Increasing boreal fires reduce future global warming and sea ice loss

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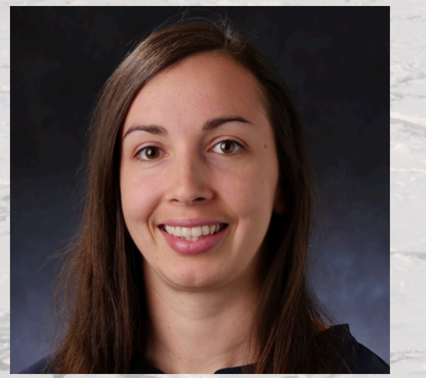

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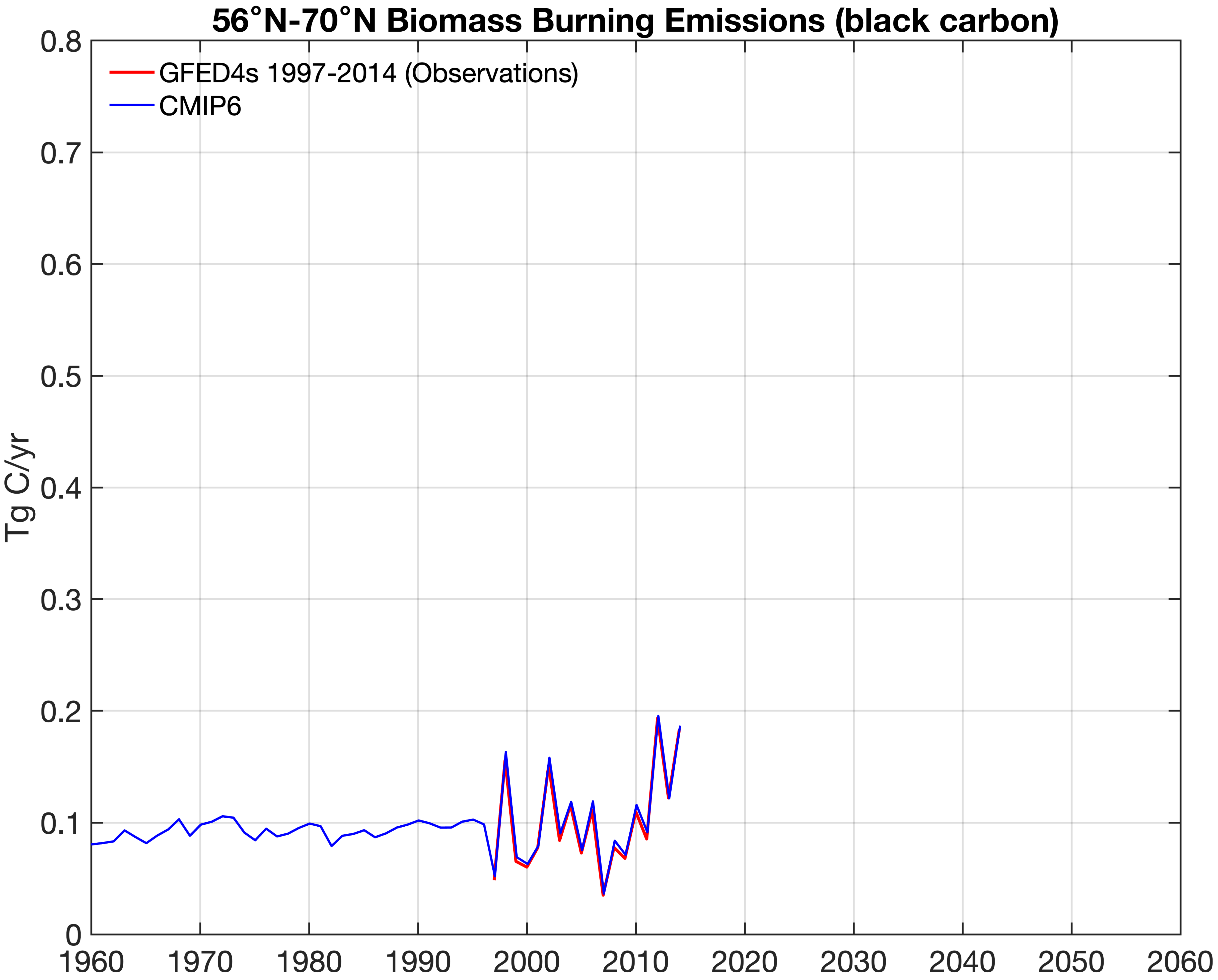
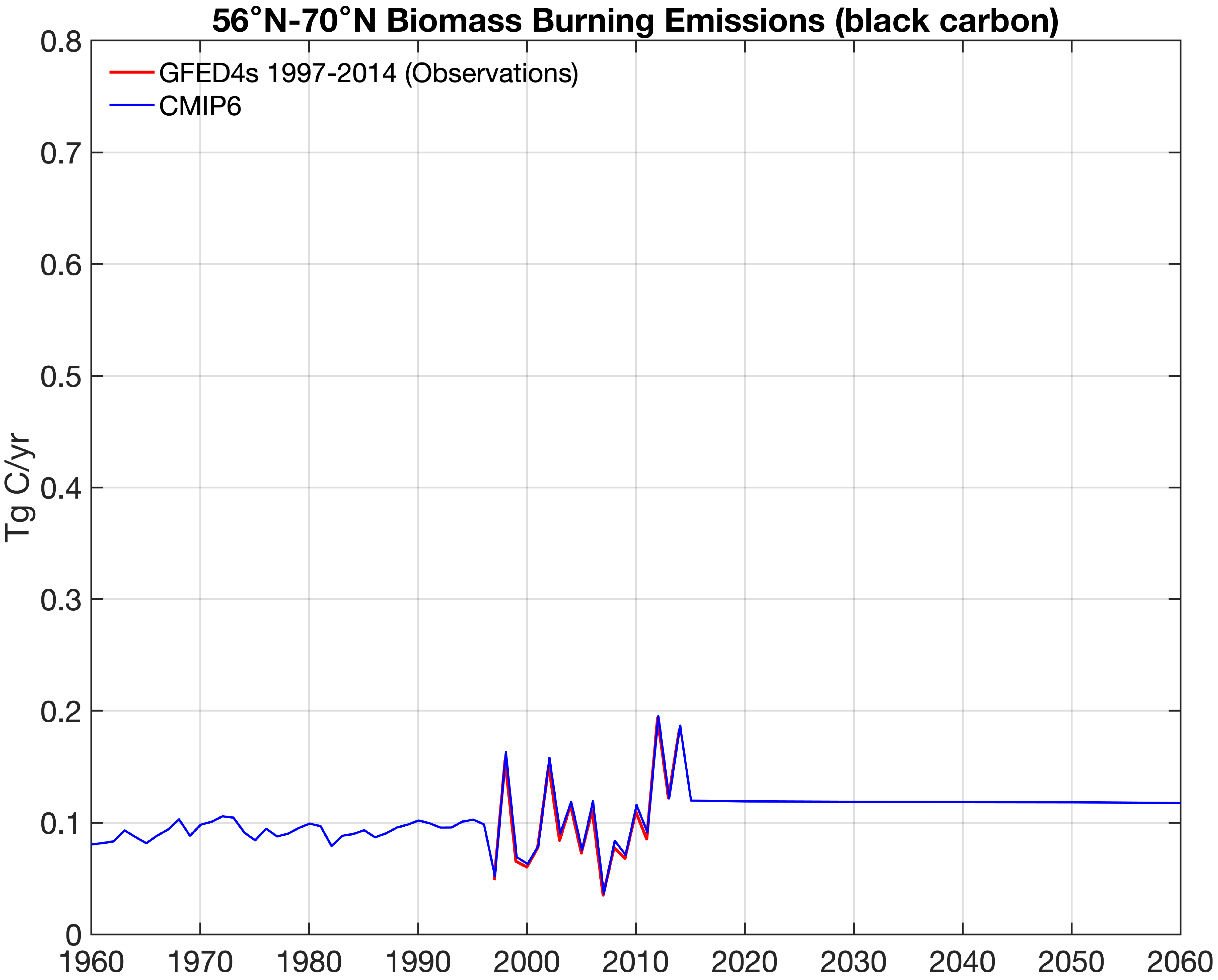
Atmospheric and Climate science, University of Washington



56°N-70°N Biomass Burning Emissions (black carbon)
GFED4s 1997-2014 (Observations)
CMIP6
Tg C/yr
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060


56°N-70°N Biomass Burning Emissions (black carbon)
GFED4s 1997-2014 (Observations)
CMIP6
Tg C/yr
0.8
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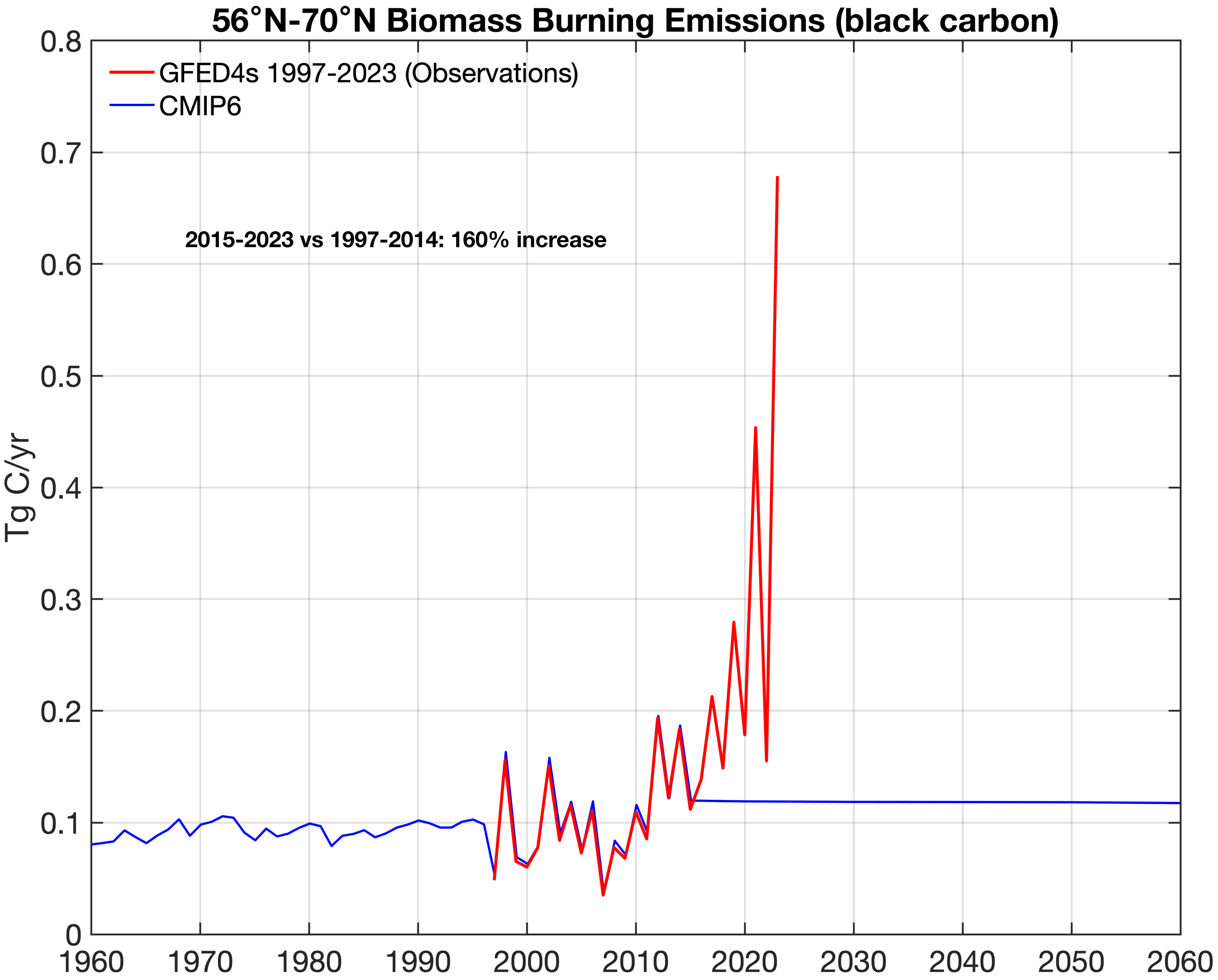
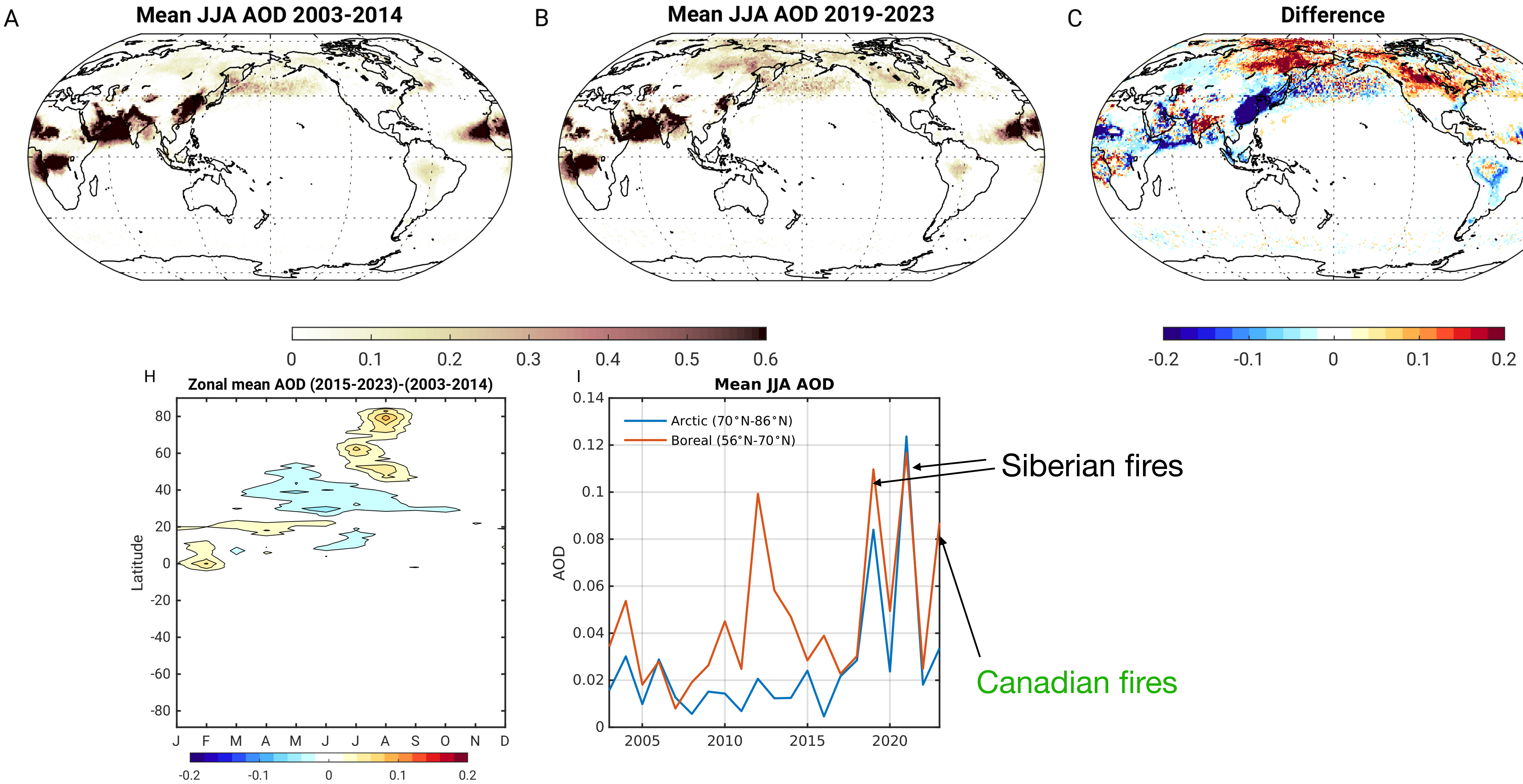
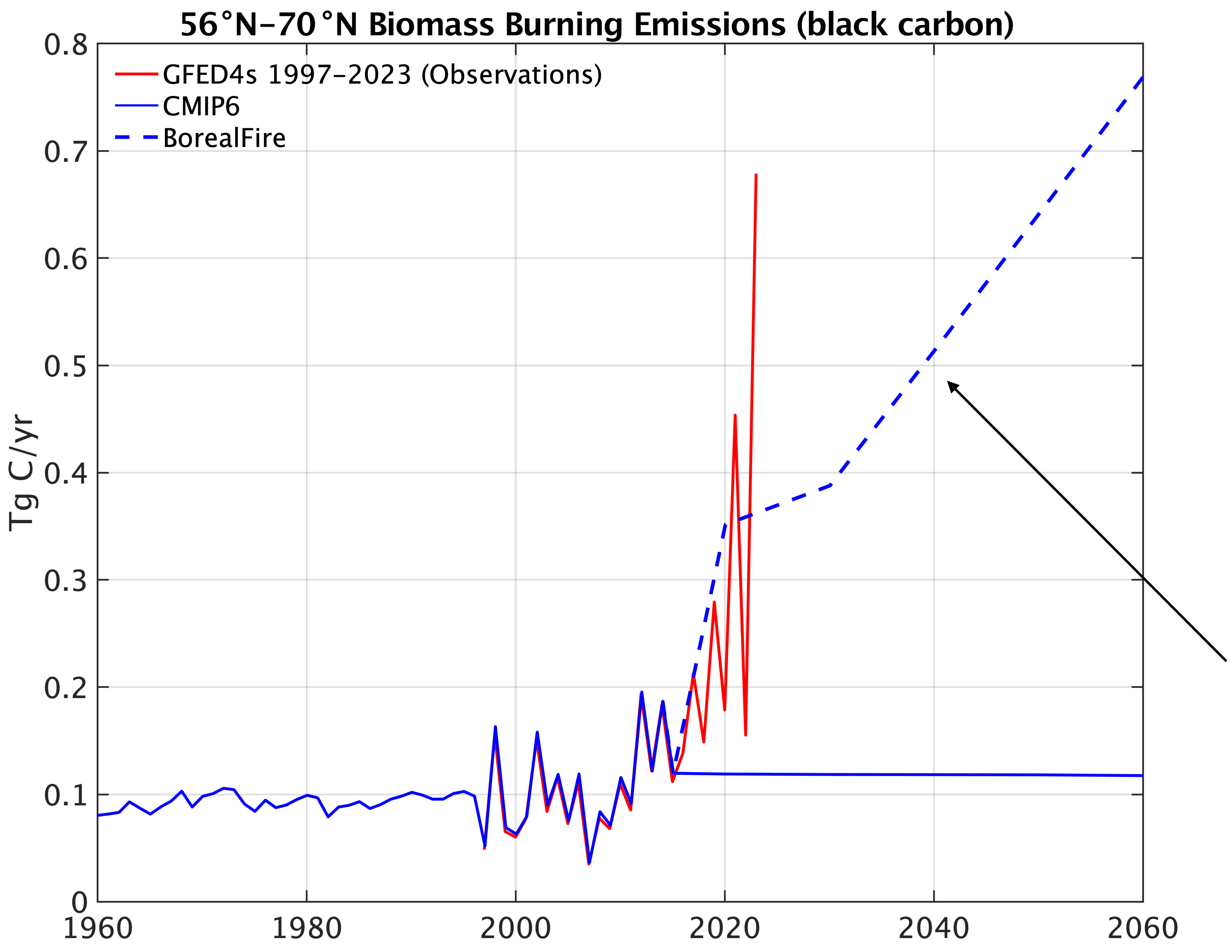
0.5
0.4
0.3
0.2
0.1
0
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060



56°N-70°N Biomass Burning Emissions (black carbon)
GFED4s 1997-2023 (Observations)
CMIP6
2015-2023 vs 1997-2014: 160% increase
Tg C/yr
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060

Summer aerosol optical depth (MODIS/Aqua) has increased over the boreal regions and the Arctic



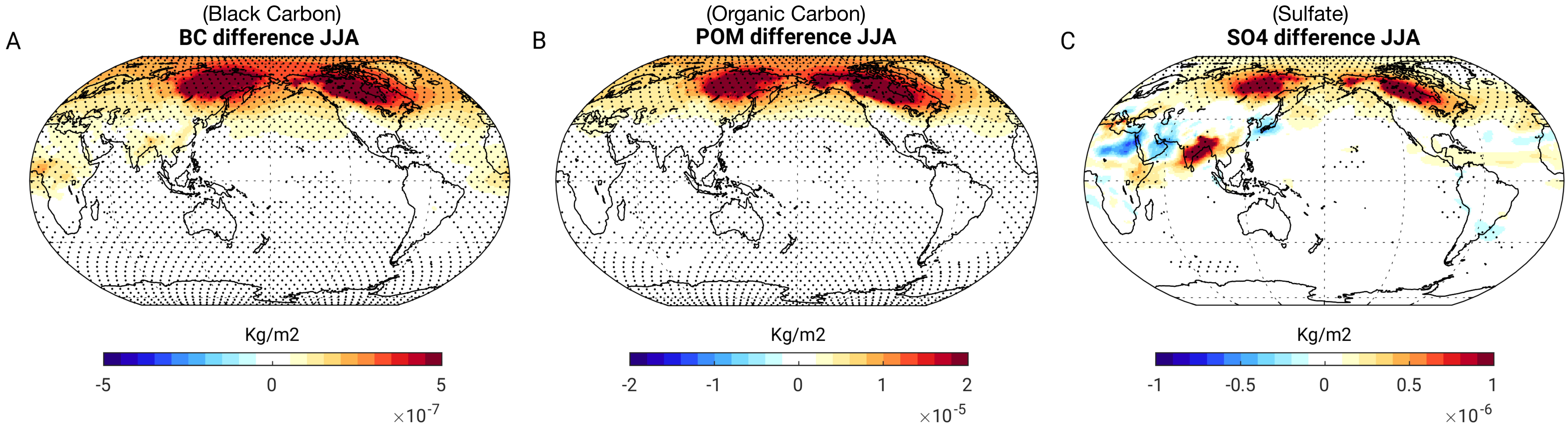


Produced new ensemble with CESM2, over 2015-2060, 9 members, branched off CESM2-LE in 2015

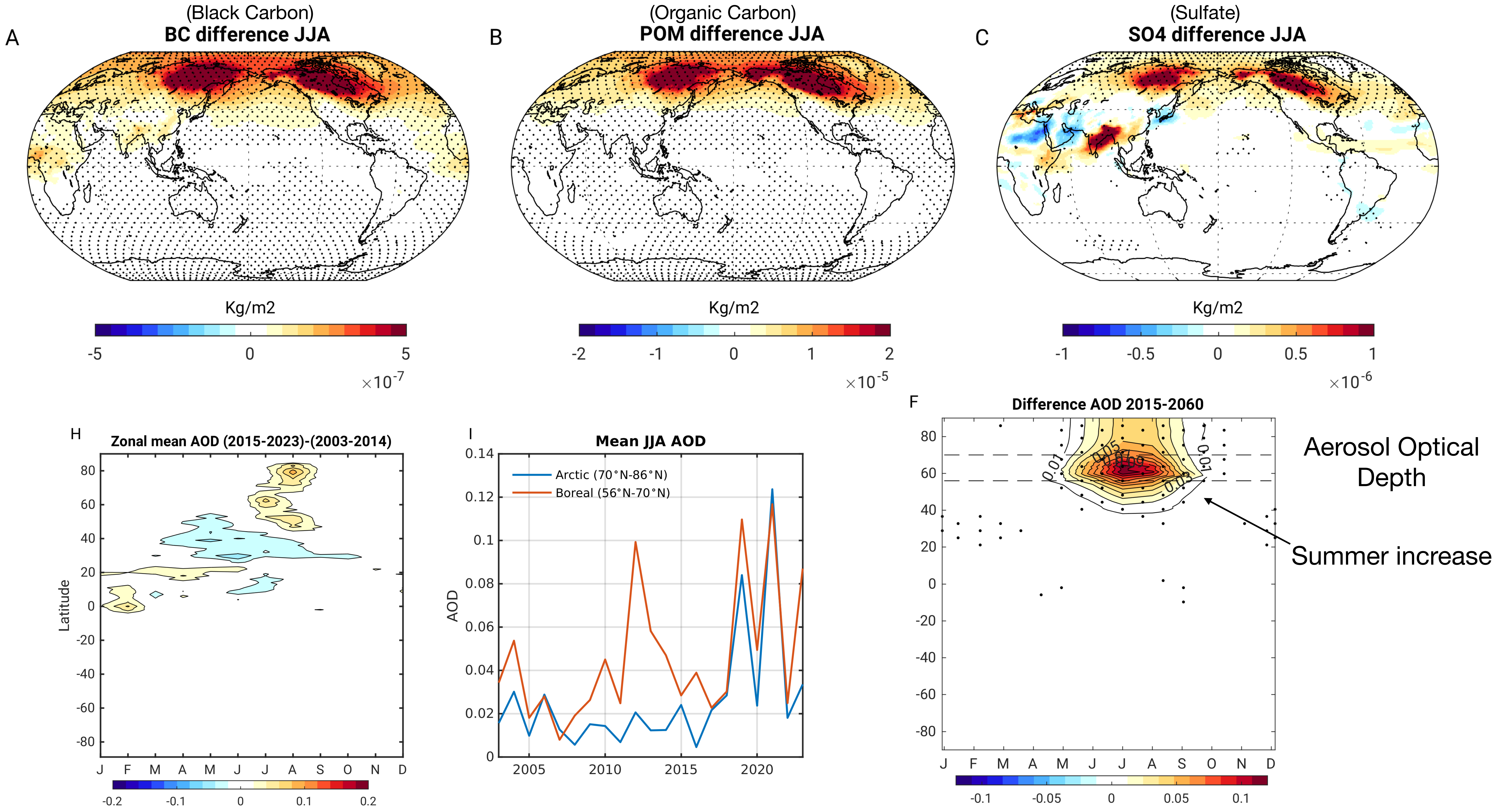
Same CMIP6 forcings as CESM2-LE (SSP370 scenario)

Except for boreal biomass burning emissions, which follow observations/observed trends

Black carbon, sulfate, organic carbon (POM) are all updated



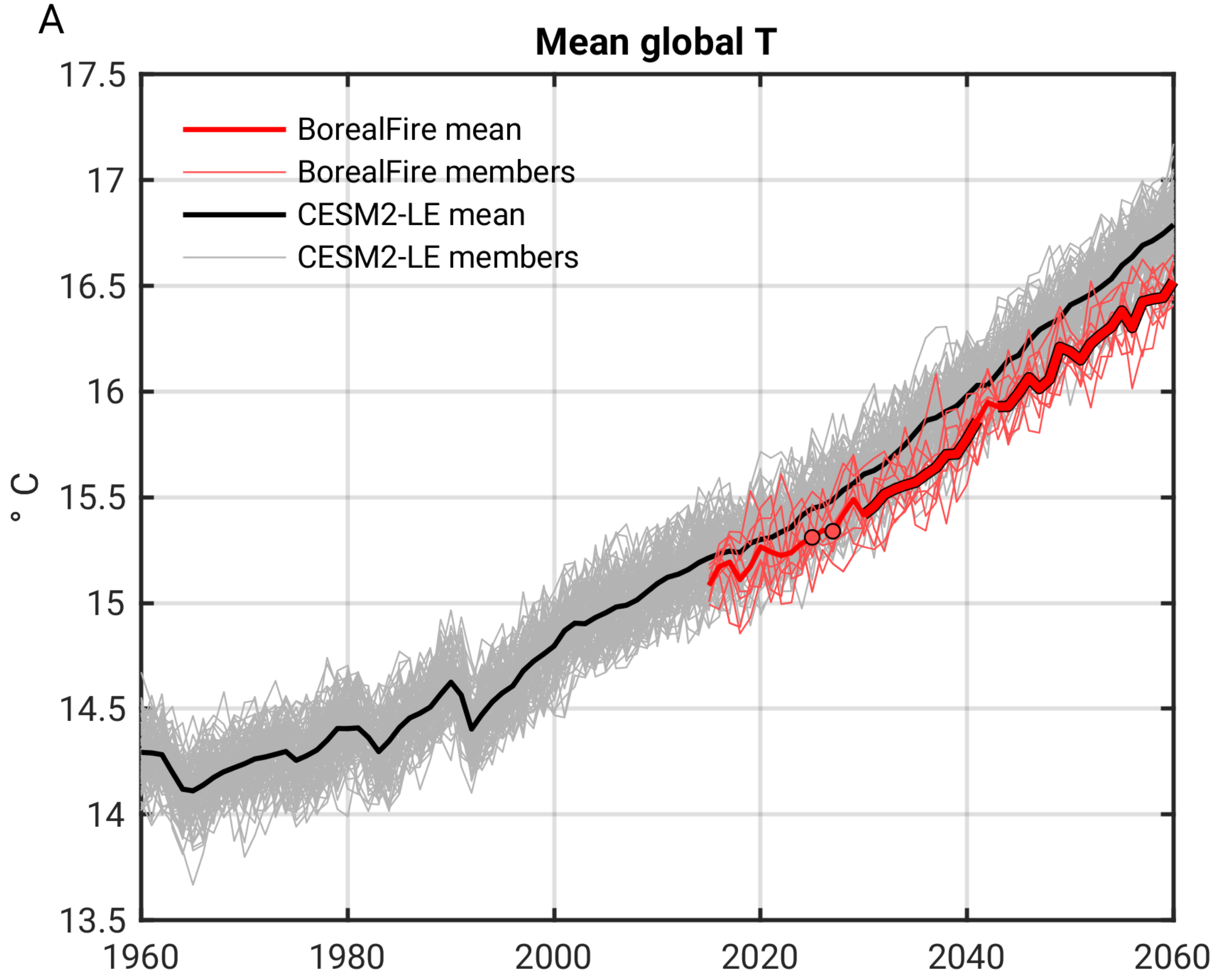
BorealFire - CESM2-LE, JJA column burden differences



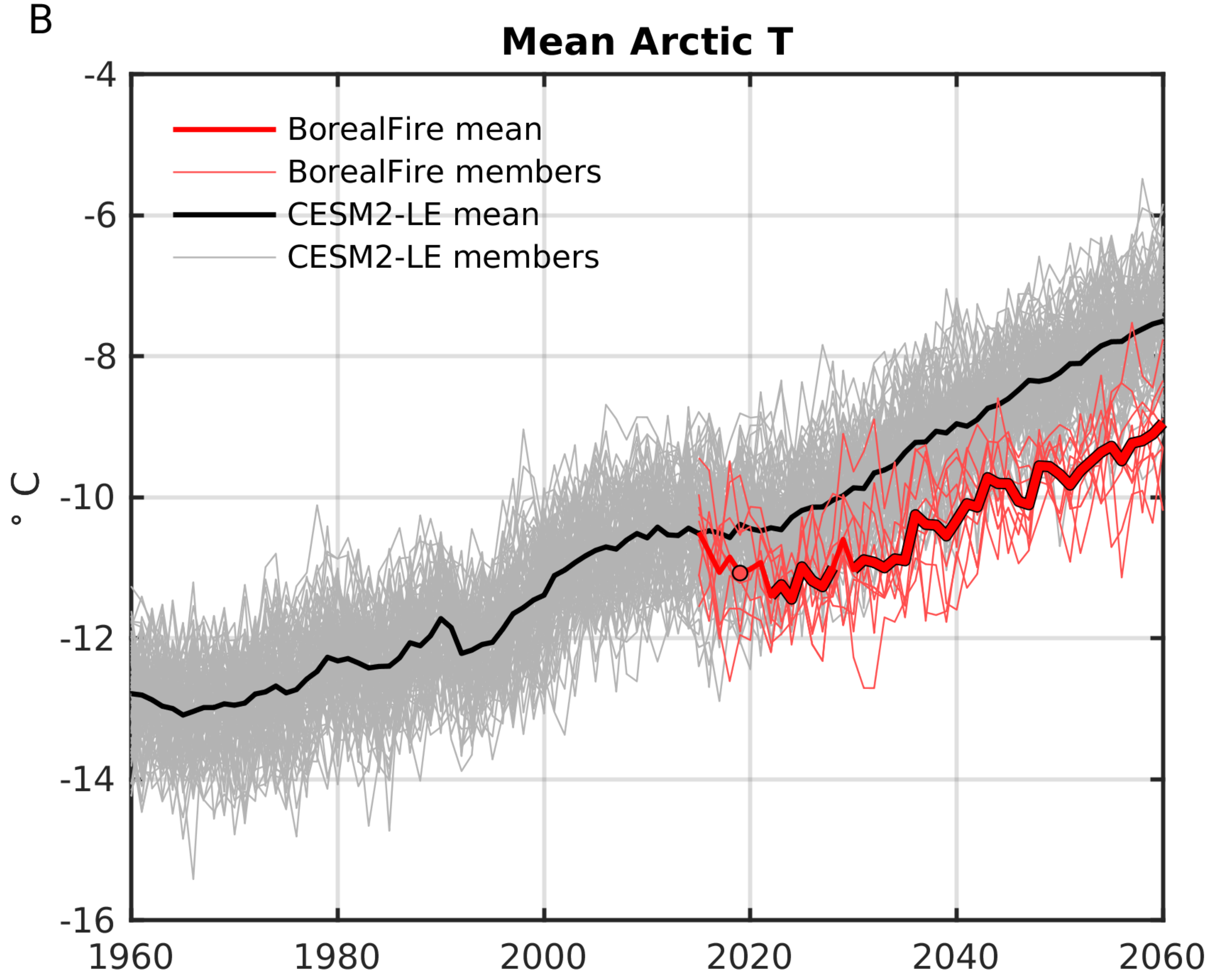
A
(Black Carbon)
BC difference JJA
Kg/m2
-5
0
5
×10^-7
B
(Organic Carbon)
POM difference JJA
Kg/m2
-2
-1
0
1
2
×10^-5
C
(Sulfate)
SO4 difference JJA
Kg/m2
-1
-0.5
0
0.5
1
×10^-6
H
Zonal mean AOD (2015-2023)-(2003-2014)
Latitude
80
60
40
20
0
-20
-40
-60
-80
J F M A M J J A S O N D
-0.2
-0.1
0
0.1
0.2
I
Mean JJA AOD
Arctic (70°N-86°N)
Boreal (56°N-70°N)
AOD
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
2005
2010
2015
2020
F
Difference AOD 2015-2060
80
60
40
20
0
-20
-40
-60
-80
J F M A M J J A S O N D
-0.1
-0.05
0
0.05
0.1
Aerosol Optical Depth
Summer increase

Mean annual temperature

A



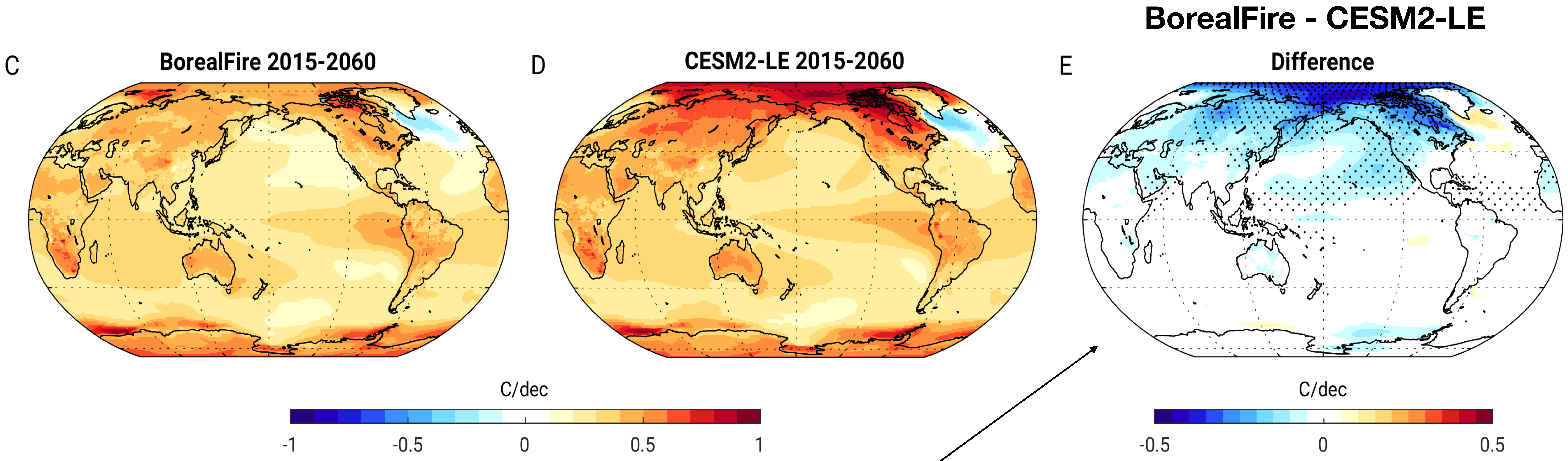
B



0.33°C/decade warming in BorealFire
0.37°C/decade warming in CESM2-LE
(12% reduction)

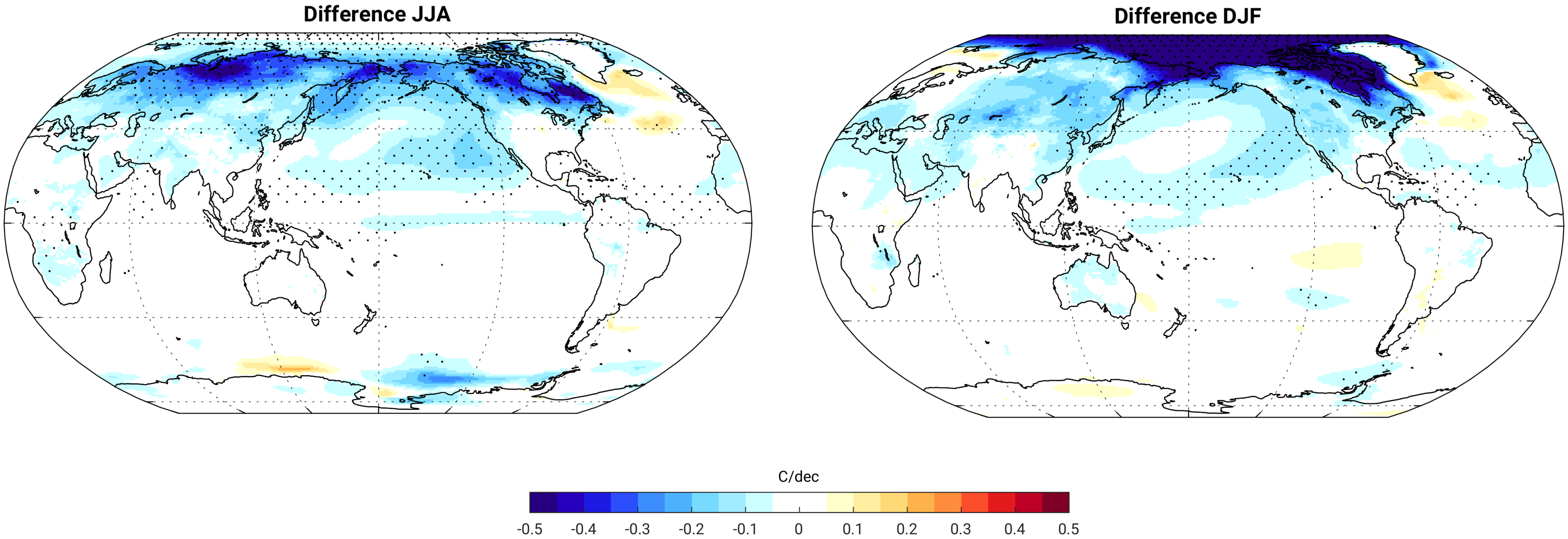
0.49°C/decade warming in BorealFire
0.78°C/decade warming in CESM2-LE
(38% reduction)

Annual temperature trends



Relative cooling in the Arctic, northern continents (>40°N), North Pacific (but not North Atlantic). No change in Southern Hemisphere.

Seasonal temperature trend differences BorealFire - CESM2-LE

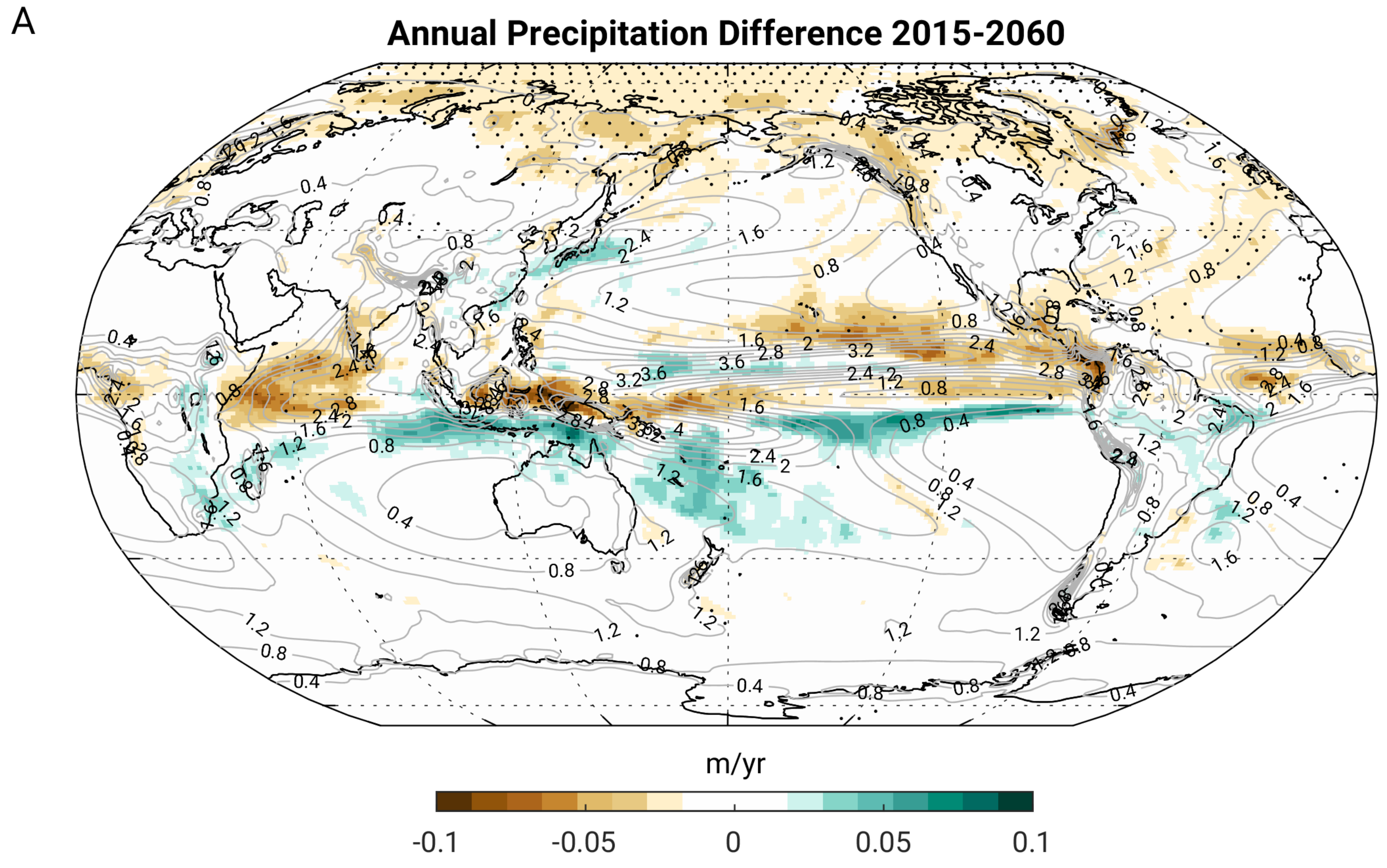


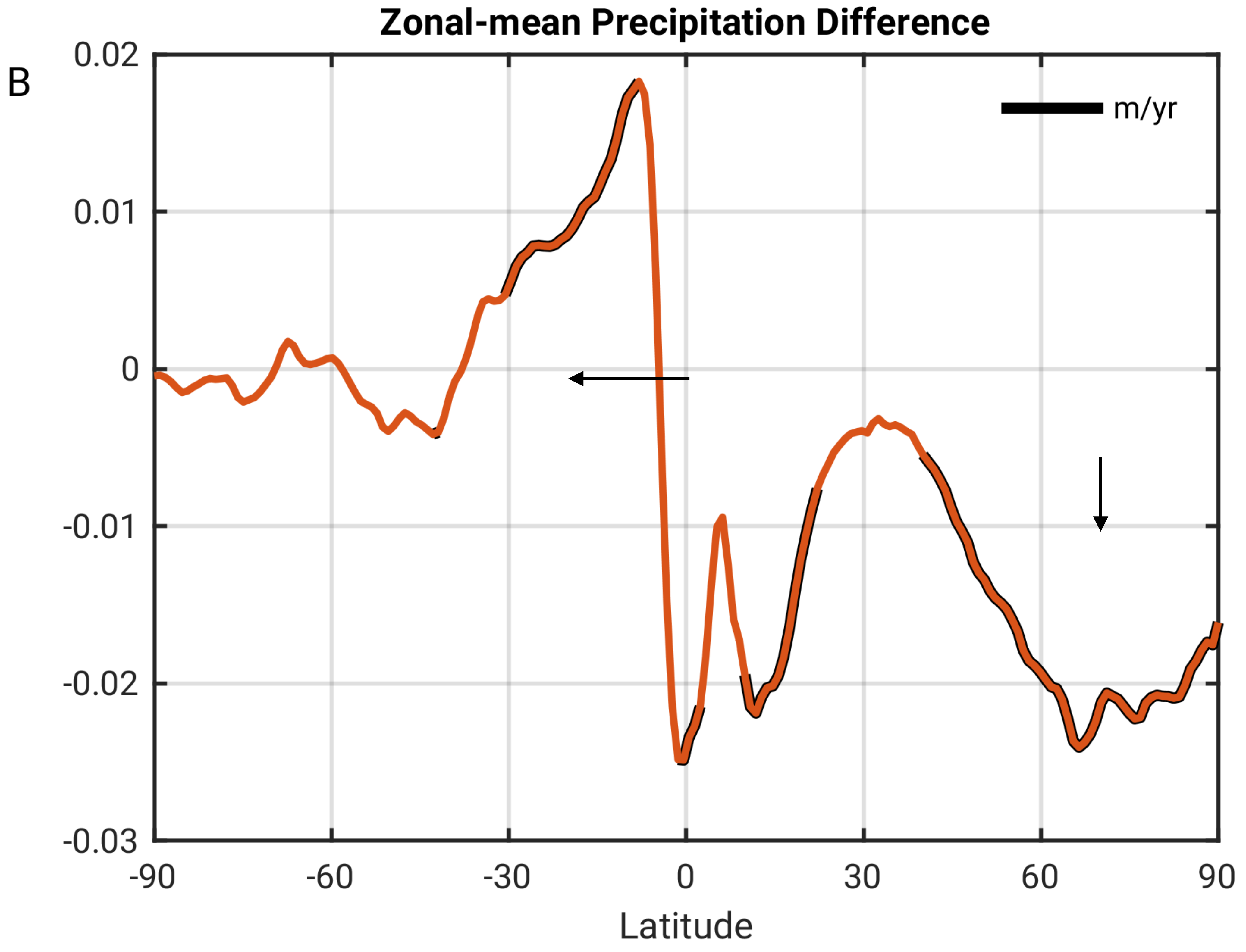
Local Summer boreal peak cooling

Winter and fall Arctic peak cooling

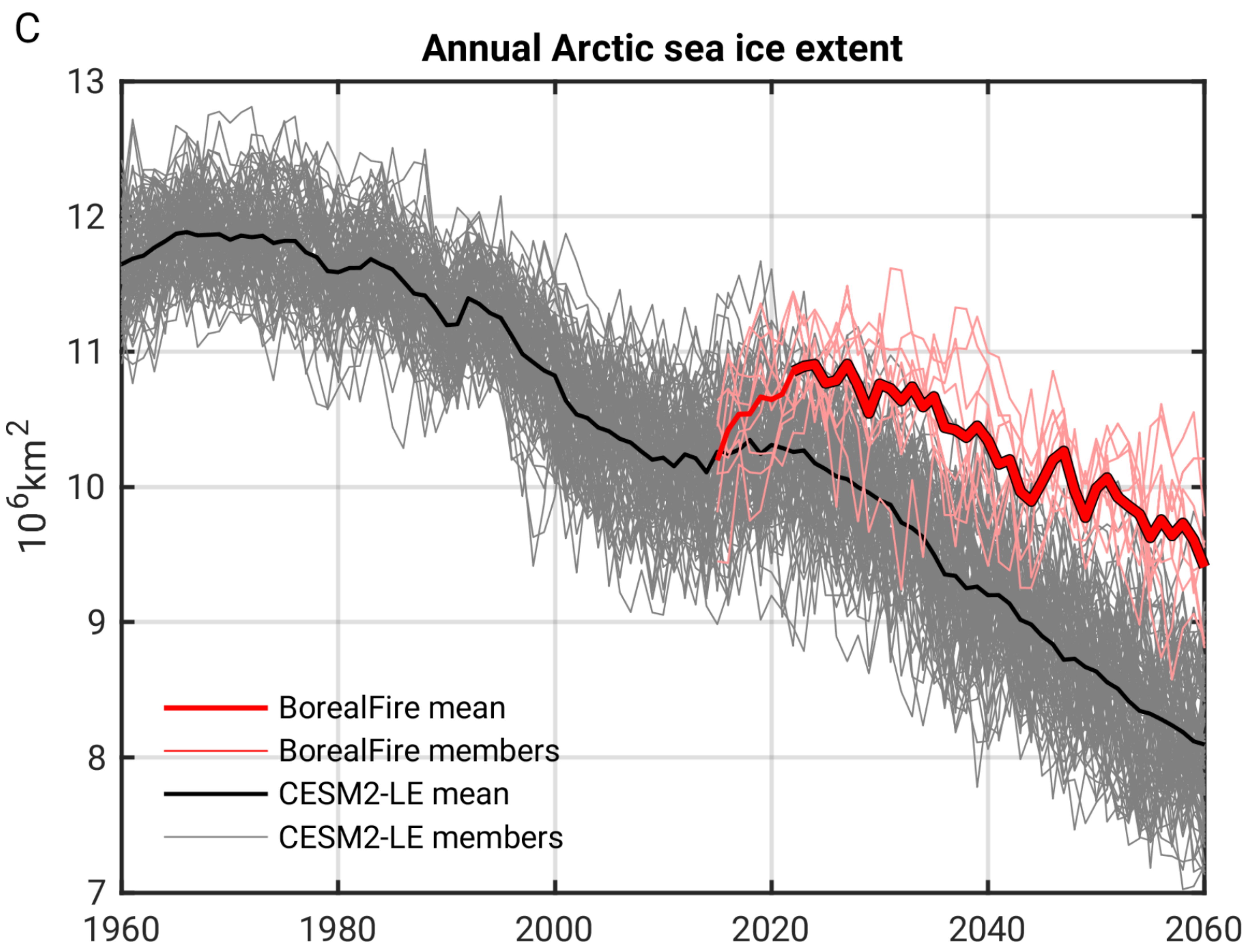
Year-round in North Pacific

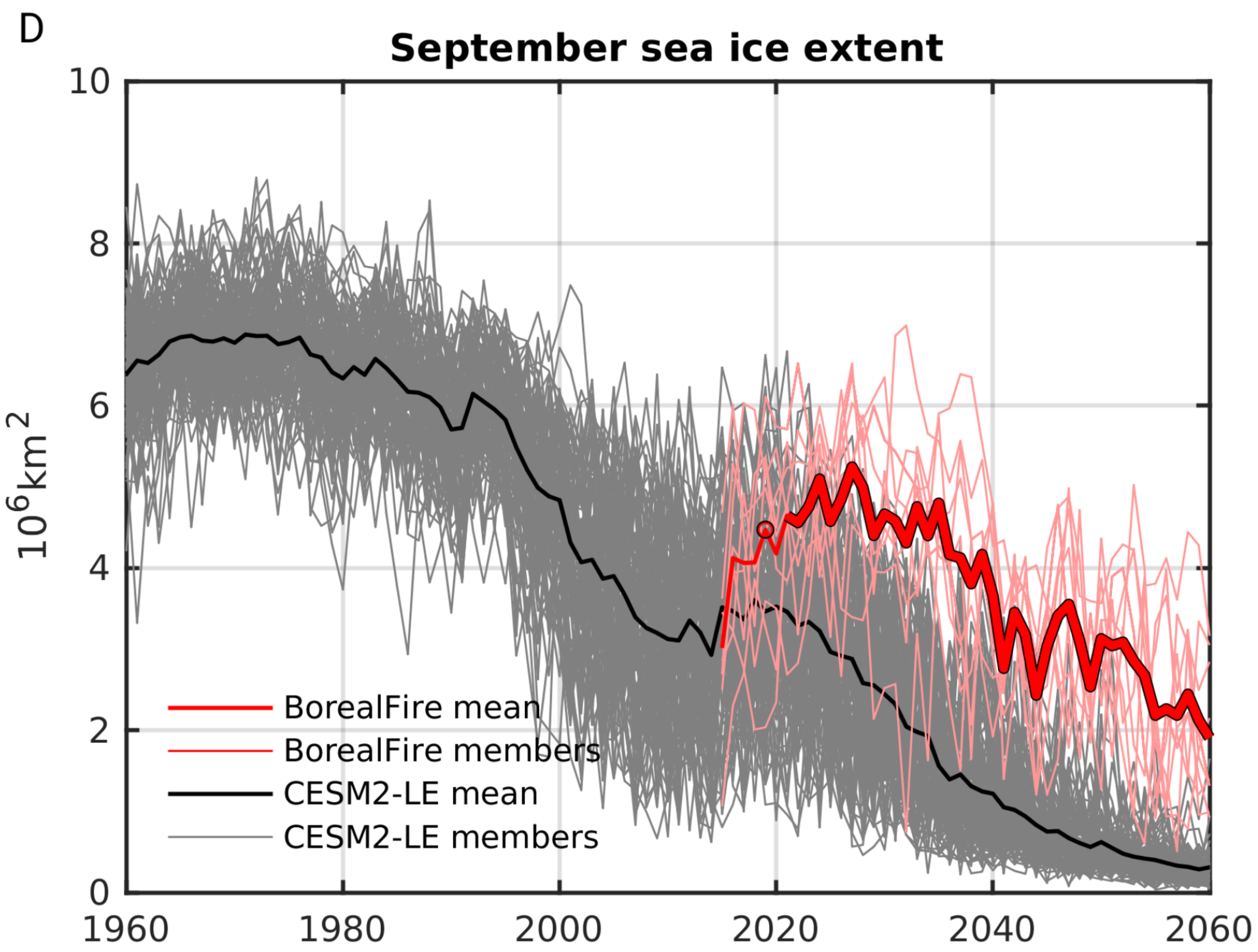
Southward shift in tropical precipitation (consistent with Chiang and Bitz, 2005)





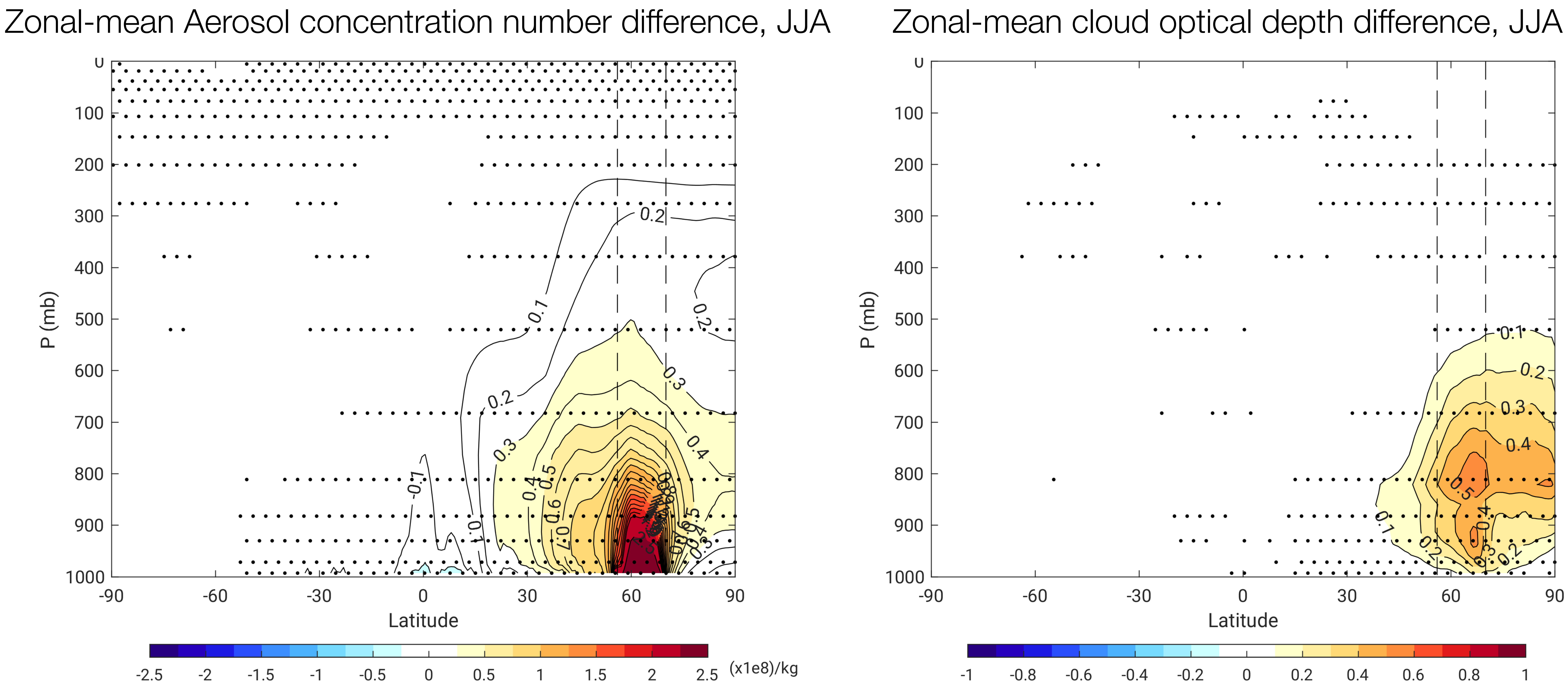
Decrease in high northern latitude precipitation (a cooler Arctic is a drier Arctic, and emissions suppress boreal precipitation in JJA)





Reduction in Arctic sea ice loss, especially in summer

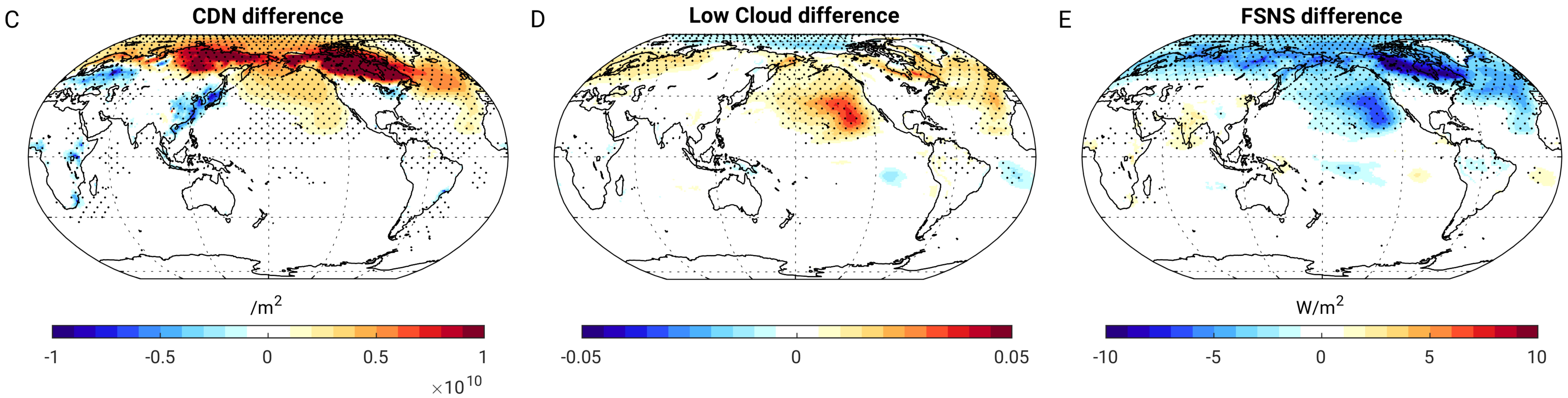
Why does all this happen



(BorealFire-CESM2)

Annual-mean differences in:

Cloud droplet number | Low Cloud fraction | Net solar at surface



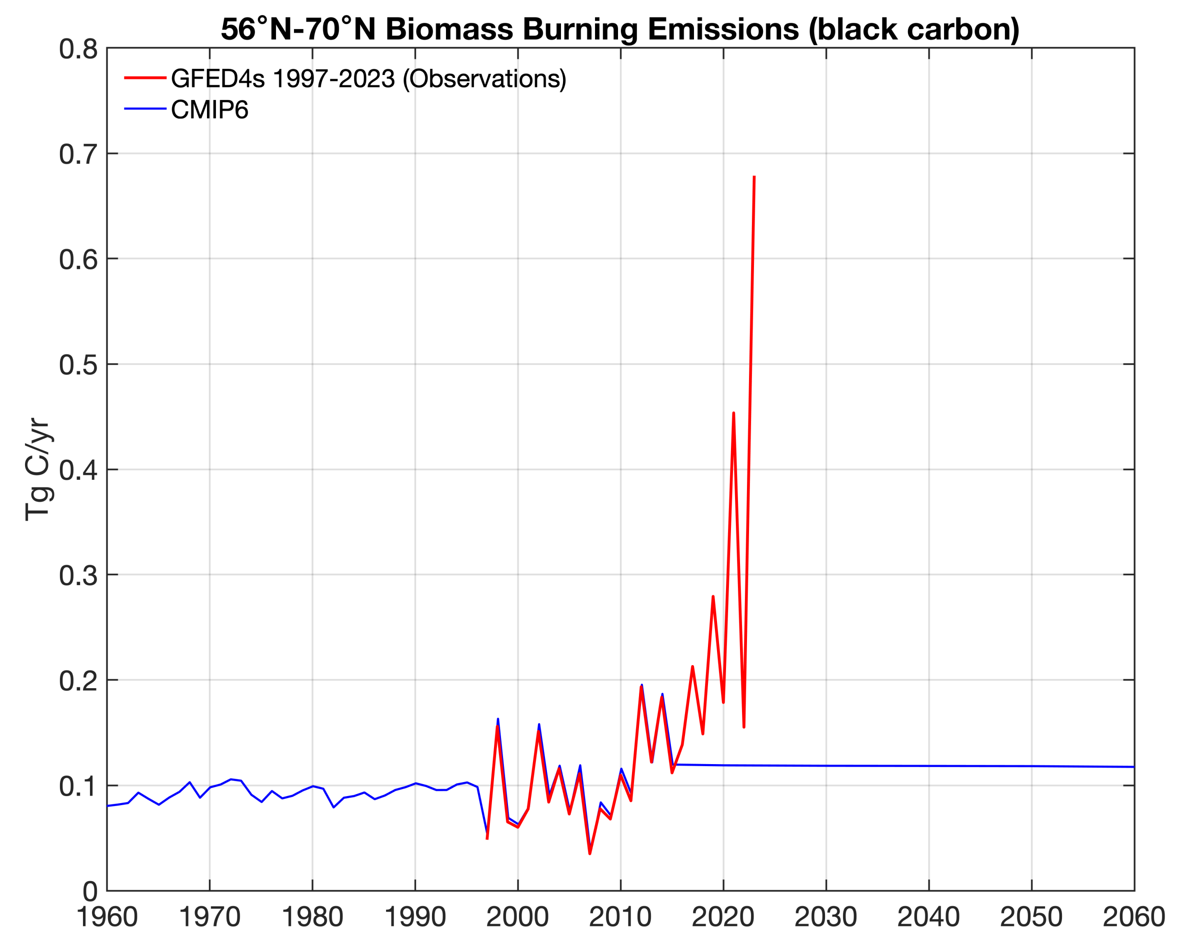
Over Canada / Siberia and Arctic, no change in summer cloud cover, but enhanced albedo (reflectivity) of existing clouds -> reduced solar flux, less summer sea ice melt

Thicker/larger sea ice cover drives cooler temperatures in fall/winter

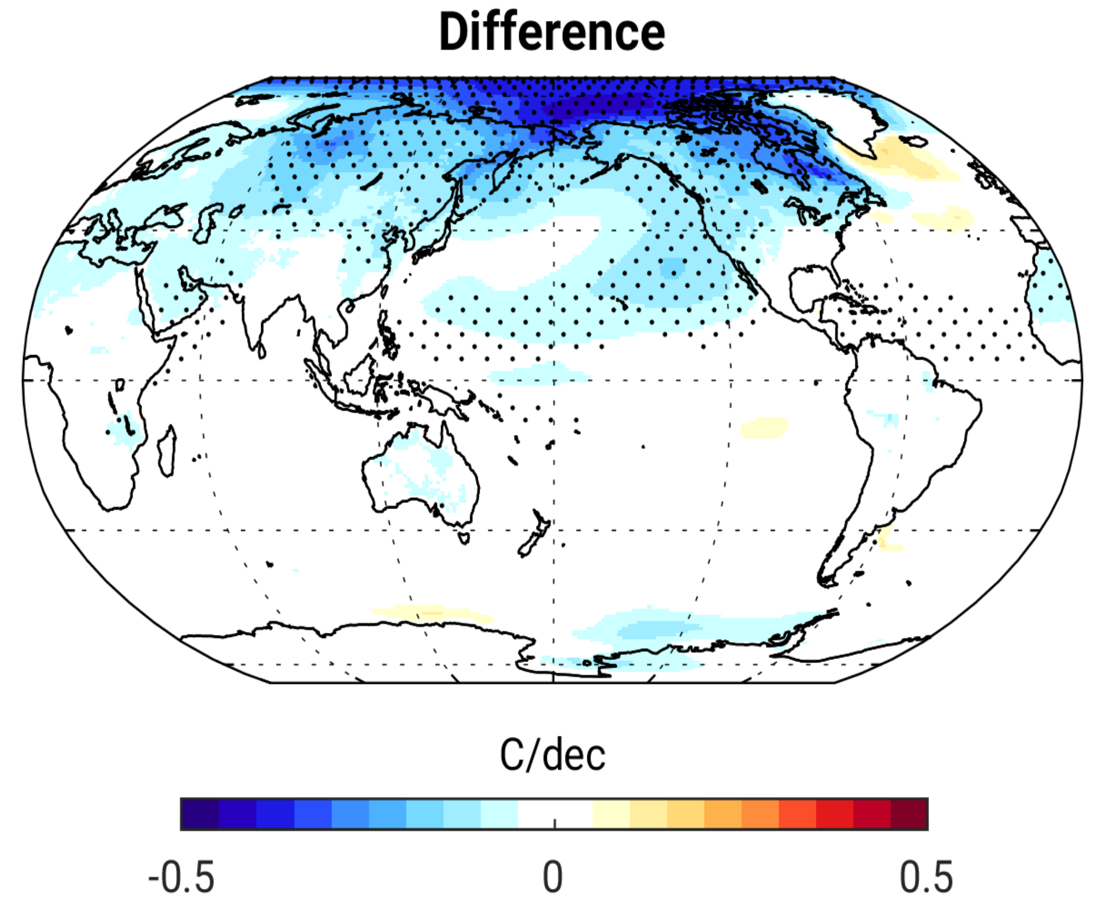
In North Pacific and North Atlantic, greater low cloud fraction -> reduced solar flux at surface

In summary

Boreal biomass burning emissions have increased drastically in observations in recent years, in contrast to CMIP6 2015-2100 scenarios, which have no trend. Observed aerosol optical depth over the Arctic has increased.



Running CESM2 with increasing boreal emission scenarios over 2015-2060 shows **a slowdown in global warming (12%), Arctic warming (38%), less sea ice loss, and changes in tropical precipitation.** Summer forcings result in year-round impacts beyond boreal region.



Boreal emissions matter, and CMIP7 should not simply repeat CMIP5/6 scenarios.

Blanchard-Wrigglesworth, E., DeRepentigny, P., & Frierson, D. M. (2025). Increasing boreal fires reduce future global warming and sea ice loss. *Proceedings of the National Academy of Sciences*, *122*(23), e2424614122.

Extra slides

What's next?

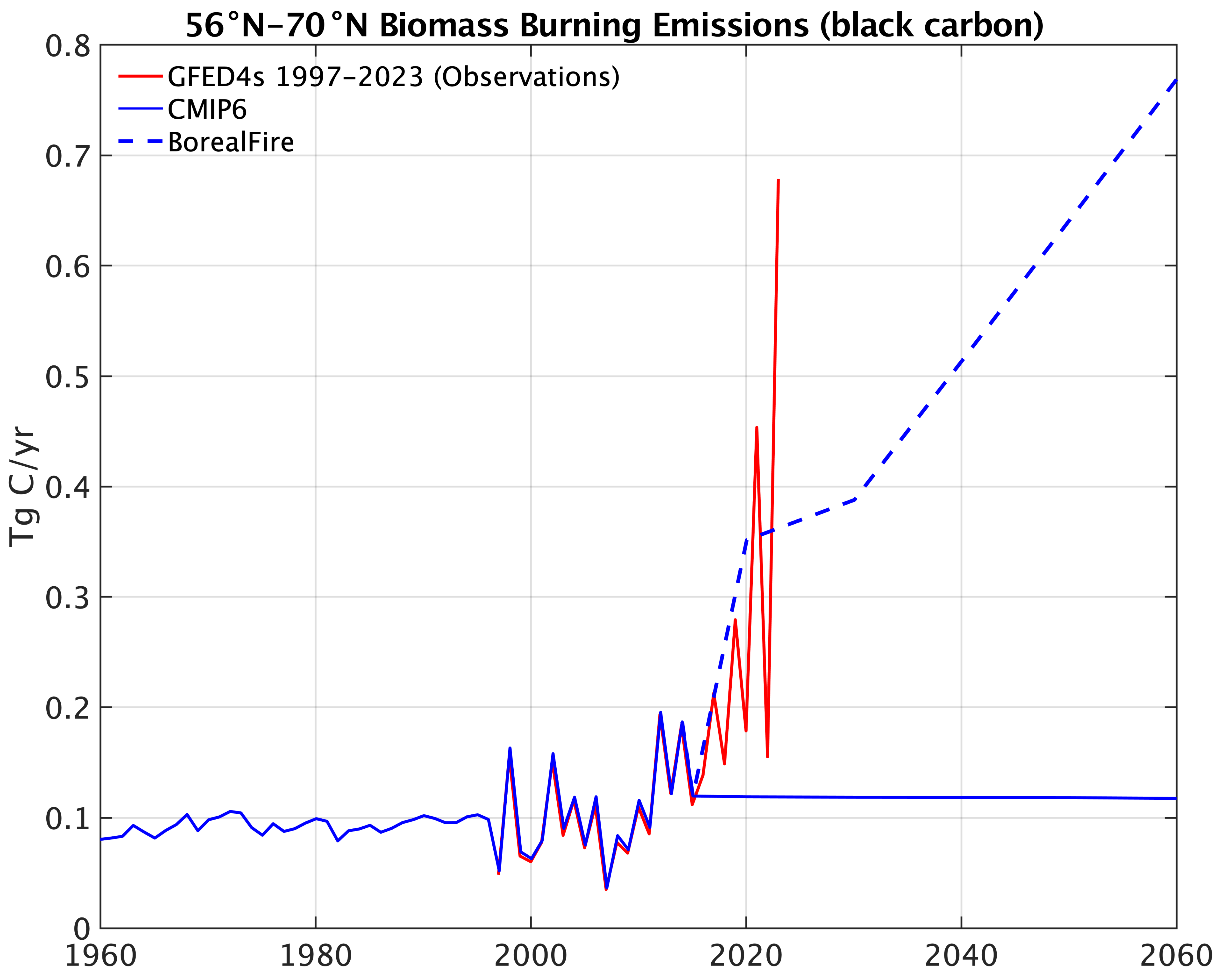
Test sensitivity of results with other GCMs (run mini-MIP). Friends with a GCM? First results with EC-Earth3, upcoming with E3SM.

Test sensitivity to forcings: add inter-annual variability, ramping up followed by ramp down of BBEs, changing seasonality (more early season fires, longer fire season).

How/what observations can we use to validate simulations?

Reach out to CMIP7 working groups.

How much does coupling of weather and fire matter to aerosol transport / lifetimes



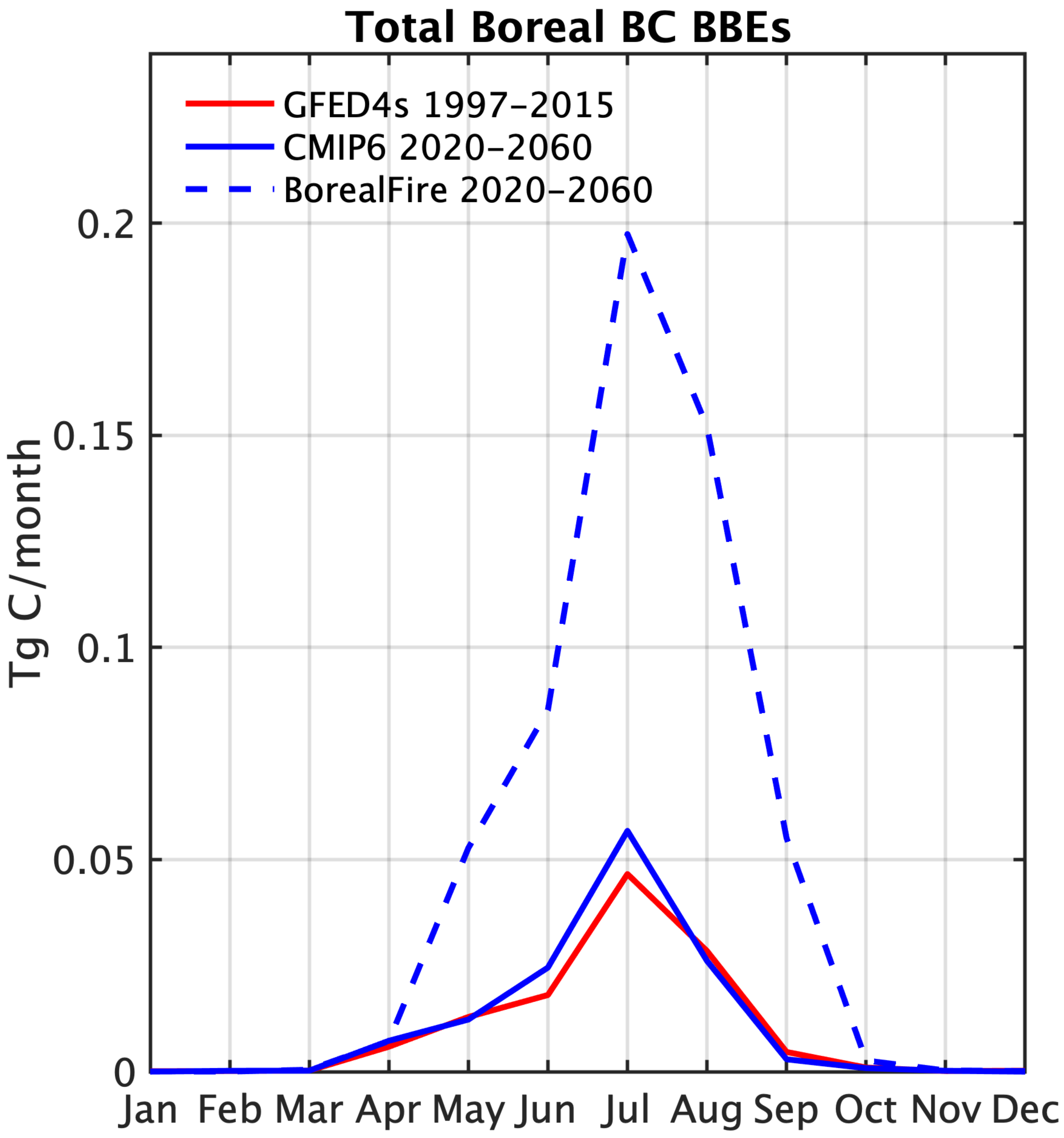
Default 2015-2100 emission files set-up in CESM2: monthly emissions for 2015, 2020, 2030, etc (model interpolates in between years).

Our new CESM2-BorealFire ensemble:

2020: mean observed 2019-2023 emissions.

2030-2060: extrapolated observed 1997-2023 trends for each grid cell and each calendar month.

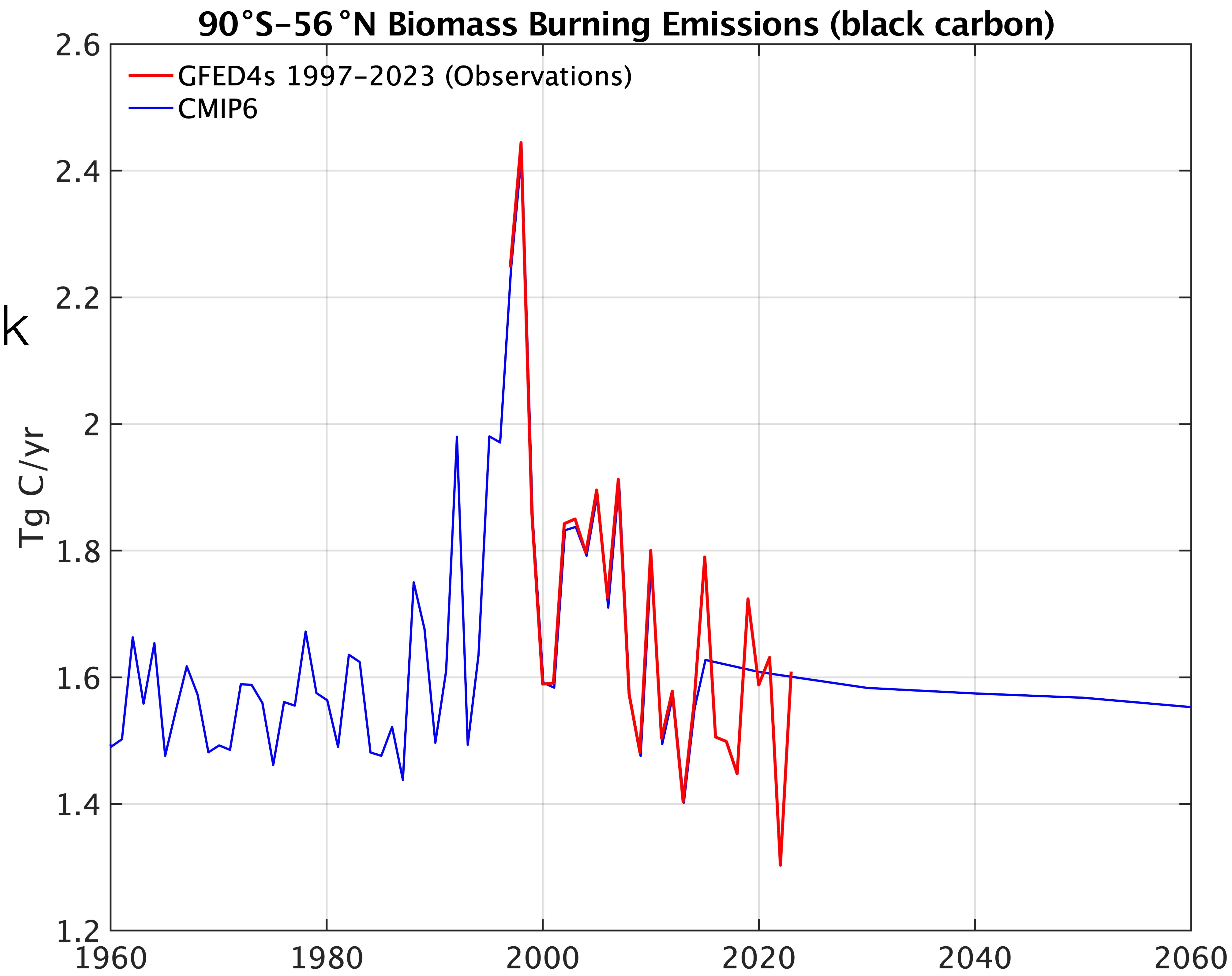
May be conservative: linear extrapolation, not exponential.
No new fires in grid cells & months that had none in 1997-2023.
Most of BorealFire emissions are precedented in observations (2023)

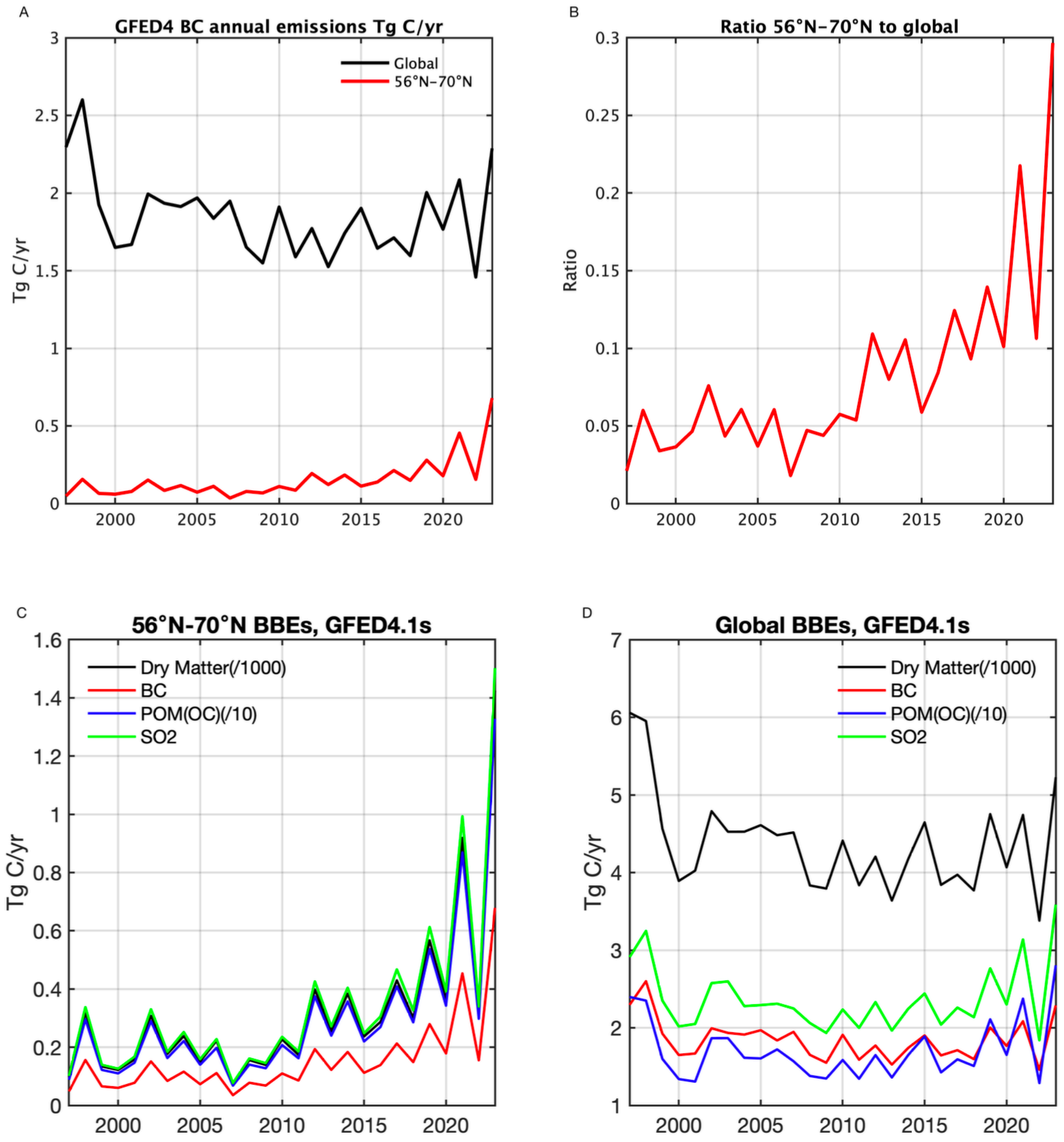


Enhanced emissions take place in the summer months

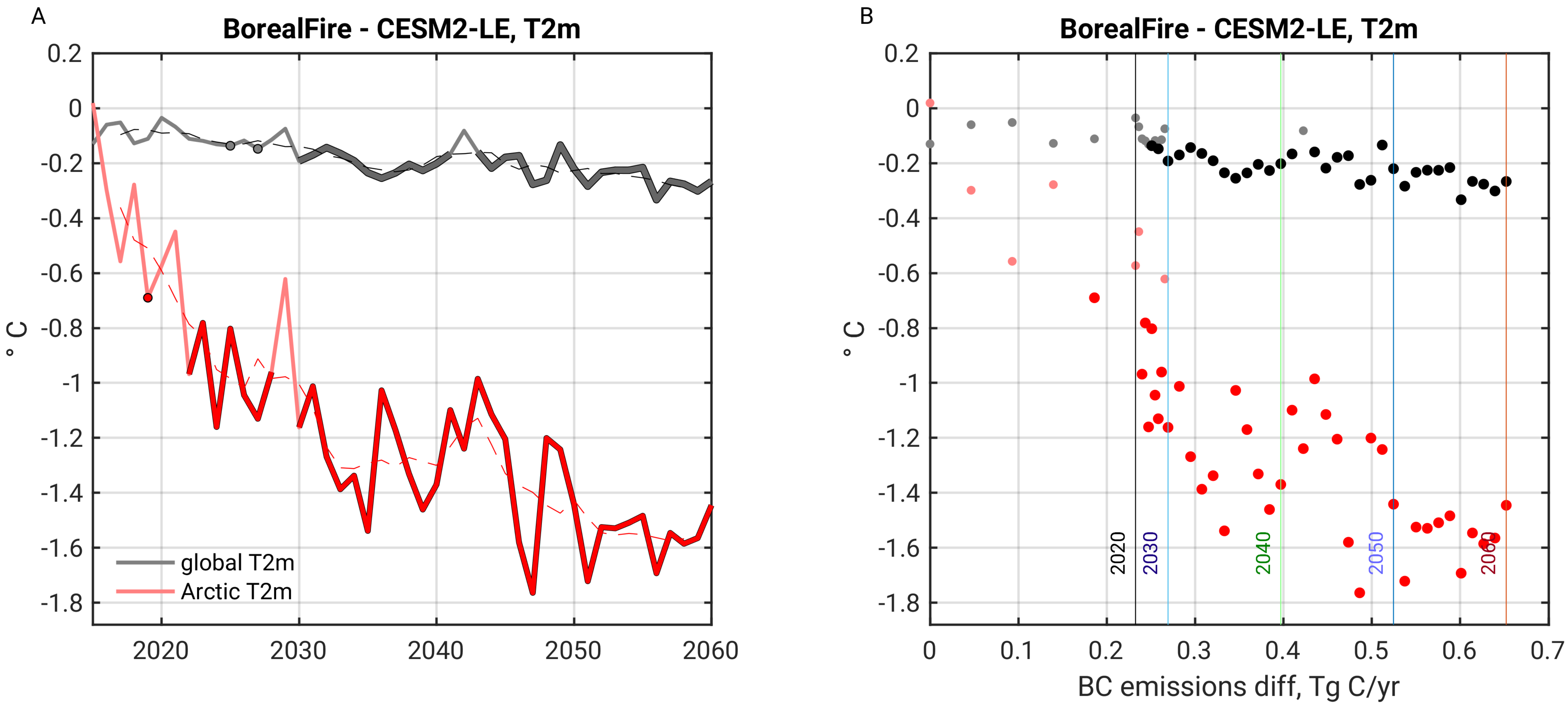
No change in cold season (no fires in winter)

Non-boreal emissions look ok in CMIP6

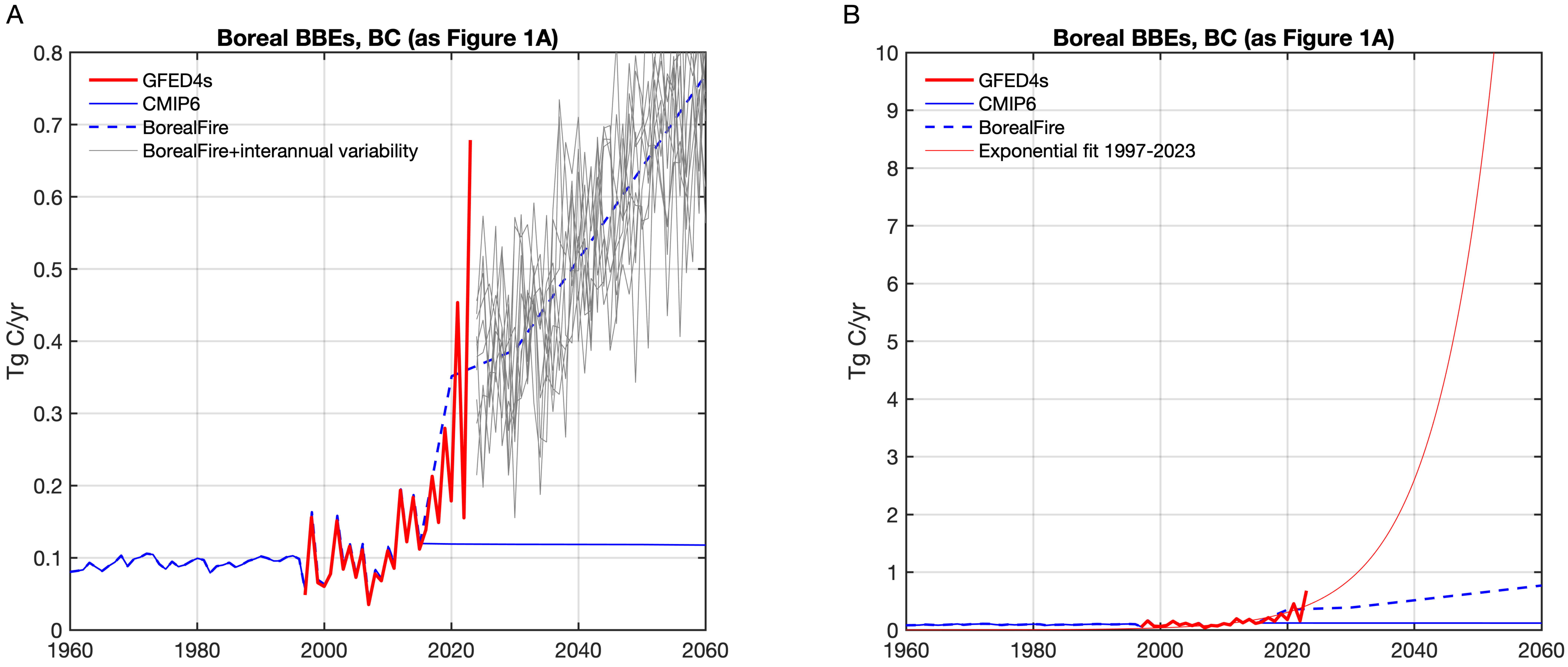


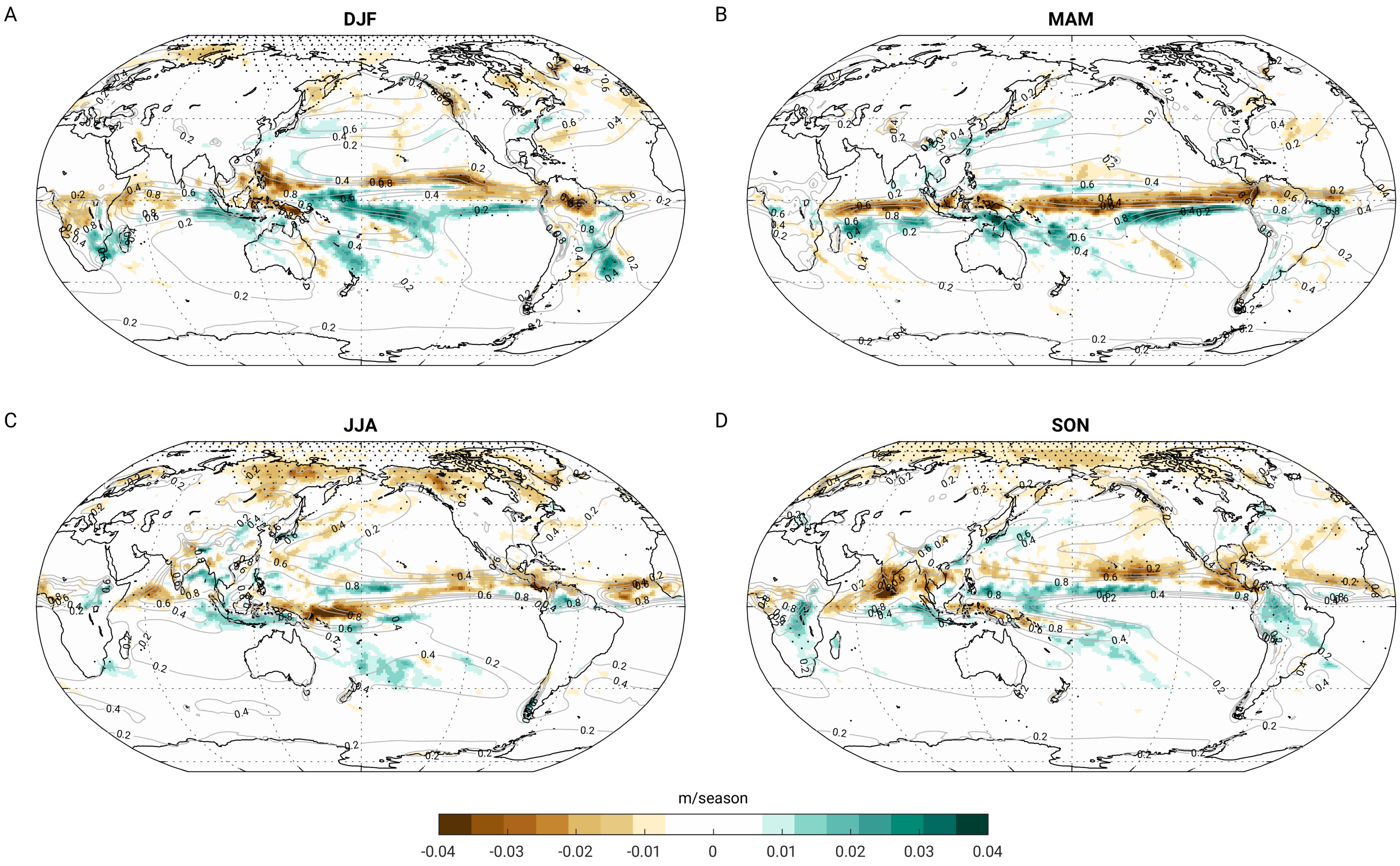


A
GFED4 BC annual emissions Tg C/yr
Global
56°N-70°N
Tg C/yr
B
Ratio 56°N-70°N to global
Ratio
C
56°N-70°N BBEs, GFED4.1s
Dry Matter(/1000)
BC
POM(OC)(/10)
SO2
Tg C/yr
D
Global BBEs, GFED4.1s
Dry Matter(/1000)
BC
POM(OC)(/10)
SO2
Tg C/yr



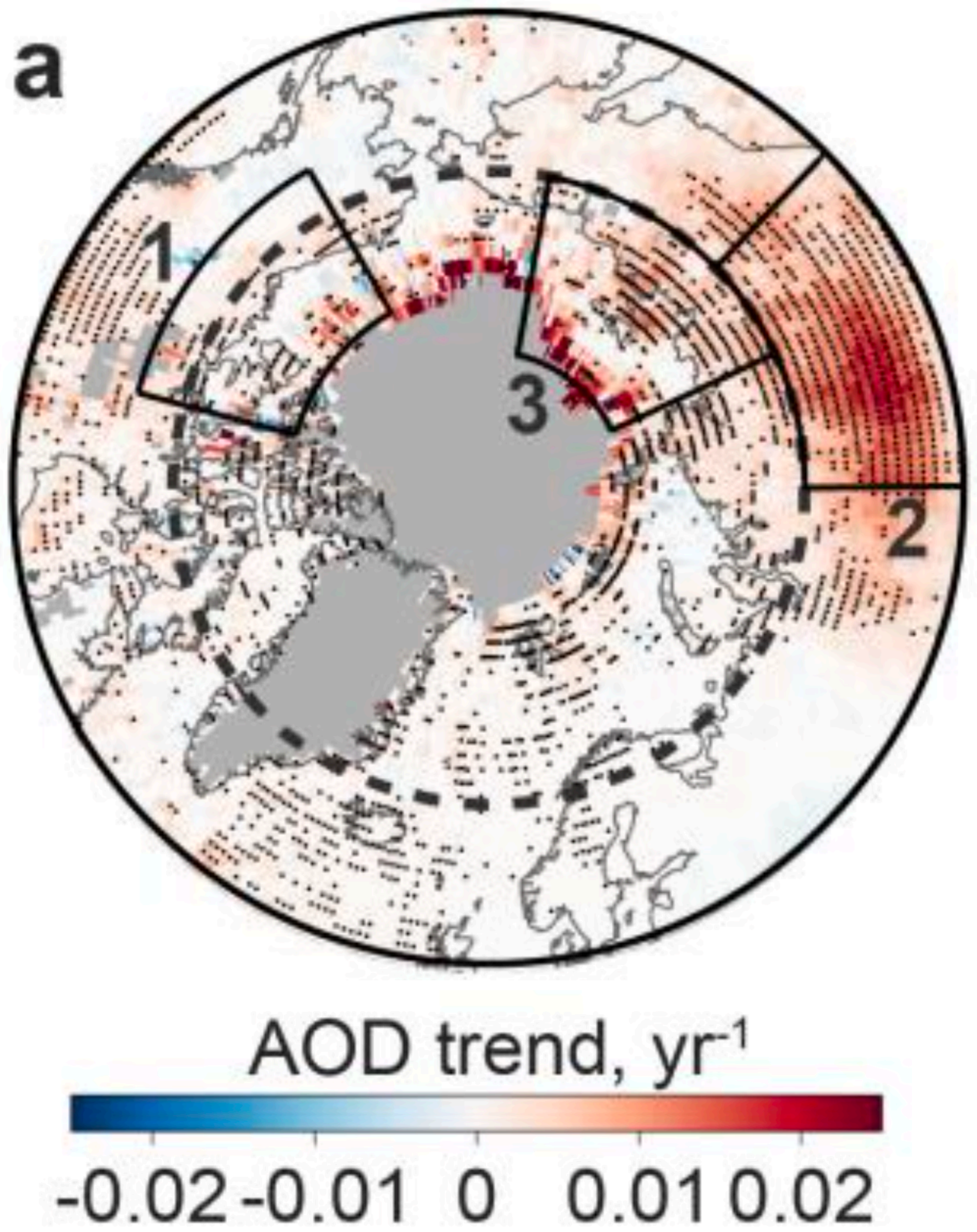
A
BorealFire - CESM2-LE, T2m
° C
global T2m
Arctic T2m
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
2020
2030
2040
2050
2060
B
BorealFire - CESM2-LE, T2m
° C
2020
2030
2040
2050
2060
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
BC emissions diff, Tg C/yr


A
Boreal BBEs, BC (as Figure 1A)
GFED4s
CMIP6
BorealFire
BorealFire+interannual variability
Tg C/yr
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1960
1980
2000
2020
2040
2060
B
Boreal BBEs, BC (as Figure 1A)
GFED4s
CMIP6
BorealFire
Exponential fit 1997-2023
Tg C/yr
0
1
2
3
4
5
6
7
8
9
10
1960
1980
2000
2020
2040
2060



A
DJF
B
MAM
C
JJA
D
SON
m/season
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04

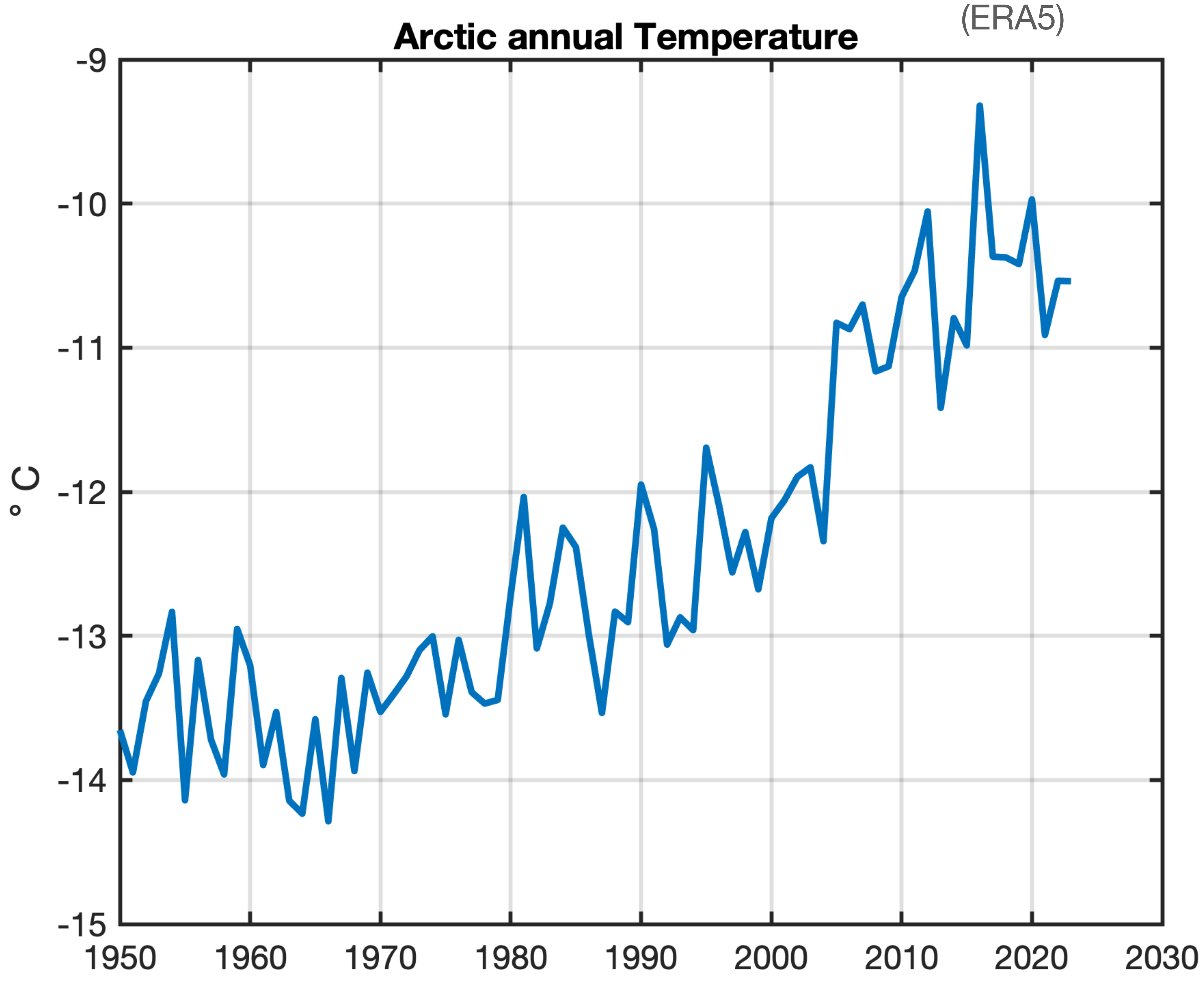
So… is there any evidence of all this in observations

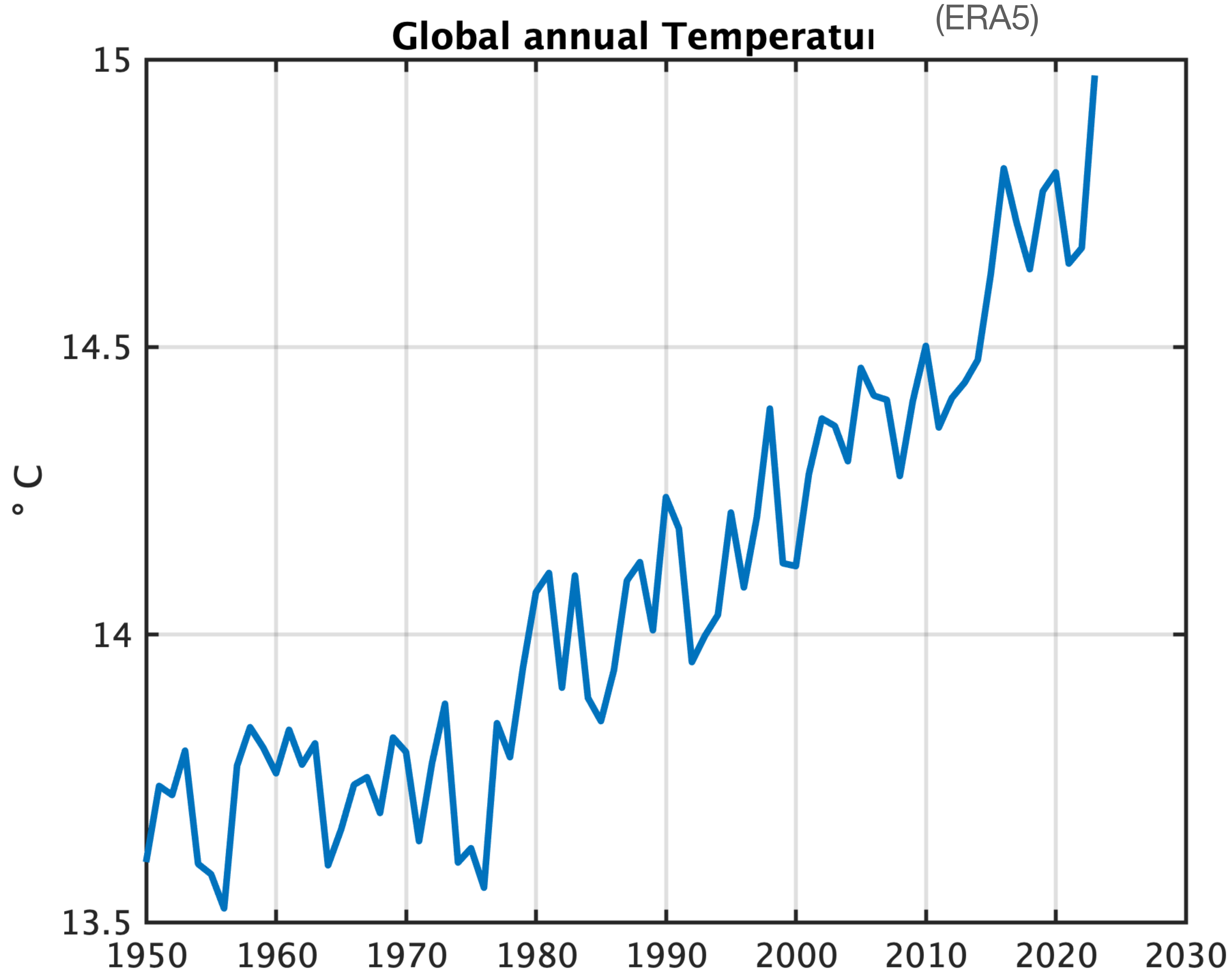


Summer (JJA) AOD trends, 2000-2020, from MODIS (Zhong et al, in review)

So… is there any evidence of all this in observations

(Getting speculative now in some plots I made yesterday)





So… is there any evidence of all this in observations

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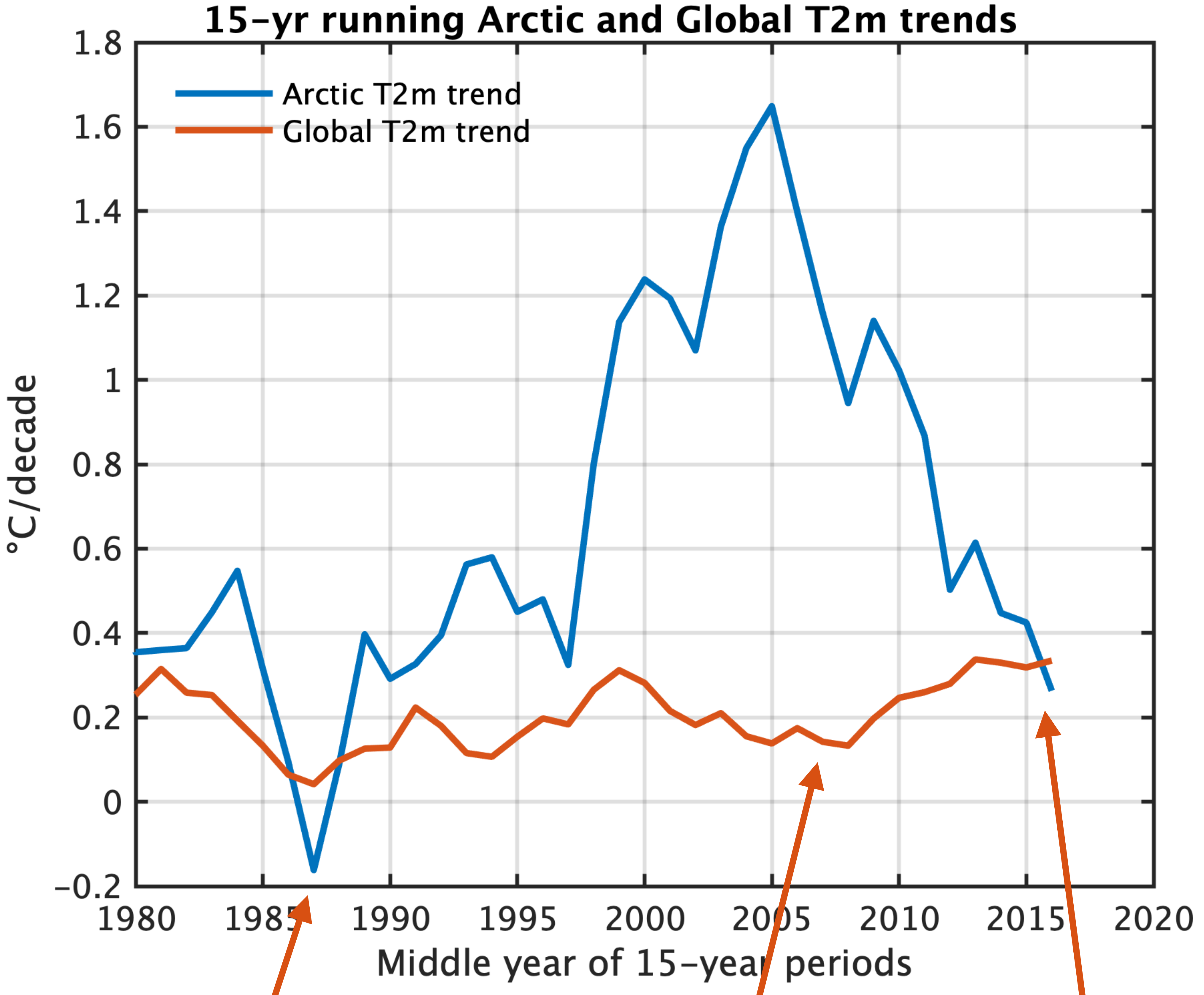
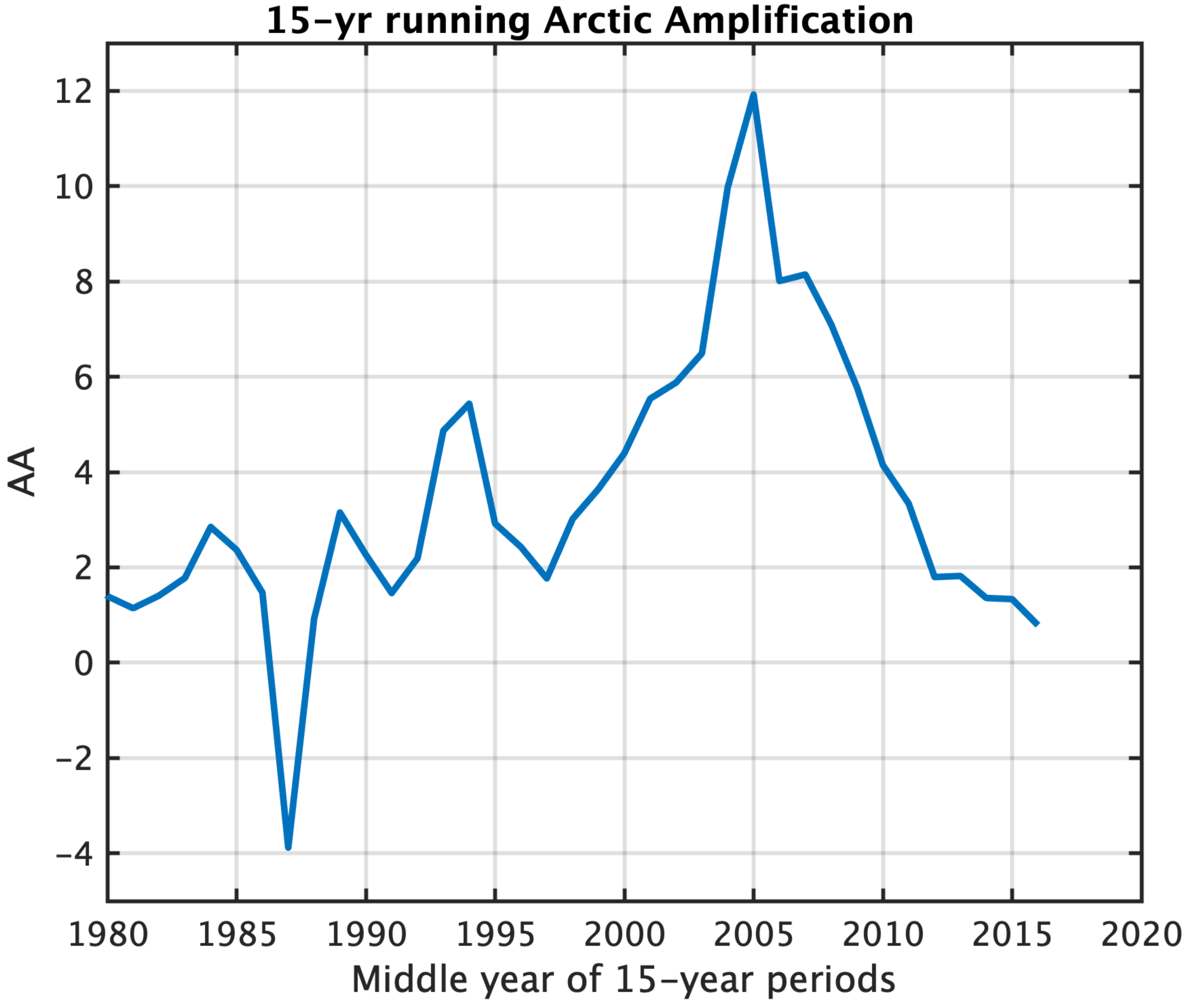




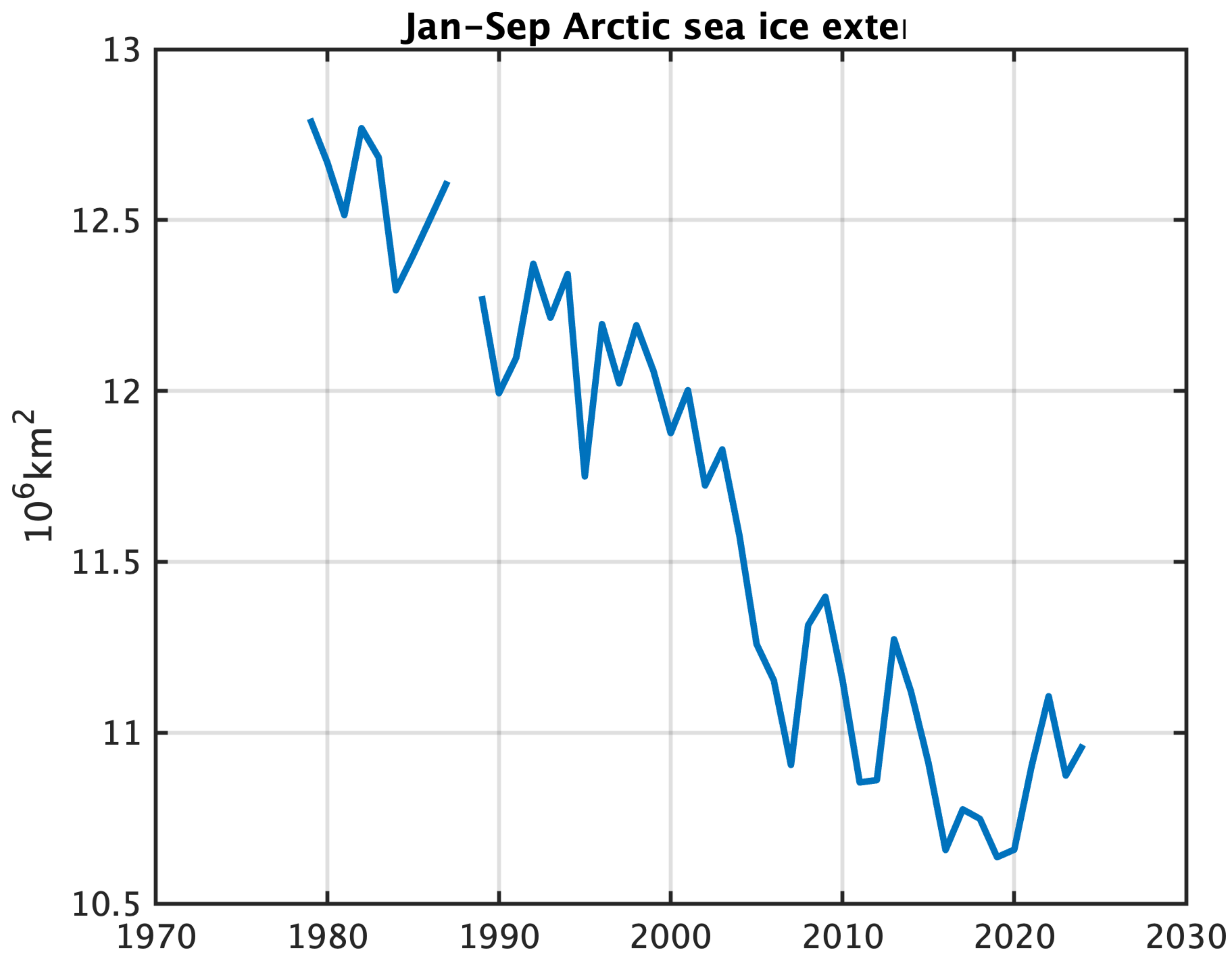
1982/83 ENSO - Pinatubo combo

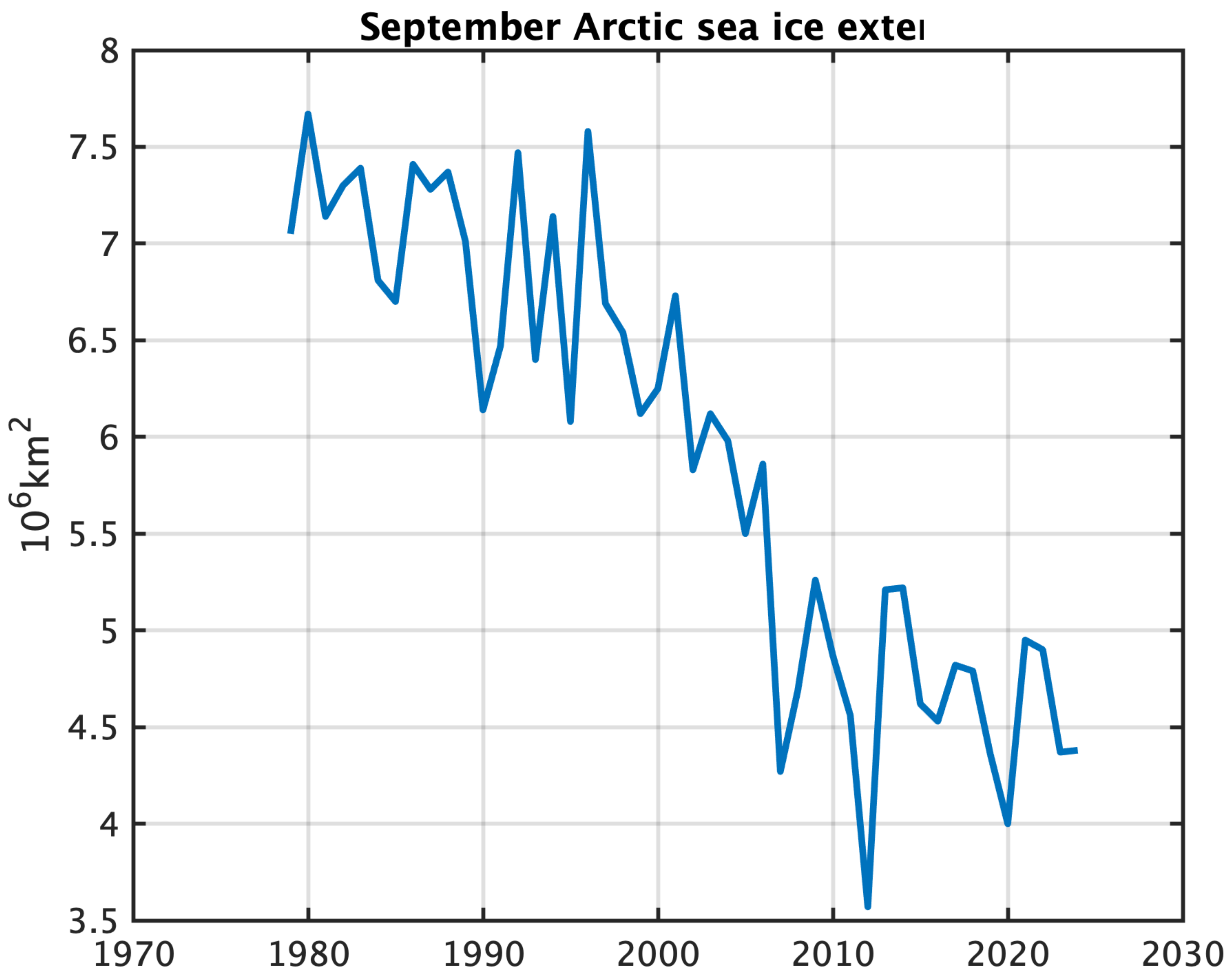
'Hiatus'

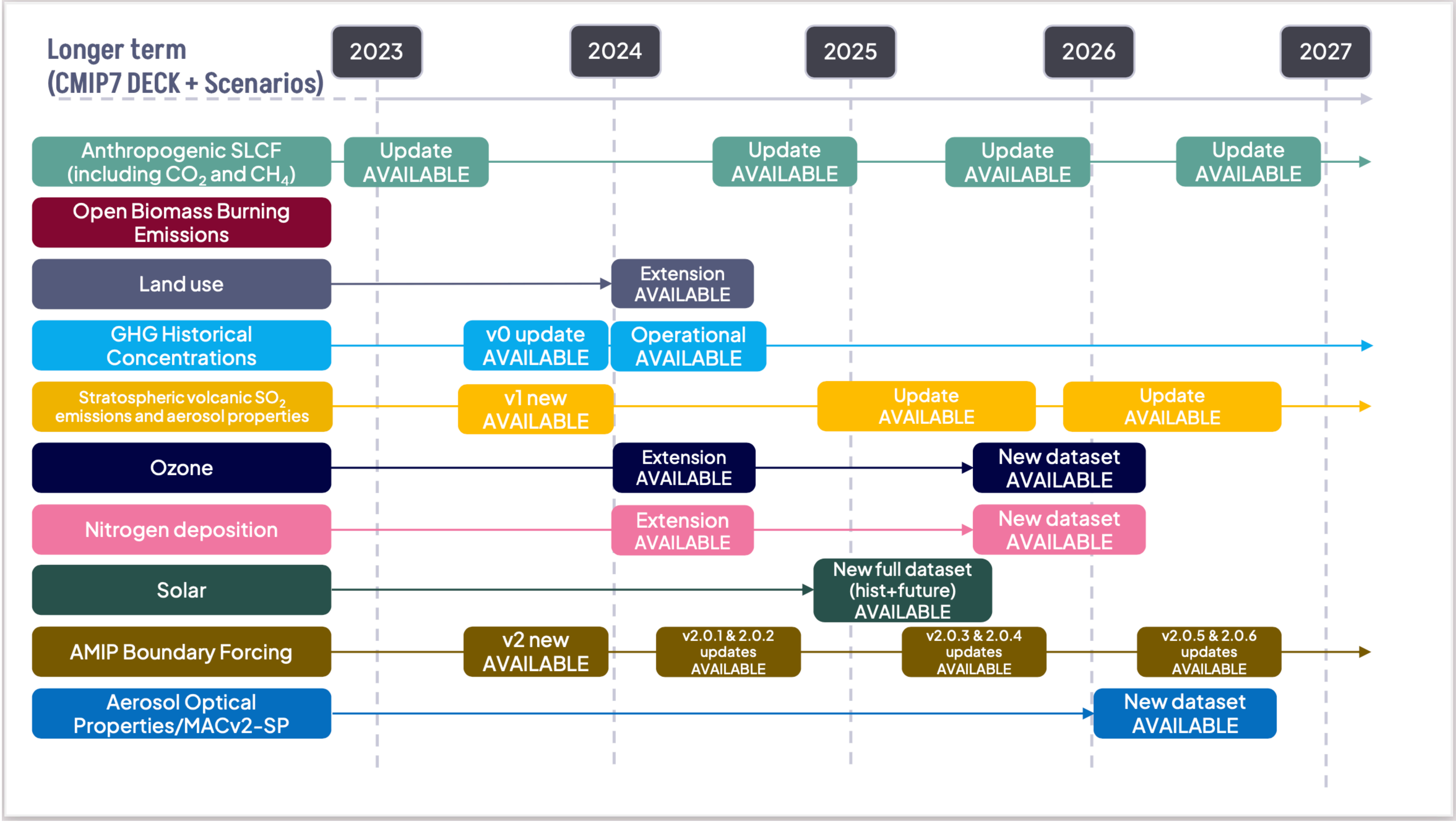
Recent 'acceleration' GW

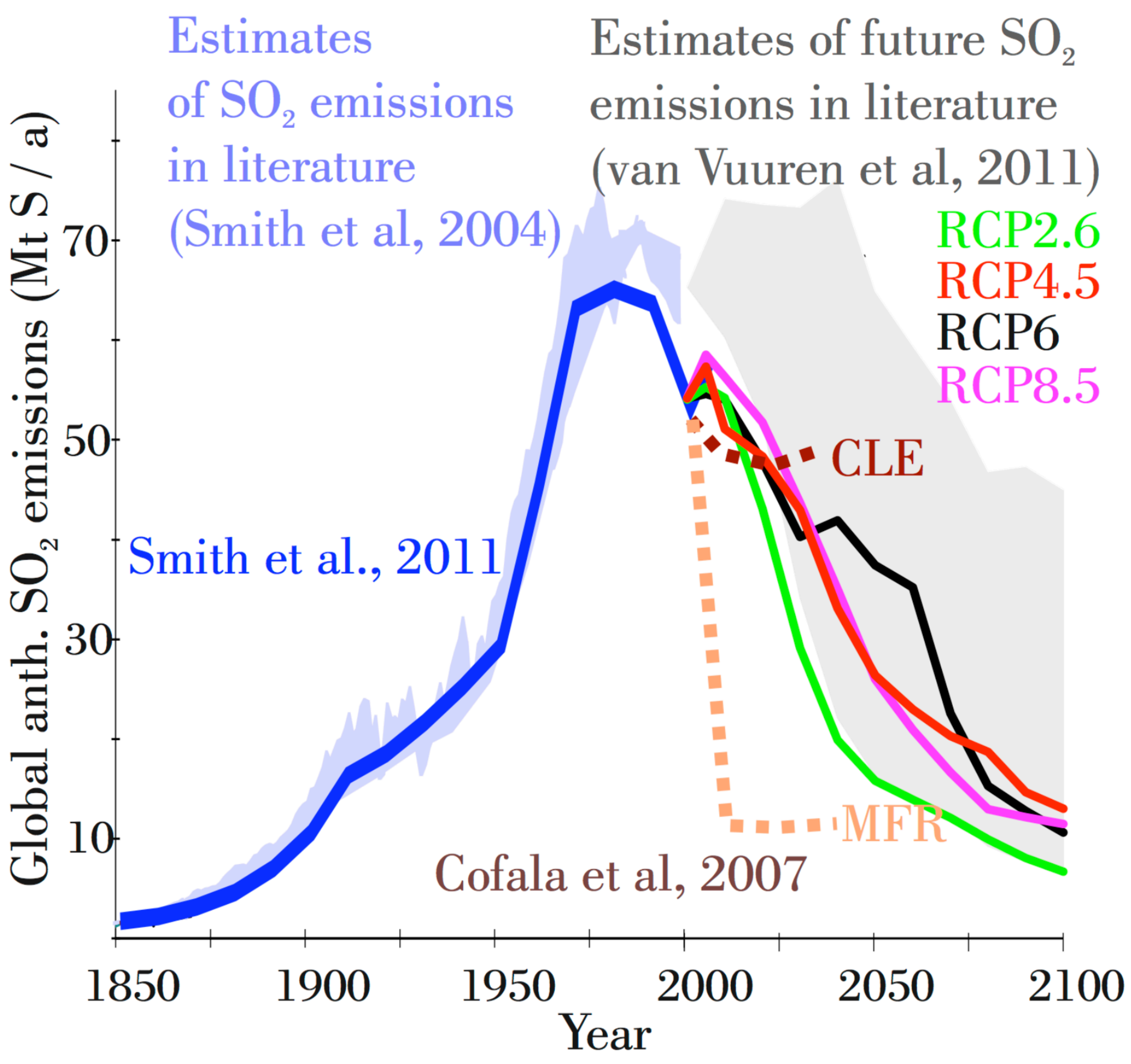
So… is there any evidence of all this in observations

(Getting speculative now in some plots I made yesterday)






Longer term
(CMIP7 DECK + Scenarios)
2023
2024
2025
2026
2027
Anthropogenic SLCF (including CO_2 and CH_4)
Update AVAILABLE
Update AVAILABLE
Update AVAILABLE
Update AVAILABLE
Open Biomass Burning Emissions
Land use
Extension AVAILABLE
GHG Historical Concentrations
v0 update AVAILABLE
Operational AVAILABLE
Stratospheric volcanic SO_2 emissions and aerosol properties
v1 new AVAILABLE
Update AVAILABLE
Update AVAILABLE
Ozone
Extension AVAILABLE
New dataset AVAILABLE
Nitrogen deposition
Extension AVAILABLE
New dataset AVAILABLE
Solar
New full dataset (hist+future) AVAILABLE
AMIP Boundary Forcing
v2 new AVAILABLE
v2.0.1 & 2.0.2 updates AVAILABLE
v2.0.3 & 2.0.4 updates AVAILABLE
v2.0.5 & 2.0.6 updates AVAILABLE
Aerosol Optical Properties/MACv2-SP
New dataset AVAILABLE



Estimates
of SO_2 emissions
in literature
(Smith et al, 2004)
Estimates of future SO_2
emissions in literature
(van Vuuren et al, 2011)
RCP2.6
RCP4.5
RCP6
RCP8.5
CLE
Smith et al., 2011
MFR
Cofala et al, 2007
Global anth. SO_2 emissions (Mt S / a)
70
50
30
10
1850
1900
1950
2000
2050
2100
Year

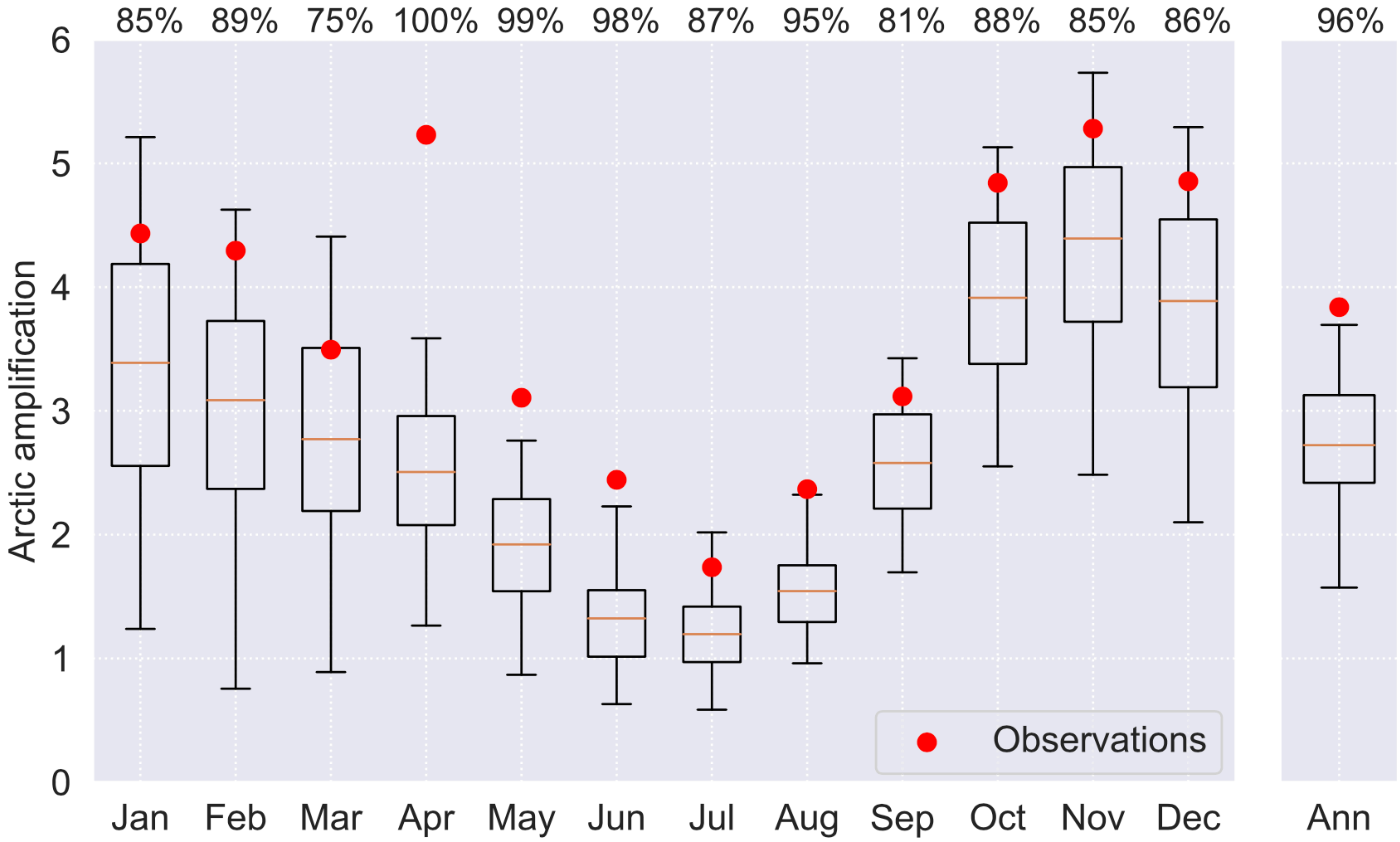
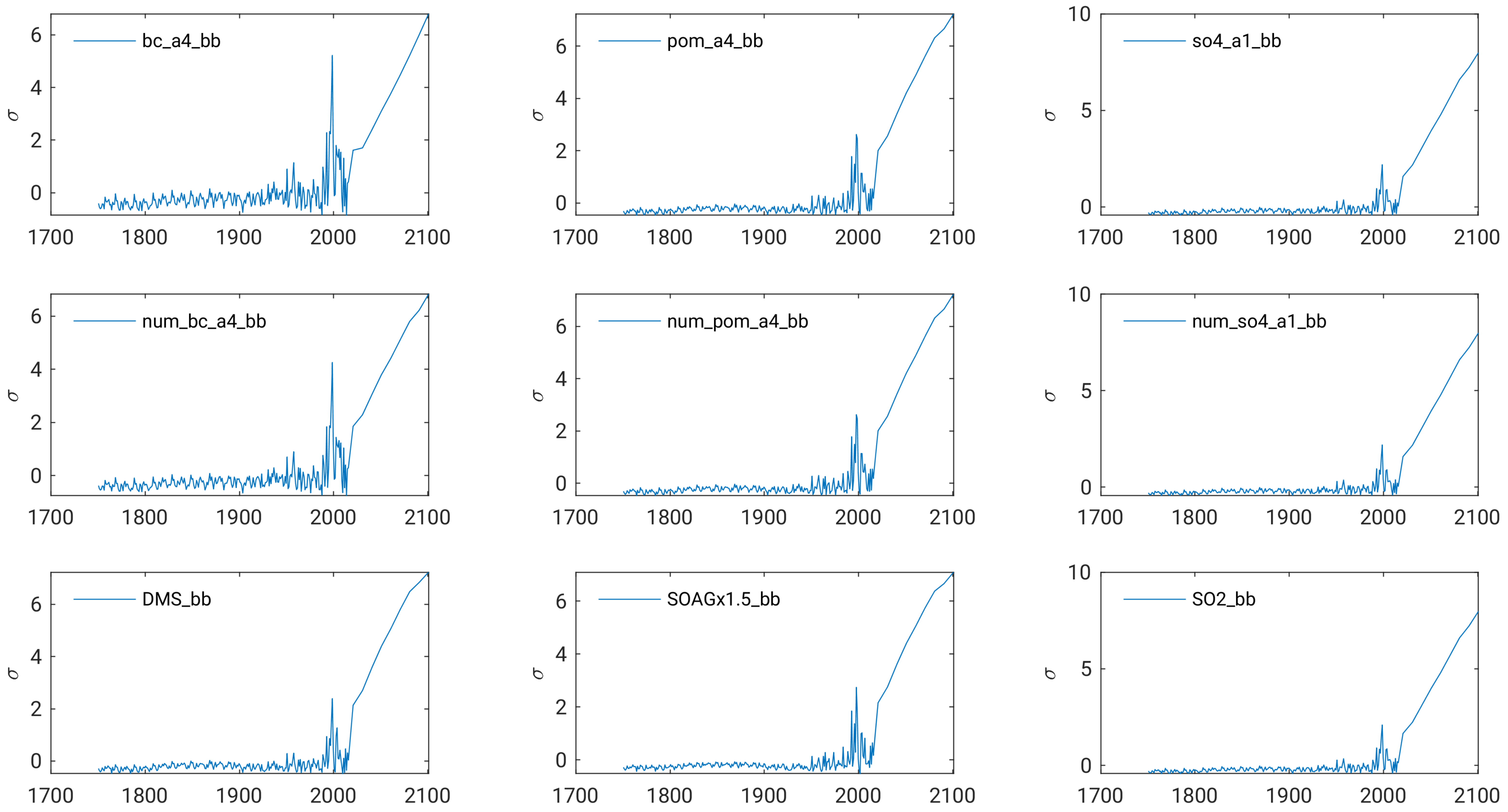
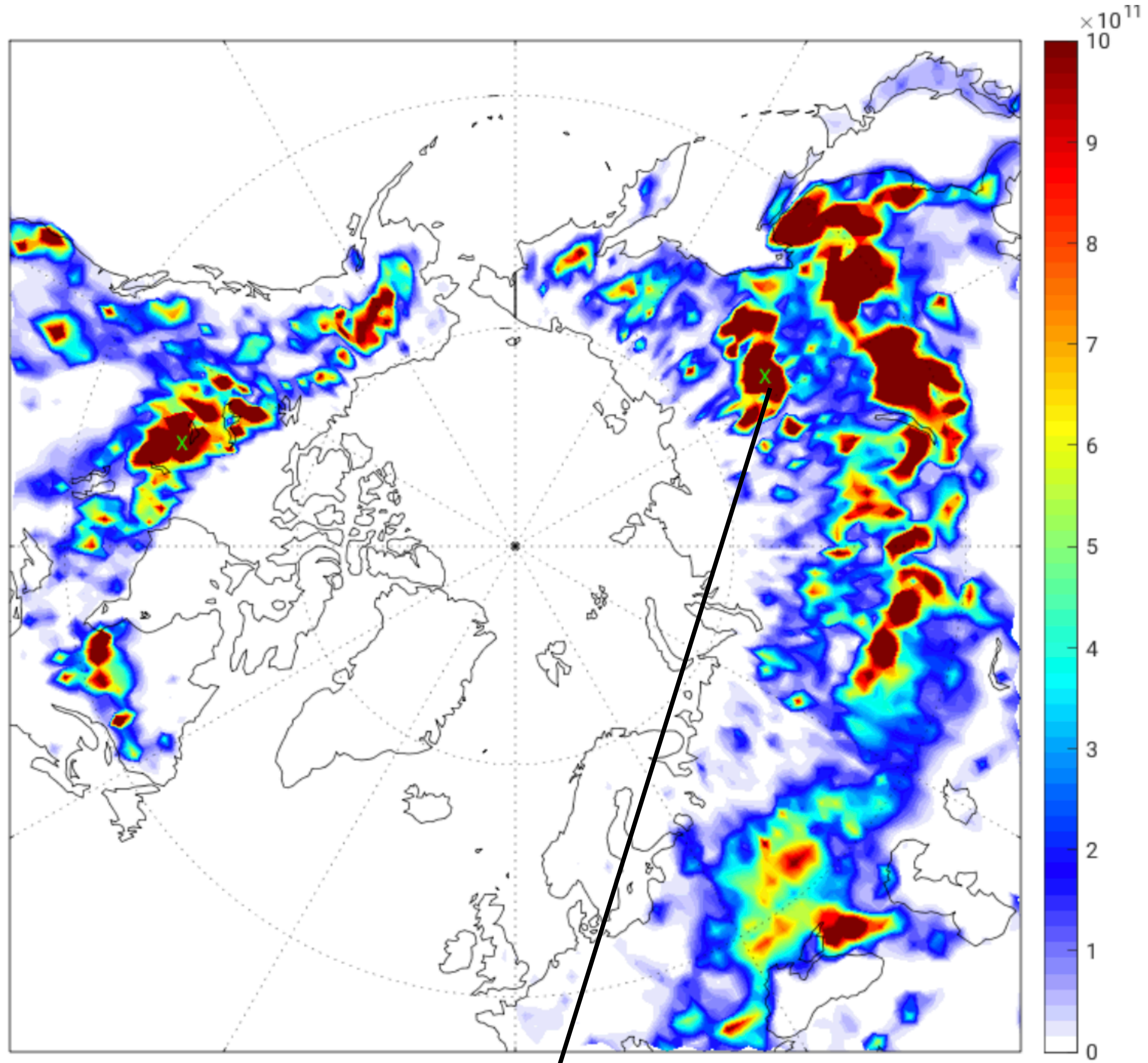
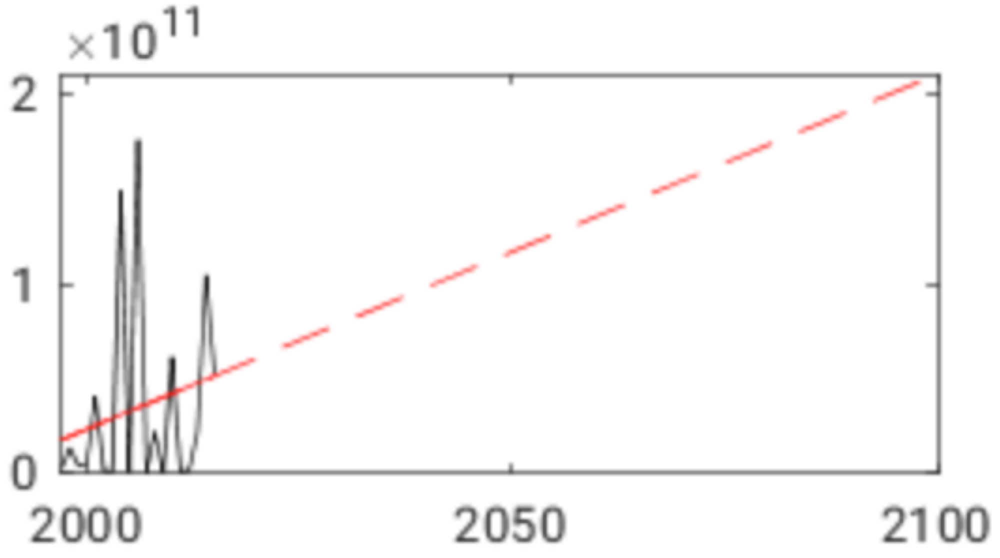


Fig. 5 Seasonality of the 43-year (1979–2021) Arctic amplification ratio.

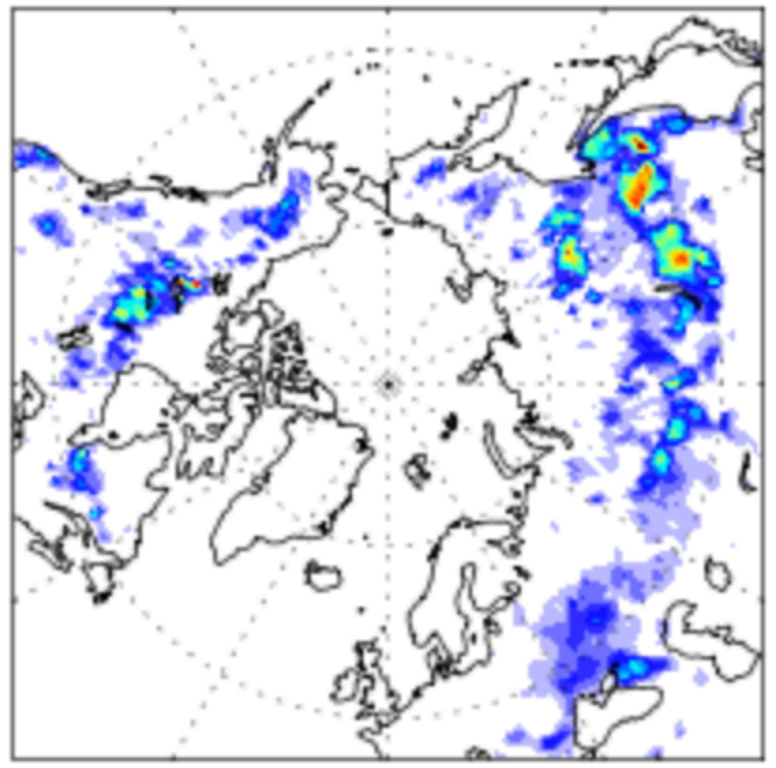
Rantanen et al, 2022


bc_a4_bb
pom_a4_bb
so4_a1_bb
num_bc_a4_bb
num_pom_a4_bb
num_so4_a1_bb
DMS_bb
SOAGx1.5_bb
SO2_bb
σ
1700
1800
1900
2000
2100

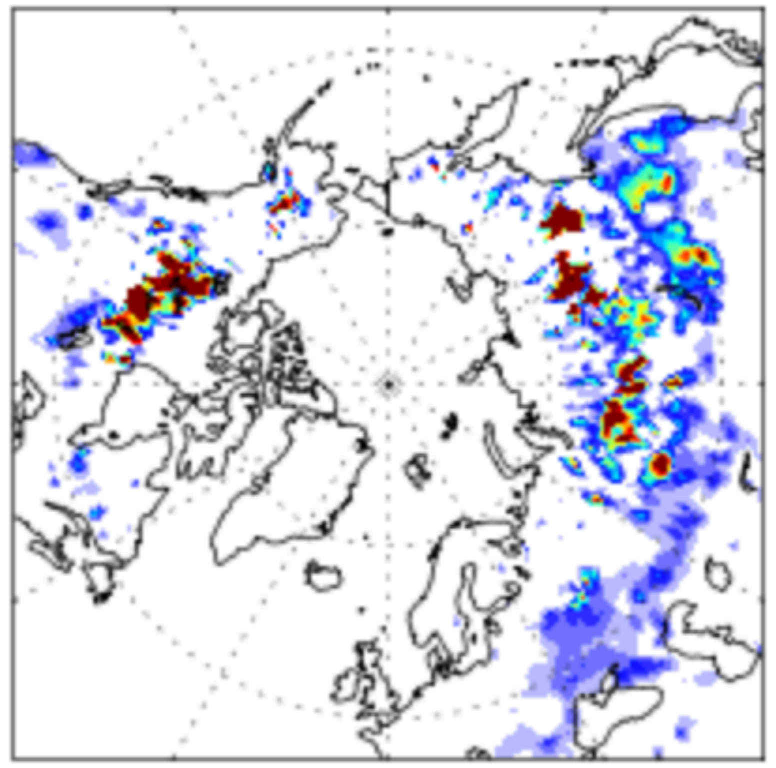




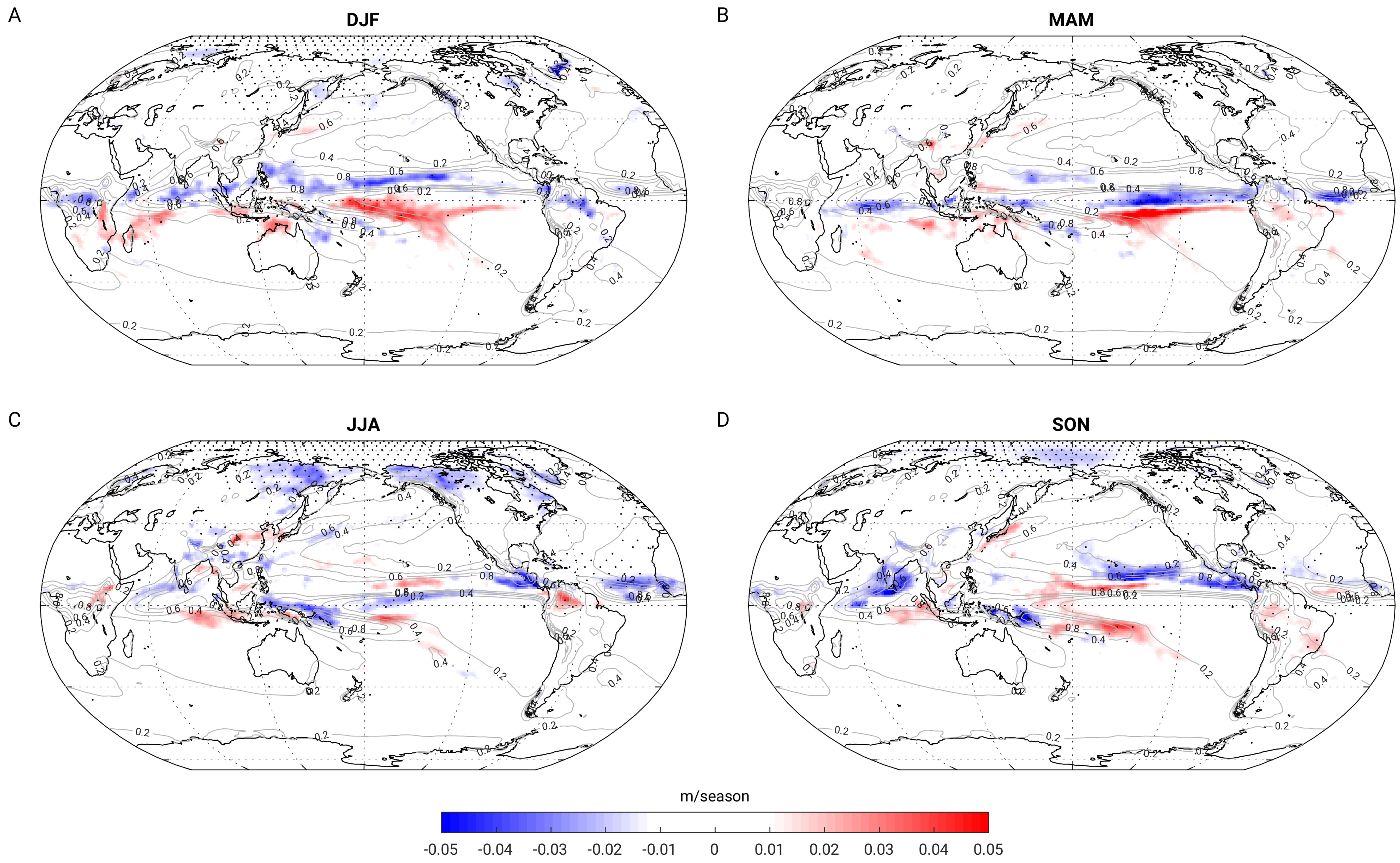
1997-2015

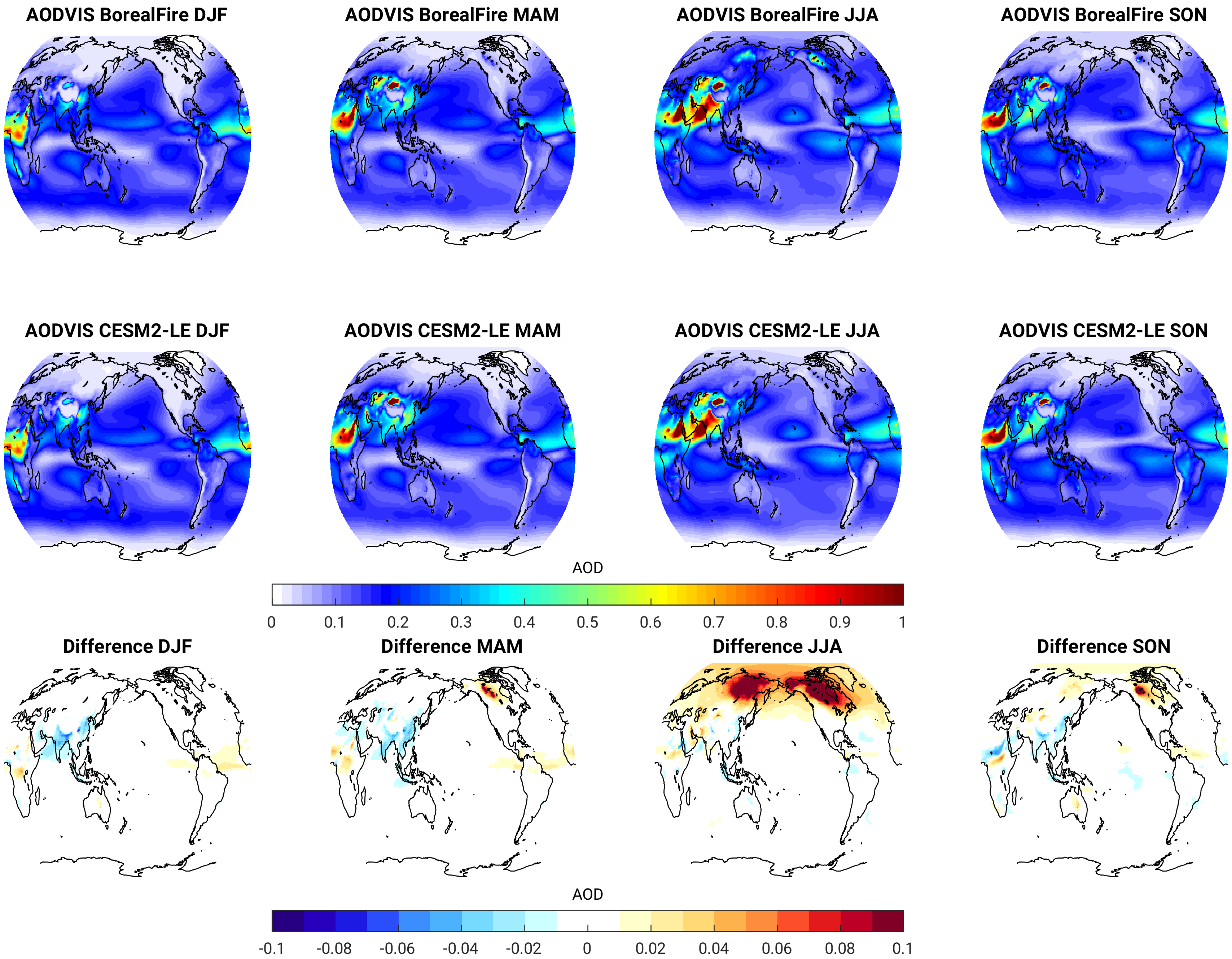


New forcing 2020-2100

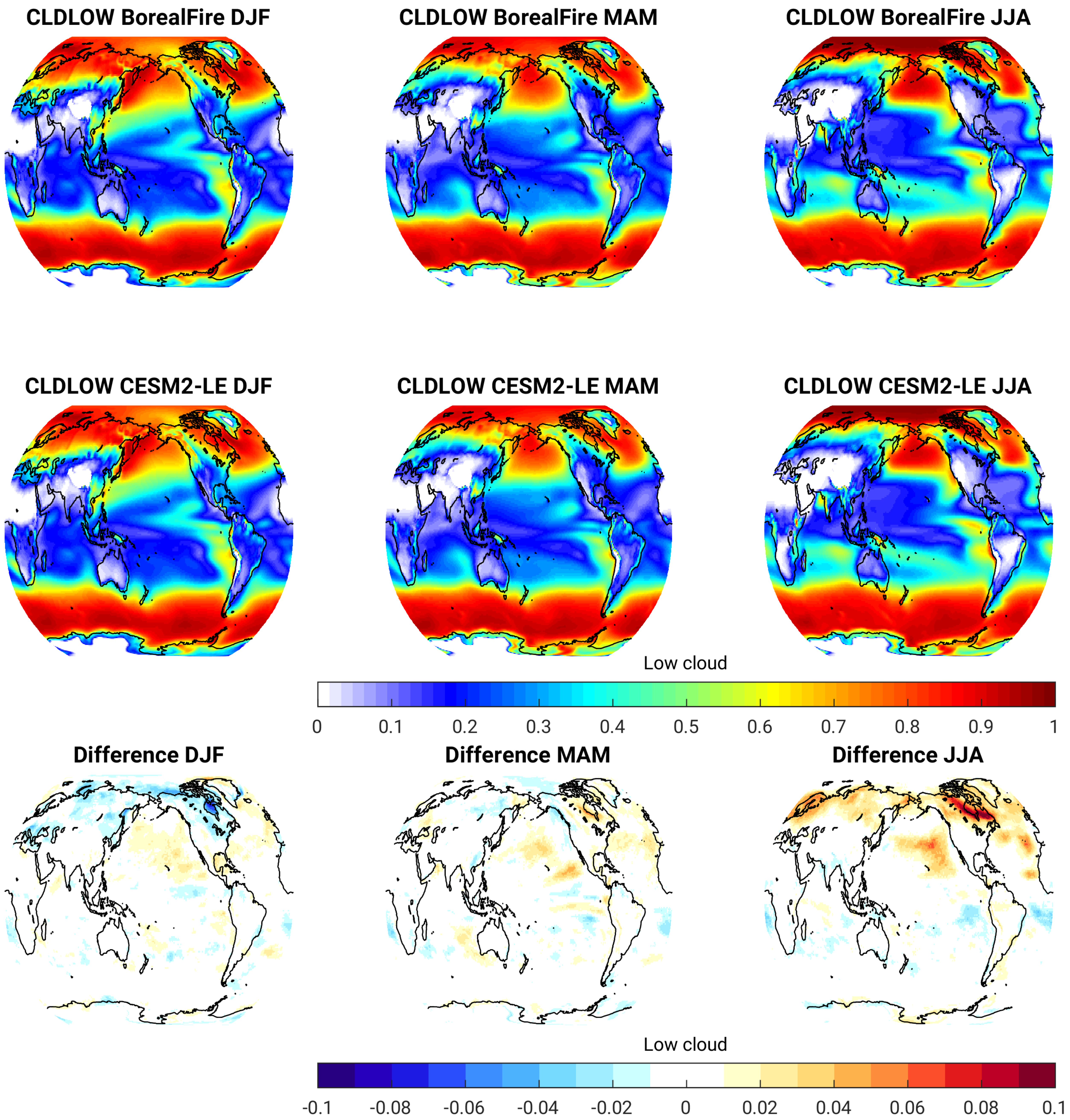


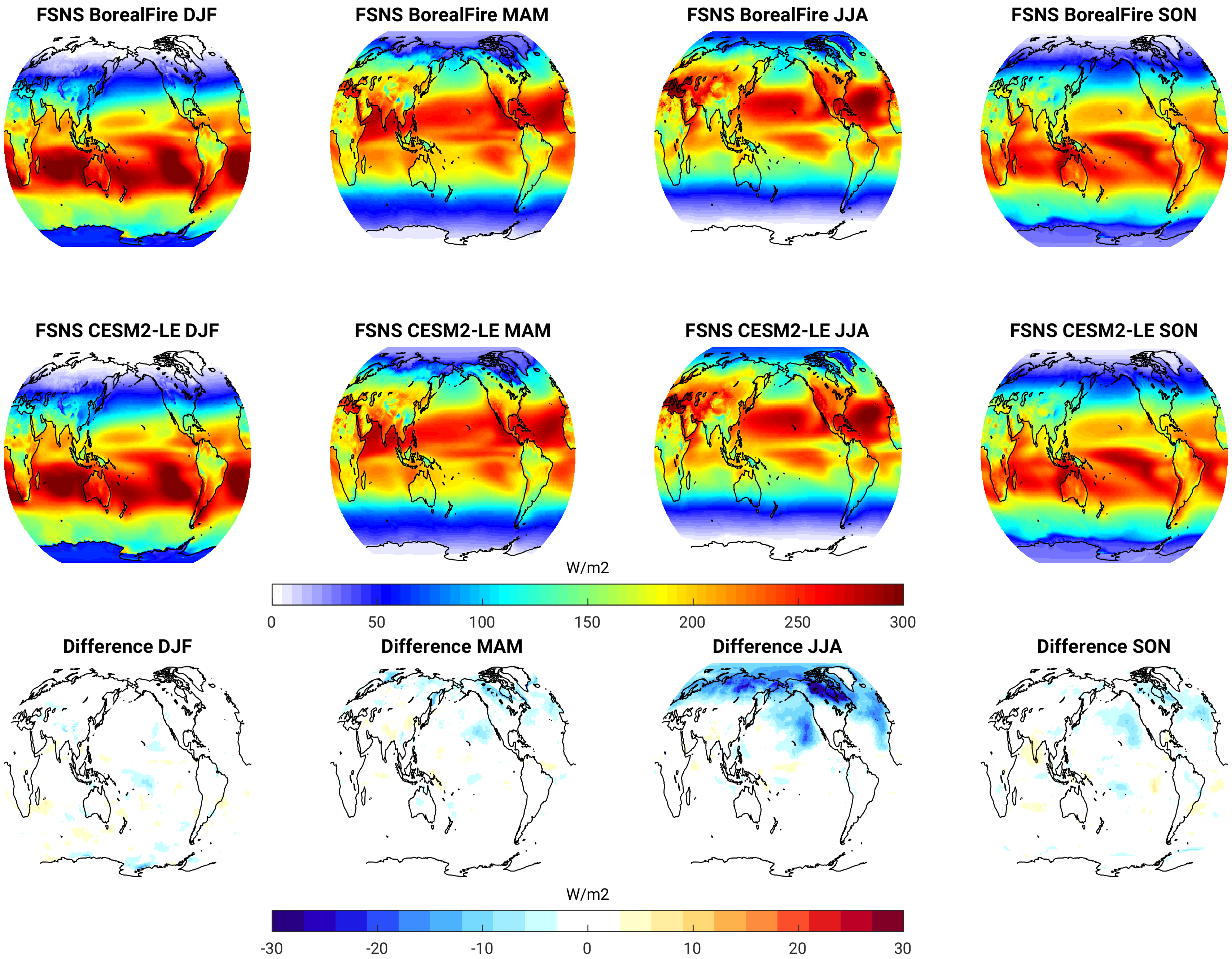
Seasonal changes in precipitation

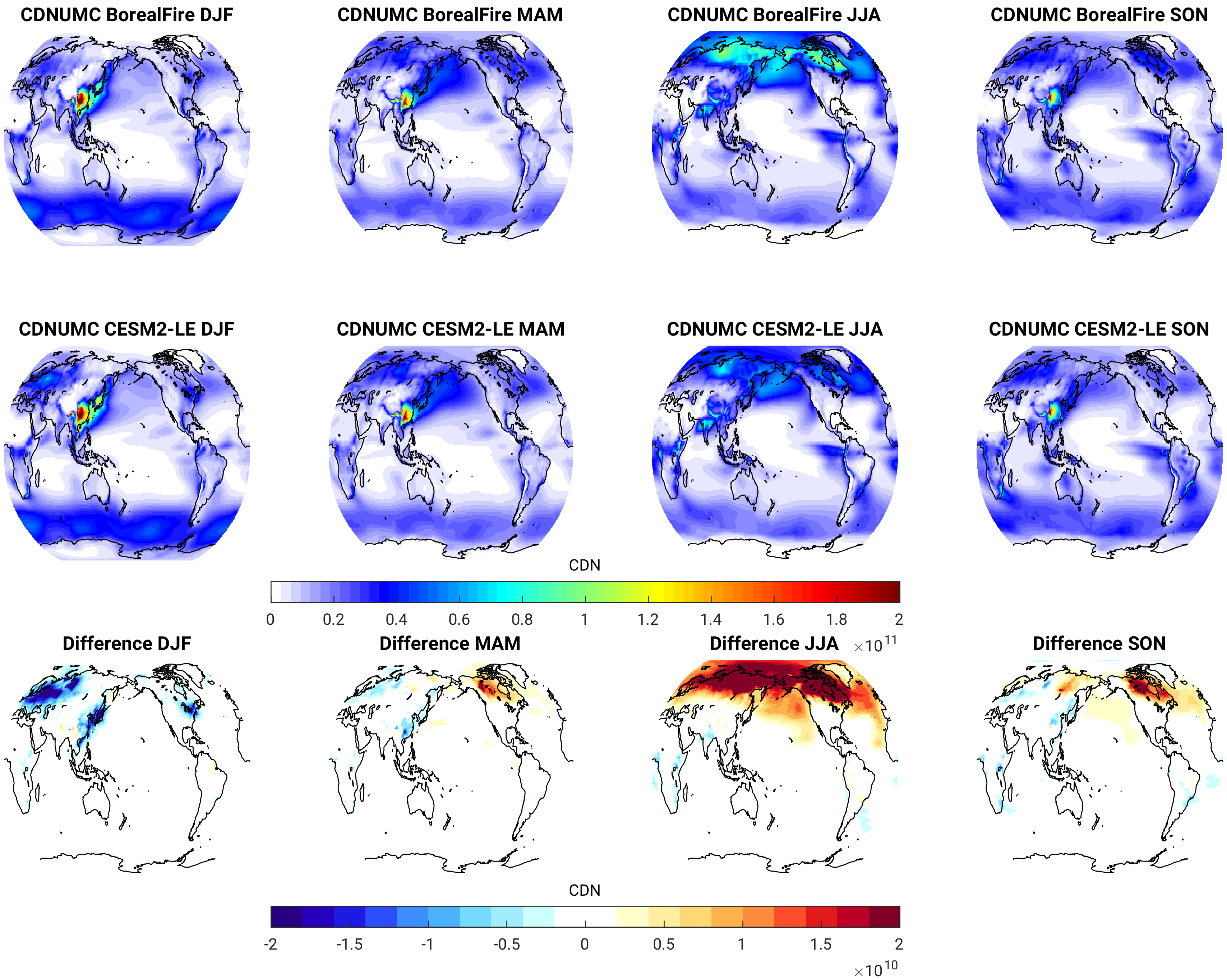




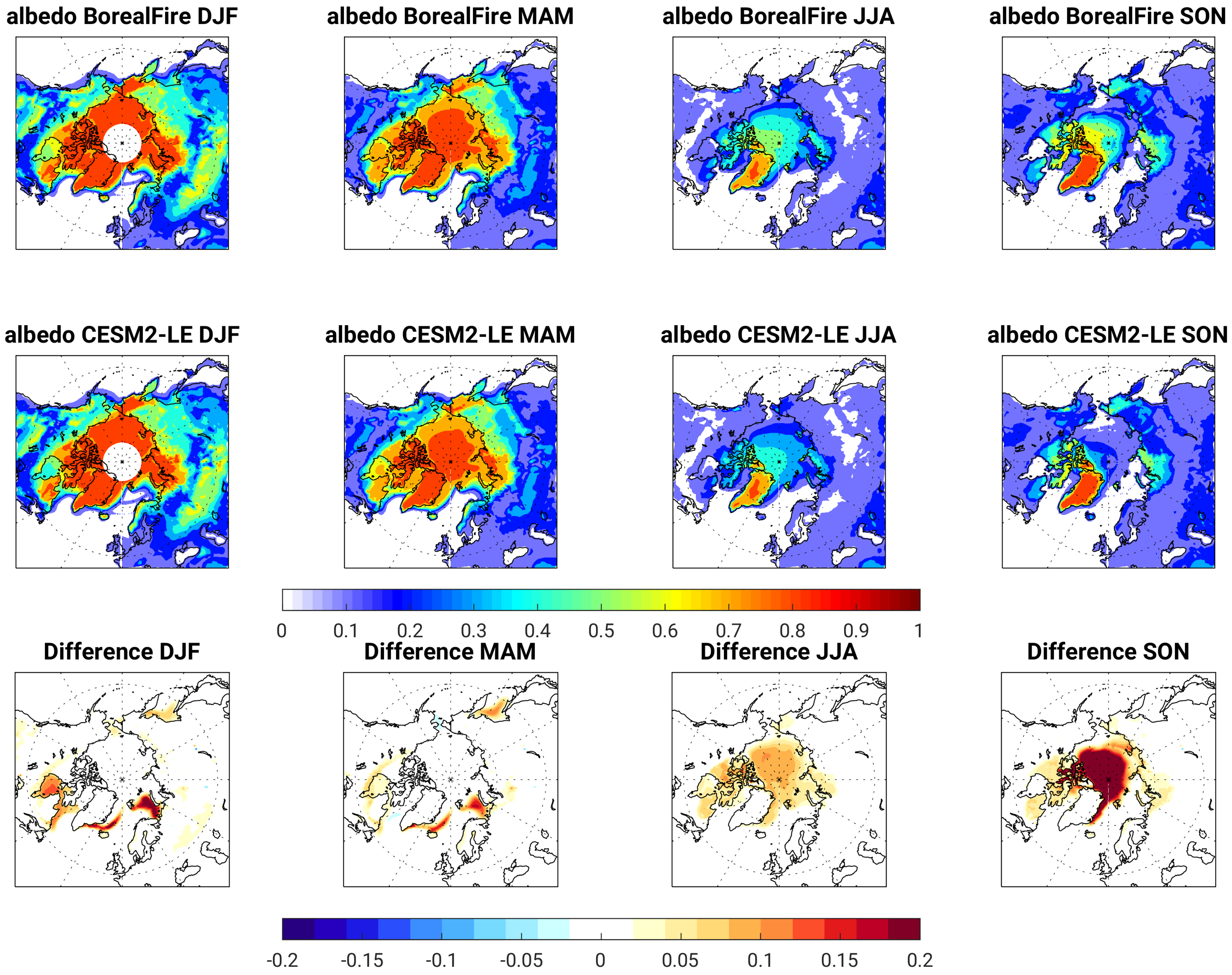
AODVIS BorealFire DJF
AODVIS BorealFire MAM
AODVIS BorealFire JJA
AODVIS BorealFire SON
AODVIS CESM2-LE DJF
AODVIS CESM2-LE MAM
AODVIS CESM2-LE JJA
AODVIS CESM2-LE SON
AOD
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Difference DJF
Difference MAM
Difference JJA
Difference SON
AOD
-0.1 -0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1


CLDLOW BorealFire DJF
CLDLOW BorealFire MAM
CLDLOW BorealFire JJA
CLDLOW BorealFire SON
CLDLOW CESM2-LE DJF
CLDLOW CESM2-LE MAM
CLDLOW CESM2-LE JJA
CLDLOW CESM2-LE SON
Low cloud
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Difference DJF
Difference MAM
Difference JJA
Difference SON
Low cloud
-0.1 -0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1

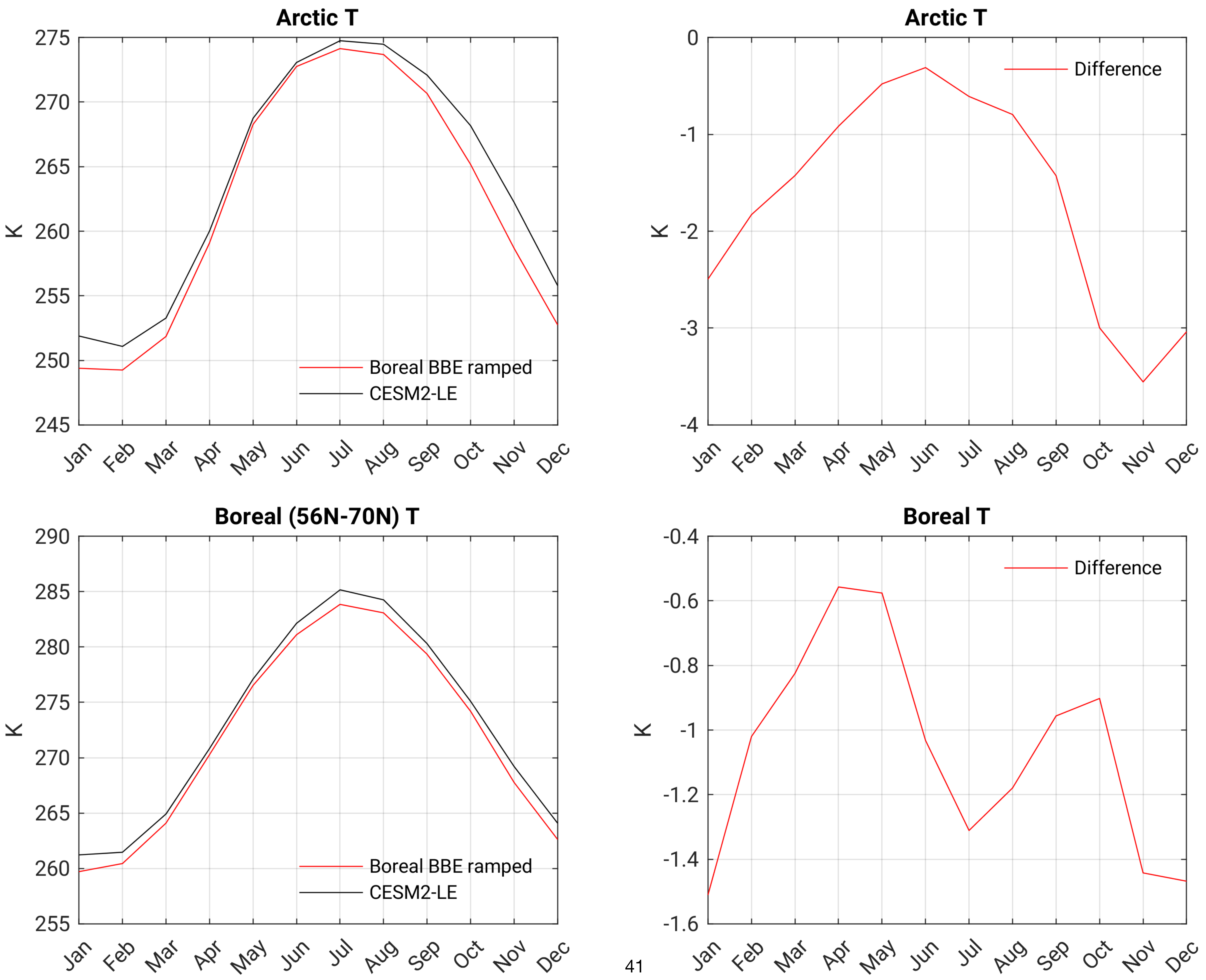

FSNS BorealFire DJF
FSNS BorealFire MAM
FSNS BorealFire JJA
FSNS BorealFire SON
FSNS CESM2-LE DJF
FSNS CESM2-LE MAM
FSNS CESM2-LE JJA
FSNS CESM2-LE SON
W/m2
0
50
100
150
200
250
300
Difference DJF
Difference MAM
Difference JJA
Difference SON
W/m2
-30
-20
-10
0
10
20
30



CDNUMC BorealFire DJF
CDNUMC BorealFire MAM
CDNUMC BorealFire JJA
CDNUMC BorealFire SON
CDNUMC CESM2-LE DJF
CDNUMC CESM2-LE MAM
CDNUMC CESM2-LE JJA
CDNUMC CESM2-LE SON
CDN
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
$\times 10^{11}$
Difference DJF
Difference MAM
Difference JJA
Difference SON
CDN
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
$\times 10^{10}$



albedo BorealFire DJF
albedo BorealFire MAM
albedo BorealFire JJA
albedo BorealFire SON
albedo CESM2-LE DJF
albedo CESM2-LE MAM
albedo CESM2-LE JJA
albedo CESM2-LE SON
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Difference DJF
Difference MAM
Difference JJA
Difference SON
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2

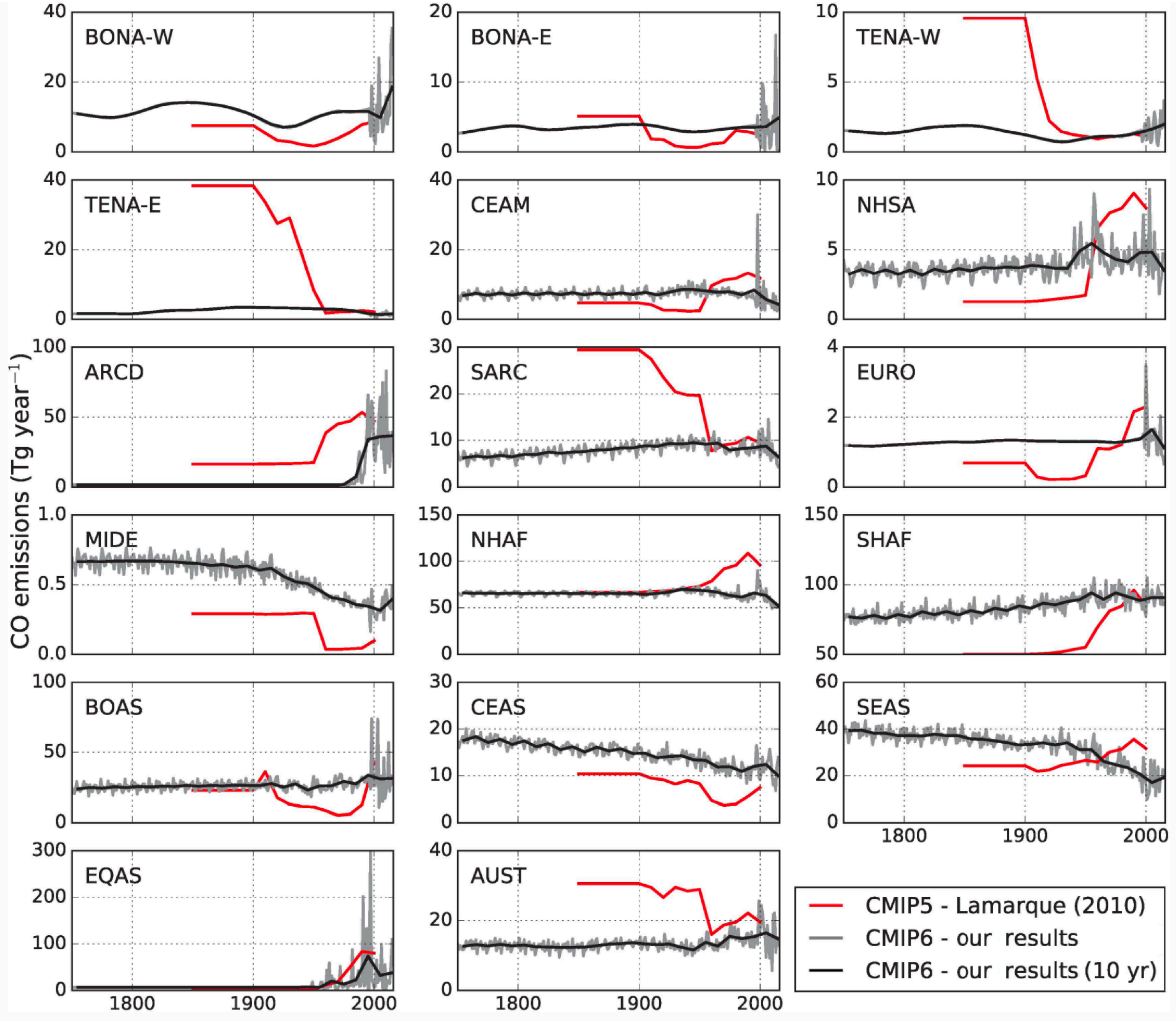

Arctic T
K
Boreal BBE ramped
CESM2-LE
Arctic T
Difference
Boreal (56N-70N) T
Boreal T
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Appendix C: Overview of emission factors used in this study

Table C1. Emission factors in grams of species per kilogram dry matter (DM) burned. Note that NO_x is listed as NO. SAVA: savanna, grassland, and shrubland fires; BORF: boreal forest fires; TEMF: temperate forest fires; DEFO: tropical deforestation and degradation; PEAT: peat fires; and AGRI: agricultural waste burning.

	SAVA	BORF	TEMF	DEFO	PEAT	AGRI
DM	1000	1000	1000	1000	1000	1000
C	488.27	464.99	489.42	491.75	570.05	480.35
BC	0.37	0.5	0.5	0.52	0.04	0.75
CH_4	1.94	5.96	3.36	5.07	20.8	5.82
CO	63	127	88	93	210	102
H_2	1.7	2.03	2.03	3.36	3.36	2.59
N_2O	0.2	0.41	0.16	0.2	0.2	0.1
NH_3	0.52	2.72	0.84	1.33	1.33	2.17
NO	3.9	0.9	1.92	2.55	1	3.11
OC	2.62	9.6	9.6	4.71	6.02	2.3
SO_2	0.48	1.1	1.1	0.4	0.4	0.4
C_2H_6	0.66	1.79	0.63	0.71	0.71	0.91
CH_3OH	1.18	2.82	1.74	2.43	8.46	3.29
C_2H_5OH	0.024	0.055	0.1	0.037	0.037	0.035
C_3H_8	0.1	0.44	0.22	0.126	0.126	0.28
C_2H_2	0.24	0.18	0.26	0.44	0.06	0.27
C_2H_4	0.82	1.42	1.17	1.06	2.57	1.46
C_3H_6	0.79	1.13	0.61	0.64	3.05	0.68
C_5H_8	0.039	0.15	0.099	0.13	1.38	0.38
$C_{10}H_{16}$	0.081	2.003	2.003	0.15	0.15	0.005
C_7H_8	0.08	0.48	0.19	0.26	1.55	0.19
C_6H_6	0.2	1.11	0.27	0.39	3.19	0.15
C_8H_{10}	0.014	0.18	0.13	0.11	0.11	0.114
Toluene lump	0.27	1.63	0.54	0.70	4.36	0.42
Higher alkenes	0.13	0.38	0.37	0.27	0.27	0.33
Higher alkanes	0.05	0.35	0.22	0.07	0.07	0.34
CH_2O	0.73	1.86	2.09	1.73	1.4	2.08
C_2H_4O	0.57	0.77	0.77	1.55	3.27	1.24
C_3H_6O	0.16	0.75	0.54	0.63	1.25	0.45
C_2H_6S	0.0013	0.00465	0.008	0.00135	0.00135	0.0013
HCN	0.41	1.52	0.72	0.42	8.11	0.29
HCOOH	0.21	0.57	0.28	0.79	0.38	1
CH_3COOH	3.55	4.41	2.13	3.05	8.97	5.59
MEK	0.181	0.22	0.13	0.5	0.5	0.9
CH_3COCHO	0.73	0.73	0.73	0.73	0.73	0.73
$HOCH_2CHO$	0.25	0.86	0.86	0.74	0.74	0.71

Appendix D: Regional comparison between CMIP6 and CMIP5



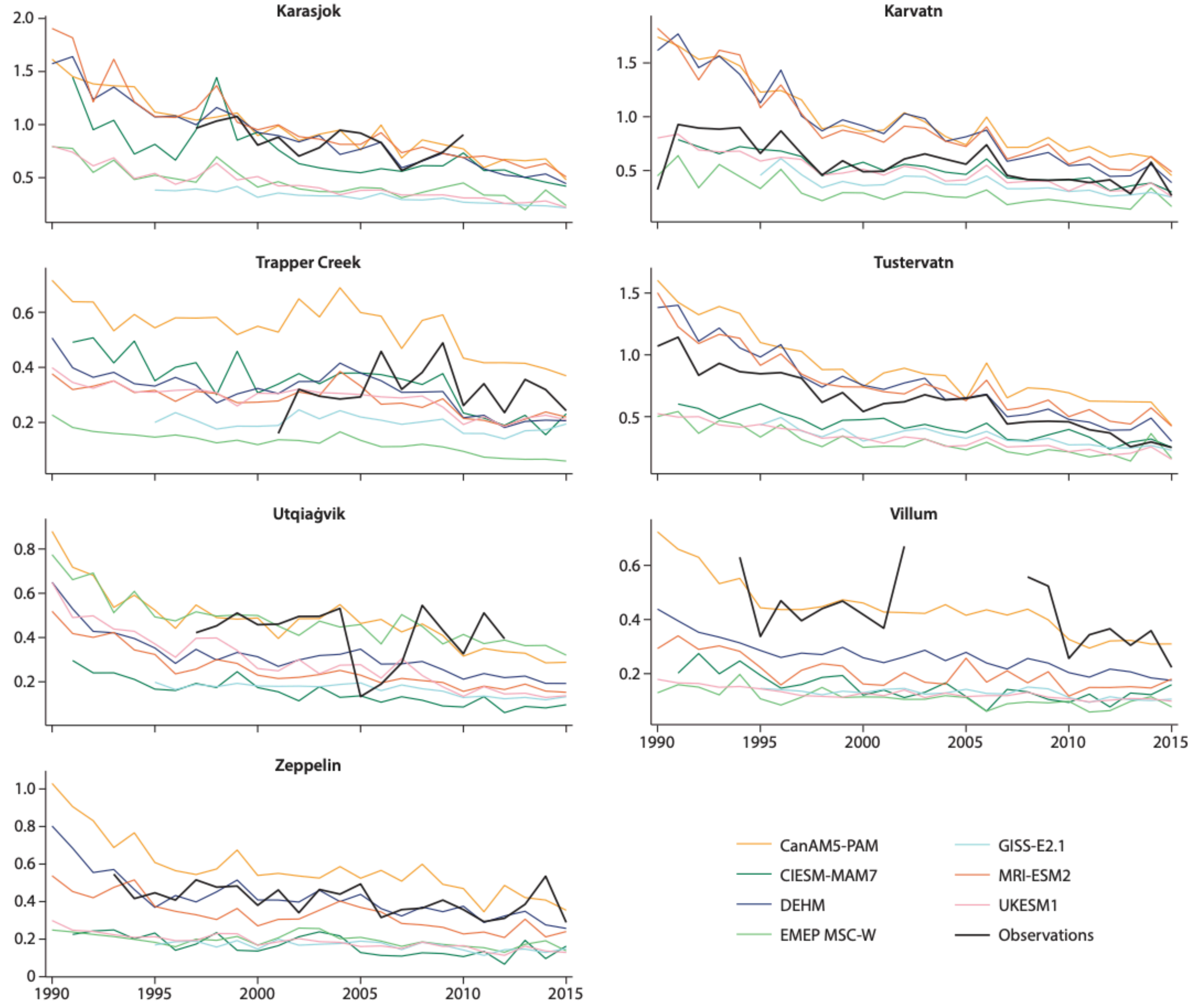


Figure 7.36 Measured and modeled annual mean time series of surface-level SO_4 at 13 Arctic locations.