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Historical (1700–2012) Global Multi-model Estimates of the Fire Emissions from the Fire Modeling Intercomparison Project (FireMIP)

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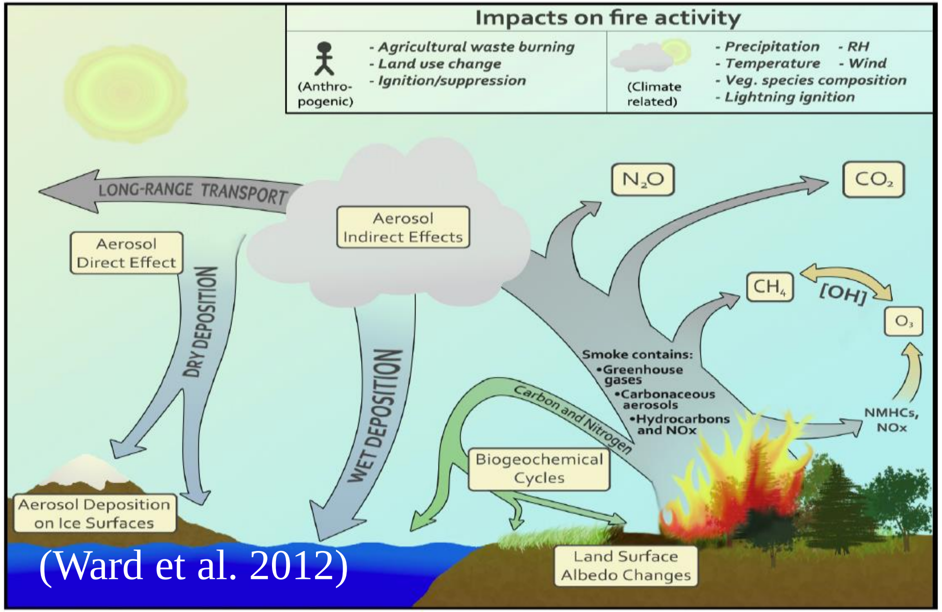
With FireMIP

Li, F., Val Martin, M., Andreae, M. O., Arneth, A., Hantson, S., Kaiser, J. W., Lasslop, G., Yue, C., Bachelet, D., Forrest, M., Kluzek, E., Liu, X., Mangeon, S., Melton, J. R., Ward, D. S., Darmenov, A., Hickler, T., Ichoku, C., Magi, B. I., Sitch, S., van der Werf, G. R., Wiedinmyer, C., and Rabin, S. S.: Historical (1700–2012) global multi-model estimates of the fire emissions from the Fire Modeling Intercomparison Project (FireMIP), Atmos. Chem. Phys., 19, 12545–12567, https://doi.org/10.5194/acp-19-12545-2019, 2019. https://www.atmos-chem-phys.net/19/12545/2019/

Background



(Ward et al. 2012)

Importance of fire emissions

- Key component of land C budget
- Major source of greenhouse gases
- Largest contributor of primary carbonaceous aerosols globally
- Affect climate, C/nutrient cycles, Air quality & human health

- **Regional/global fire emissions**

➢ **No observations**

➢ **Estimates methods:**

Satellite-based (e.g. GFED) global but only present-day

Fire proxy records (e.g. GCD): long-term but limited spatial extent

DGVM with fire modeling (e.g. FireMIP): local to global scales for past, present, and future

- **Earlier studies: one single time series / based on one DGVM**

- ➢ **quantify uncertainty in historical fire emis.** (**NO**)
- ➢ **understand inter-model discrepancy in historical reconstruction and future projections (NO)**

Our study:

- ➢ **provides a new dataset of multi-model global gridded fire emis.** (9 DGVMs, 1700-2012, C and 33 aerosols & trace gases)
- ➢ **comprehensively evaluates the model-based estimates**
- ➢ **analyzes simulated long-term changes, inter-model diff., & their drivers**

Methods and data

- **FireMIP Models**

➢ **9 DGVMs**

Inc. all fire schemes used in CMIP6/IPCC AR6

Also inc. GlobFIRM (most commonly used in CMIP5/IPCC AR5)

median of six of them determines historical changes over most regions of the world in CMIP6 fire emis. (as input data of CMIP6 CSMs/ESMs)

DGVMs	tem. res. of model outputs	spatial res. of model outputs	period	natural veg. distrib.	fire scheme ref.	DGVM ref.
CLM4.5 but CLM5 fire model (CLM4.5)	monthly	~1.9° (lat) ×2.5° (lon)	1700–2012	P	Li et al. (2012, 2013) Li and Lawrence (2017)	Oleson et al. (2013)
CTEM	monthly	2.8125°	1861–2012	P	Arora and Boer (2005) Melton and Arora (2016)	Melton and Arora (2016)
JSBACH-SPITFIRE (JSBACH)	monthly	1.875°	1700–2012	P	Lasslop et al. (2014) Thonicke et al. (2010)	Brovkin et al. (2013)
JULES-INFERNO (JULES)	monthly	~1.2° (lat) ×1.9°(lon)	1700–2012	M	Mangeon et al. (2016)	Best et al. (2011) Clark et al. (2011)
LPJ-GUESS-GlobFIRM (LGG)	annual	0.5°	1700–2012	M	Thonicke et al. (2001)	Smith et al. (2014) Lindeskog et al. (2013)
LPJ-GUESS-SPITFIRE (LGS)	monthly	0.5°	1700–2012	M	Lehsten et al. (2009) Rabin et al. (2017)	Smith et al. (2001) Ahlstrom et al. (2012)
LPJ-GUESS-SIMFIRE -BLAZE (LGSB)	monthly	0.5°	1700–2012	M	Knorr et al. (2016)	Smith et al. (2014) Lindeskog et al. (2013) Nieradzik et al. (2017)
MC2	annual	0.5°	1901–2008	M	Bachelet et al. (2015) Sheehan et al. (2015)	Bachelet et al. (2015) Sheehan et al. (2015)
ORCHIDEE-SPITFIRE (ORCHIDEE)	monthly	0.5°	1700–2012	P	Yue et al. (2014, 2015) Thonicke et al. (2010)	Krinner et al. (2005)

P: prescribed M: modeled

➢ Global fire schemes in FireMIP DGVMs

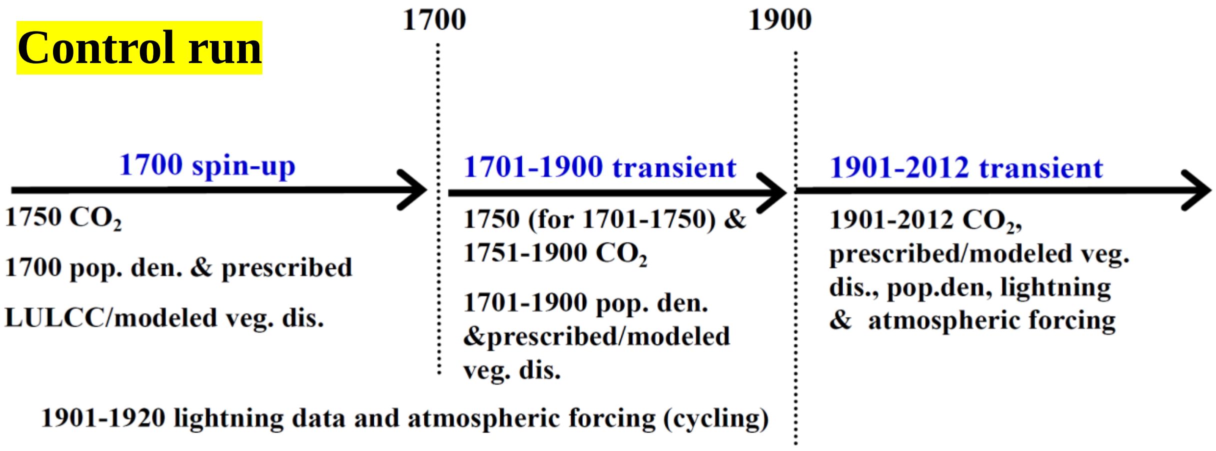
Fire C emissions
= burned area (BA) × fuel load
× combustion completeness (CC)

[a] PD: population density
[b] fire suppression increases with PD and GDP, different between tree PFTs and grass/shrub PFTs
[c] fire suppression increases with PD
[d] Assume no fire in grid cell when pre-calculated rate of spread, fireline intensity, and energy release component are lower than thresholds
[e] CLM4.5 outputs in FireMIP include biomass and litter burning due to peat fires, but don't include burning of soil organic matter
[f] Coarse Woody Debris
[g] 100-hour fuels and 1000-hour fuel classes

DGVMs	crop fire	tropical human defor. fire	human ignition	human fire suppression	peat fire	pasture	combust. complete. range of woody tissue
CLM4.5	yes	yes	increase with PD[a]	occurrence & spread area[b]	yes[e]	as natural grassland	27–35% (stem) 40% (CWD[f])
CTEM	no	no	increase with PD	occurrence & duration[c]	no	as natural grassland	6% (stem) 15–18% (CWD)
JSBACH	as grass fire	no	increase with PD	occurrence & duration[c]	no	high fuel bulk den.	0–45%
JULES	no	no	increase with PD	occurrence[c]	no	as natural grassland	0–40%
LGG	no	no	no	no	no	harvest	70–90%
LGS	no	no	increase with PD	occurrence[c]	no	as natural grassland	0–98% (100h[g]) 0–80% (1000h[g])
LGSB	no	no	increase with PD	burned area[c]	no	harvest	0–50%
MC2	no	no	no	occurrence[d]	no	as natural grassland	0–87% (100h) 0–43% (1000h)
ORCHIDEE	no	no	increase with PD	occurrence[c]	no	as natural grassland	0–73% (100h) 0–41% (1000h)

• FireMIP experimental protocol and input datasets

Control run



Atm.:
CRU-NCEPv5.3.2 (1901-2012)
LULCC:
Hurtt et al. (2011) (1700-2012)
Population density:
HYDE v3.1 (1700-2012)
Lightning:
Pfeiffer et al. (2013) (1901-2012)
CO2:
Le Quéré et al. (2014) (1750-2012)

5 sensitive runs:

- constant climate
- constant atmospheric [CO_2]
- constant land cover
- constant population density
- constant lightning frequency

- **Estimate fire trace gas & aerosol emis.**

➢ **Fire emis. of trace gas and aerosol species *i* and the PFT *j***

$$E_{i,j} = EF_{i,j} \times CE_j/[C]$$

***EF*: emission factors** (Andreae, 2019) →

CE: fire carbon emis. output from FireMIP DGVMs

[C]=0.5×10^3 g C (kg DM)$^{-1}$ unit conversion factor

EF Table

No.	Species	grassland /savanna	tropical forest	temperate forest	boreal forest	cropland
1	CO_2	1647	1613	1566	1549	1421
2	CO	70	108	112	124	78
3	CH_4	2.5	6.3	5.8	5.1	5.9
4	NMHC	5.5	7.1	14.6	5.3	5.8
5	H2	0.97	3.11	2.09	1.66	2.65
6	NO_x	2.58	2.55	2.90	1.69	2.67
7	N_2O	0.18	0.20	0.25	0.25	0.09
8	$PM_{2.5}$	7.5	8.3	18.1	20.2	8.5
9	TPM	8.5	10.9	18.1	15.3	11.3
10	TPC	3.4	6.0	8.4	10.6	5.5
11	OC	3.1	4.5	8.9	10.1	5.0
12	BC	0.51	0.49	0.66	0.50	0.43
13	SO_2	0.51	0.78	0.75	0.75	0.81
14	C_2H_6 (ethane)	0.42	0.94	0.71	0.90	0.76
15	CH_3OH (methanol)	1.48	3.15	2.13	1.53	2.63
16	C_3H_8 (propane)	0.14	0.53	0.29	0.28	0.20
17	C_2H_2 (acetylene)	0.34	0.43	0.35	0.27	0.32
18	C_2H_4 (ethylene)	1.01	1.11	1.22	1.49	1.14
19	C_3H_6 (propylene)	0.49	0.86	0.67	0.66	0.48
20	C_5H_8 (isoprene)	0.12	0.22	0.19	0.07	0.18
21	$C_{10}H_{16}$ (terpenes)	0.10	0.15	1.07	1.53	0.03
22	C_7H_8 (toluene)	0.20	0.23	0.43	0.32	0.18
23	C_6H_6 (benzene)	0.34	0.38	0.46	0.52	0.31
24	C_8H_{10} (xylene)	0.09	0.09	0.17	0.10	0.09
25	CH_2O (formaldehyde)	1.33	2.40	2.22	1.76	1.80
26	C_2H_4O (acetaldehyde)	0.86	2.26	1.20	0.78	1.82
27	C_3H_6O (acetone)	0.47	0.63	0.70	0.61	0.61
28	$C_3H_6O_2$(hydroxyacetone)	0.52	1.13	0.85	1.48	1.74
29	C_6H_5OH (Phenol)	0.37	0.23	0.33	2.96	0.50
30	NH_3 (ammonia)	0.91	1.45	1.00	2.82	1.04
31	HCN (hydrogen cyanide)	0.42	0.38	0.62	0.81	0.43
32	MEK/2-butanone	0.13	0.50	0.23	0.15	0.60
33	CH_3CN (acetonitrile)	0.17	0.51	0.23	0.30	0.25

➢ Associate DGVMs' plant functional types (PFTs) to EF Table's land cover types

T: tree; S: shrub; W: woodland; F: forest; G: grass; P: pasture; Sava: Savanna; N: needleleaf; E: evergreen; B: broadleaf; D: deciduous; R: raingreen; SI: shaded-intolerant; SG: summer-green; M: mixed; I: irrigated; RF: rainfed; C/W: cool or warm; S/W: spring or winter, Tro: Tropical; Tem: Temperate; Bor: Boreal; Sub-Tro: subtropical; Ex-Tro: Extratropical; A: Arctic

[a] split tree PFTs into tropical, temperate, and boreal groups following rules of Nemani and Running (1996) that also used to make CLM land surface data by Peter et al. (2007; 2012) since CLM version 3;

[b] LGG and LGBS did not outputs PFT-level fire carbon emissions, so land cover classified using its dominant vegetation type

[c] MC2 classifies tropical savannas and tropical deciduous woodland regions, and the latter mainly represents tropical deciduous forests

LCT / Models	Grassland /Savannas	Tropical Forest	Temperate Forest	Boreal Forest	Cropland
CLM4.5	A C3/C3/C4 G	Tro BE T	Tem NE T	Bor NE T	Crop
	Bor BD S	Tro BD T	Tem BE T	Bor ND T	
	Tem BE/BD S		Tem BD T	Bor BD T	
CTEM	C3/C4 G	BE T[a]	NE/BE T[a]	NET[a], ND T	C3/C4 Crop
		Other BD T[a]	Other BD T[a]	Cold BD T	
JSBACH	C3/C4 G/P	Tro E/D T	Ex-Tro E/D T[a]	Ex-Tro E/D T[a]	Crop
JULES	C3/C4 G	Tro BE T	Tem BE T	BD/NE T[a]	
	E/D S	BD T[a]	BD/NE T[a]	NDT	
LGG[b]	C3/C4 G	Tro BE/BR T	Tem NSG/BSG/BE T	Bor NE T	R/I S/W Wheat
	C3/C4 G in P	Tro SI BE T	Tem SI SG B T	Bor SI NE T	R/I Maize
LGS	C3/C4 G	Tro BE/BR T	Tem SI/&SG B T	Bor NE T	
		Tro SI BE T	Tem B/N E T	Bor SI/&SG NE/N T	
LGSB[b]	C3/C4 G	Tro BE/BR T	Tem NSG/BSG/ BE T	Bor NE T	R/I S/W Wheat
	C3/C4 G in P	Tro SI BE T	Tem SI SG B T	Bor SI NE T	R/I Maize
MC2	Tem C3 G/S	Tro BE T	Maritime NE F	Bor NE F	
	Sub-Tro C4 G/S	Tro D W[c]	Sub-Tro NE/BD/BE/M F	Subalpine F	
	Tro S/G/Sava		Tem NE/BD F	Cool N F	
	Bor M W		Tem C/W M F		
	Tem/Sub-Tro				
	NE/B/M W				
	Tundra				
	Taiga-Tundra				
ORCHIDEE	C3/C4 G	Tro B E/R T	Tem N/B E T	Bor N E/D T	C3/C4 Crop
			Tem BD T	Bor BT T	

- **Benchmarks**

	Name	Method	Fire data sources	Peat burning	Start year	reference
Satellite-based	GFED4	Bottom-up: fuel consumption,	MODIS,VIRS/ATSR	Y	1997	van der Werf et al. (2017)
	GFED4s	burned area &active fire counts		Y	1997	
	GFAS1.2	(GFED4&4s), FRP (GFAS1),	MODIS	Y	2001	Kaiser et al. (2012)
	FINN1.5	active fire counts (FINN1.5), emis. factor	MODIS	N	2003	Wiedinmyer et al. (2011)
	FEER1	Top-down: FRP, satellite AOD	MODIS, SEVIRI	Y	2003	Ichoku and Ellison (2014)
	QFED2.5	constrained, emis. factor	MODIS	N	2001	Darmenov and da Silva (2015)
Multi-source merged	CMIP5	Merged decadal fire trace gas and aerosol emis.	GFED2, GICC, RETRO (model GlobFIRM used)	Y	1850	Lamarque et al. (2010)
	CMIP6	Merged monthly fire carbon emis., present-day veg. dist., emis. factor	GFED4s, median of six FireMIP model sims., GCDv3 charcoal records, WMO visibility obs.	Y	1750	van Marle et al. (2017)

GFED4: Global Fire Emissions Dataset version 4; GFED4s: GFED4 with small fires; GFAS1.2: Global Fire Assimilation System version 1.2; FINN1.5: Fire Inventory from NCAR version 1.5; FRP: fire radiative power; FEER1: Fire emissions from the Fire Energetics and Emissions Research version1; QFED2.5: Quick Fire Emissions Dataset version 2.5; AOD: aerosol optical depth; GFED2: GFED version 2; RETRO: REanalysis of the TROpospheric chemical composition; GICC: Global Inventory for Chemistry-Climate studies; GCDv3: Global Charcoal Database version 3

Results: Evaluation of present-day fire emissions

- **Global amounts**

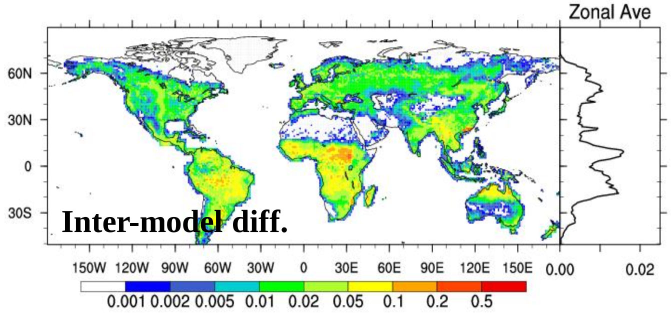
within benchmarks' range, except for MC2 (small BA) & LGG (high CC)

Global totals of fire emis. (2003~2008)

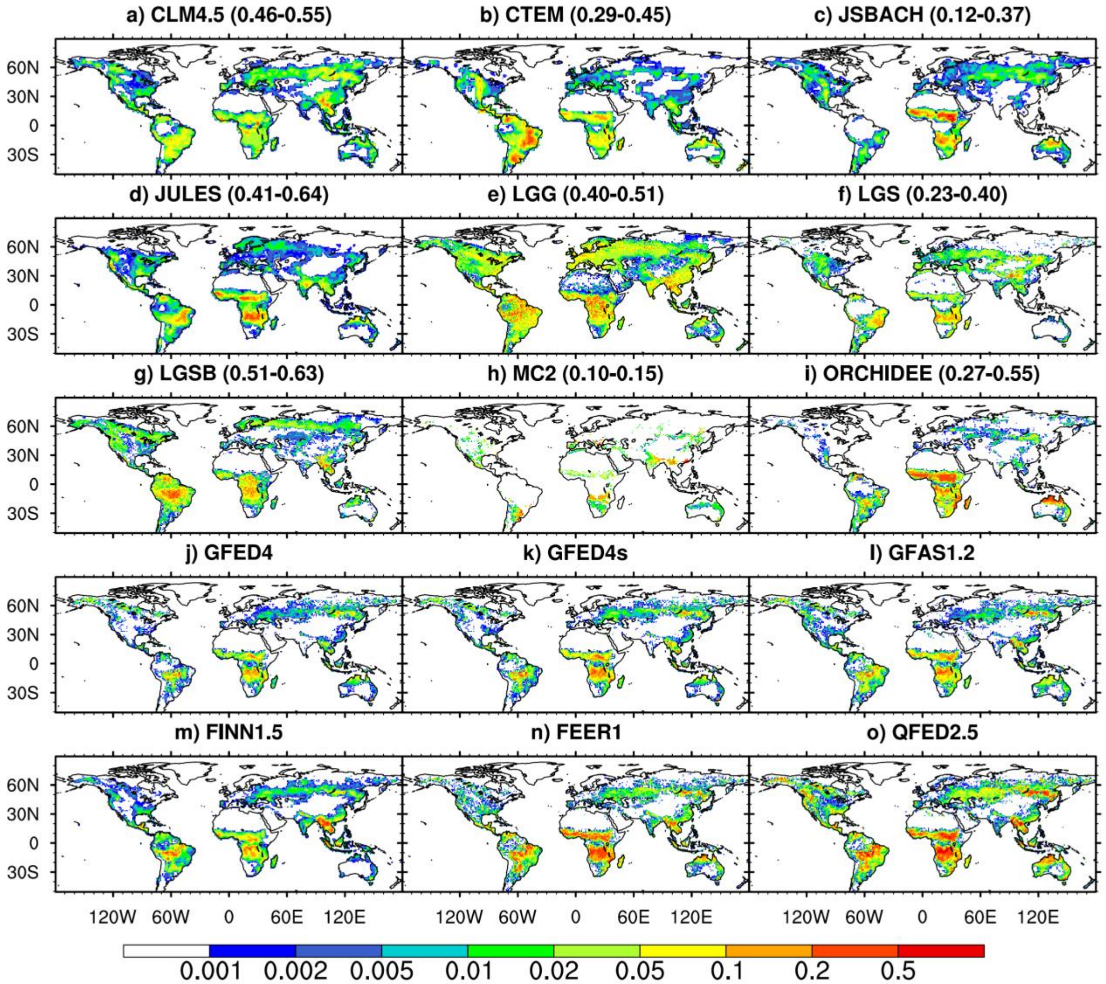
Source	C	CO_2	CO	CH_4	BC	OC	$PM_{2.5}$
FireMIP							
CLM4.5	2.1	6.5	0.36	0.018	0.0021	0.020	0.042
CTEM	3.0	8.9	0.48	0.025	0.0028	0.030	0.060
JSBACH	2.1	6.5	0.32	0.013	0.0020	0.016	0.036
JULES	2.1	6.9	0.44	0.024	0.0022	0.020	0.039
LGG	4.9	15.4	0.90	0.047	0.0050	0.048	0.097
LGS	1.7	5.6	0.26	0.011	0.0017	0.012	0.027
LGSB	2.5	7.7	0.48	0.025	0.0025	0.024	0.047
MC2	1.0	3.1	0.18	0.008	0.0011	0.012	0.025
ORCHIDEE	2.8	9.2	0.44	0.018	0.0029	0.020	0.045
Benchmarks							
GFED4	1.5	5.4	0.24	0.011	0.0013	0.012	0.025
GFED4s	2.2	7.3	0.35	0.015	0.0019	0.016	0.036
GFAS1.2	2.1	7.0	0.36	0.019	0.0021	0.019	0.030
FINN1.5	2.0	7.0	0.36	0.017	0.0021	0.022	0.039
FEER1	4.2	14.0	0.65	0.032	0.0042	0.032	0.054
QFED2.5	---	8.2	0.39	0.017	0.0060	0.055	0.086

- **Spatial pattern**

- Overall ok, except for MC2
- CLM4.5, JULES, and LGSB are better
- Inter-model diff. mainly in tropics

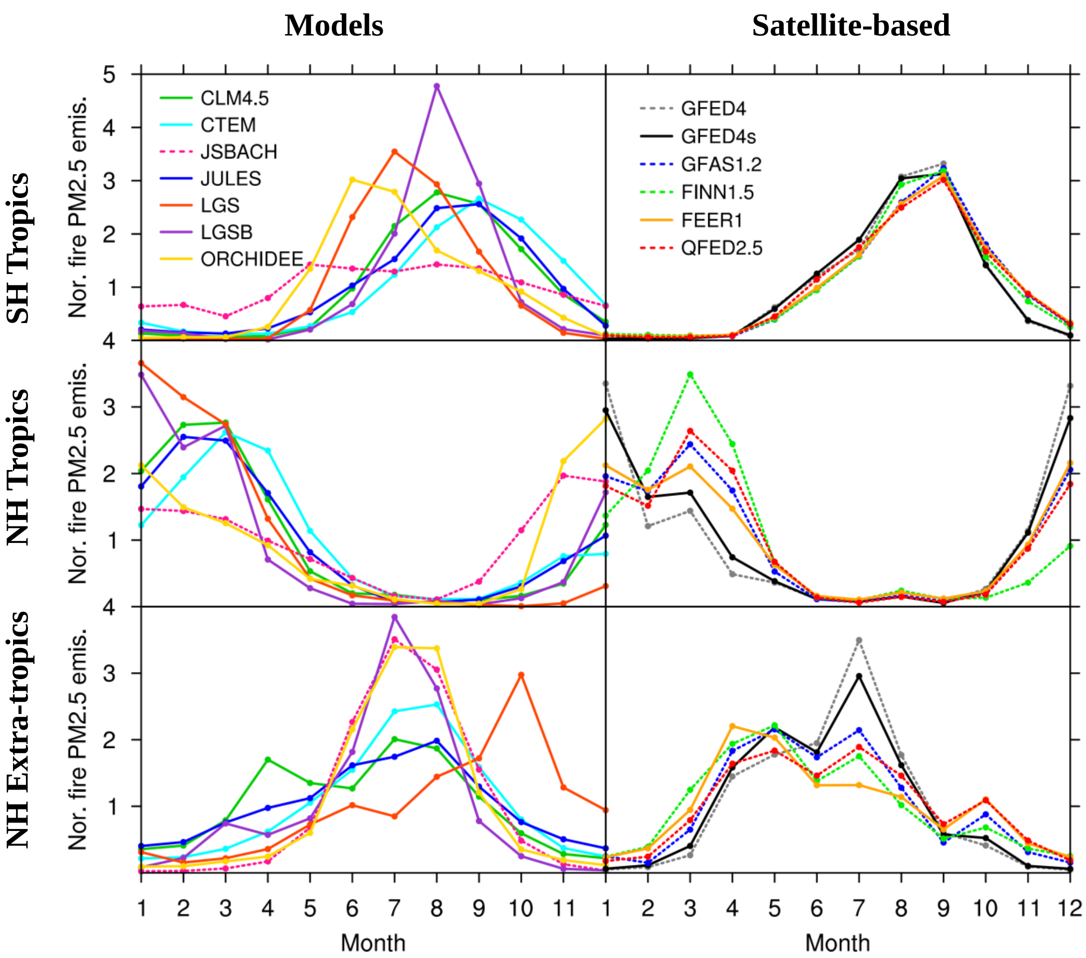


Spatial pattern of 2003~2008 annual fire BC & sim.-obs. Cor



- **Seasonal cycle**

> - **overall ok**
> - **SPITFIRE family** (ORCHIDEE, JSBACH, LGS) **is poorer in SH**
> - **Only CLM4.5 can capture two peak periods in NH extra-tropics** (only CLM4.5 models crop fires)



- # Interannual variability

- **Overall fail**
  partly due to a lack of modeling peat fires & tropical deforestation fires

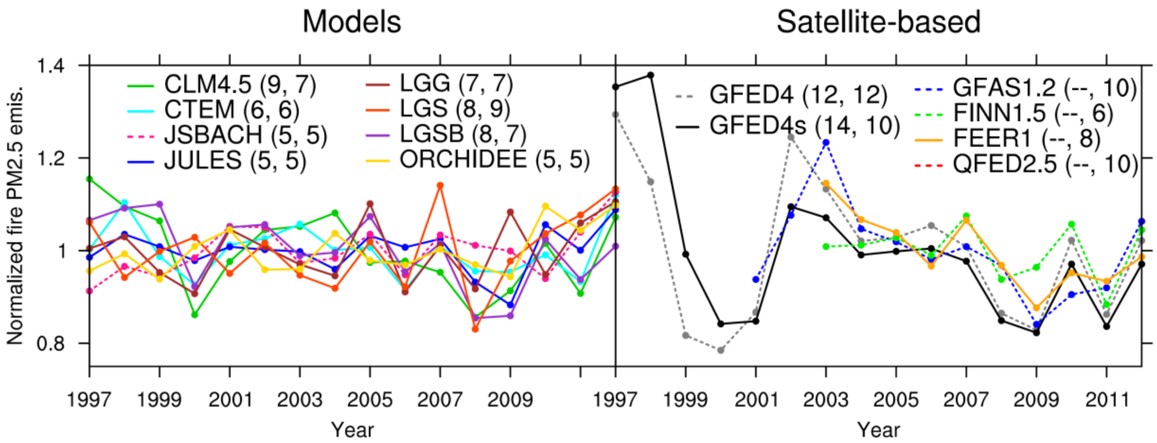
- **CLM4.5, CTEM, & LGSB are better**

Sim. – obs. Cor. of annual global fire $PM_{2.5}$ emis.

DGVMs	GFED4	GFED4s	GFAS1.2	FINN1.5	FEER1	QFED2.5
CLM4.5	0.73***	0.79***	0.63**	0.62*	0.55*	0.58**
CTEM	0.51**	0.54**	0.63**	0.60*	0.52	0.68**
JSBACH	–0.18	–0.42	0.10	0.02	–0.04	0.32
JULES	0.33	0.31	0.31	0.56*	0.29	0.39
LGG	0.08	0.03	–0.15	0.01	–0.20	–0.03
LGS	0.12	0.04	–0.00	0.40	–0.01	0.08
LGSB	0.51**	0.64***	0.39	0.72**	0.56*	0.55*
ORCHIDEE	–0.13	–0.25	–0.16	0.29	–0.10	–0.10

* (P<0.1) ** (P<0.05) *** (P<0.01)

Temporal change & CVs for 1997–2012, 2003–2012

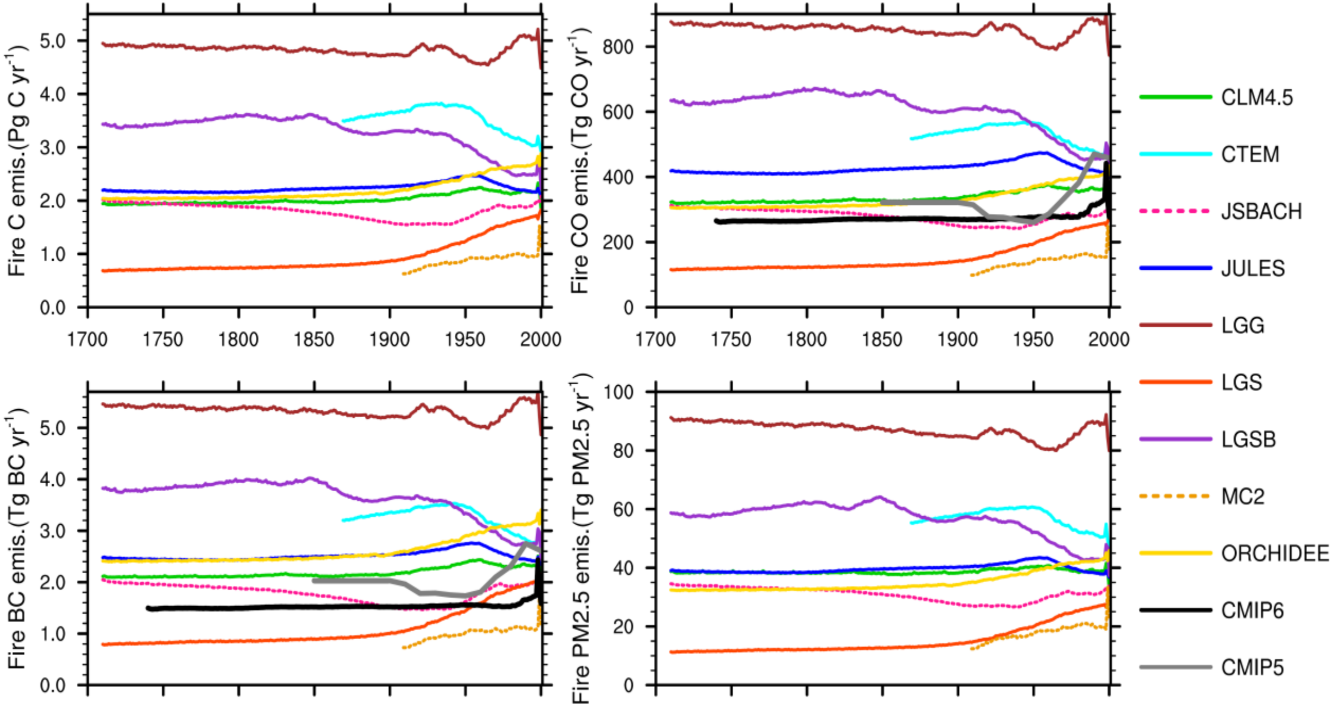


Historical changes and drivers

- **Historical global changes**

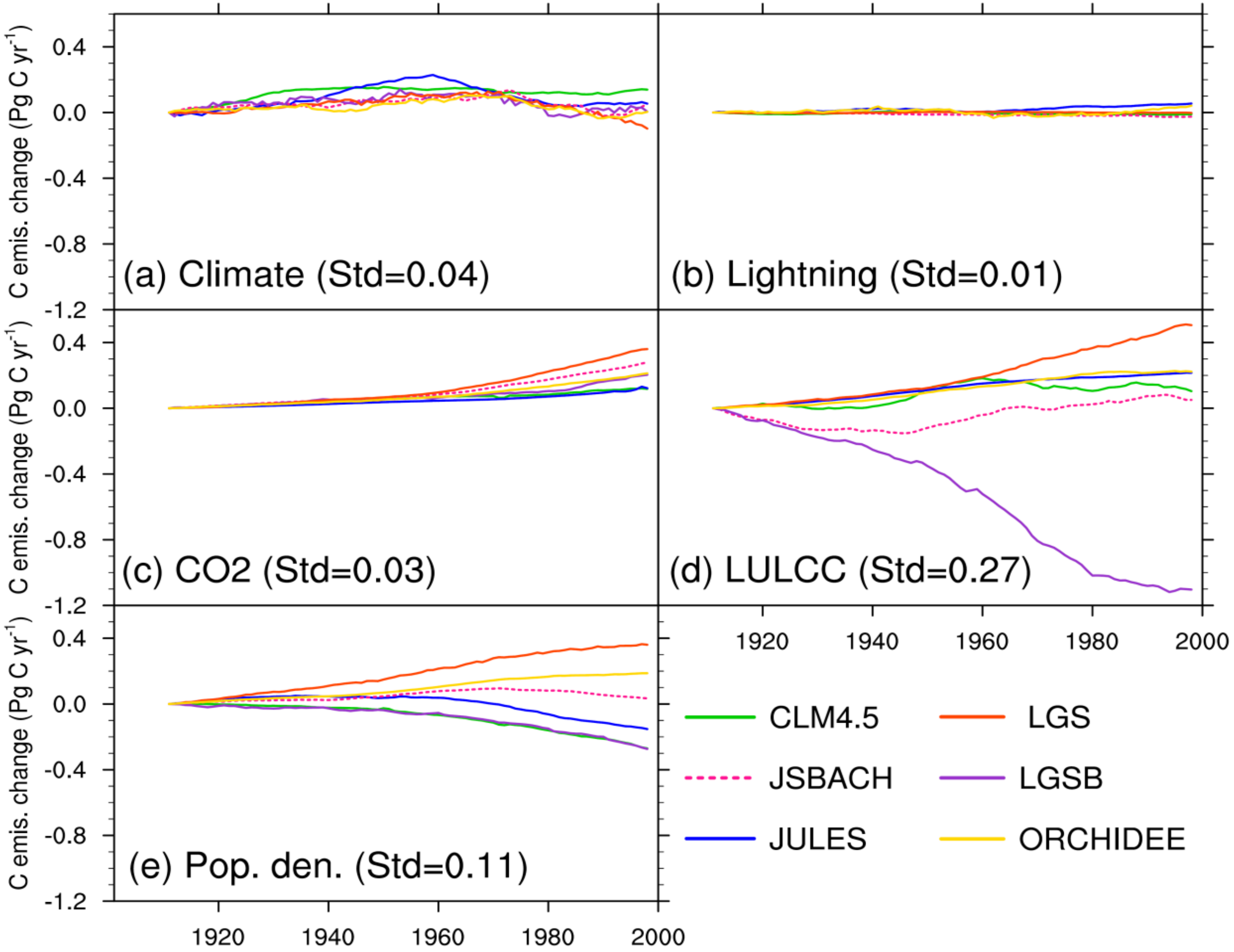
➢ **All models show a weak trend before 1850s, as CMIP6**

➢ **Inter-model diff. is large for the 20^{th} century**



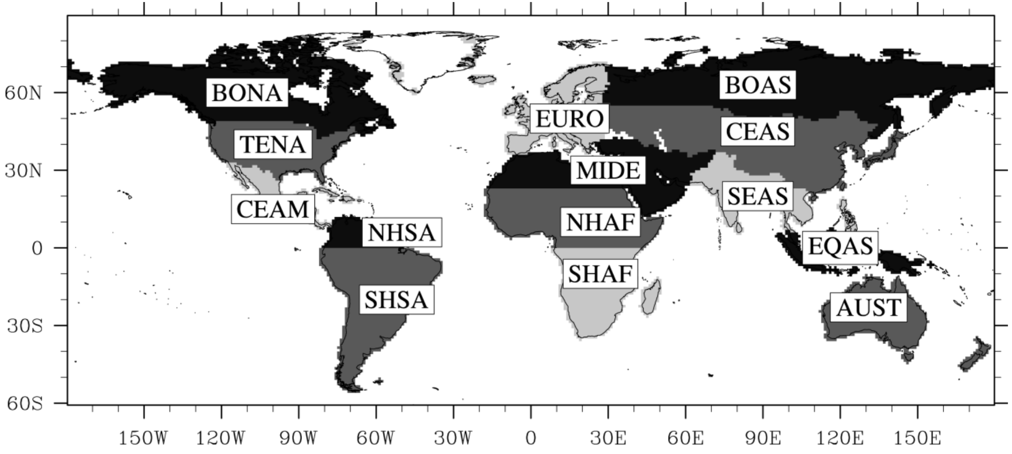
- **Drivers**

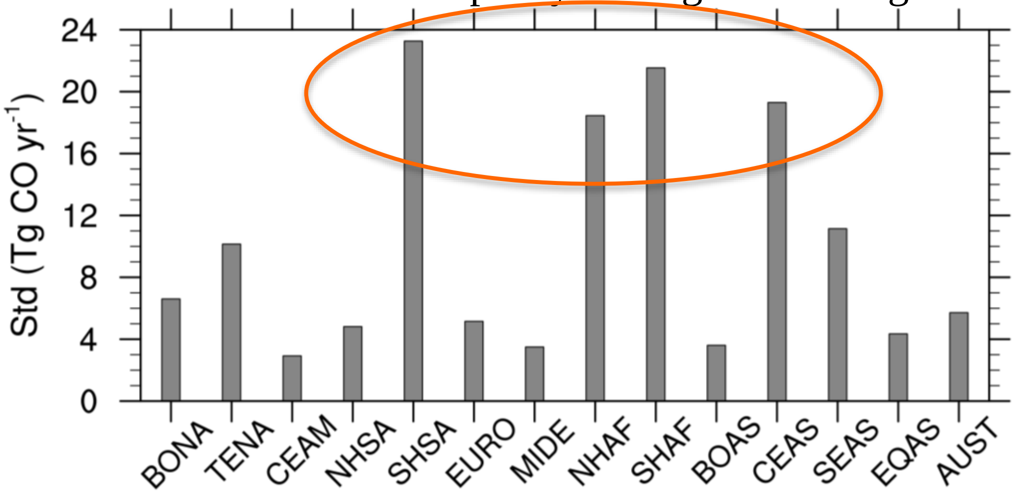
mainly LULCC & human population density change



- **Regional long-term changes**

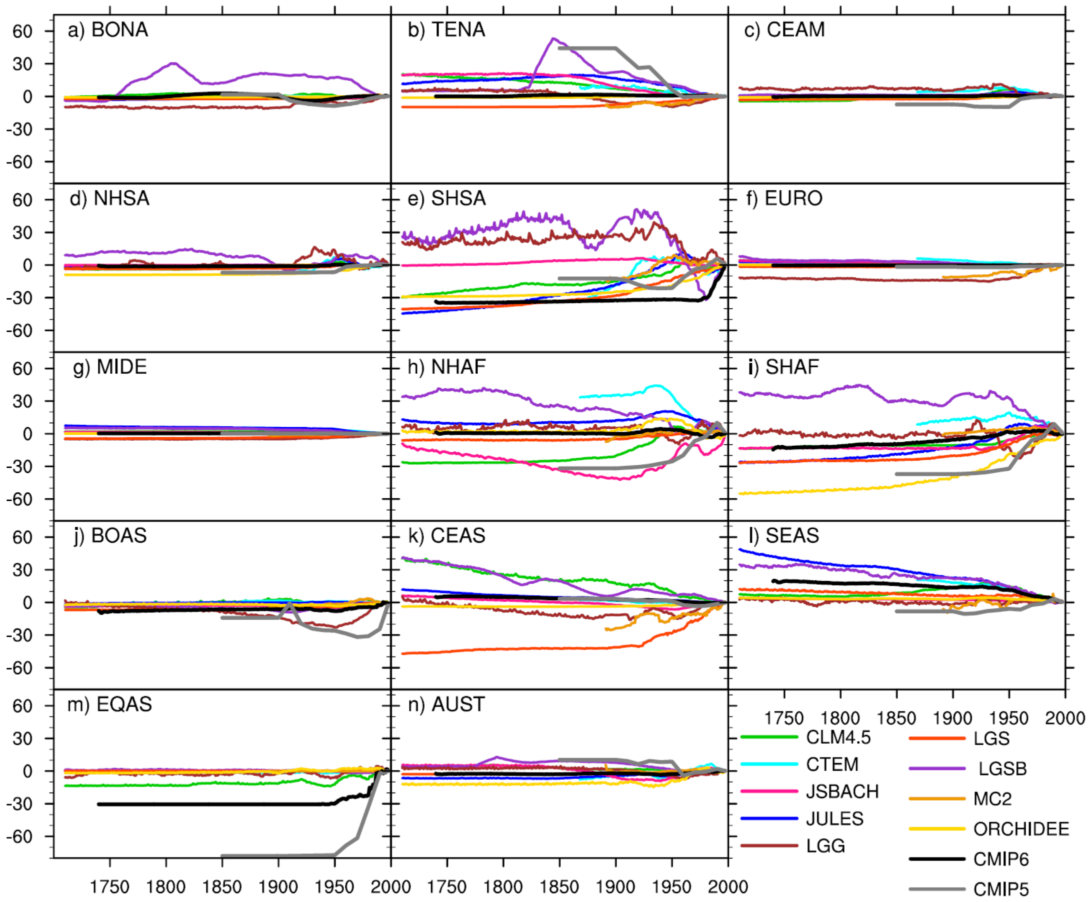
➢ **Inter-model diff. is largest in SH South America (SHSA), Africa (NHAF & SHAF), & central Asia (CEAS)**





- **Most models reproduce the upward trends in the CMIP6/CMIP5 estimates since 1950s in SHSA and till ~1950 in Africa**

- **Long-term trends in regional fire emis. in SHSA, Africa, and CEAS broadly explain simulated global trends**



Summary and outlook

1. Dataset: https://zenodo.org/record/3386620#.XXaE1eRYaP8 **with wide-ranging use:**

- Develop multi-source merged fire emis. products and methods
- for the first time, allows end users to select all or a subset of model-based reconstruction for their regional or global inter-annual ~ multi-decadal research
- quantify uncertainty range of past fire emis. and their impacts

2. Recent state of fire model performance: most models can overall reproduce the amount, spatial pattern, and seasonality, but fail to simulate the interannual variability

3. population density and LULCC are the primary uncertainty sources in long-term trend simulation

→ **Fire models need improve modeling of human effect on fire**