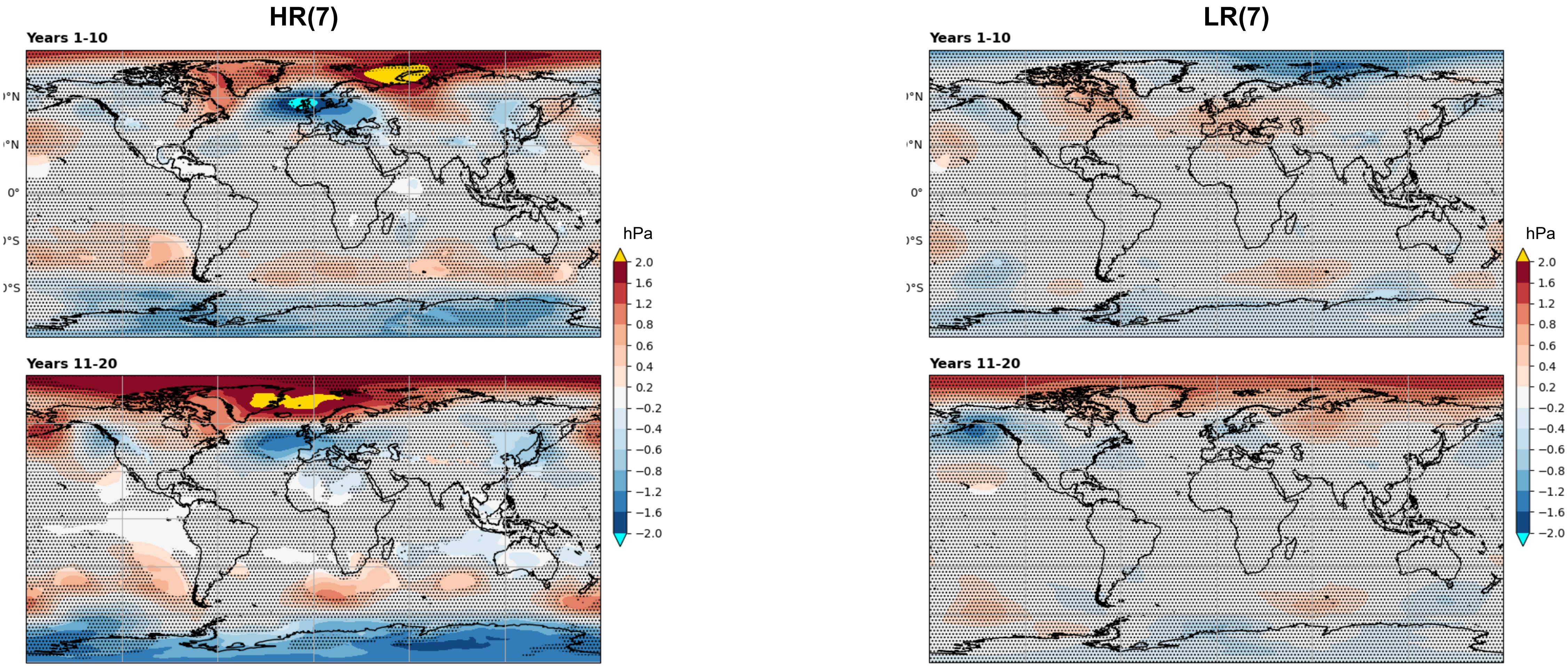
- Much higher S2N in HR





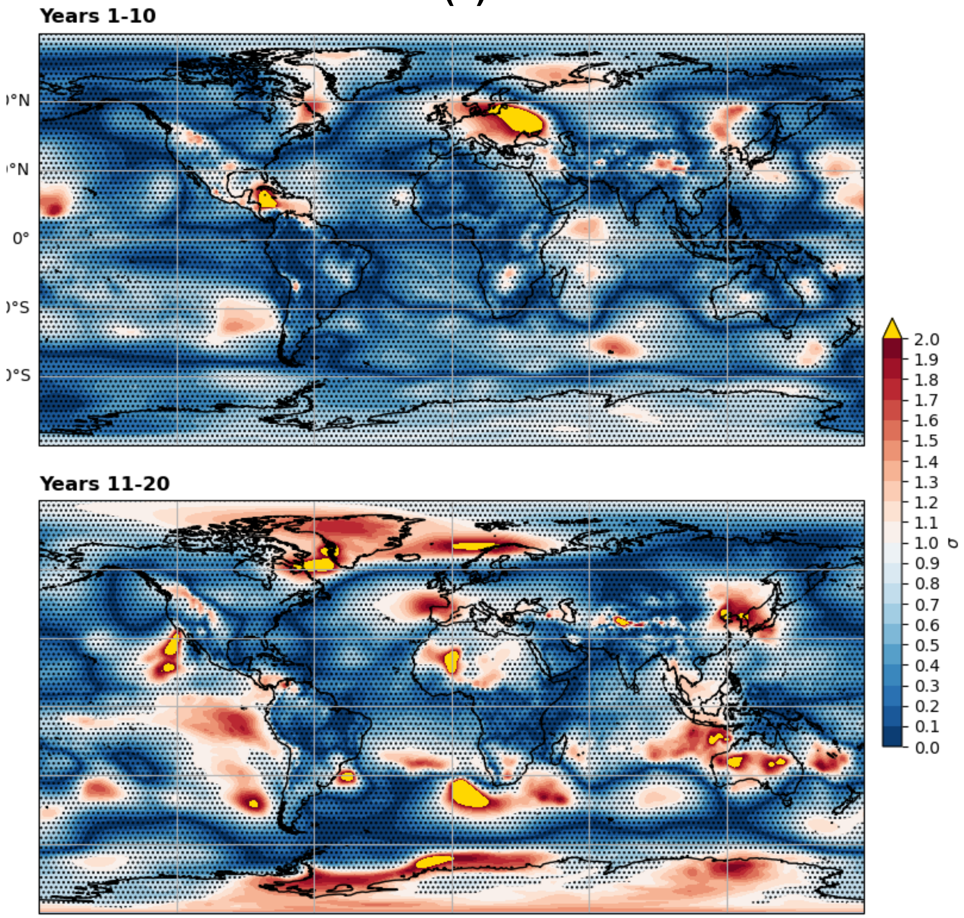
FMA SLP

- LR: no significant SLP response
- HR: - NAO+/EAP pattern during forcing
  - strong NAO- & positive SAM when AMV is fully developed

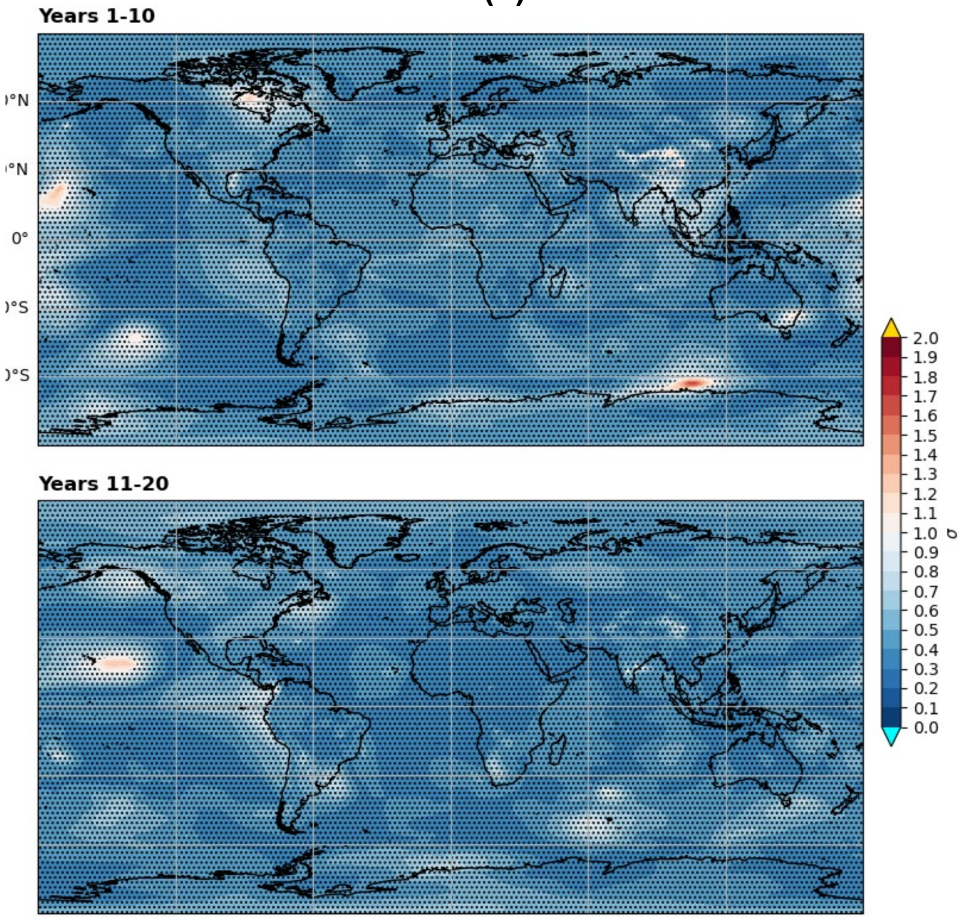


FMA SLP S2N

HR(7)

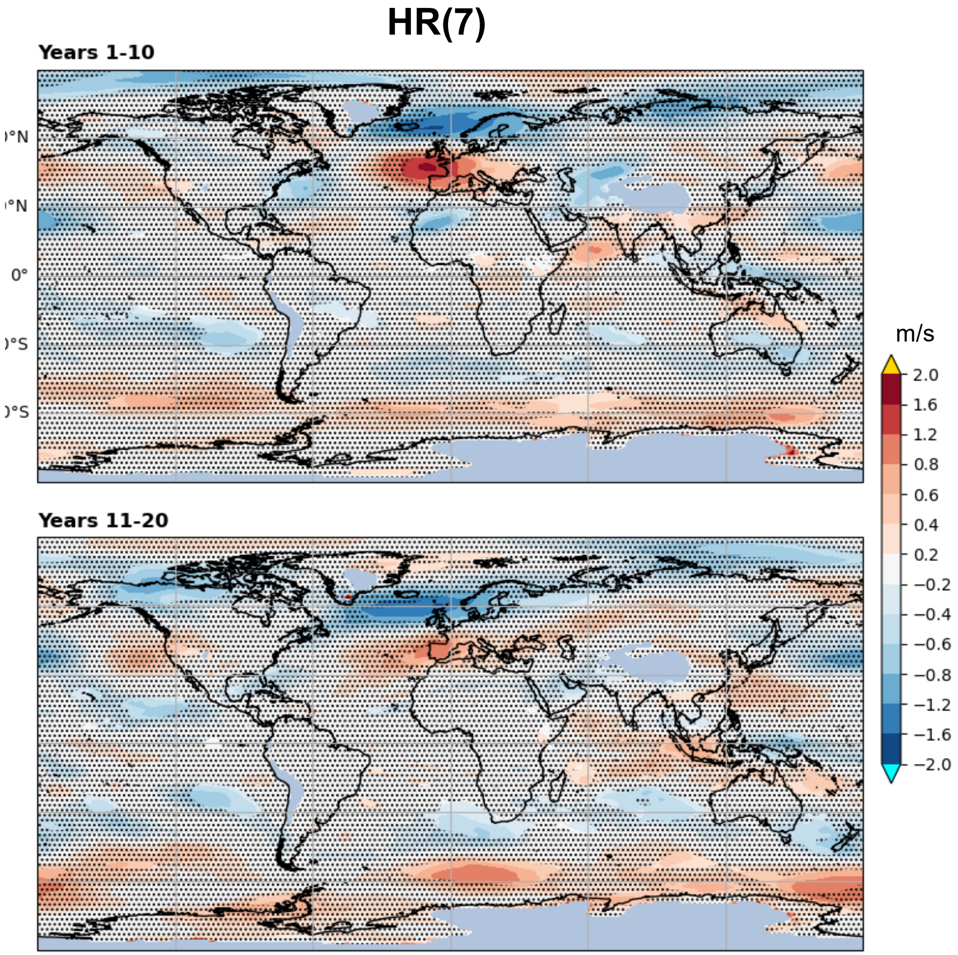


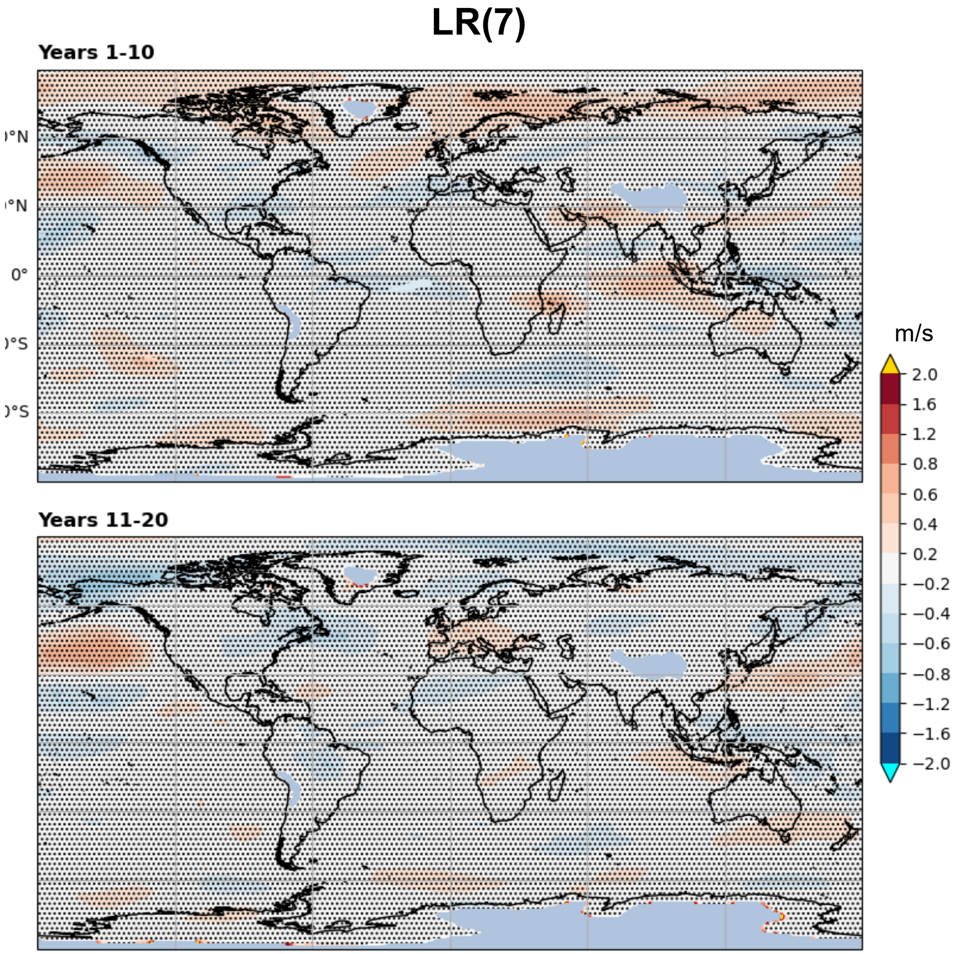
LR(7)



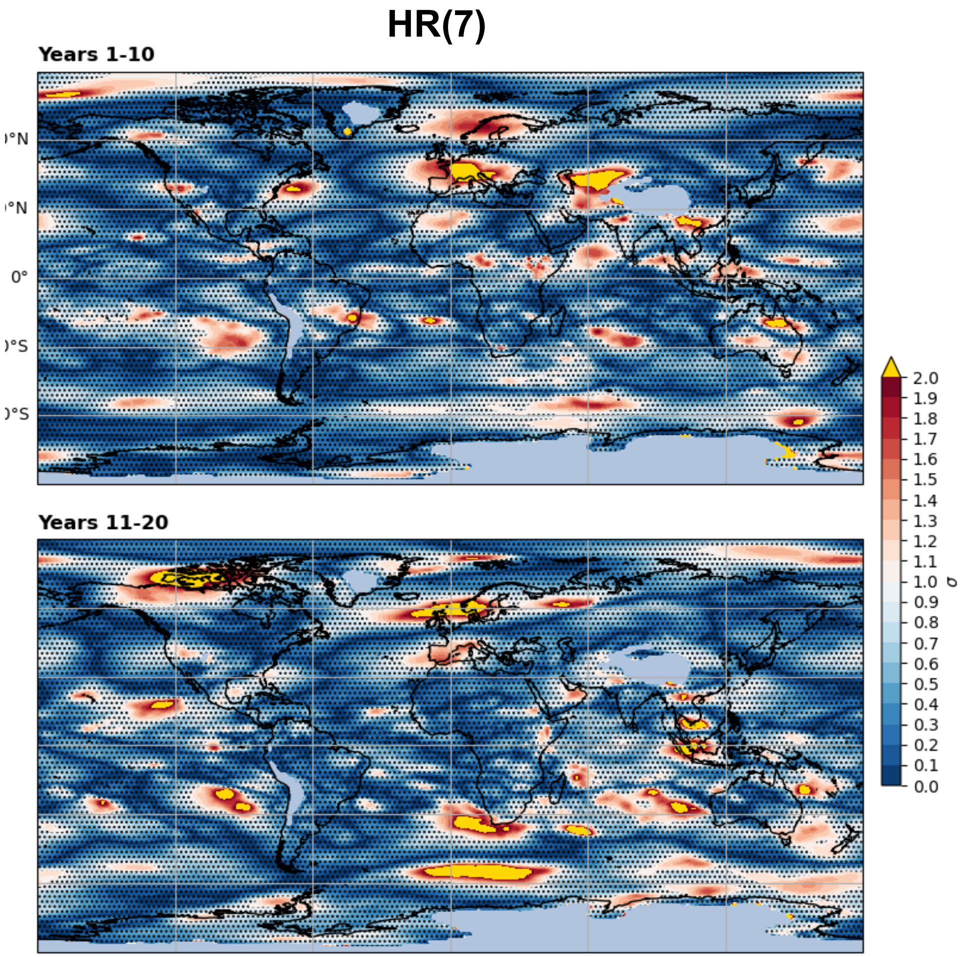
FMA U700

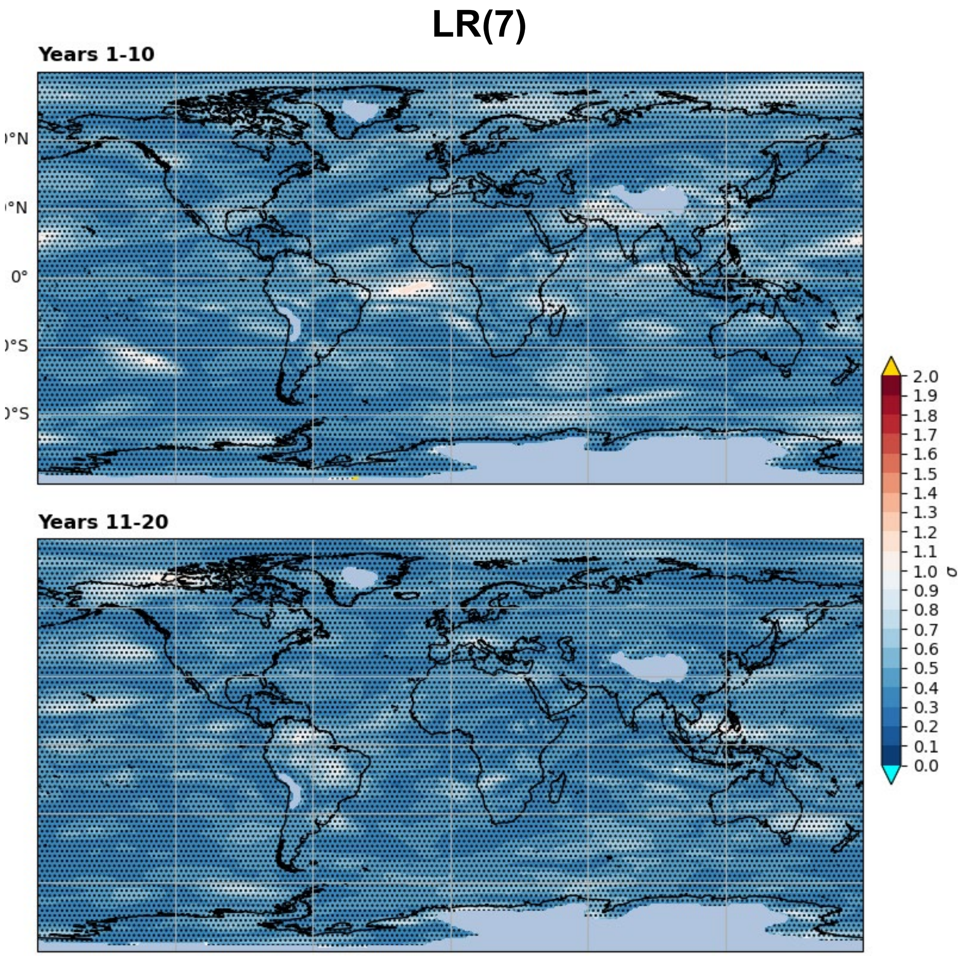
- LR: no significant U700 response
- HR: - significant N. Atlantic signals both during/after forcing
  - delayed increase in Southern Ocean westerlies





FMA U700 S2N

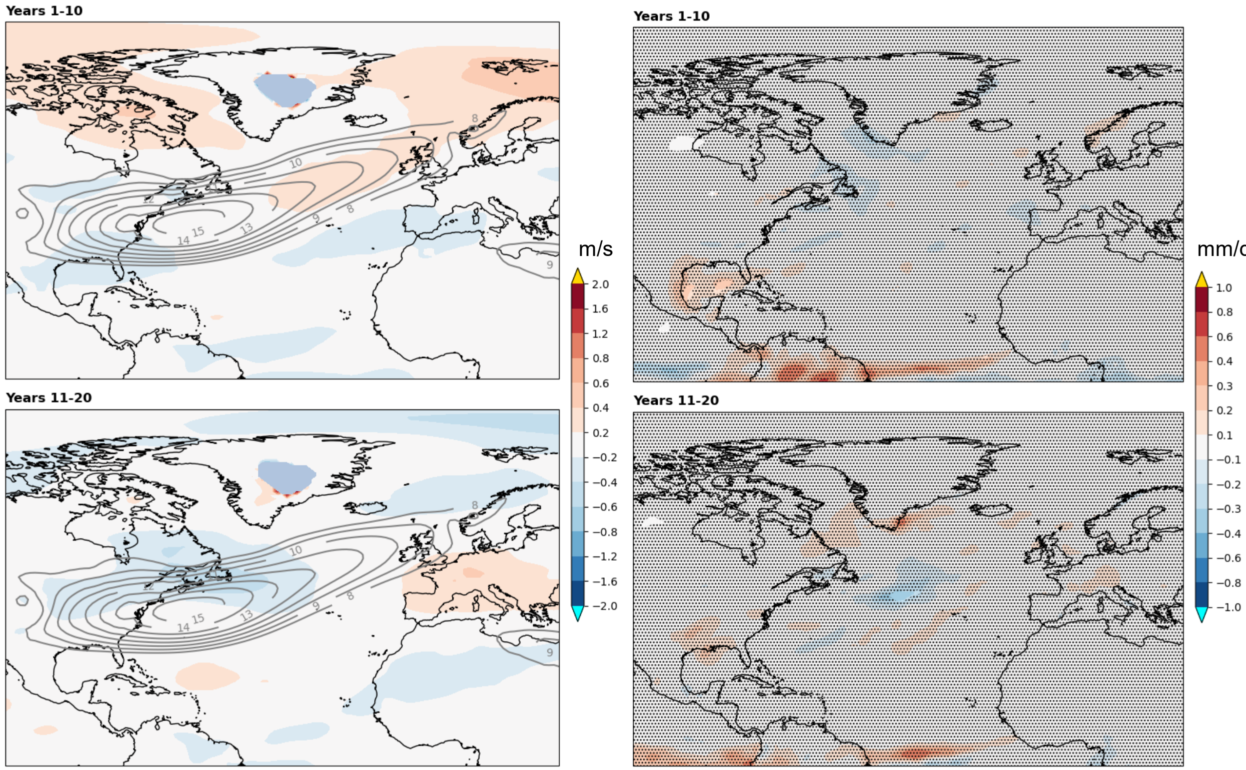




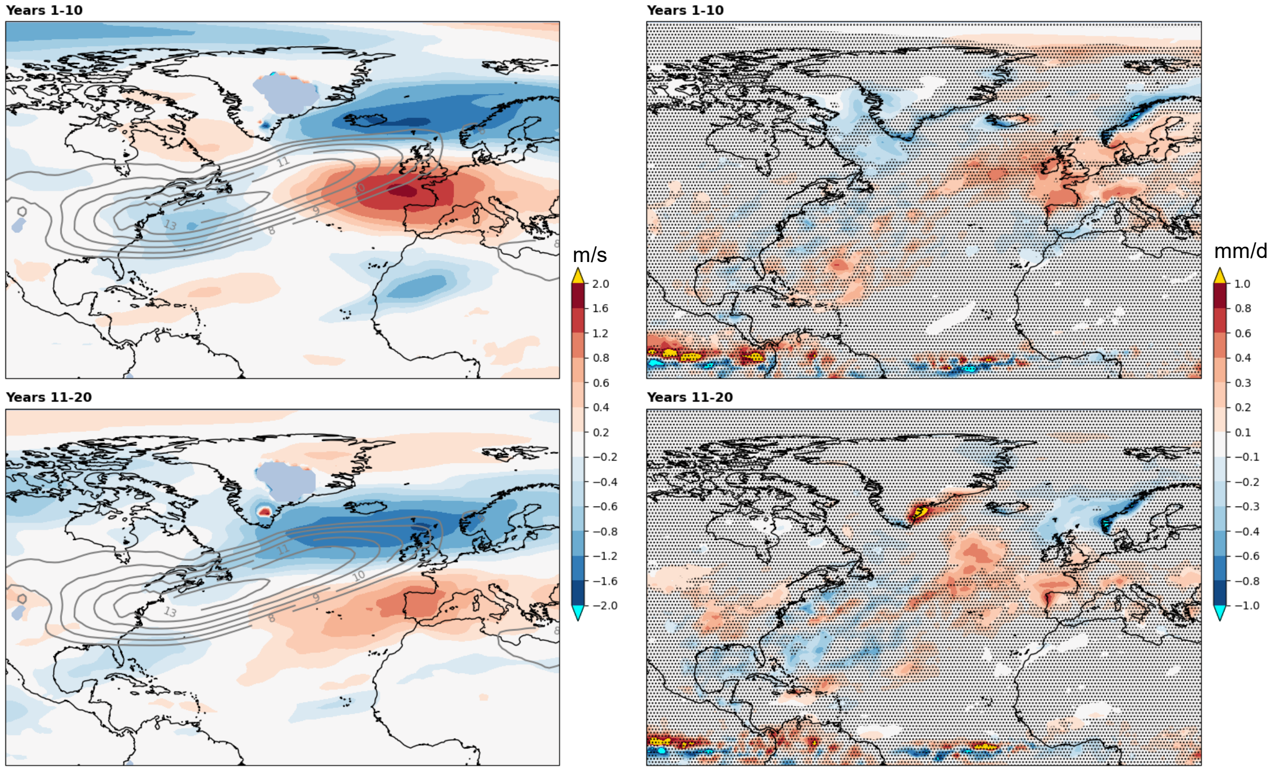
NSF NCAR Operated by UCAR

FMA U700 & Precip

LR(7)



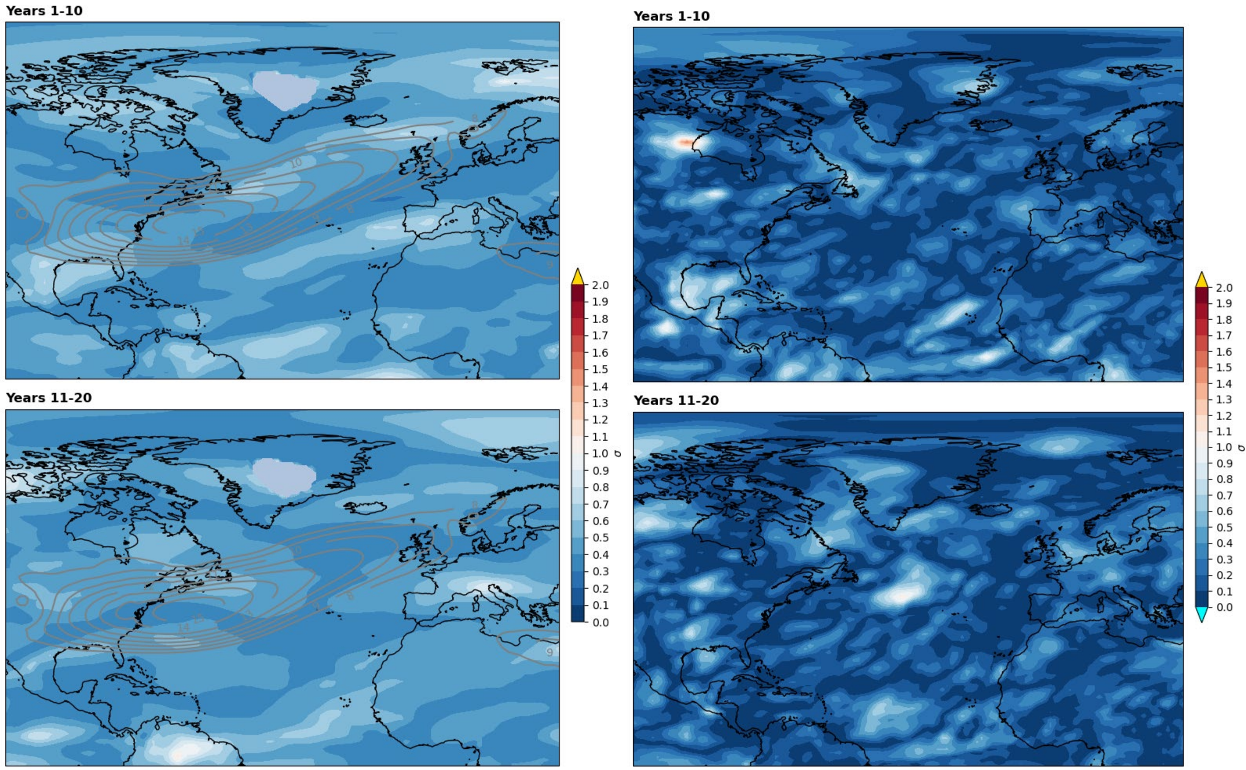
HR(7)



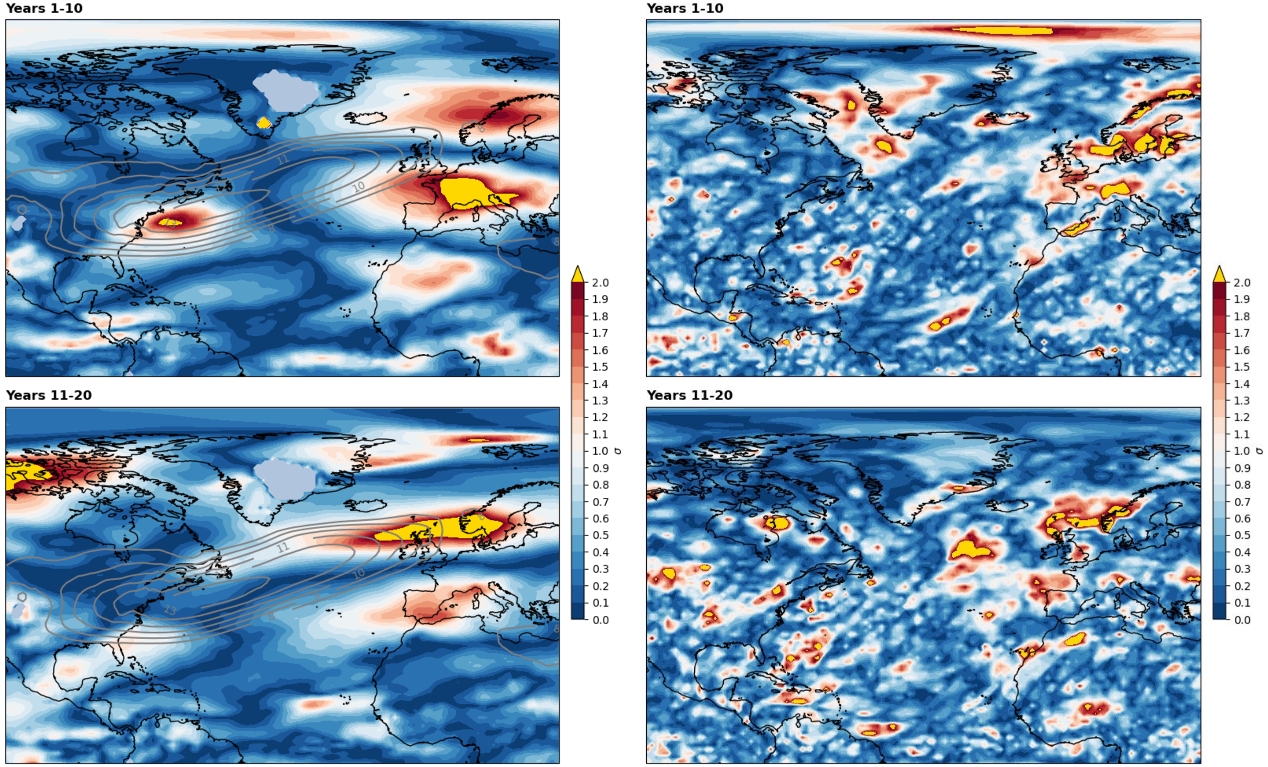
- AMOC/AMV-related late winter N. Atlantic Jet & Precip shifts seen in HR but not LR

FMA U700 & Precip S2N

LR(7)



HR(7)



- AMOC/AMV-related late winter N. Atlantic Jet & Precip shifts seen in HR but not LR

SUMMARY

- Perturbed forcing coupled ensembles allow for clean study of NAO/AMOC/SST/Impacts causal chain under equivalent forcing that circumvents model intrinsic NAO bias

- Strong sensitivity to horizontal resolution of coupled model response to persistent NAO heat flux
  - implies an important role for small-scale (generally unresolved) processes in ocean, atmosphere, and their interface

- Stronger subtropical AMOC response (greater meridional coherence) in HR

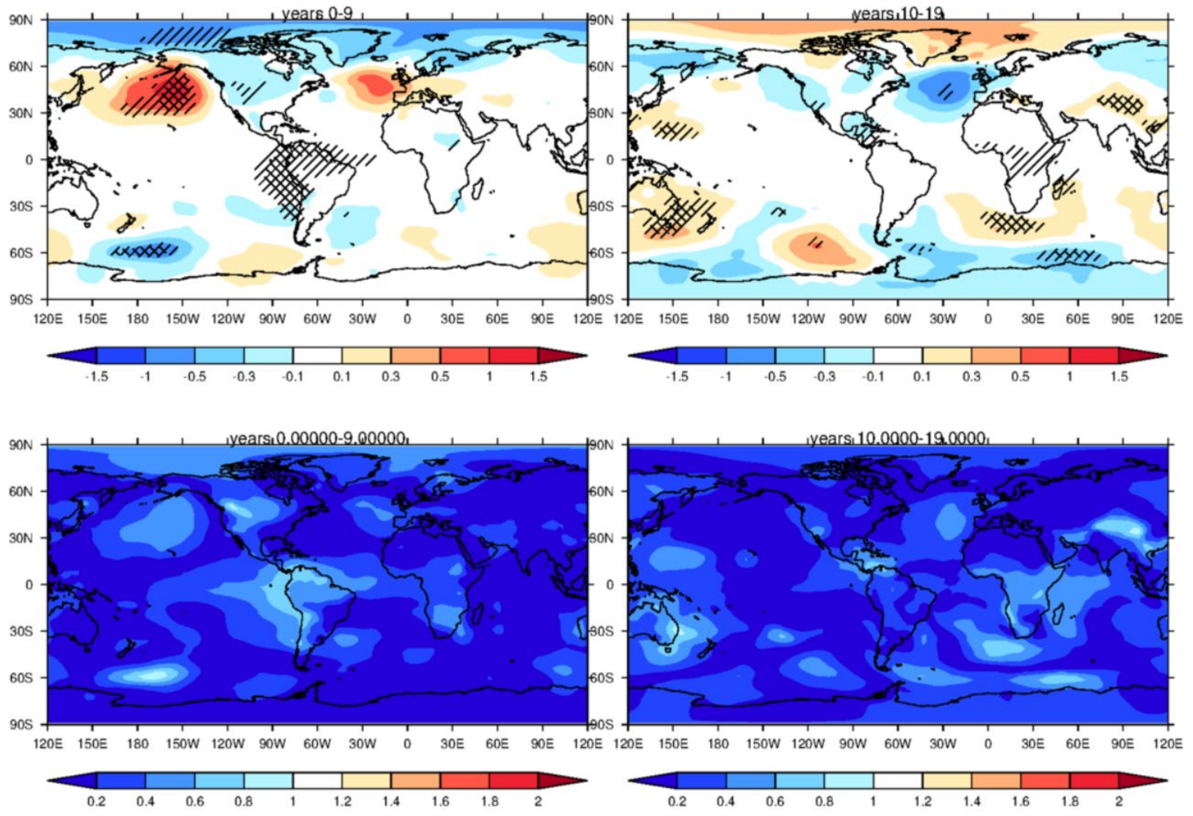
- Larger amplitude climate response (SAT, SLP, U700, Precip) with higher signal-to-noise in HR
  - Global response to AMV SST in HR, including Southern Ocean
  - may shed light on signal-to-noise paradox seen in LR climate prediction systems

- HR appears to show a (more) realistic relationship between AMV and N. Atlantic Jet (late winter)
  - implications for climate prediction over W. Europe

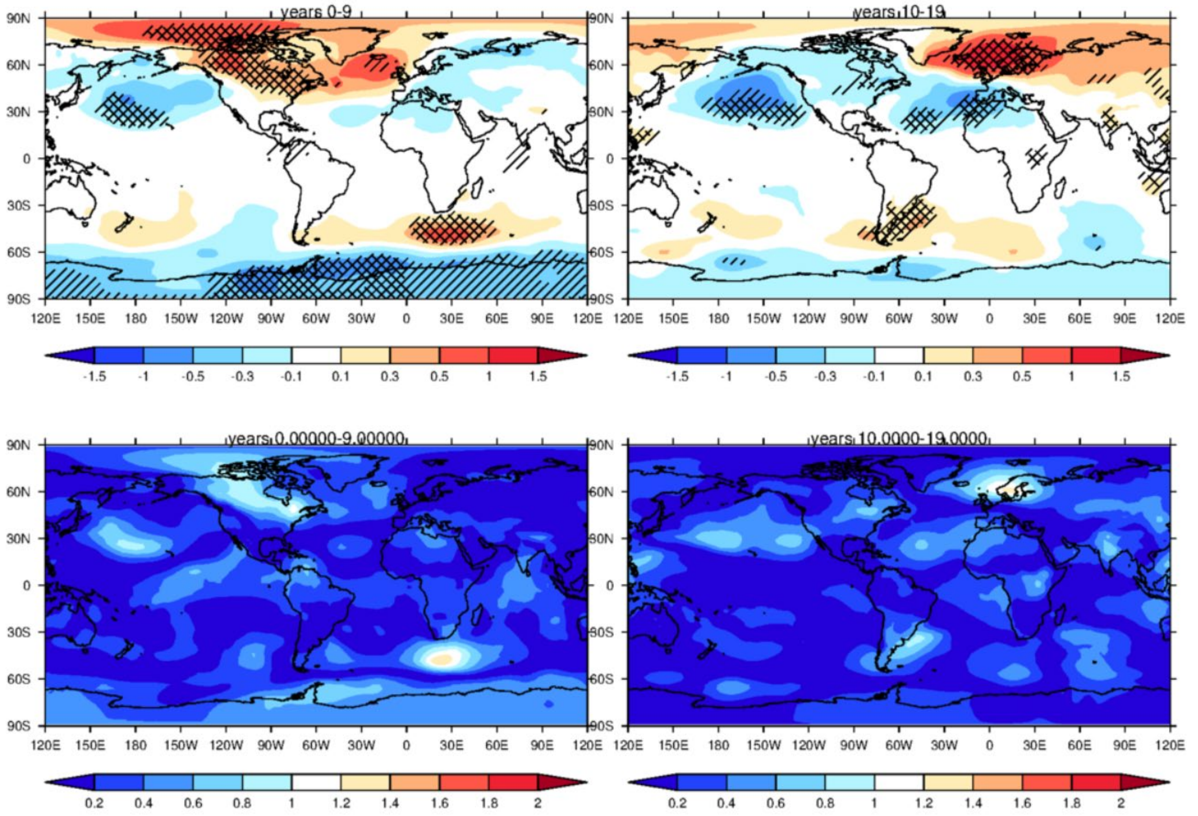
- Work is ongoing to:
  - Understand stronger SST signal in HR
  - Clarify whether stronger climate response in HR is the result of stronger SST forcing or stronger atmospheric response to SST
  - Determine robustness to model structure

JFM SLP

GC31_LL (150km atm; 100km ocn):



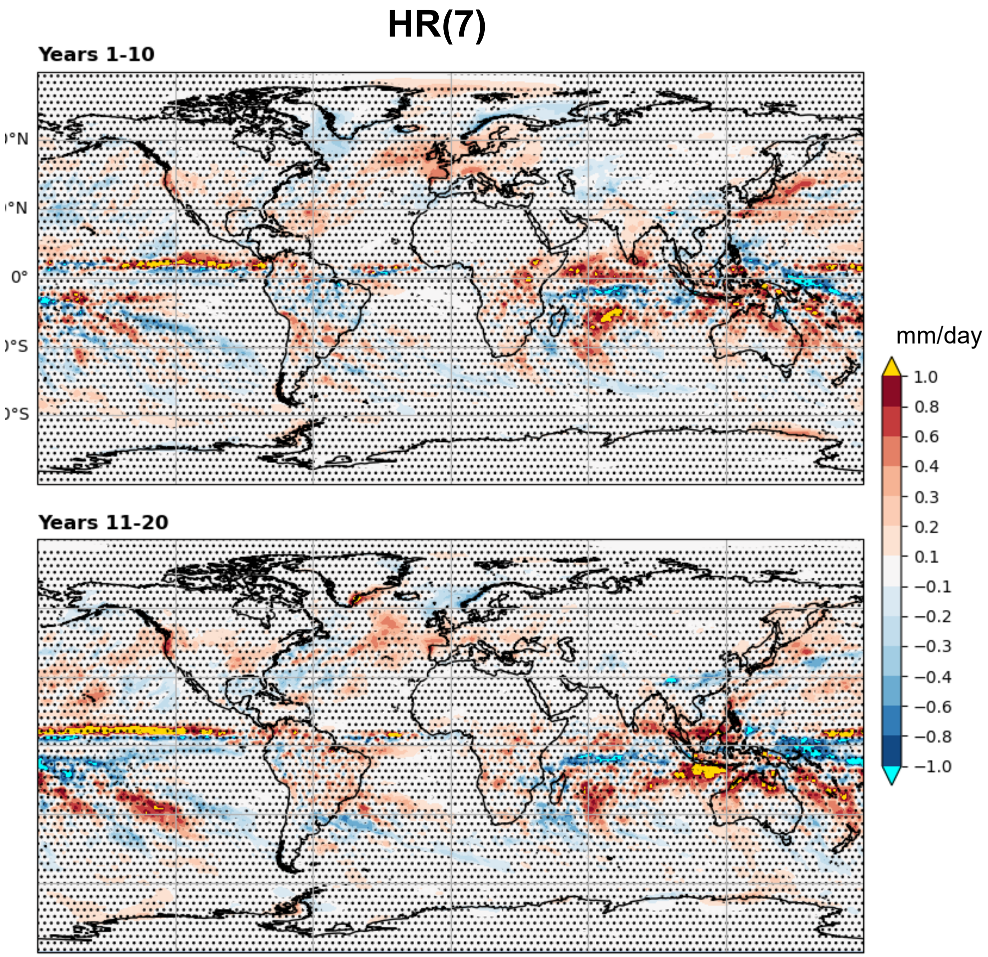
GC31_MM (60km atm; 25km ocn):

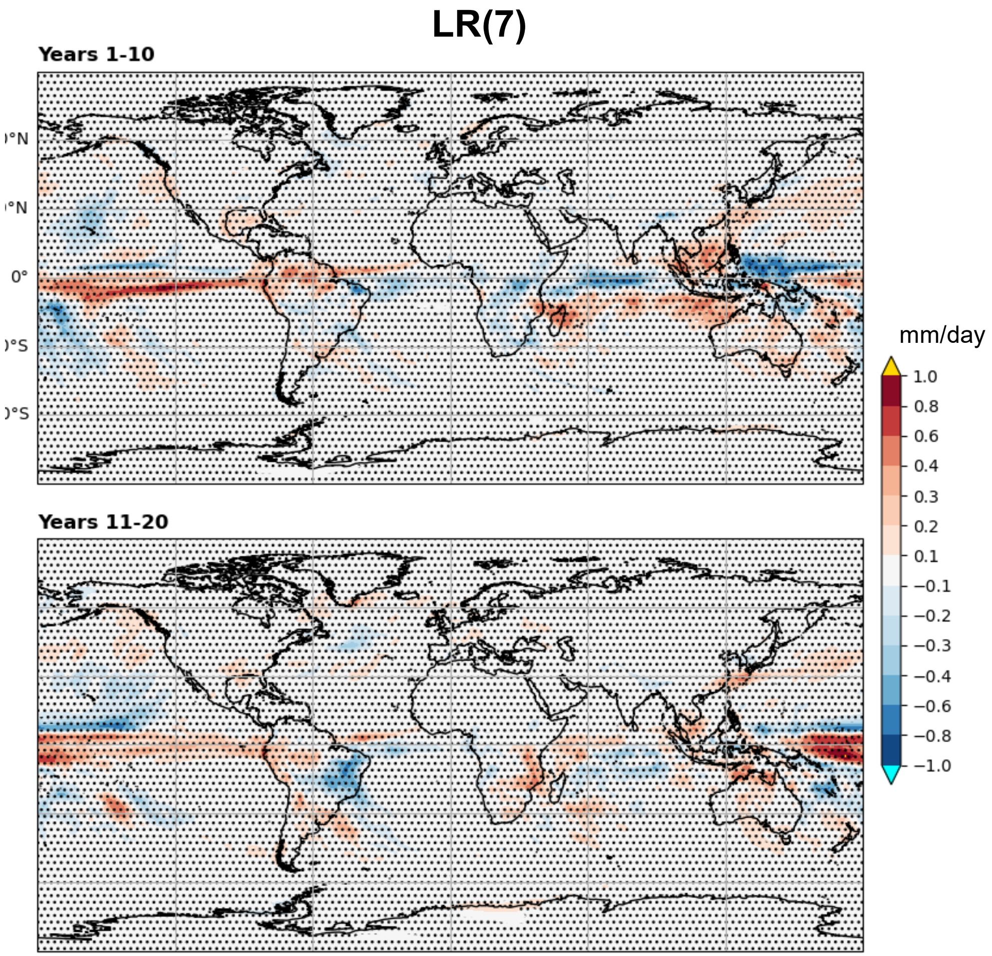


Extra Slides

FMA Precip

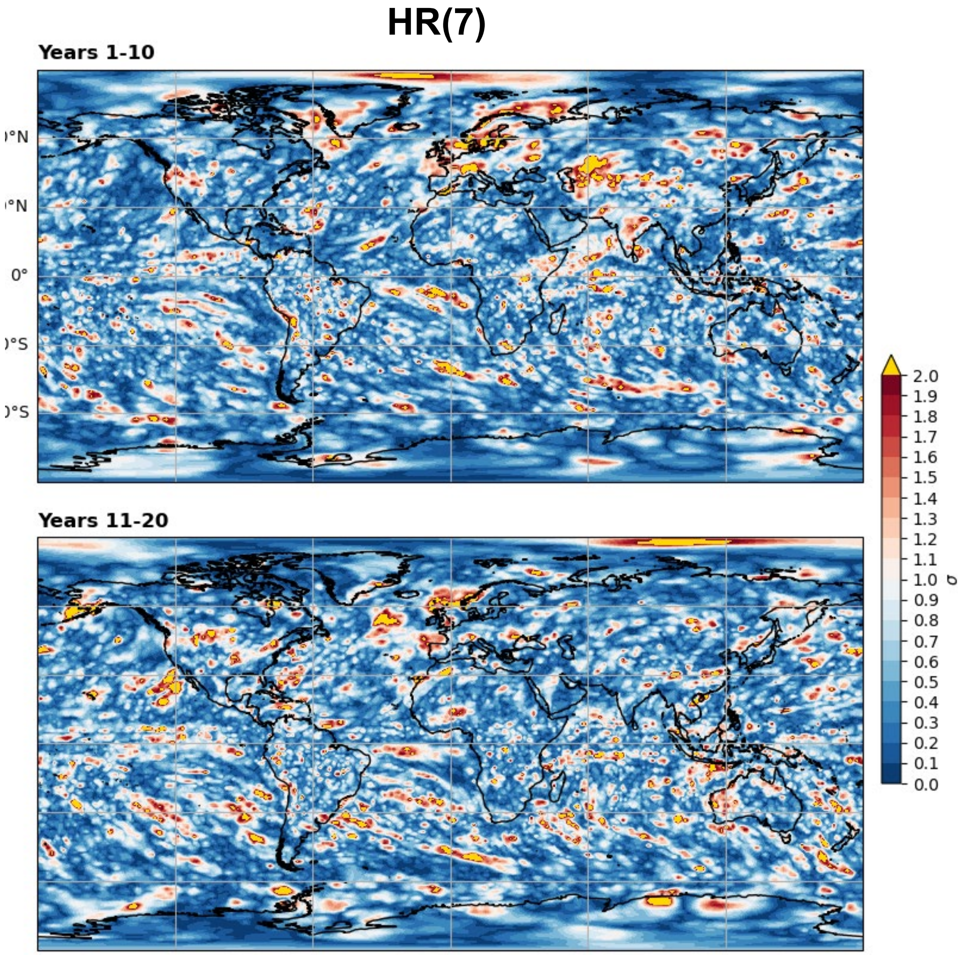
- Much stronger U700 signal in HR

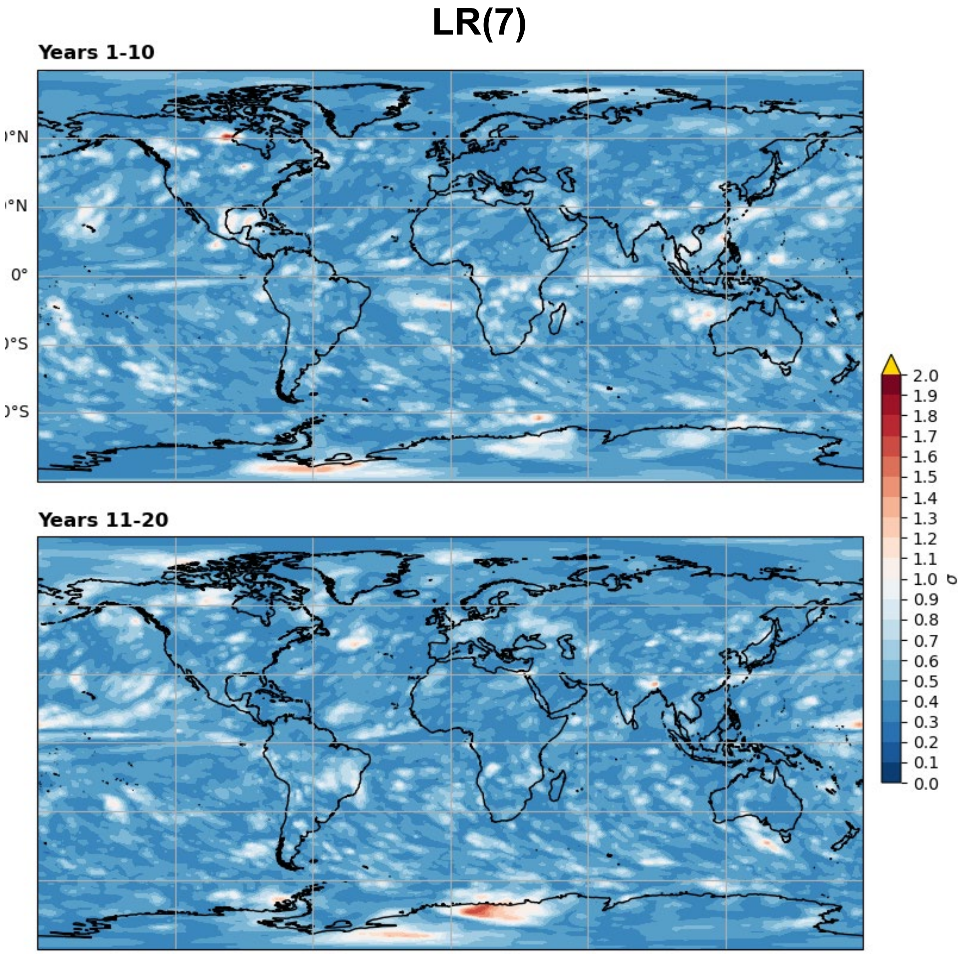




FMA Precip

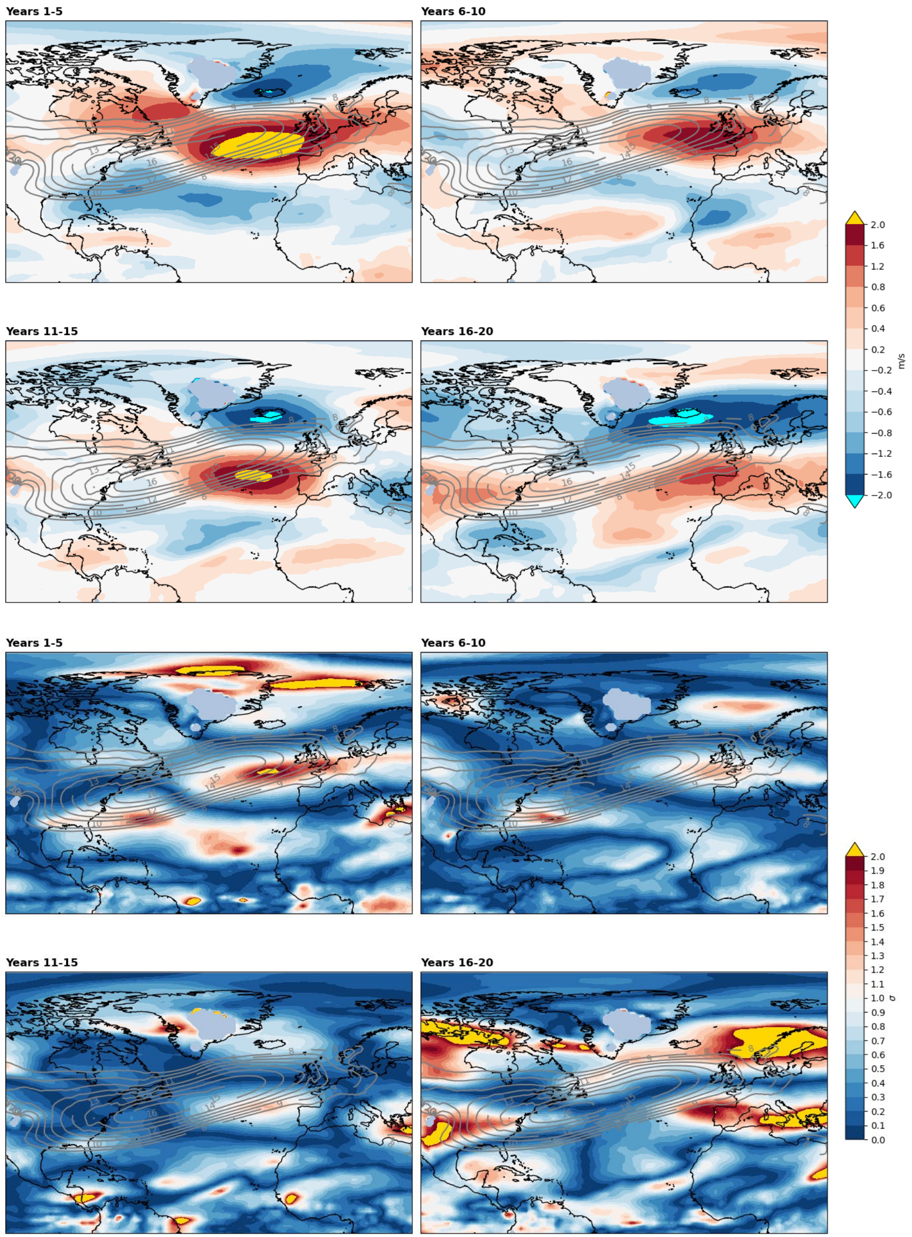
- Much stronger U700 signal in HR





JFM U700

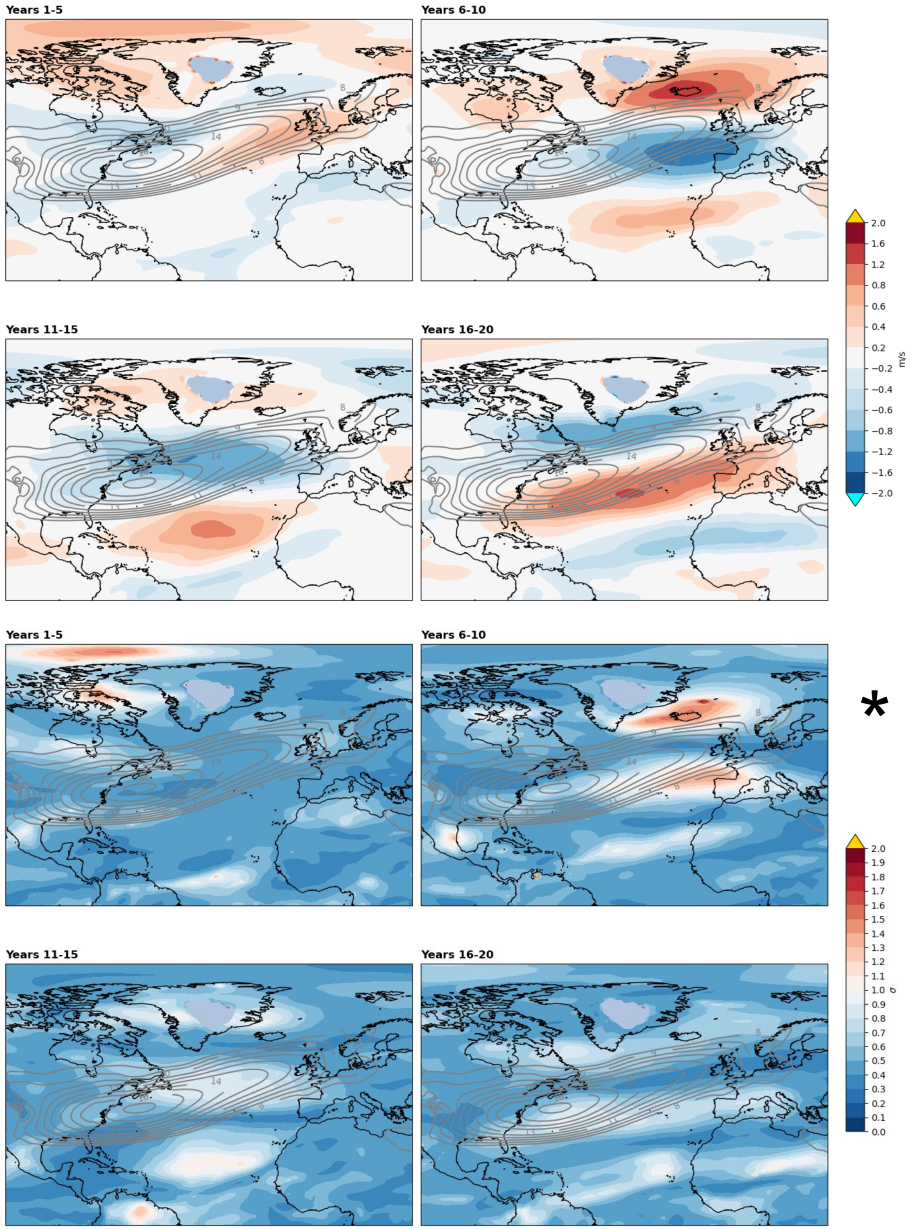
HR(6)



S

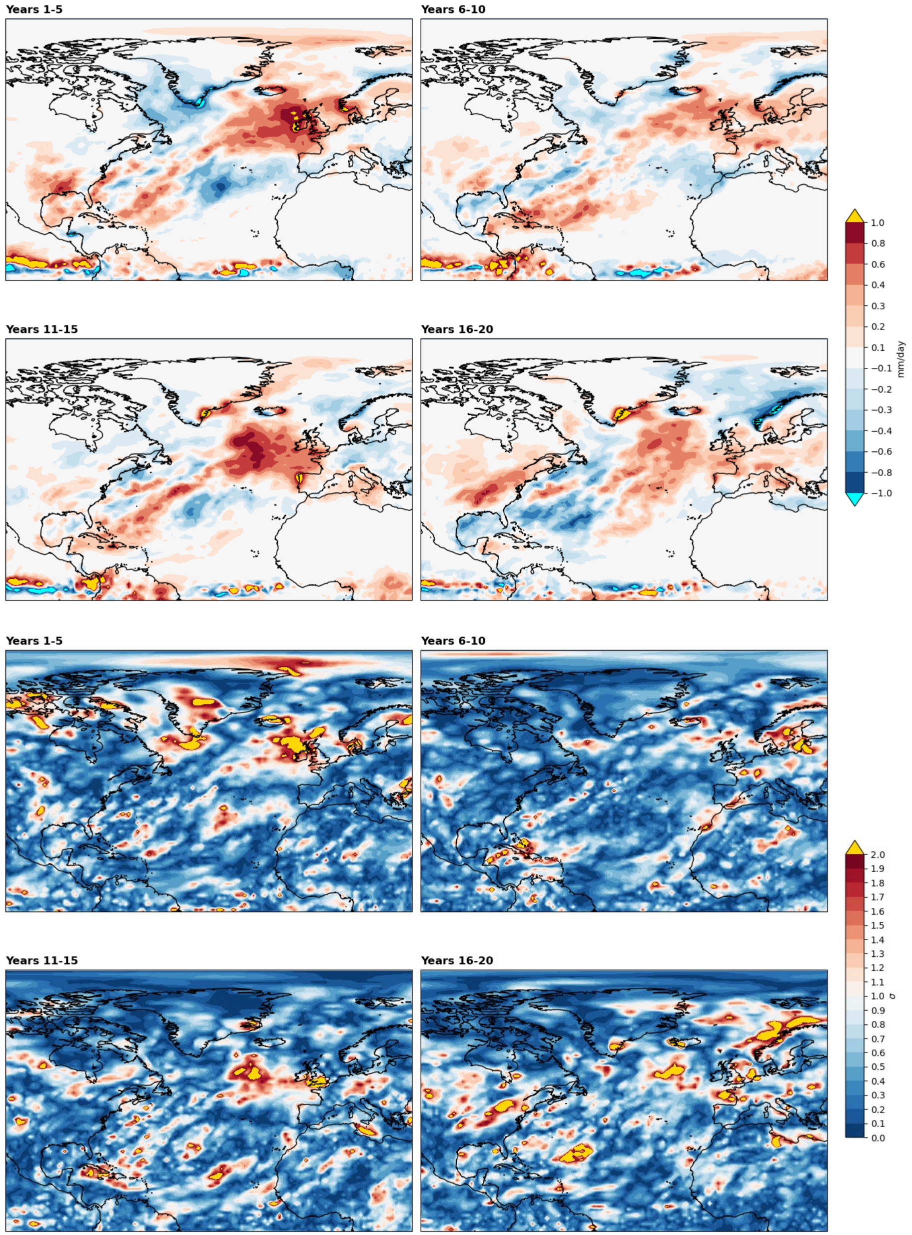
S2N

LR(20)

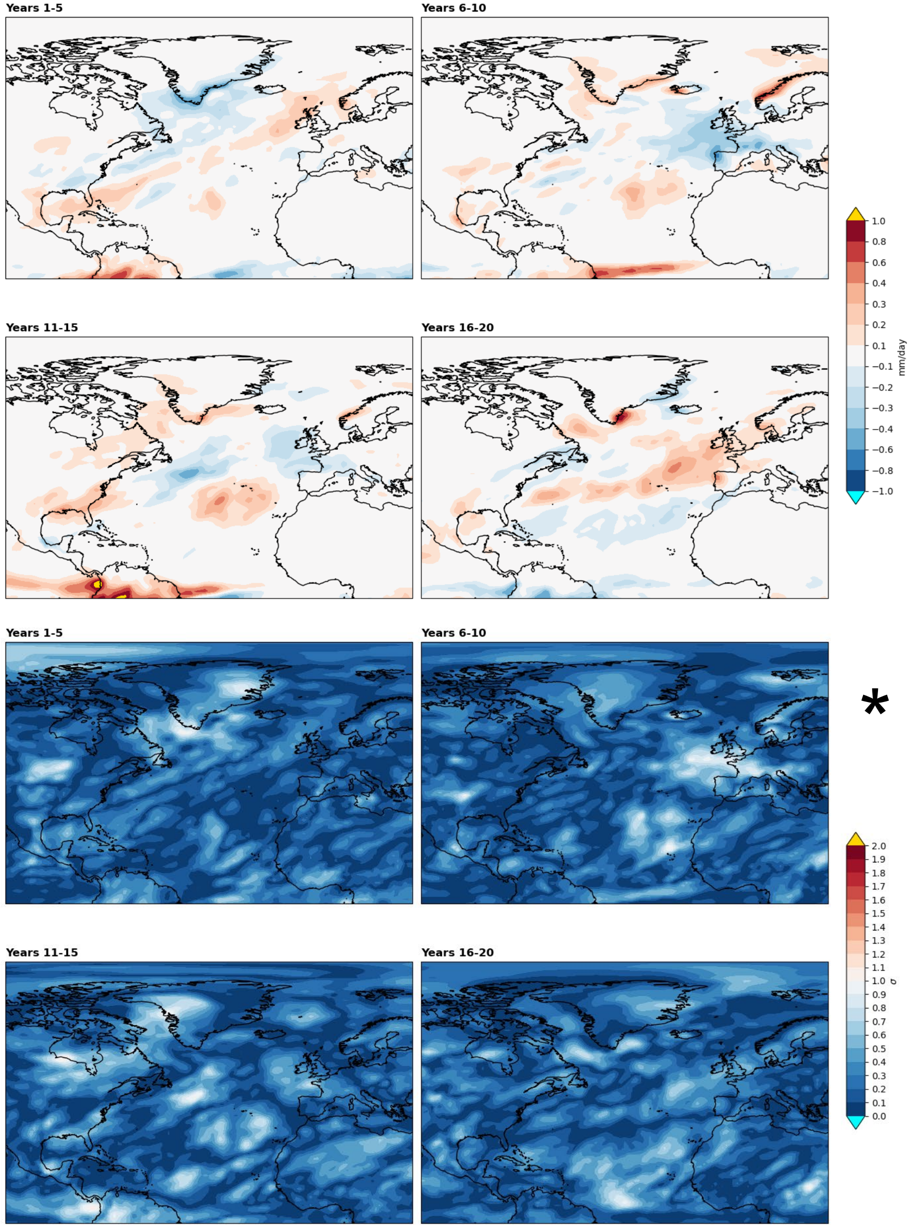


JFM Precip

HR(6)



LR(20)

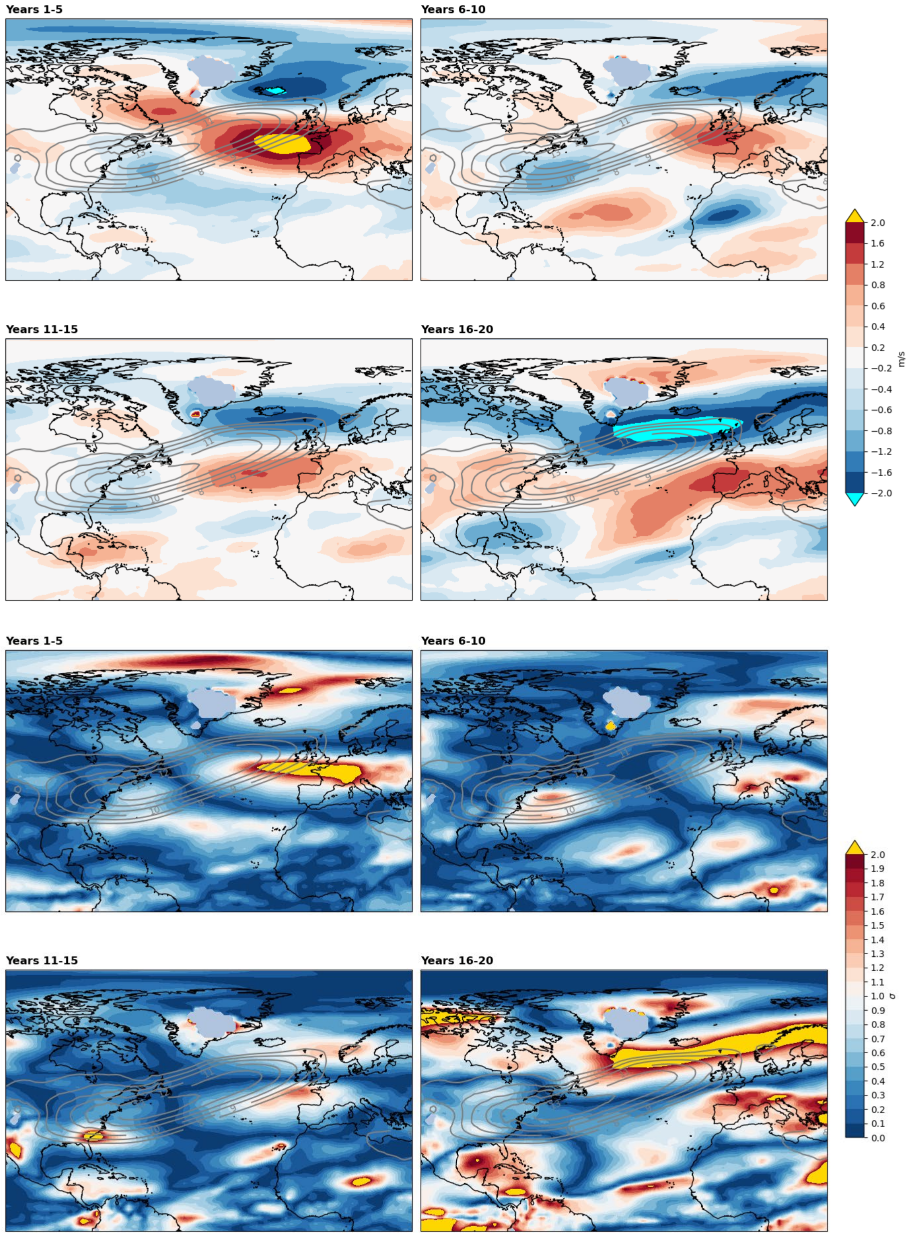


S

S2N

FMA U700

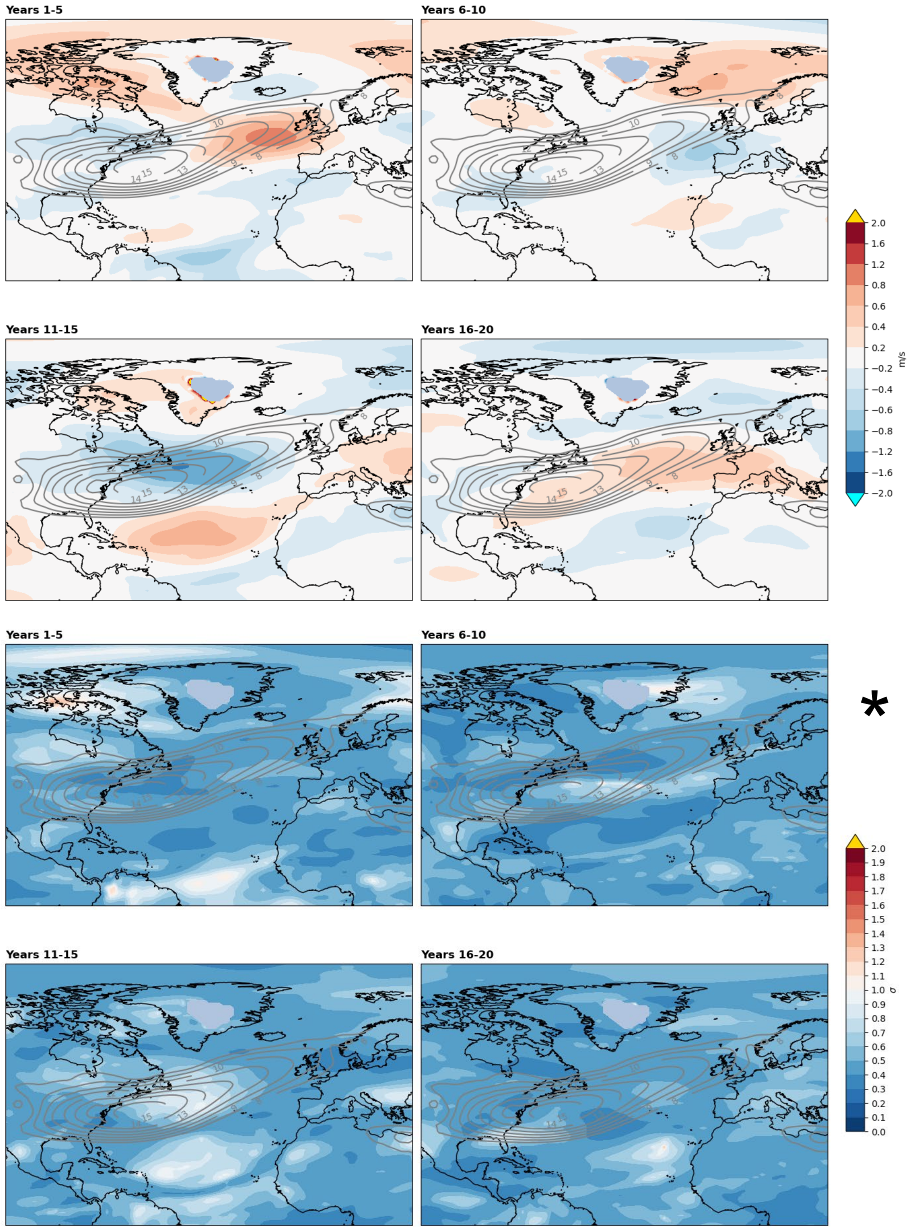
HR(6)



LR(20)

S

S2N

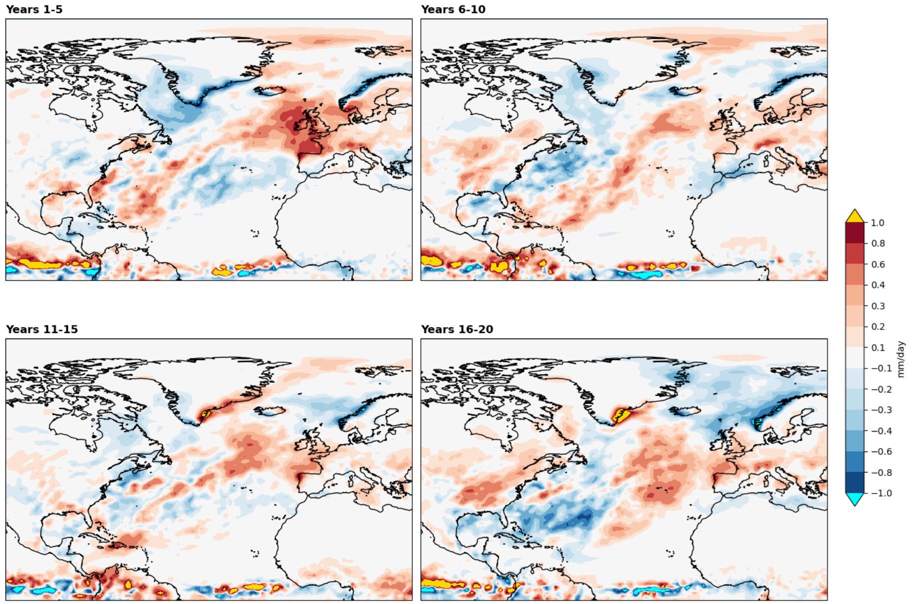


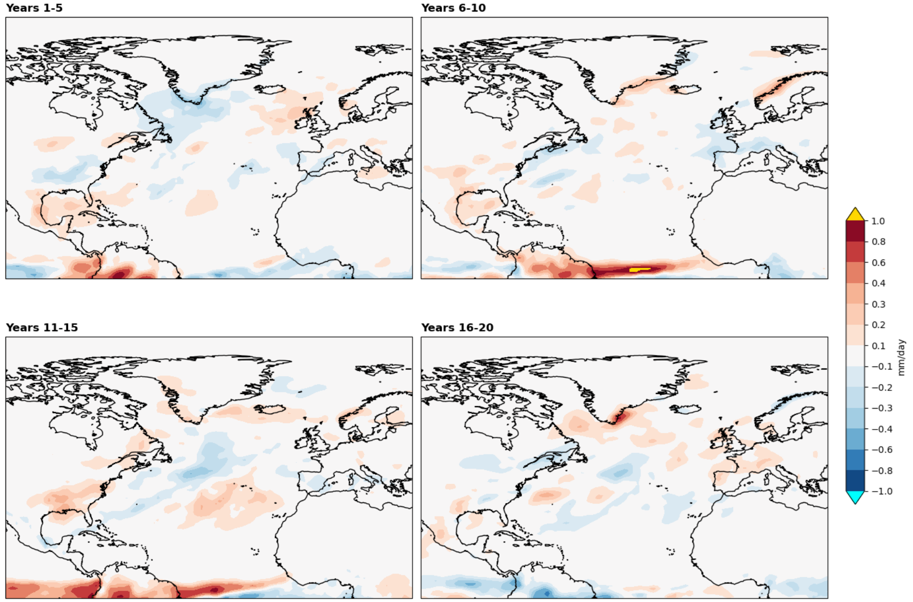
FMA Precip

HR(6)

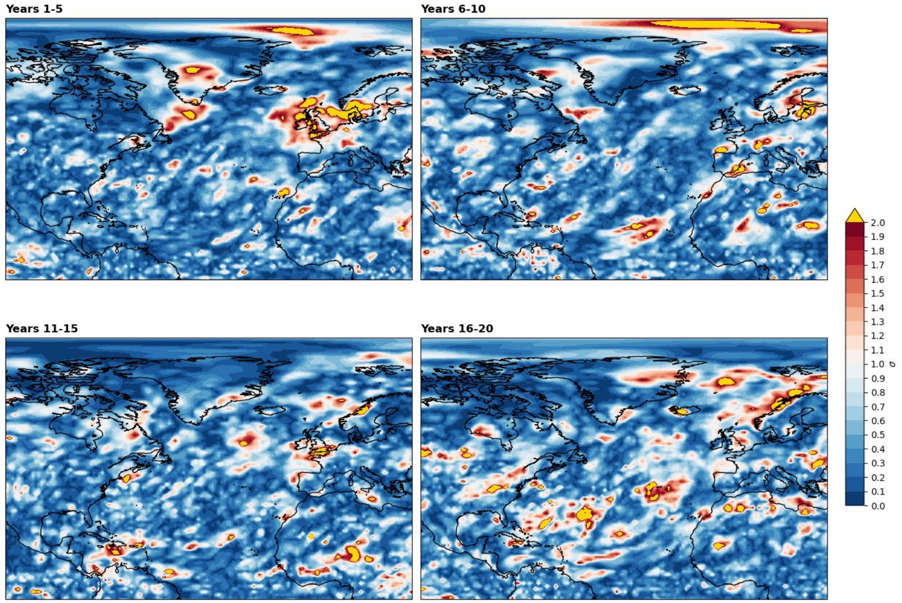
LR(20)

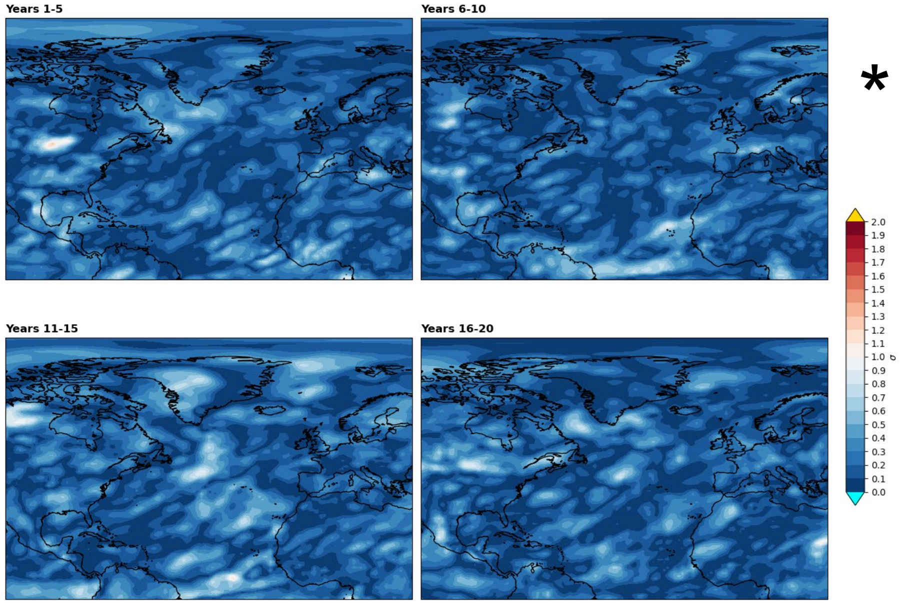
S





S2N

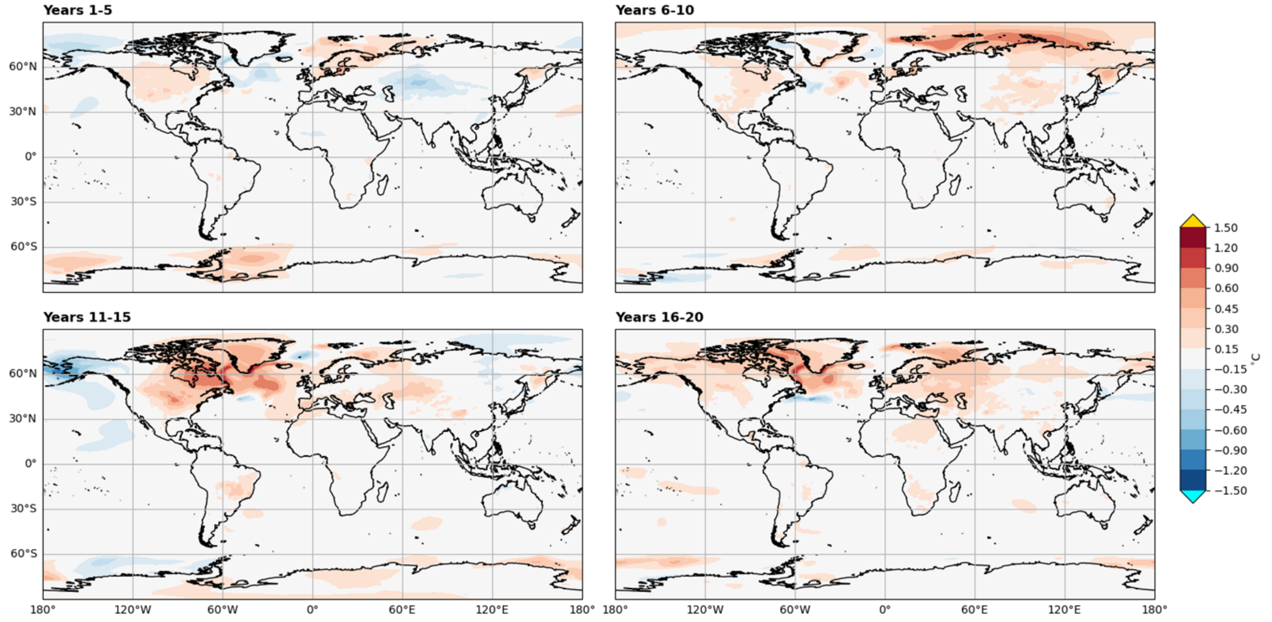




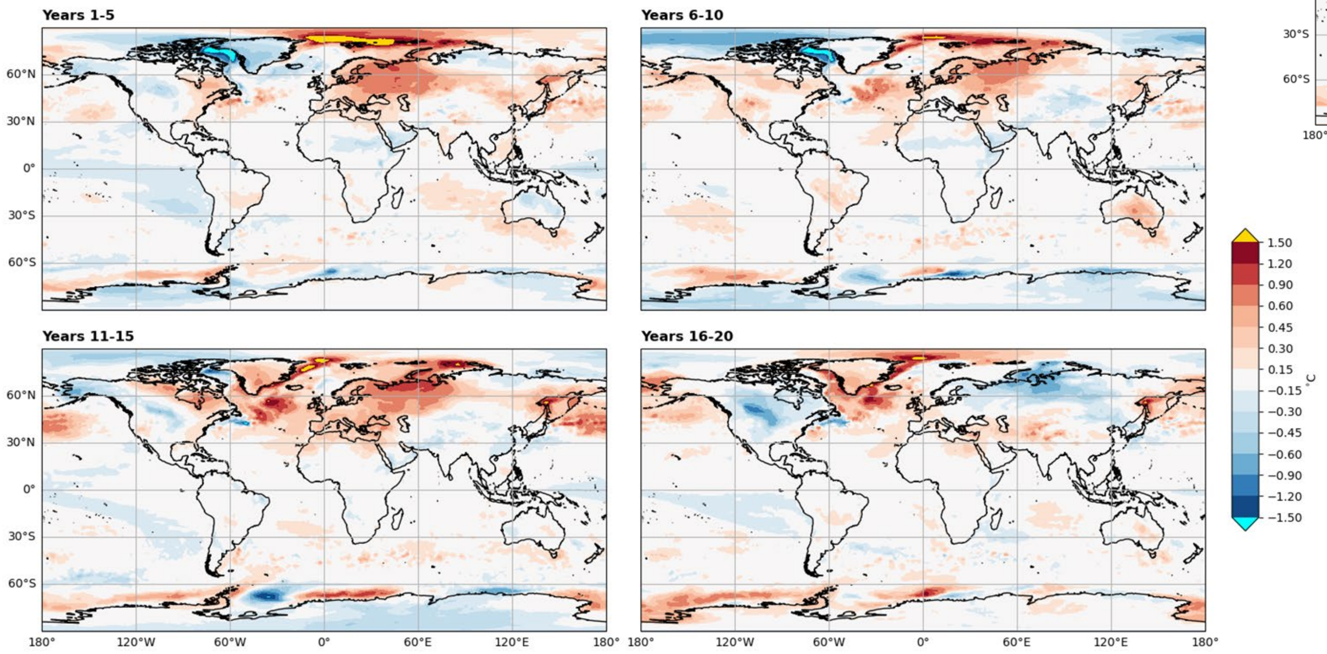
*

Annual Surface Temp

LR(20)

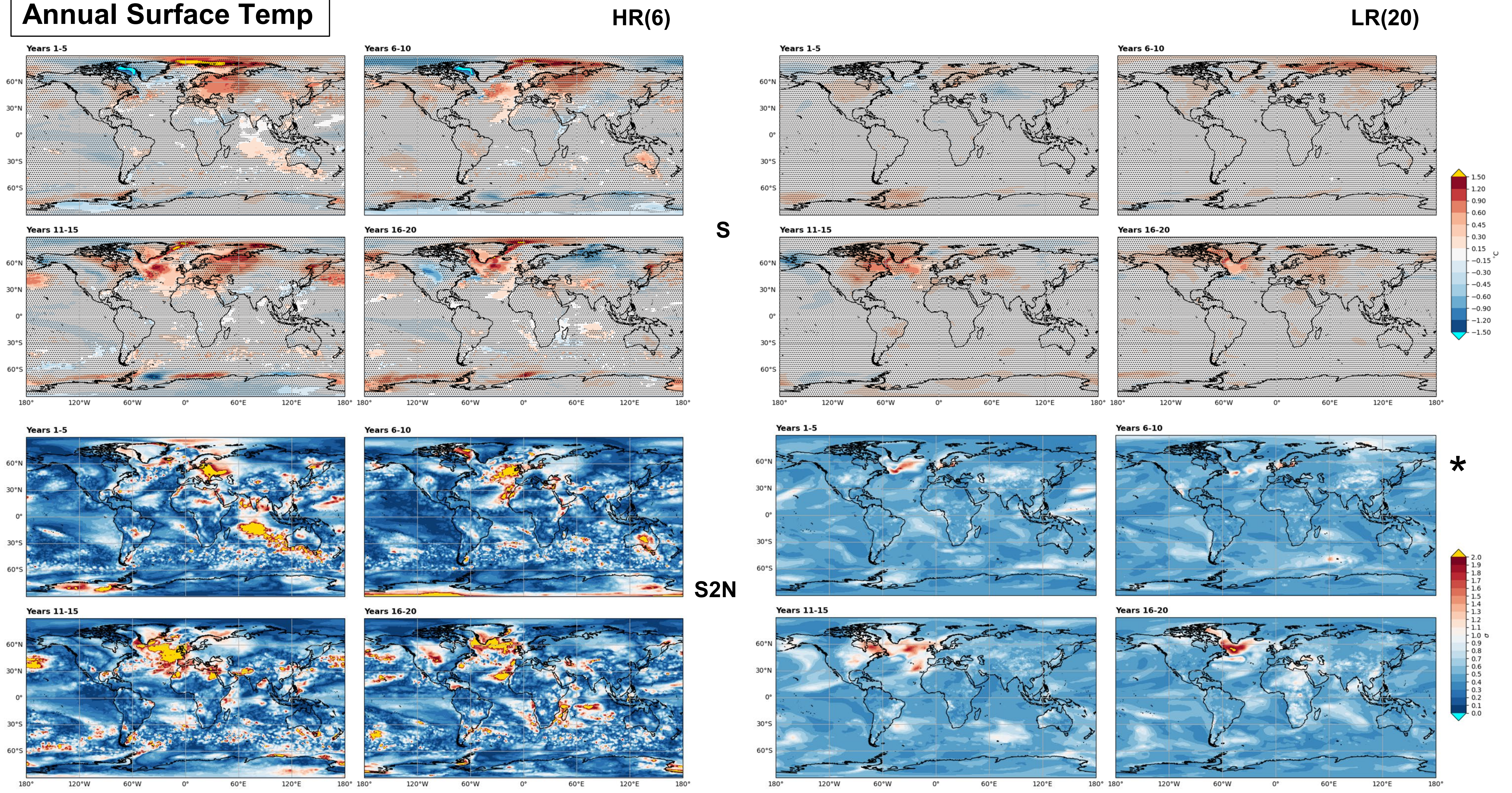


HR(6)

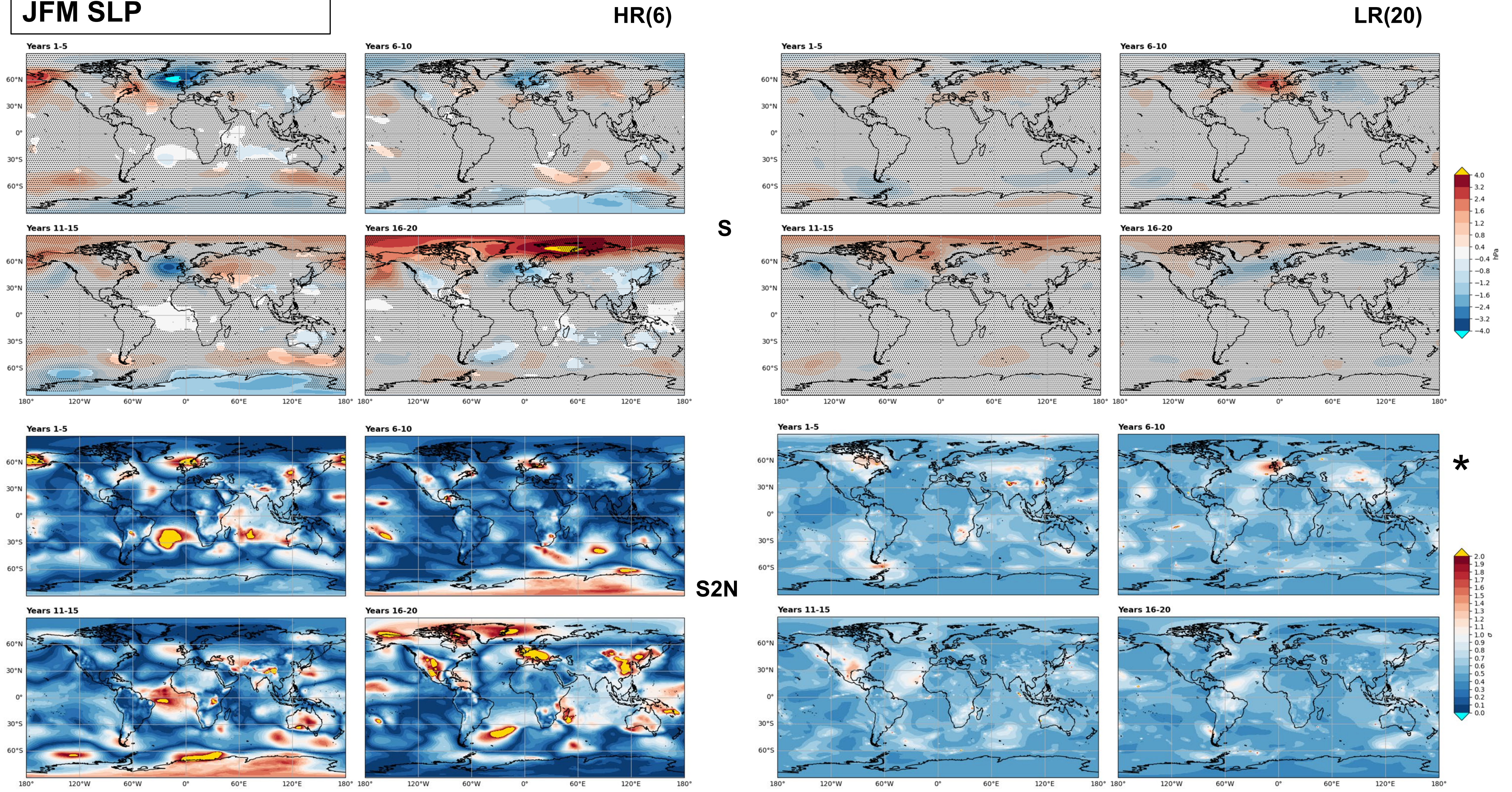


- Much stronger SPNA warming in HR
  - greater ocean heat transport efficiency in HR (Chang et al. 2020)?
  - stronger coupled feedbacks?
- Larger SAT response over land in HR
- What is signal vs. noise?

Annual Surface Temp



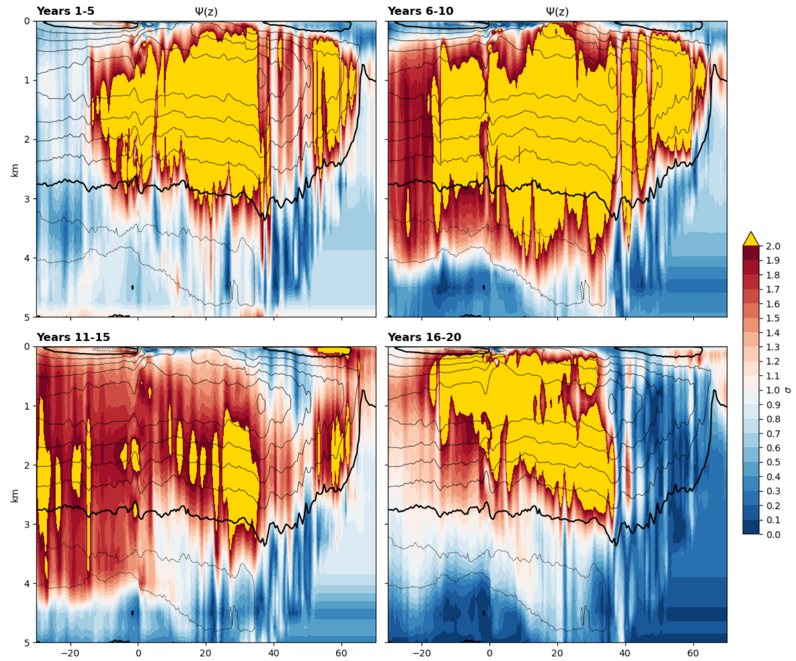
JFM SLP

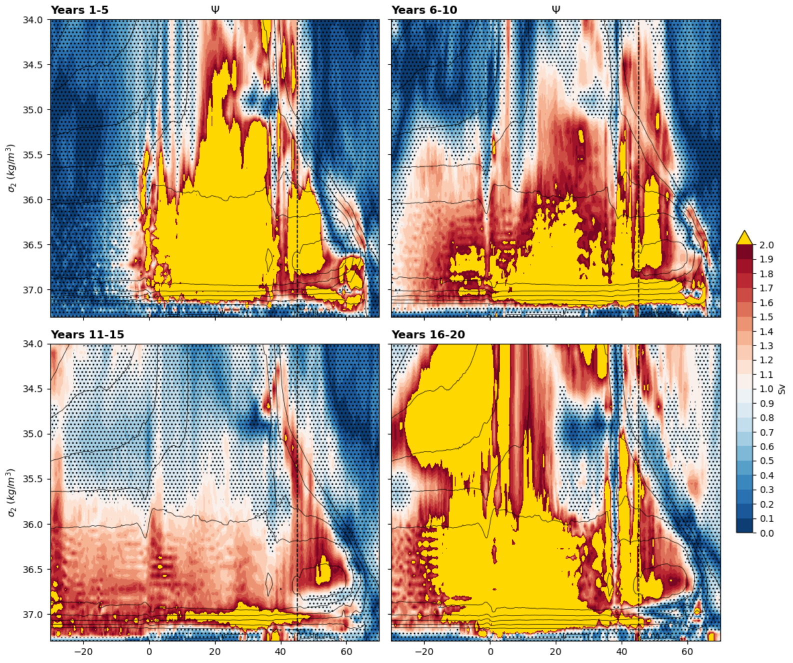


Annual AMOC S2N

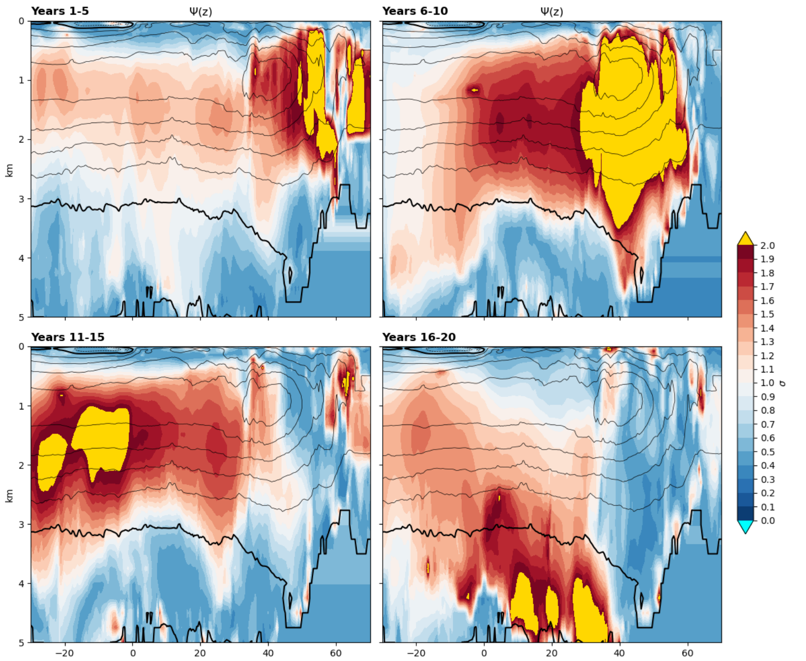
- Stippled where S2N<1

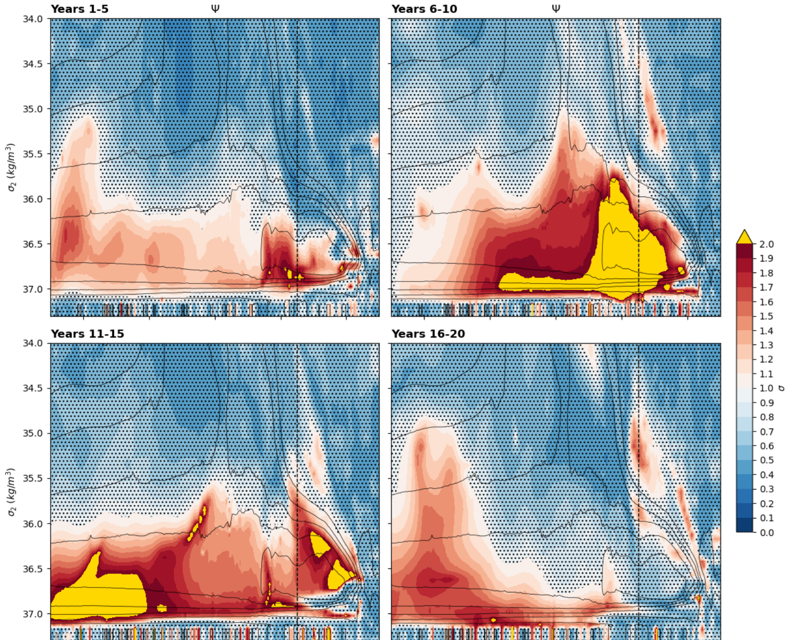
HR (6)



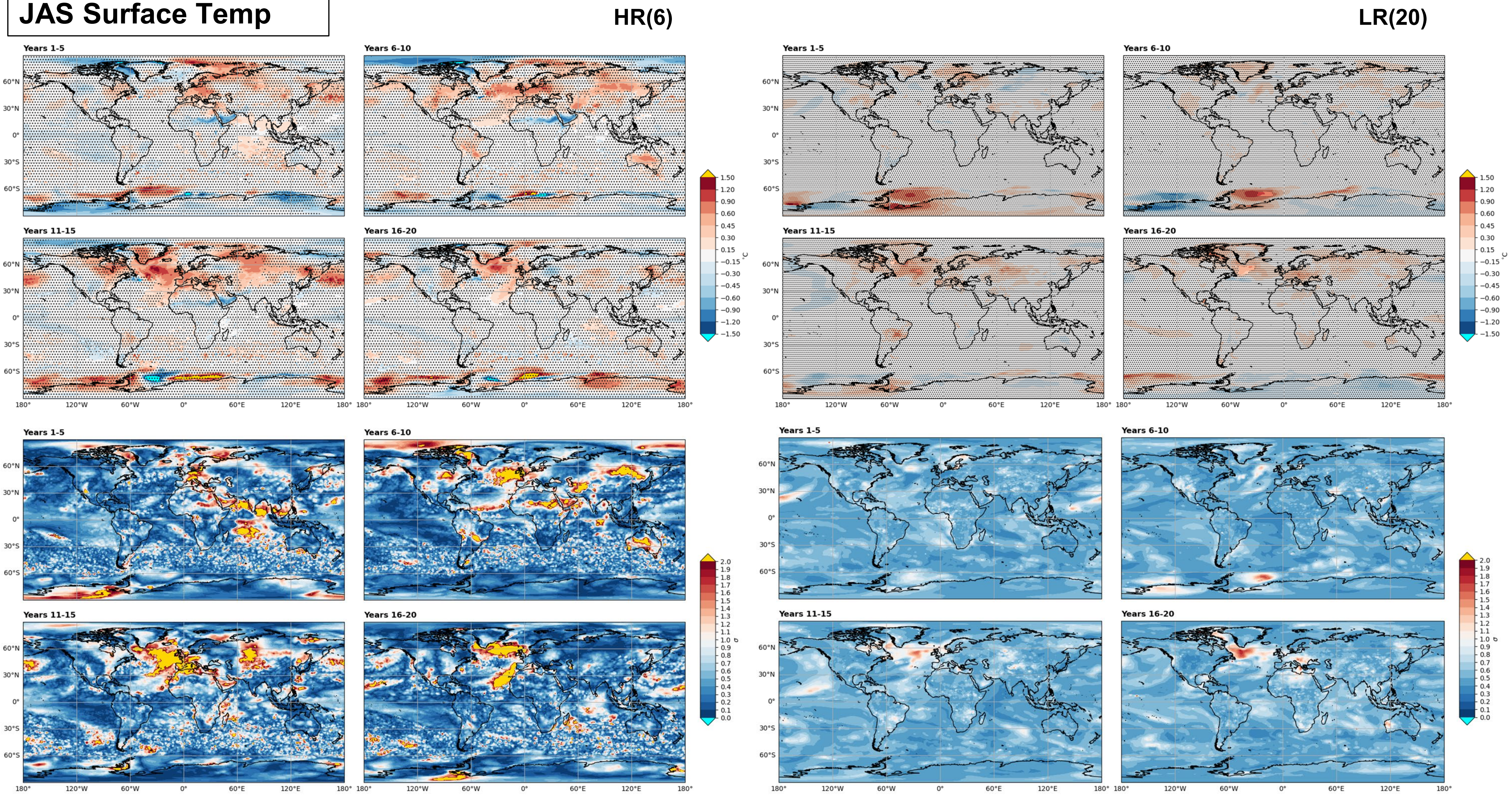


LR (6)



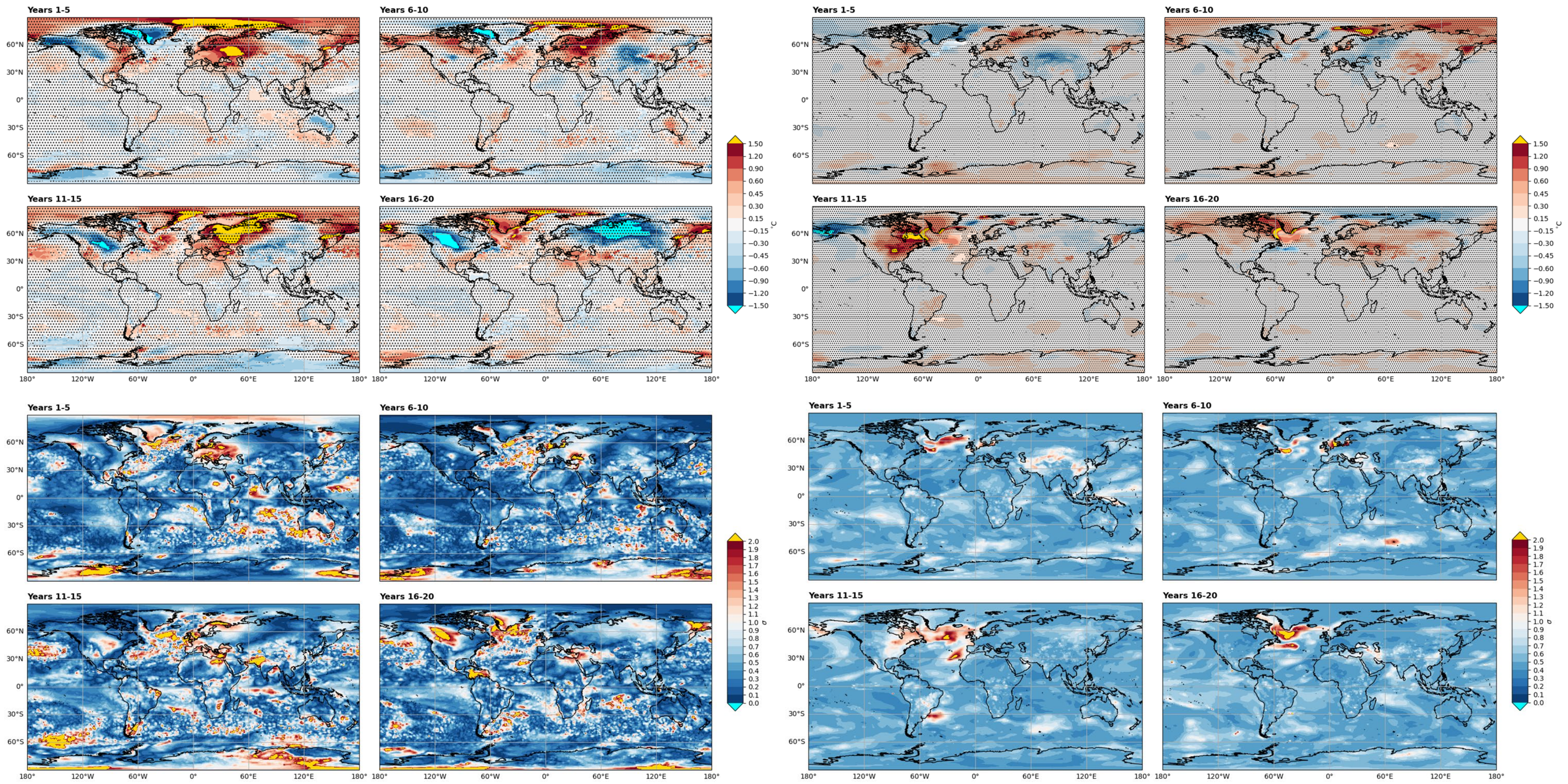


JAS Surface Temp



JFM Surface Temp

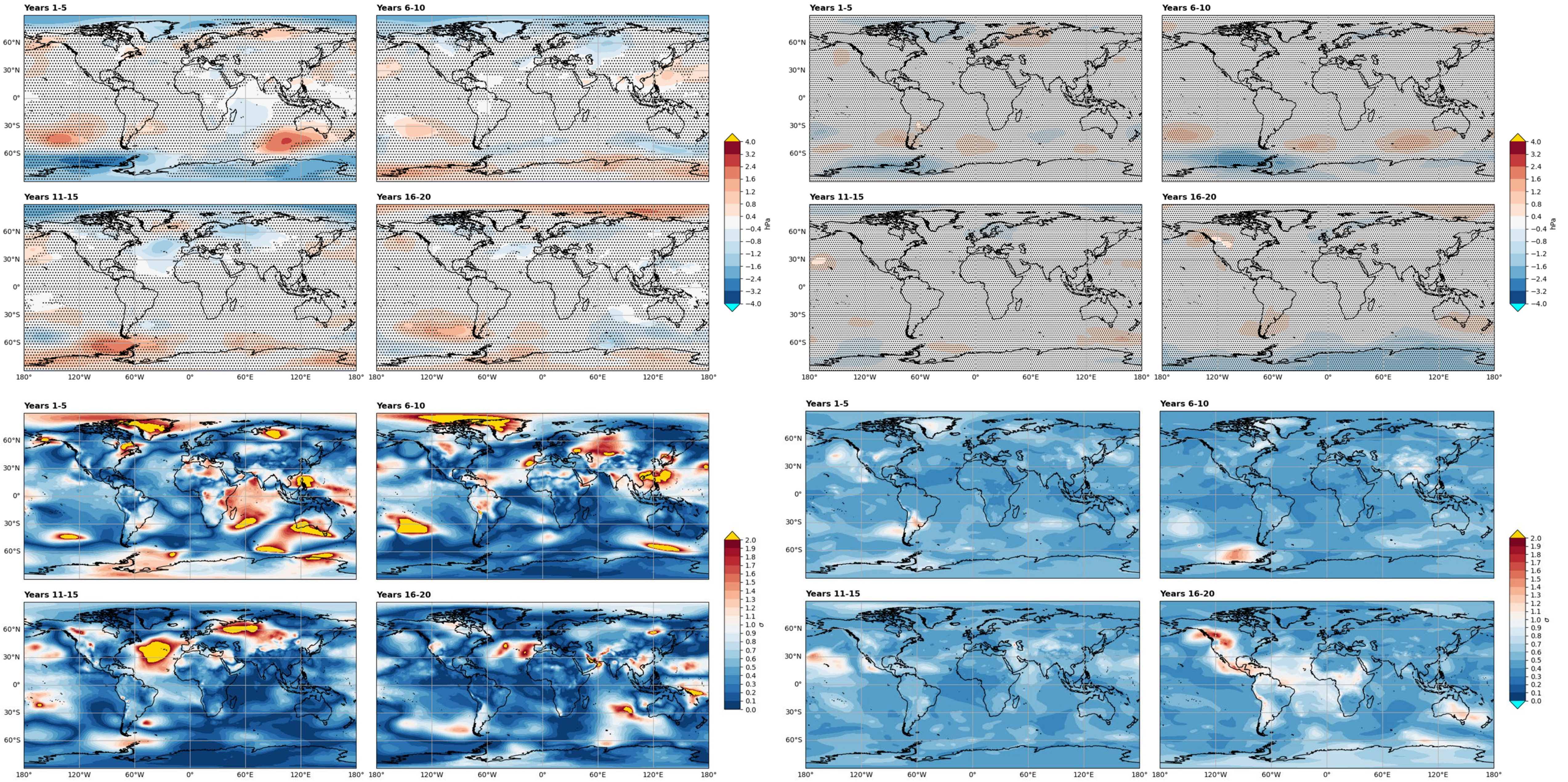
HR(6) | LR(20)



JAS SLP

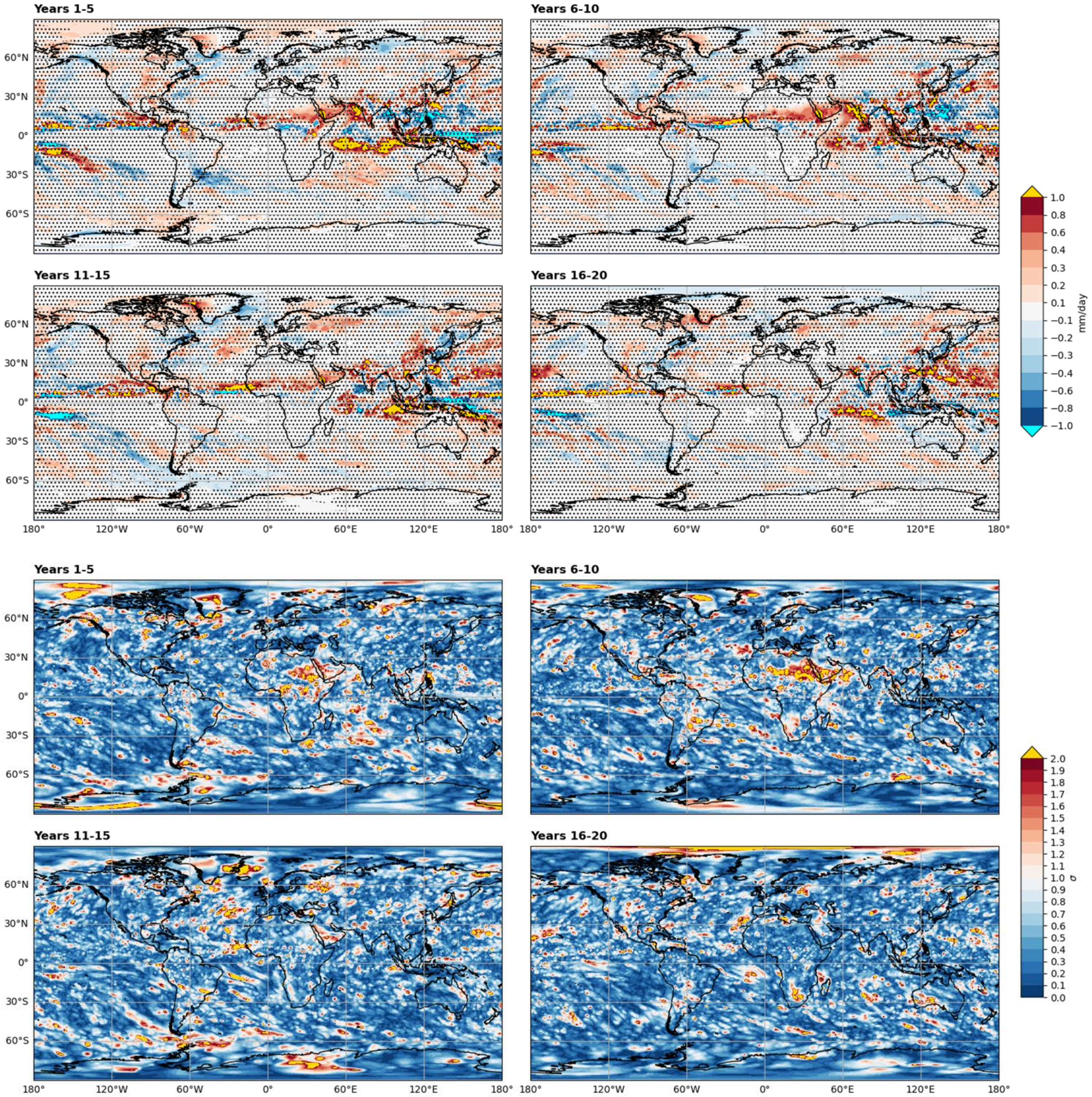
HR(6)

LR(20)

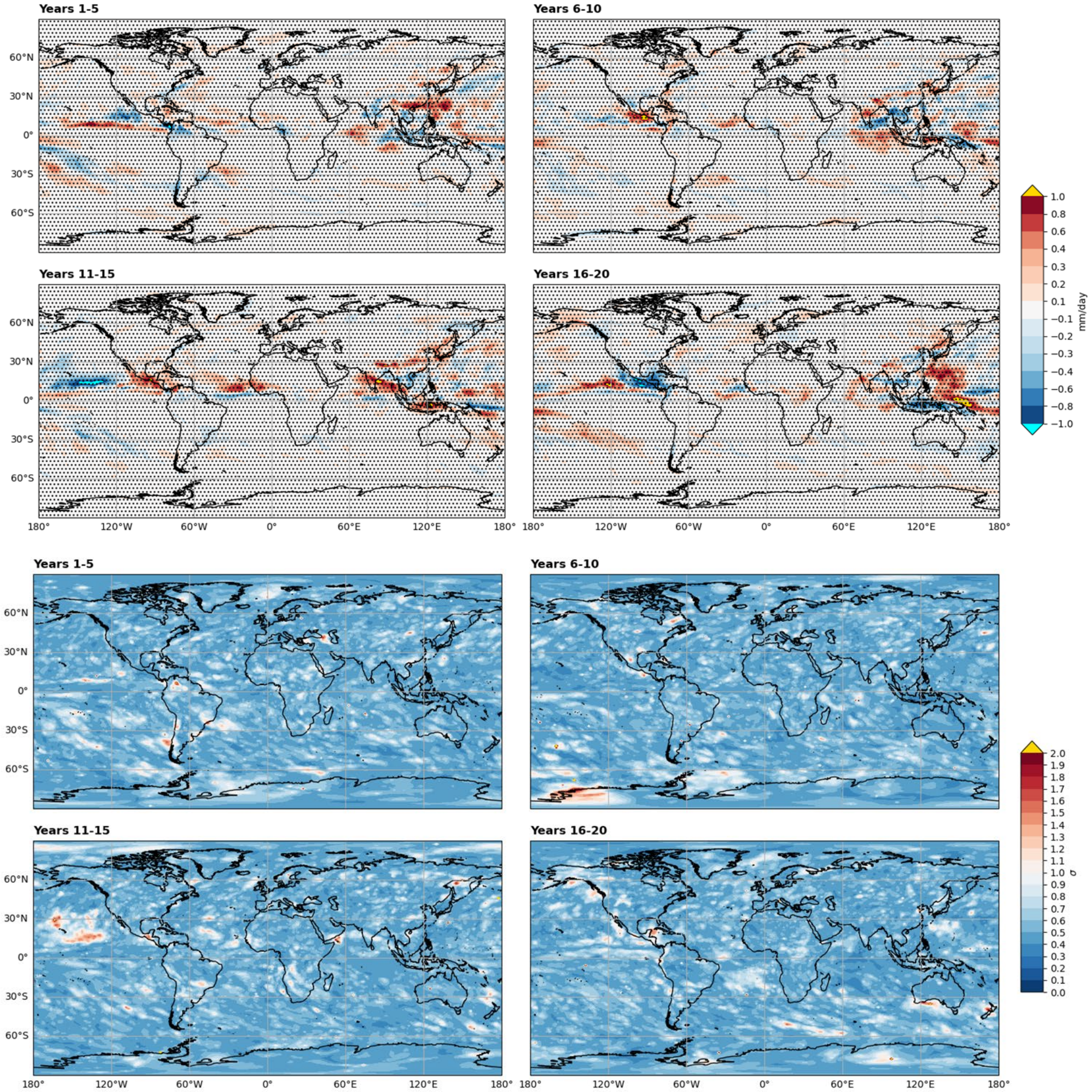


JAS Precip

HR(6)



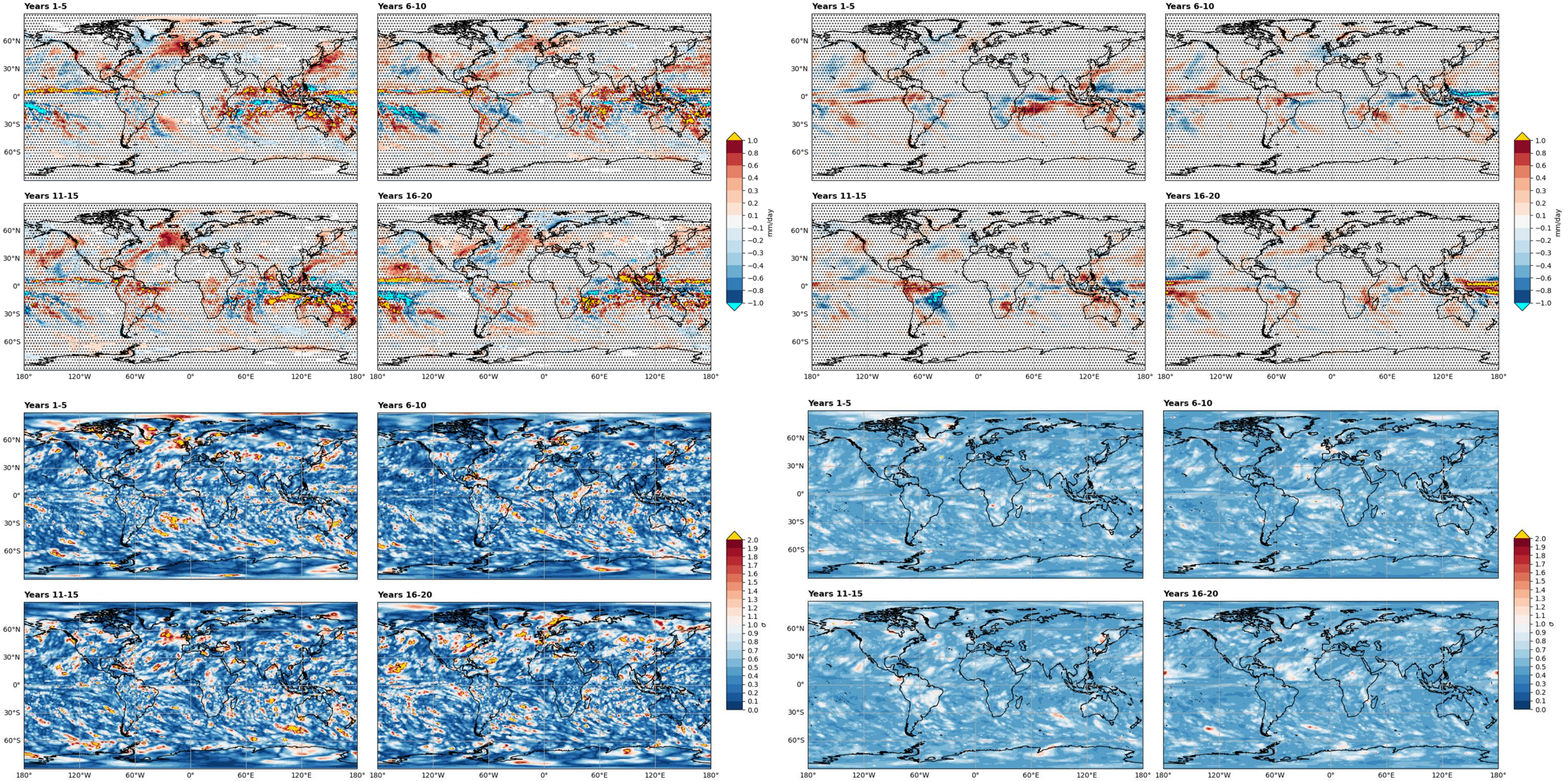
LR(20)



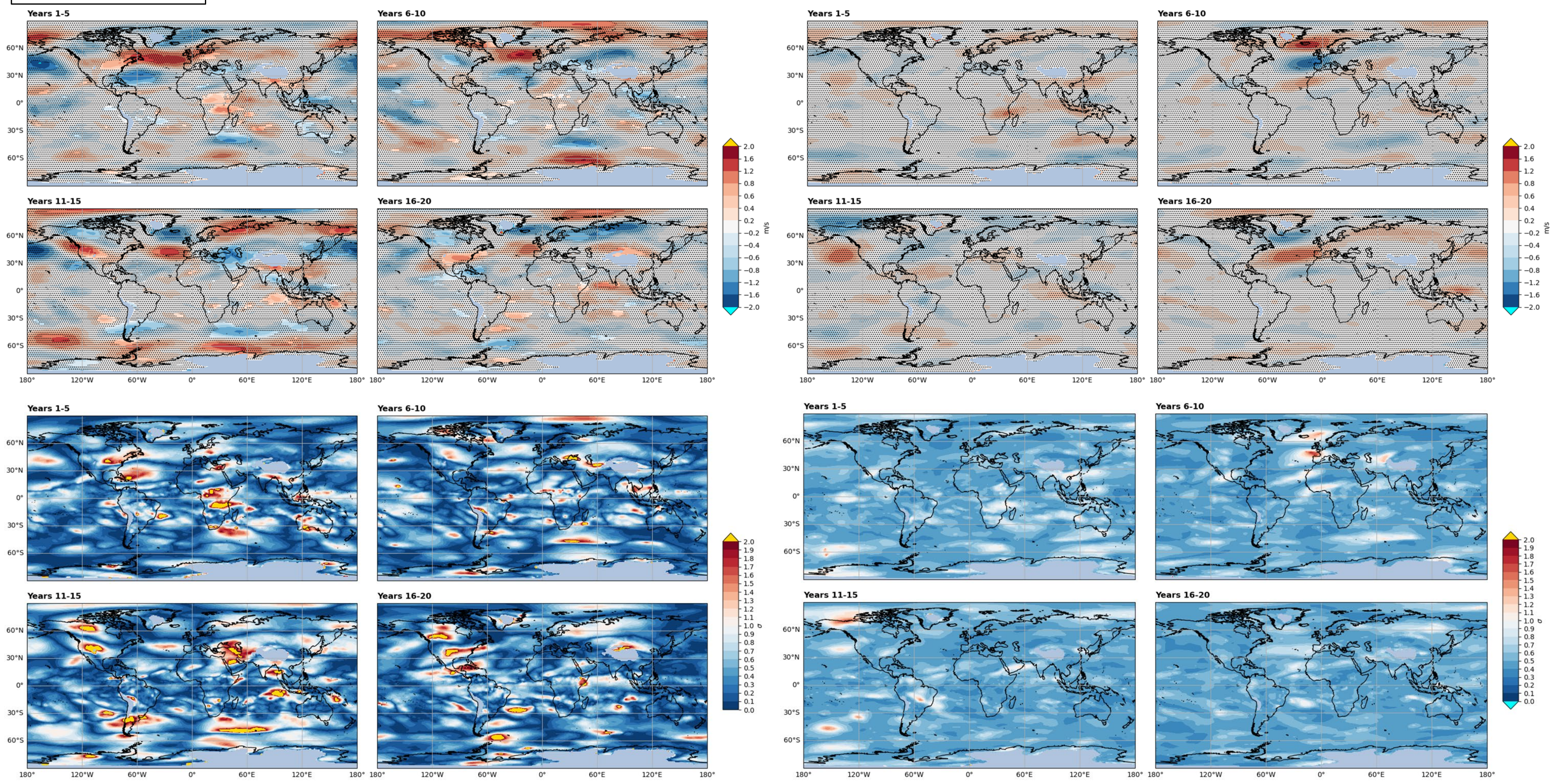
JFM Precip

HR(6)

LR(20)

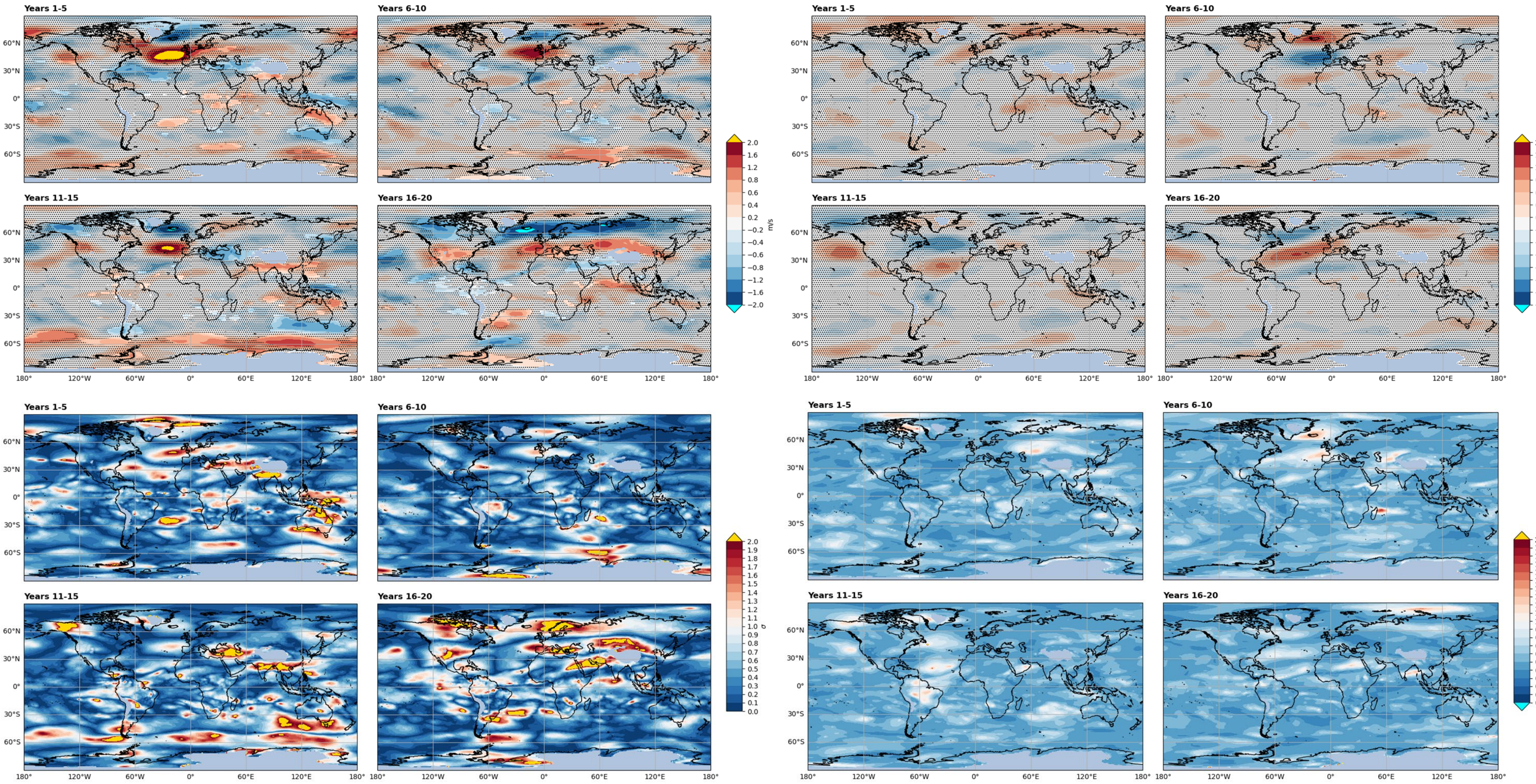


DJF U700


HR(6)
LR(20)
Years 1-5
Years 6-10
Years 11-15
Years 16-20
m/s
σ
Operated by UCAR

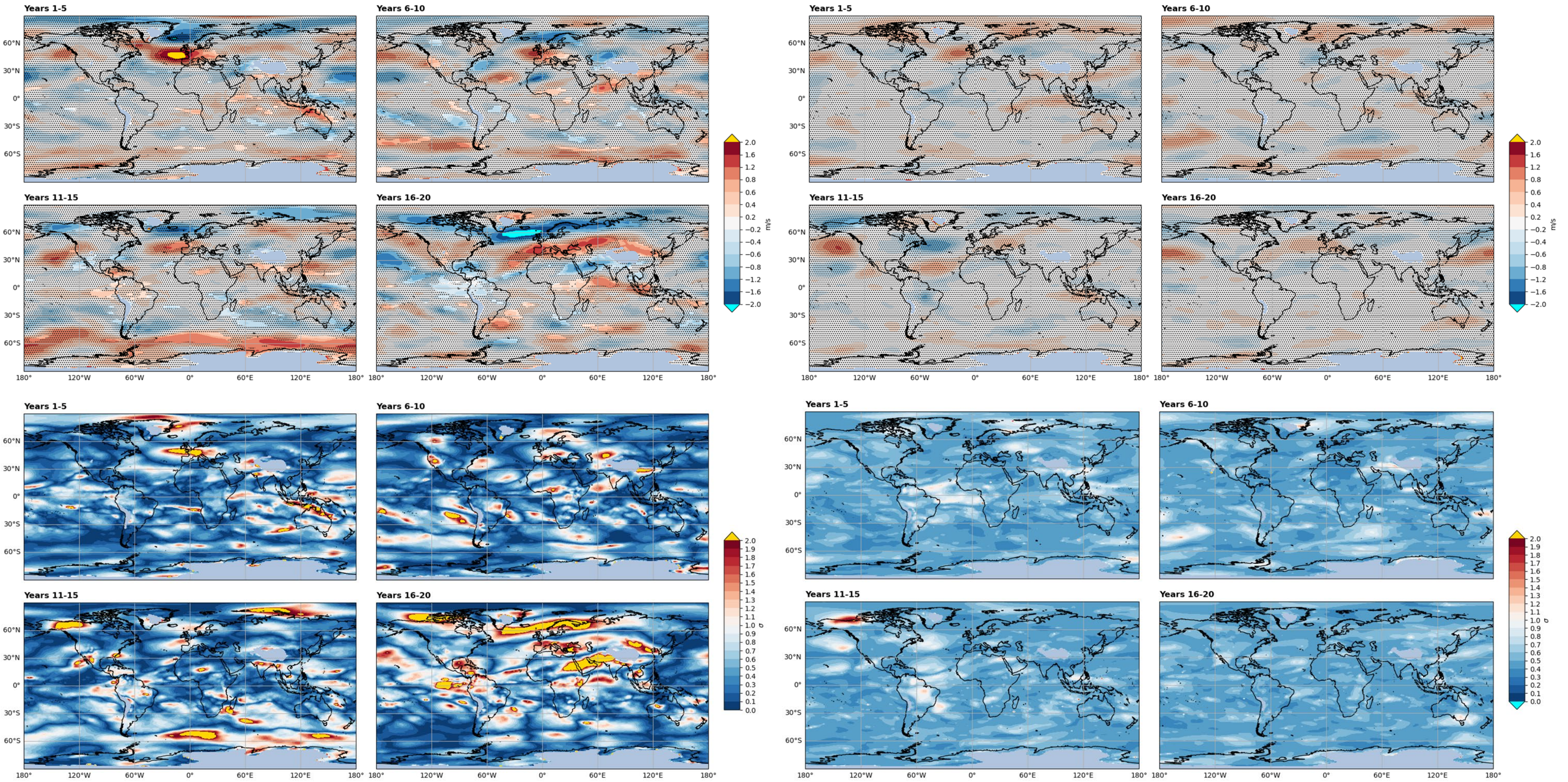
JFM U700

HR(6) LR(20)



FMA U700

HR(6) **LR(20)**



HR(6) **LR(20)**

- Mechanistic explanation:
  - if possible, explain HR/LR differences
  - relative roles of ocean/atm response in setting SST
  - 1. SST part: v-prime/t-bar, etc decomp of ocean HT
    atmos heat flux response
  - 2. **atm circ response to given SST**:
    regressions of jet response to SST (jet latitude shift per degree C) from experiments as well as PI controls
    (expect HR regression to be stronger, not just stronger SST!)
  - what is going on with sea ice? Is it playing a role in HR response?