How do air pollutant emissions influence solar energy generation?

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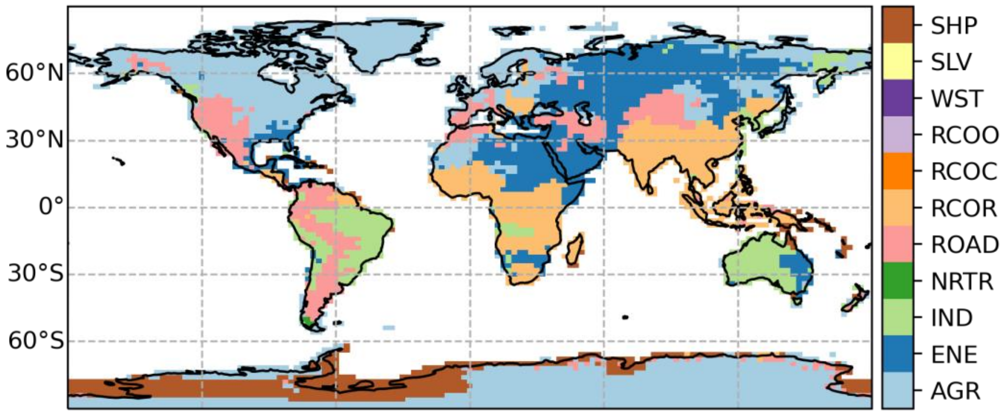
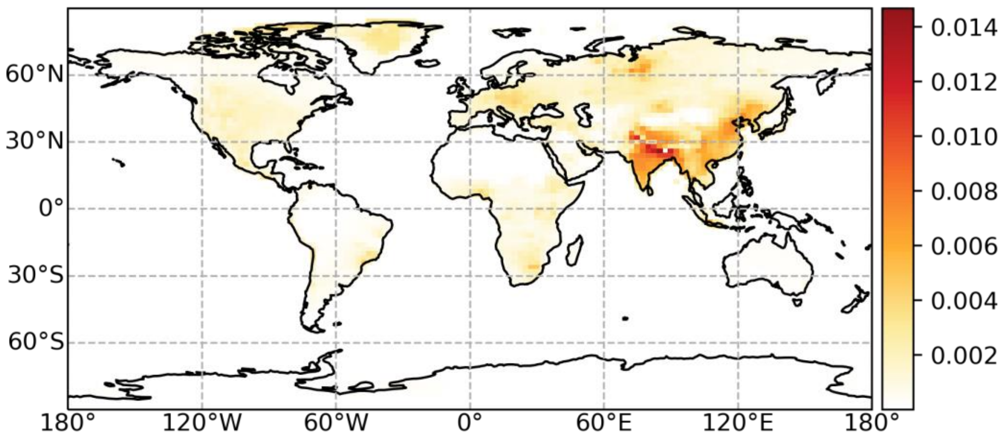
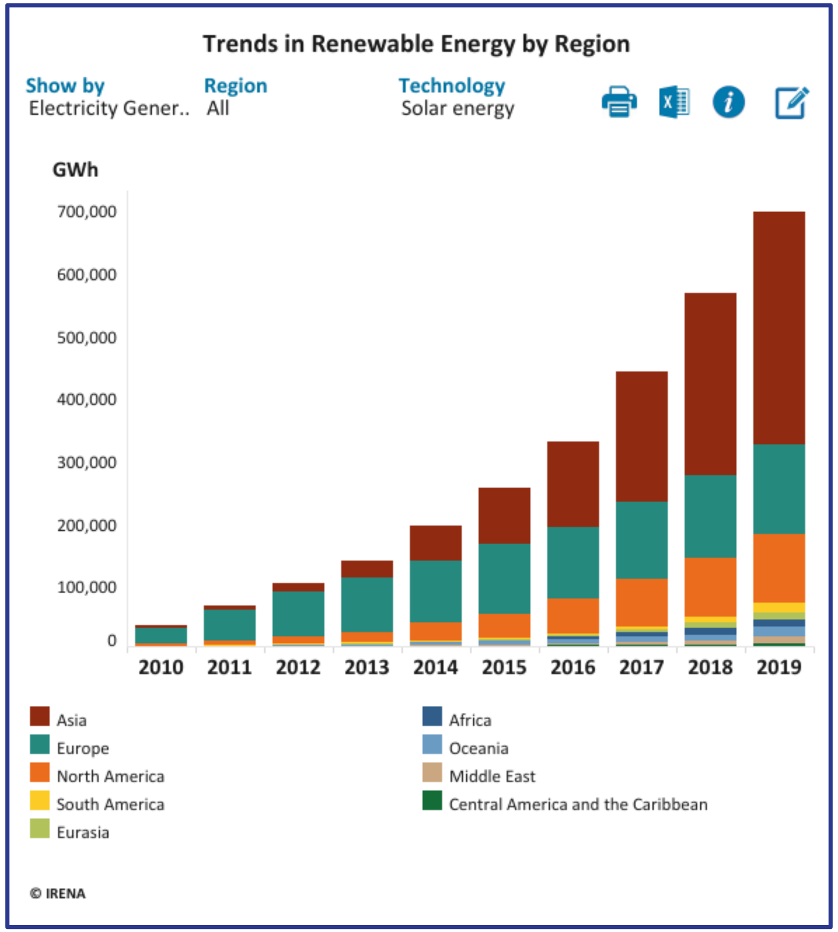


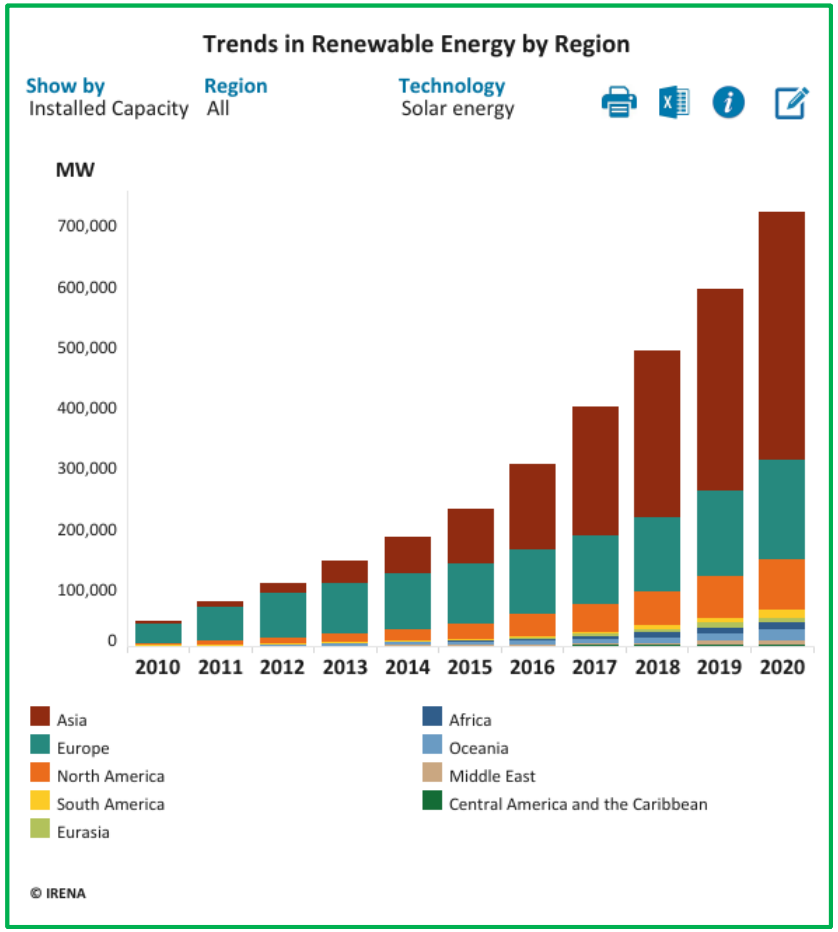
↑ Sectors where halving emissions mostly benefit PV efficiency ↓



Solar energy helps combat climate change

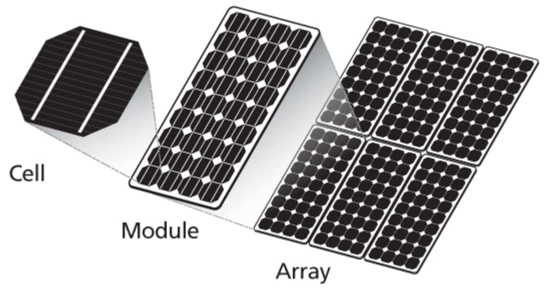
- $\text{Electricity Generation} = \int(\text{Installed Capacity} \times \text{Capacity Factor})dt$





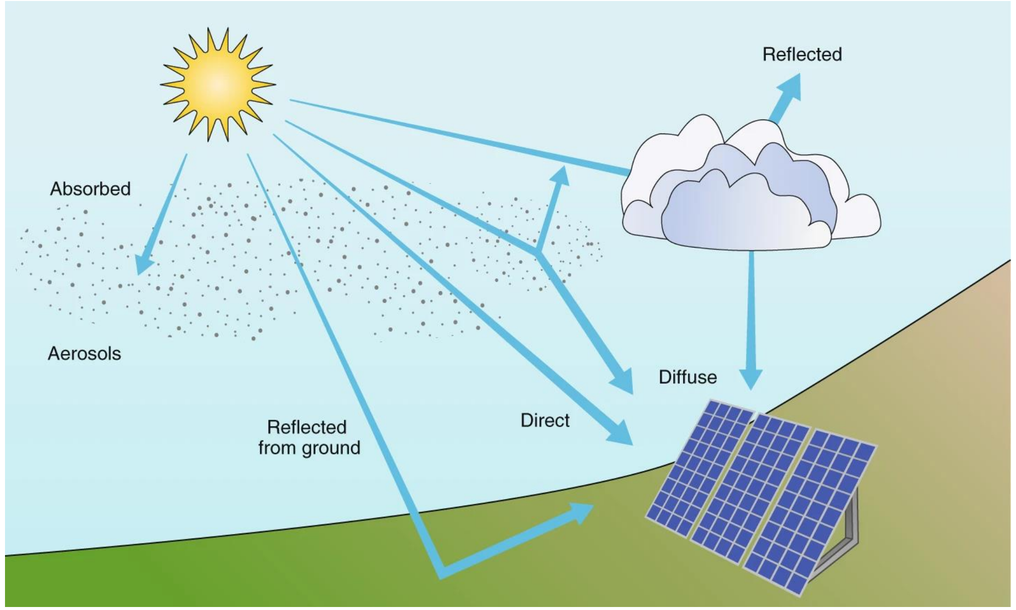
Weather conditions: irradiance, temperature, and wind speed.

Properties and configurations of Photovoltaic (PV) materials.

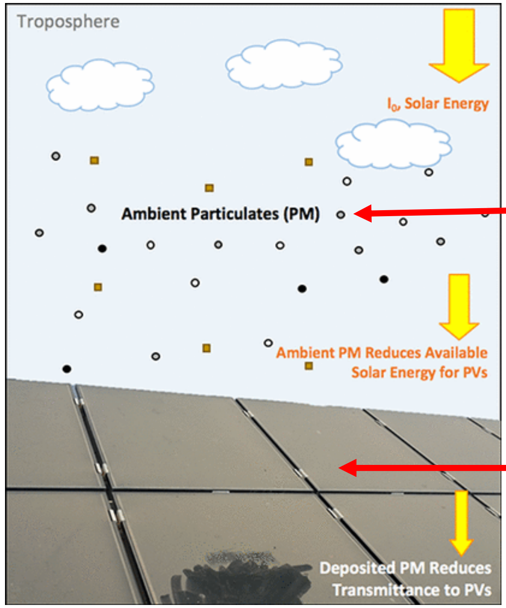


Air pollution reduces solar energy generation

Particulate matter (PM) pollution reduces PV efficiency (i.e. capacity factor) by impeding light as it passes through 1) the atmosphere (dimming), and 2) the solar panel surface where PM deposits (soiling).



Ekins-Daukes, N. and Kay, M., 2019



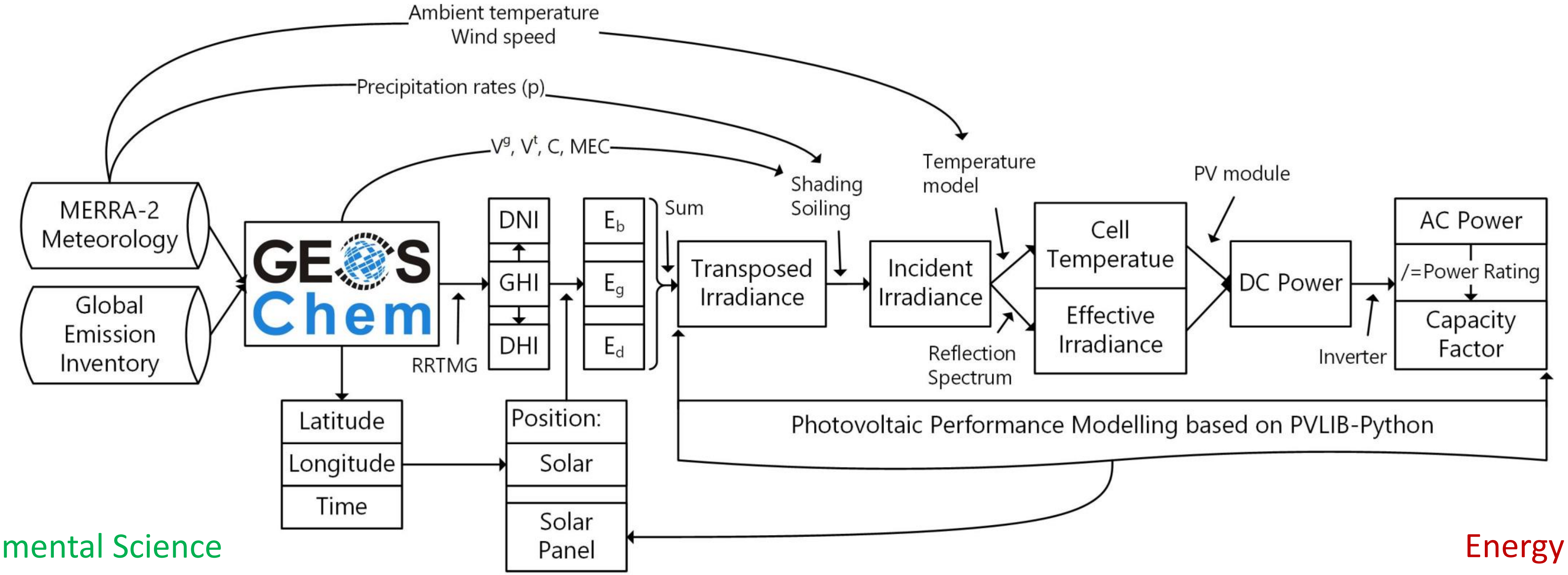
Dimming

Soiling

Bergin et al., 2017

Reducing PM sources will improve PV efficiency

- We lack a global understanding of the source sectors that would be the most effective at achieving the necessary reductions in anthropogenic PM sources.
- Natural PM sources can also be significant but are not easily controlled.



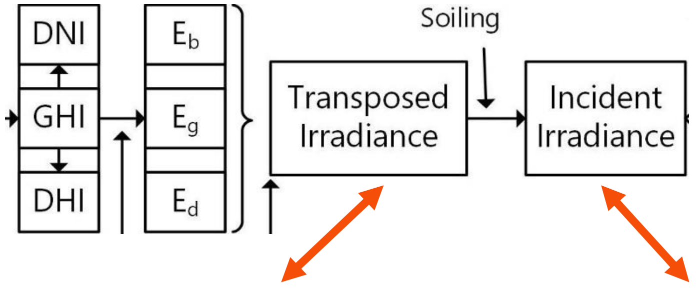
Environmental Science

Energy Science

Model configurations

GEOS-Chem v12.9.3 coupled with radiative transfer model (aka. GCRT)

- 2° x2.5° simulations during 200507-201712 driven by MERRA2 meteorology using full-chemistry in troposphere with the first 2.5 years as the spin-up.
- Emission Inventories. Anthropogenic: $\text{CEDS}_{\text{GBD-MAPS}}$ (McDuffie et al., 2020), Biogenic: MEGAN (Guenther et al., 2012), Pyrogenic: GFED (van der Warf et al., 2017), etc.
- Model outputs: all-sky global horizontal irradiance (GHI), all-sky no-aerosol GHI, surface aerosol mass concentrations (C); aerosol gravitational (V^g) and turbulent (V^t) deposition velocities, surface aerosol mass extinction coefficients (MEC).



$$POAI_{in} \times e^{-\tau} = POAI_{out}$$

$$\tau = \sum_i (MEC_i \times PM_i) \qquad PM_i = PM_i^{Accum} - PM_i^{Removal}$$

Model configurations

PM_i^{Accum} is the integral of gravitational (V_i^g) and turbulent (V_i^t) aerosol deposition fluxes ($\times\, C_i$) over time.

- V_i^g is reduced on tilt panels ($\times \cos(\theta_T)$) due to the decreased effective areas.

$$PM_i^{Accum} = \int (V_i^g \cos(\theta_T) + V_i^t) C_i dt$$

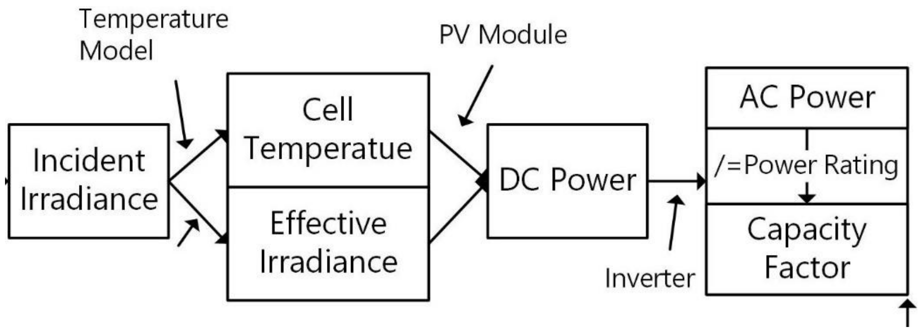
$PM_i^{Removal}$ is a function of precipitation rates (p) and aerosol properties:

- When $p < 1mmh^{-1}$, no aerosol removal occurs.
- When $1 < p < 3mmh^{-1}$, secondary inorganic aerosols are entirely removed and half of organic aerosols are removed.
- When $3 < p < 5mmh^{-1}$, secondary inorganic aerosols are entirely removed and half of all other aerosols are removed.
- When $p > 5mmh^{-1}$, all aerosols are removed.

Model configurations

PVLIB-Python v0.8.0

- A community supported tool that provides a set of functions and classes for simulating the performance of solar PV energy systems.
- Currently three most widely used solar panels are supported.
- Temperature model: Sandia Array Performance Model (King et al., 2004)
- PV module: Canadian_Solar_CS5P_220M___2009_
- Inverter: ABB__MICRO_0_25_I_OUTD_US_208__208V_

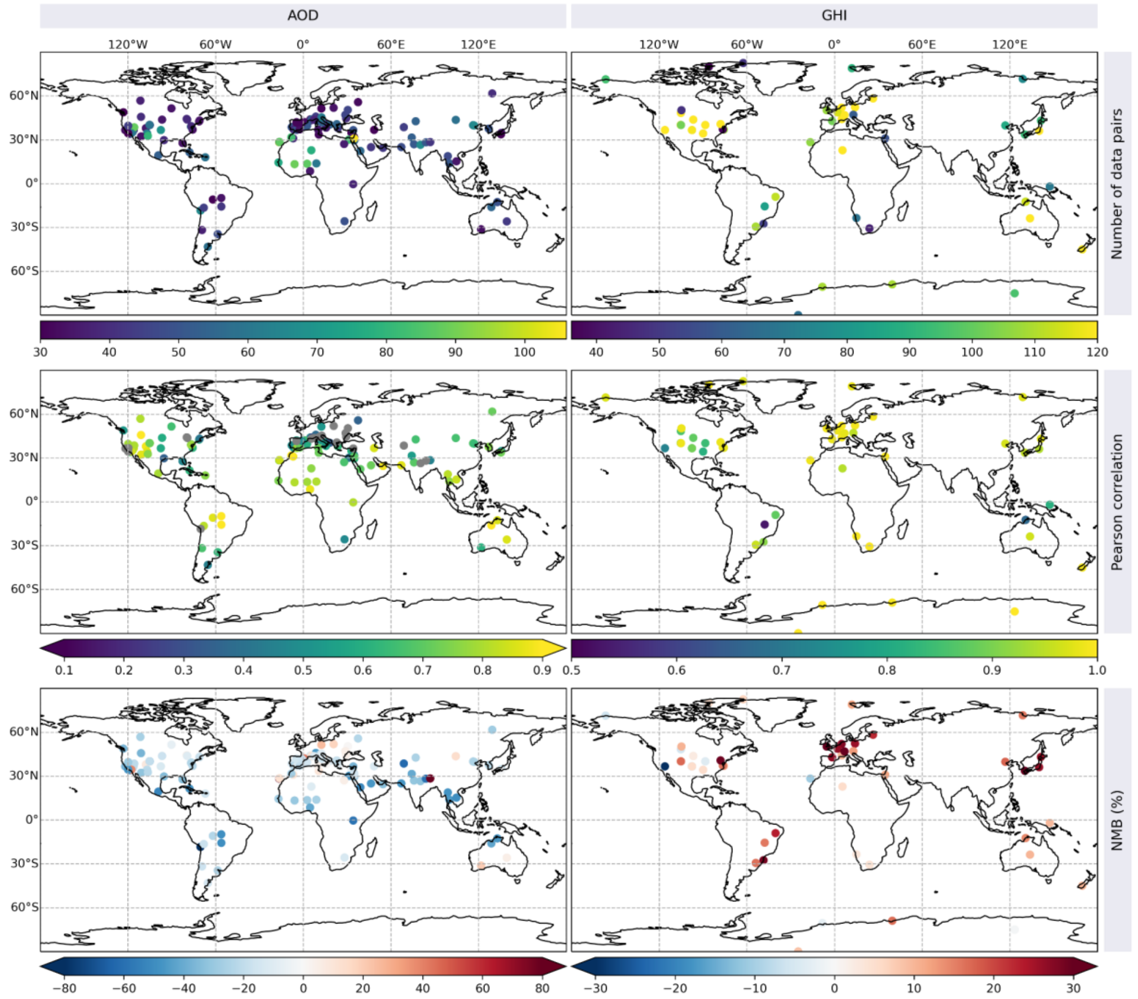


Name	Abbreviation	Descriptions
Flat solar panels	Flat	Solar panels are fixed mounted and horizontal
Latitude-tilt solar panels	Tilt	Solar panels are fixed mounted, tilted at the latitude tilt, and oriented to the equator
Single axis tracking solar panels	OAT	Solar panels rotate around one axis from east to west to track the sun throughout the day

Model evaluations

The integrated model has well captured the variations in GHI and column aerosol optical depth (AOD), which help evaluate real PV efficiency and PM dimming impacts, respectively.

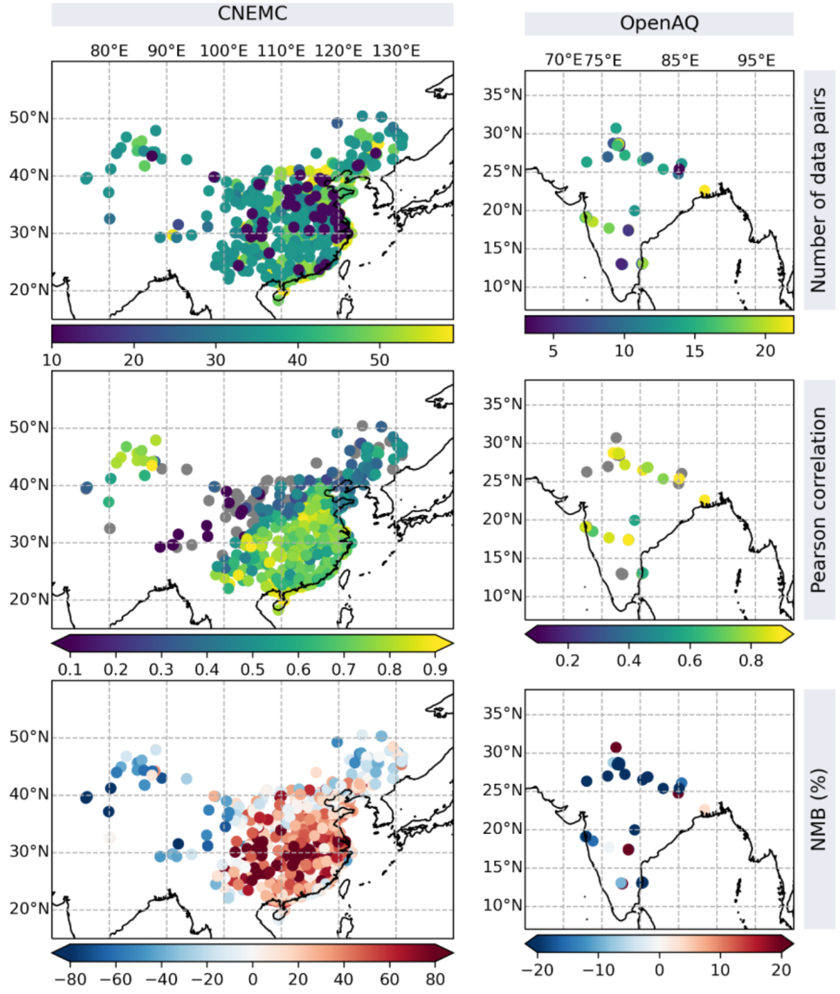
- Approximately 92% of the sites report Pearson correlation coefficients no less than 0.8 ($p<0.05$) for GHI.
- Approximately 70% of the sites report Pearson correlation coefficients no less than 0.8 ($p<0.05$) for AOD.



Model evaluations

The integrated model has well captured the variations in surface $PM_{2.5}$ (PM with aerodynamic diameter less than 2.5 µm) concentrations, which helps evaluate PM soiling impacts.

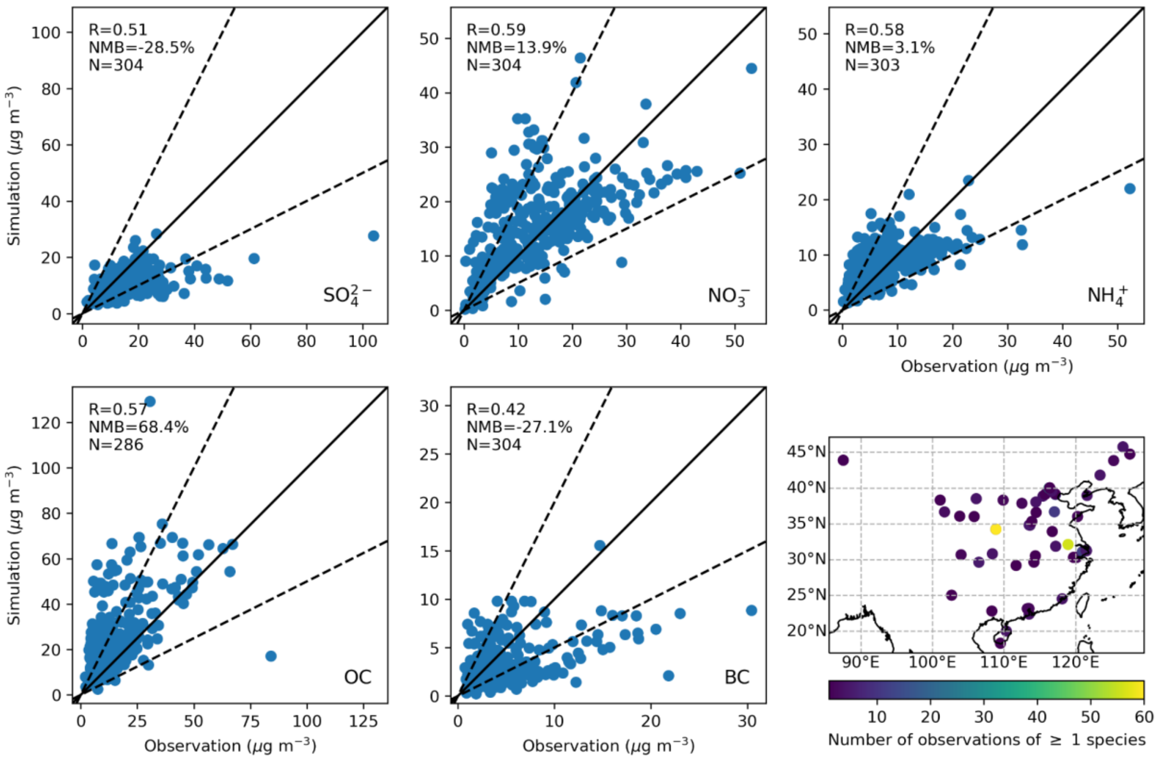
- Approximately 70% of the sites report Pearson correlation coefficients no less than 0.5 ($p<0.05$) for $PM_{2.5}$ in mainland China.
- The corresponding value is 66% in India.



Model evaluations

The integrated model has well captured the variations in surface $PM_{2.5}$ major chemical composition concentrations, which helps evaluate PM soiling impacts.

- Pearson correlation coefficients between simulated and observed $PM_{2.5}$ chemical composition concentrations range from 0.42-0.59 for different species.

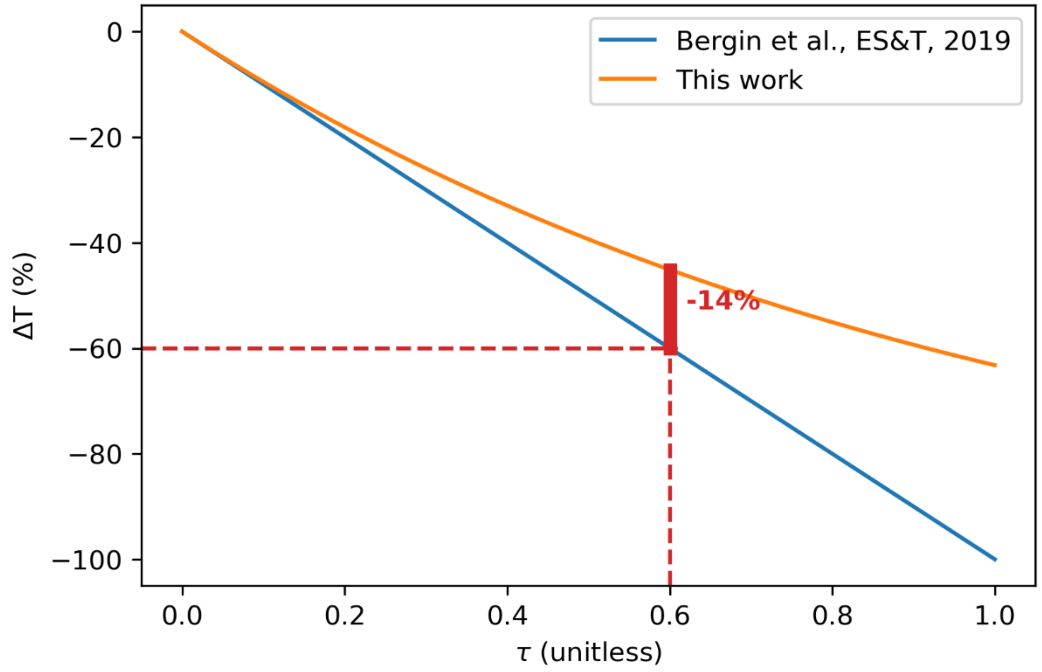


Observed data c/o Zhang et al., PNAS, 2019

N.B. Uncertainties in dry deposition velocities (won't be altered by revising emissions) have been evaluated in previous studies (Zhang et al., Atmos. Environ., 2001) and used to determine measured dry deposition fluxes (Xu et al., Sci. Data, 2019).

Model comparison to previous studies

Bergin et al., ES&T, 2017 describe $\Delta T = -\tau$, while we describe $\Delta T = e^{-\tau} - 1$. These two forms of ΔT are within 15% where the transmittance changes are less than ~60%. We argue that our treatment of τ outperforms Bergin et al., ES&T, 2017 from the theoretical perspective.



N.B. Bergin et al., ES&T, 2019 have found their estimated ΔT fall within the range of measured values. In this sense, our estimated ΔT should be at the low end of the measured values or slightly even lower. This, however, may partly counteract the slightly overestimated PM levels over Eastern China.

Experimental design

Calculate three CFs to determine:

- PM soiling impact: CF2-CF1
- PM dimming impact: CF3-CF2
- PM total impact: CF3-CF1

CF	PM dimming	PM soiling
CF1	Yes	Yes
CF2	Yes	No
CF3	No	No

Compare PM impacts across CTRL and 0.5SECTOR scenarios to determine:

- Cleaning benefit: $(CF2\text{-}CF1)_{CTRL}–(CF2\text{-}CF1)_{0.5SECTOR}$
- Brightening benefit: $(CF3\text{-}CF2)_{CTRL}–(CF3\text{-}CF2)_{0.5SECTOR}$
- Total benefit: $(CF3\text{-}CF1)_{CTRL}–(CF3\text{-}CF1)_{0.5SECTOR}$

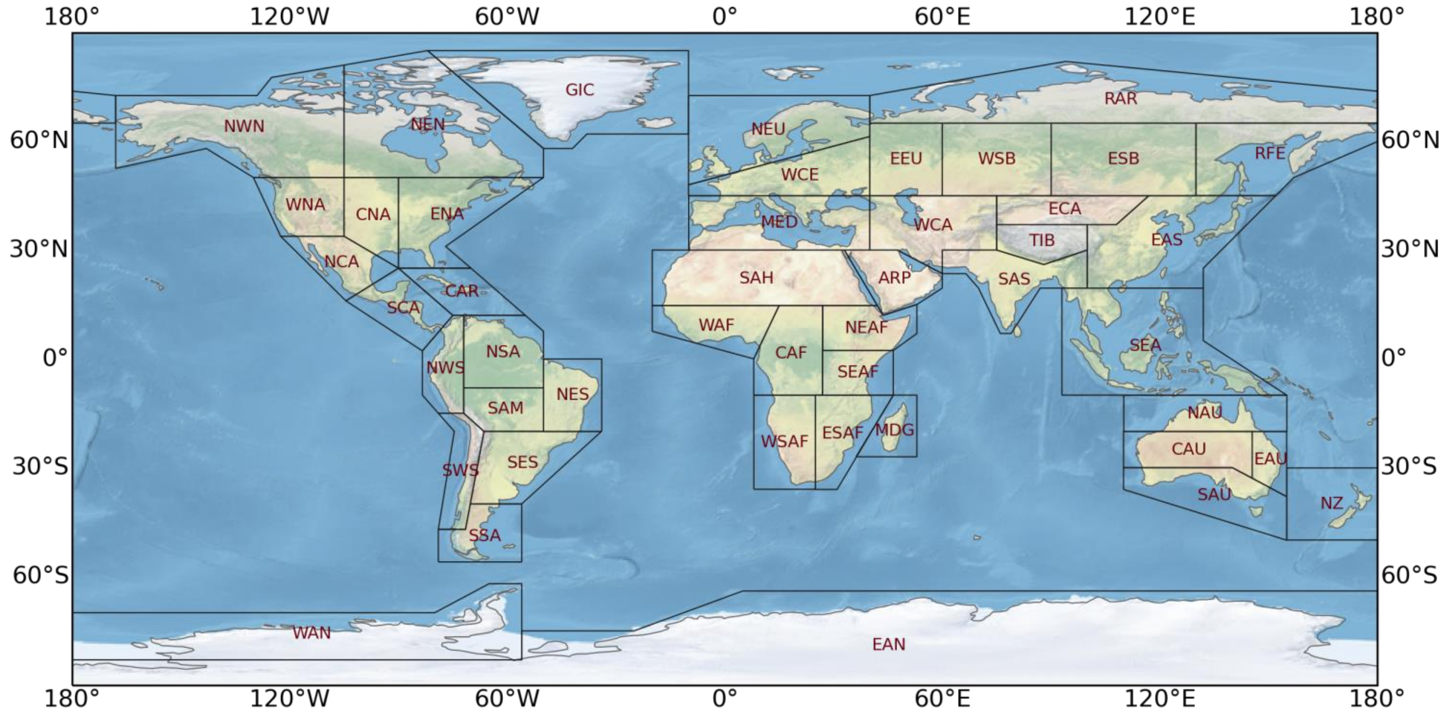
Role of precipitation: $CF1_{CTRL}\text{-}CF1_{CTRL+NOPrecip}$

Role of cleaning panels: $CF1_{CTRL+SWEEPING}\text{-}CF1_{CTRL}$

	AGR	ENE	IND	ROAD	NRTR	RCOR	RCOC	RCOO	SLV	WST	SHP
CTRL	Leave them as they are										
0.5SECTOR	Halve them one by one										
CTRL+NOPrecip	Same as CTRL but without precipitation										
CTRL+SWEEPING	Same as CTRL with solar panels cleaned periodically										

AR6 land reference region

46 land regions representing consistent regional climate features suitable for regional synthesis of climate-related observed/modelled data.



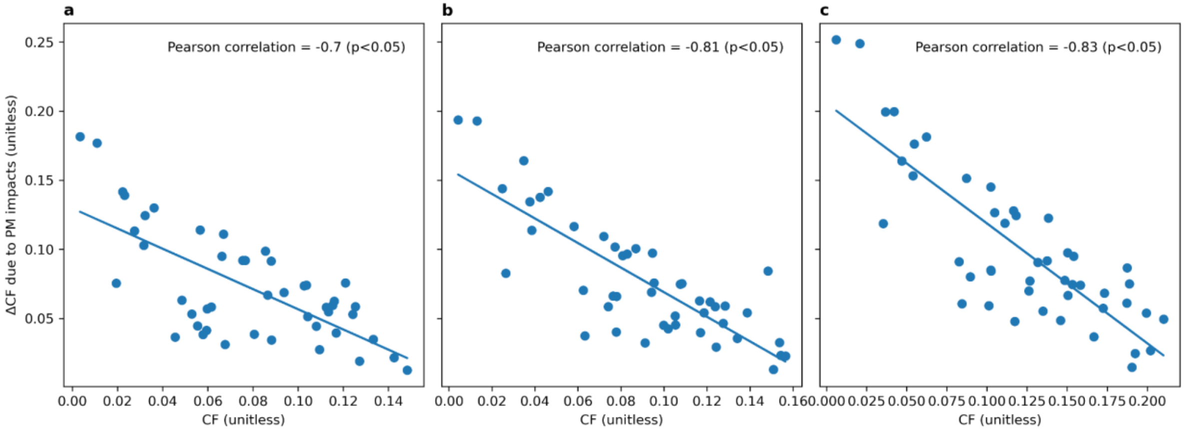
0	GIC	Greenland/Iceland	23	NEAF	N.Eastern-Africa
1	NWN	N.W.North-America	24	SEAF	S.Eastern-Africa
2	NEN	N.E.North-America	25	WSAF	W.Southern-Africa
3	WNA	W.North-America	26	ESAF	E.Southern-Africa
4	CNA	C.North-America	27	MDG	Madagascar
5	ENA	E.North-America	28	RAR	Russian-Arctic
6	NCA	N.Central-America	29	WSB	W.Siberia
7	SCA	S.Central-America	30	ESB	E.Siberia
8	CAR	Caribbean	31	RFE	Russian-Far-East
9	NWS	N.W.South-America	32	WCA	W.C.Asia
10	NSA	N.South-America	33	ECA	E.C.Asia
11	NES	N.E.South-America	34	TIB	Tibetan-Plateau
12	SAM	South-American-Monsoon	35	EAS	E.Asia
13	SWS	S.W.South-America	36	ARP	Arabian-Peninsula
14	SES	S.E.South-America	37	SAS	S.Asia
15	SSA	S.South-America	38	SEA	S.E.Asia
16	NEU	N.Europe	39	NAU	N.Australia
17	WCE	West&Central-Europe	40	CAU	C.Australia
18	EEU	E.Europe	41	EAU	E.Australia
19	MED	Mediterranean	42	SAU	S.Australia
20	SAH	Sahara	43	NZ	New-Zealand
21	WAF	Western-Africa	44	EAN	E.Antarctica
22	CAF	Central-Africa	45	WAN	W.Antarctica

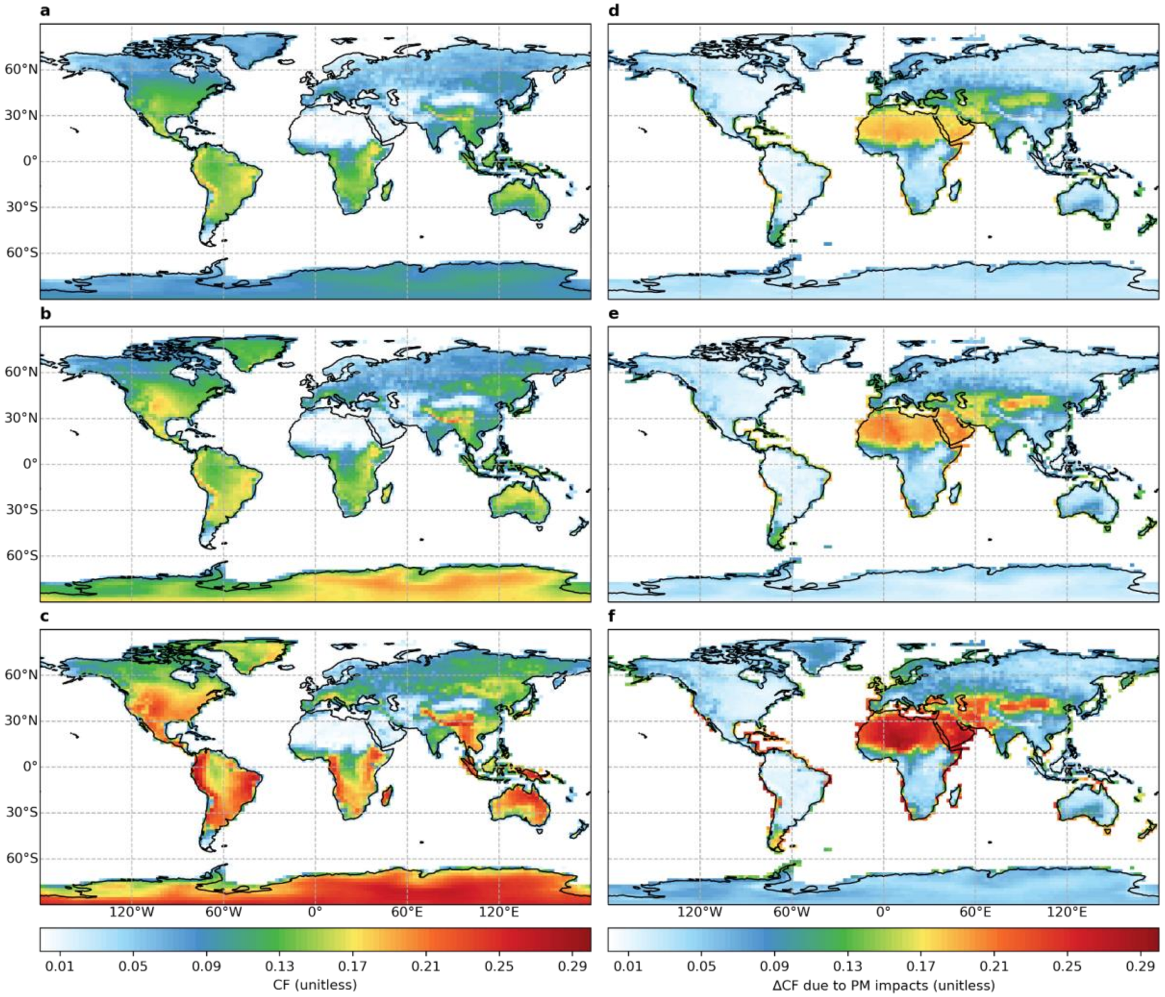
PV efficiency and PM impacts

High PV efficiency found over:

- North and South America, Eastern and Southern Africa, the Tibetan-Plateau, Southeast Asia, Australia, and (tilt and OAT panels) high-latitude regions including Greenland and Antarctica.

Regions with low PV efficiency are associated with high PM impacts.

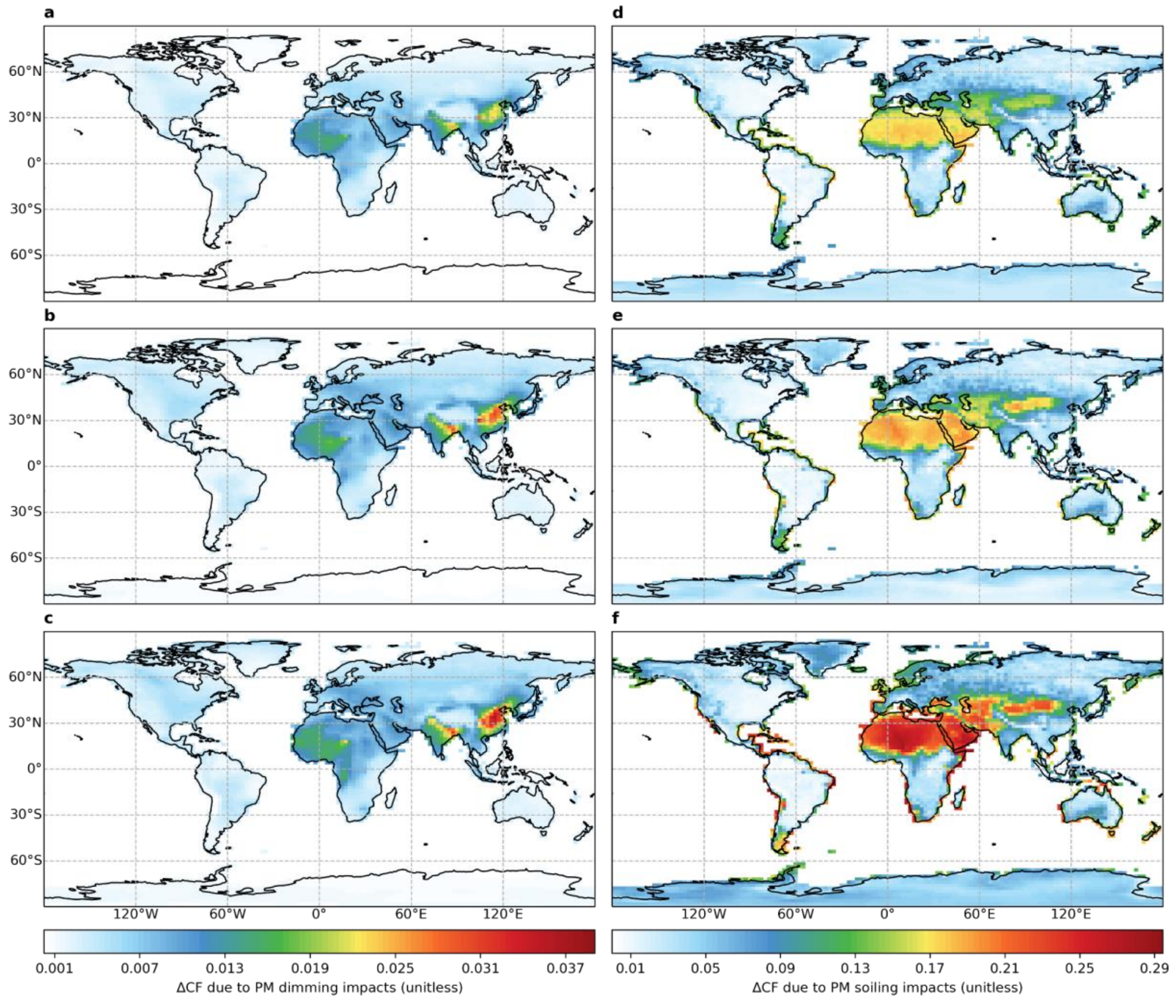




PV dimming versus soiling

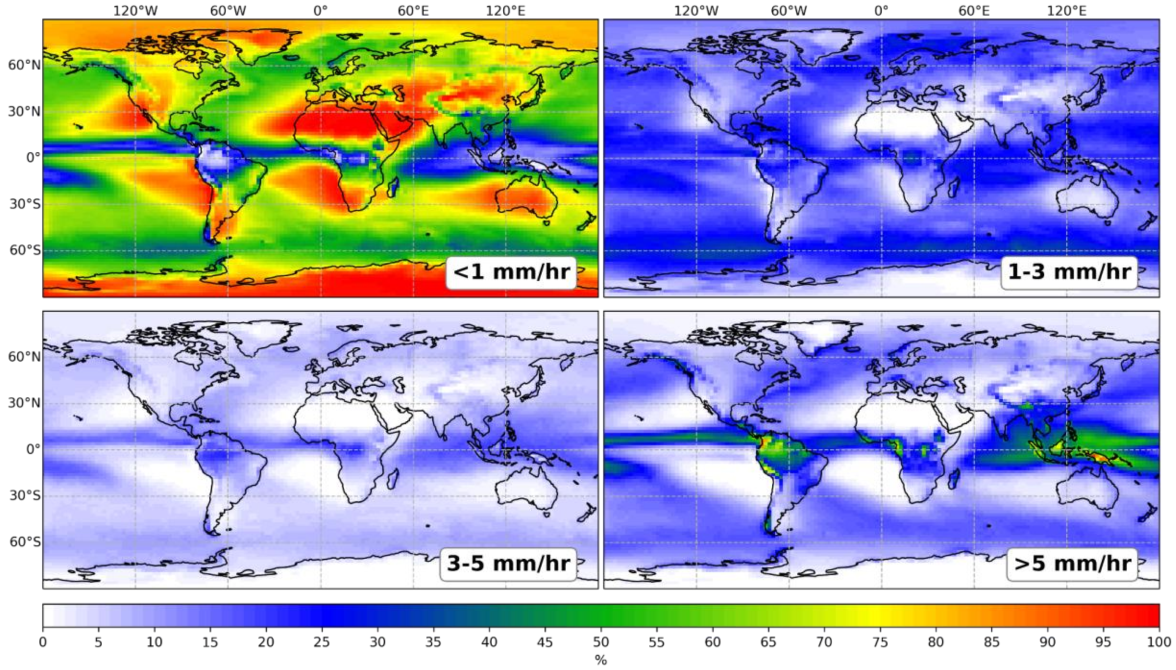
The magnitude and distribution of PM impacts is almost exclusively determined by soiling.

- East and South Asia feature high PM dimming impacts of up to 0.04.
- Desert regions (the Sahara, Arabian-Peninsula, Central Asia, and Southern South America) and coastal regions (countries around the Caribbean and Mediterranean, and over New-Zealand) feature high PM soiling impacts.

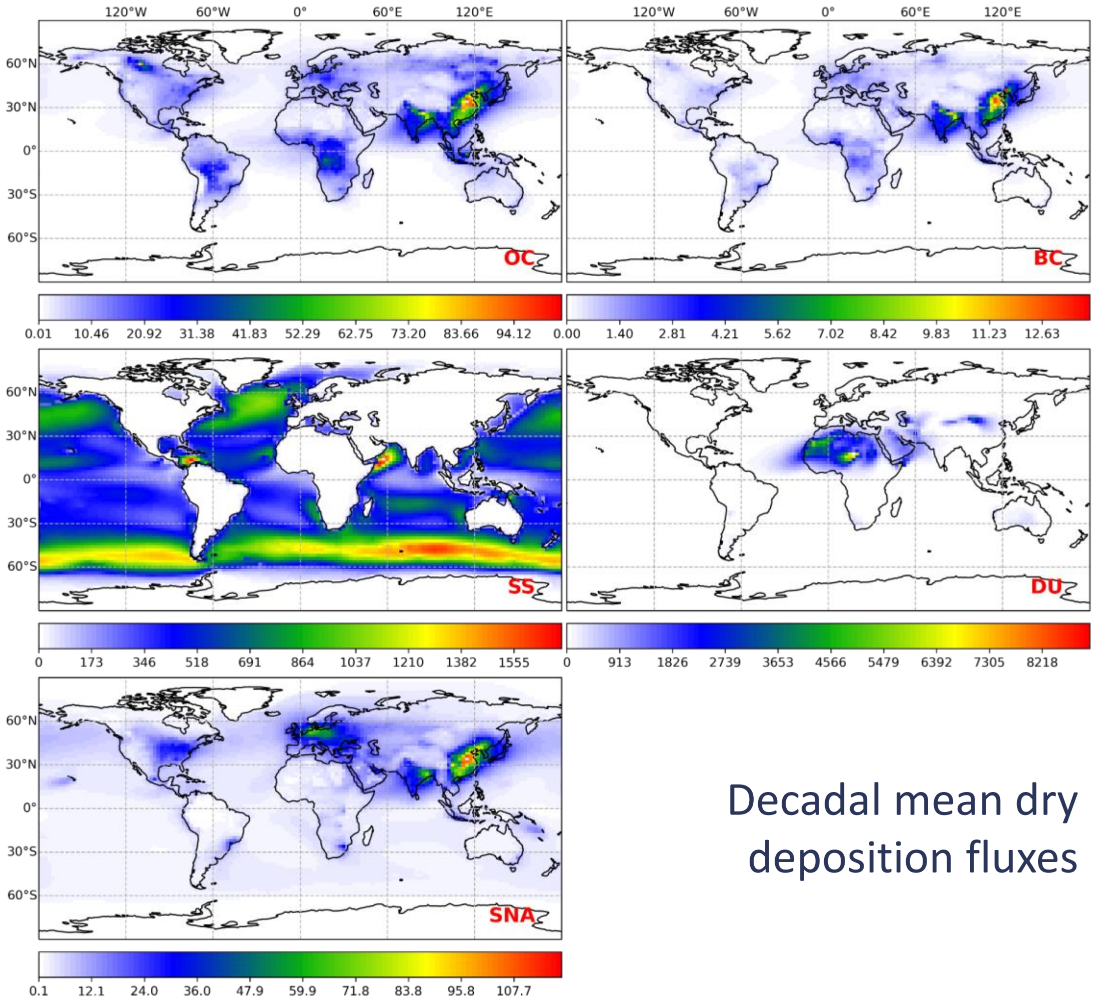


PV dimming versus soiling

The strongest PM soiling impacts over deserts are a result of rapid accumulation of dust deposited on solar panels and of limited removal by precipitation.



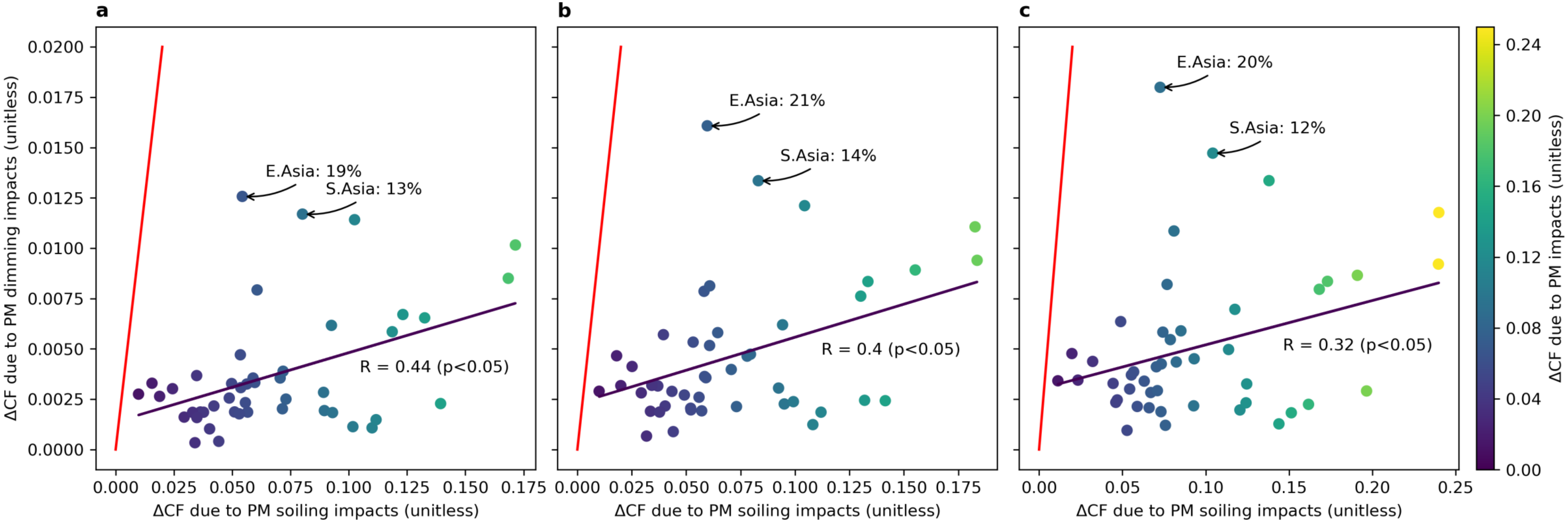
Frequency of precipitation rates



Decadal mean dry deposition fluxes

PV dimming versus soiling

PM dimming and soiling impacts are generally coincident so that decreasing emissions will help to reduce them simultaneously.



Benefits of reducing emissions

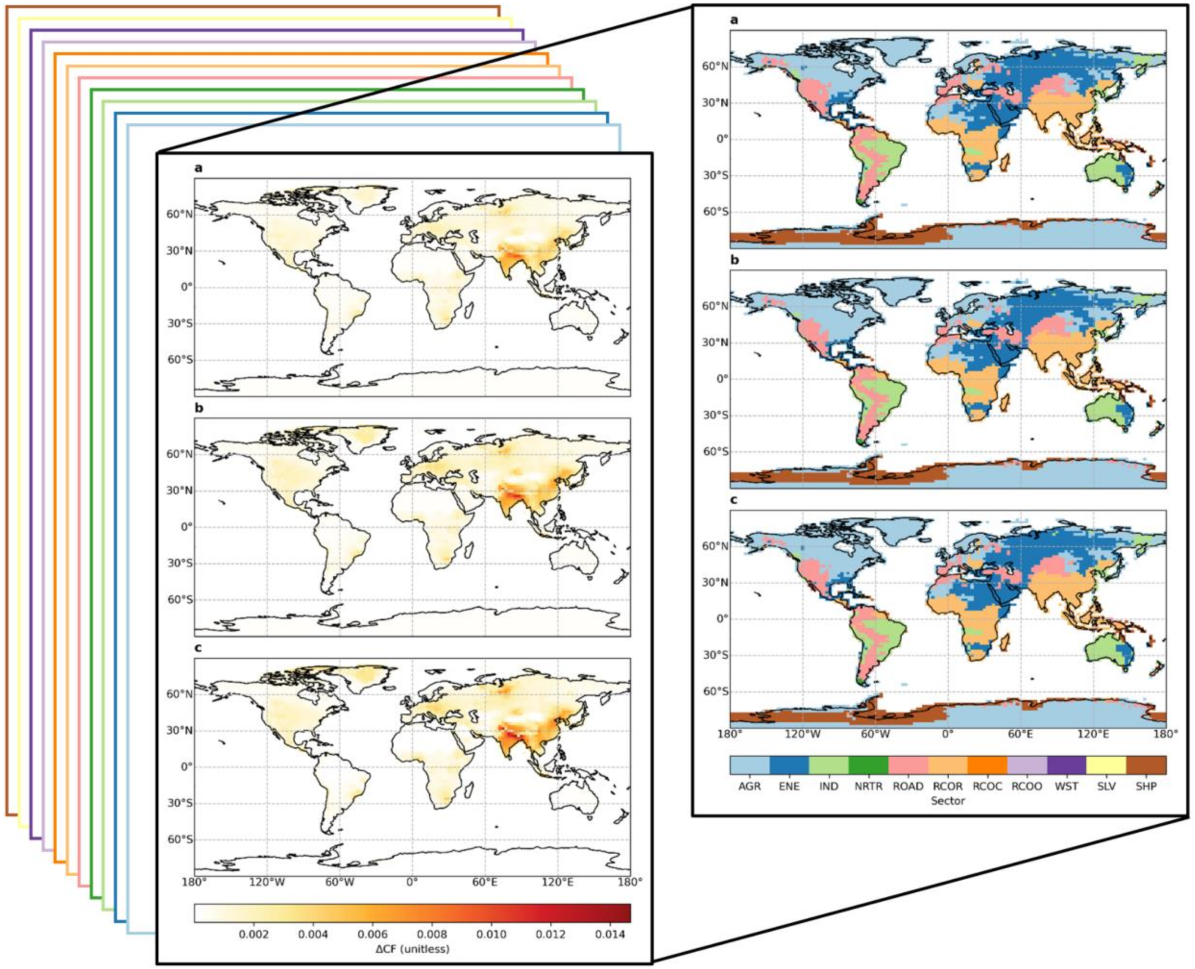
Model Integration → ΔCF by Halving Sectoral Emissions → Outstanding Sectors ↔ PV Panels

GEOS-Chem

aer Atmospheric and Environmental Research

RRTMG

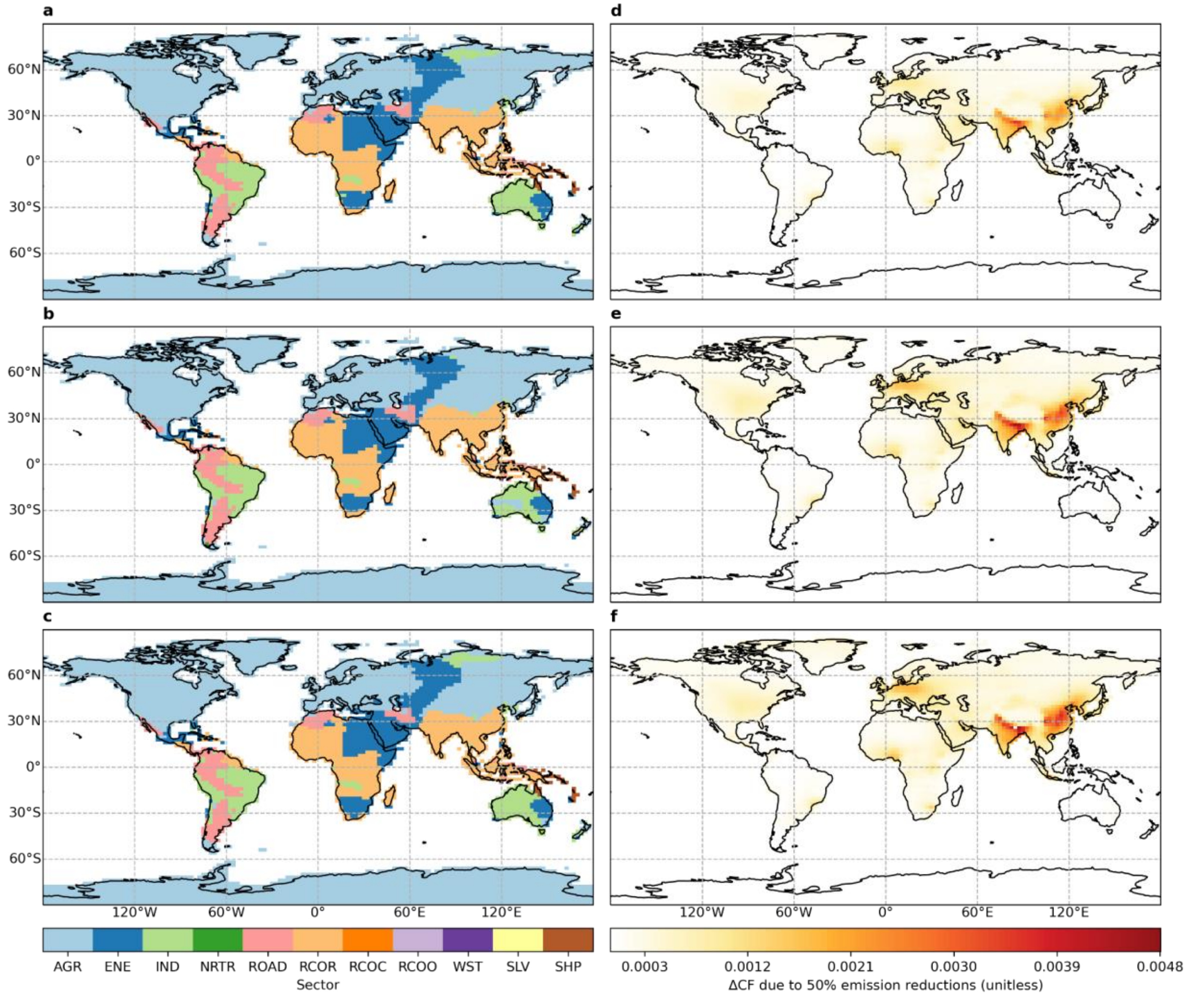
pvlib



Brightening benefits of reducing emissions

Halving residential and agricultural emissions result in widespread decreases in PM dimming.

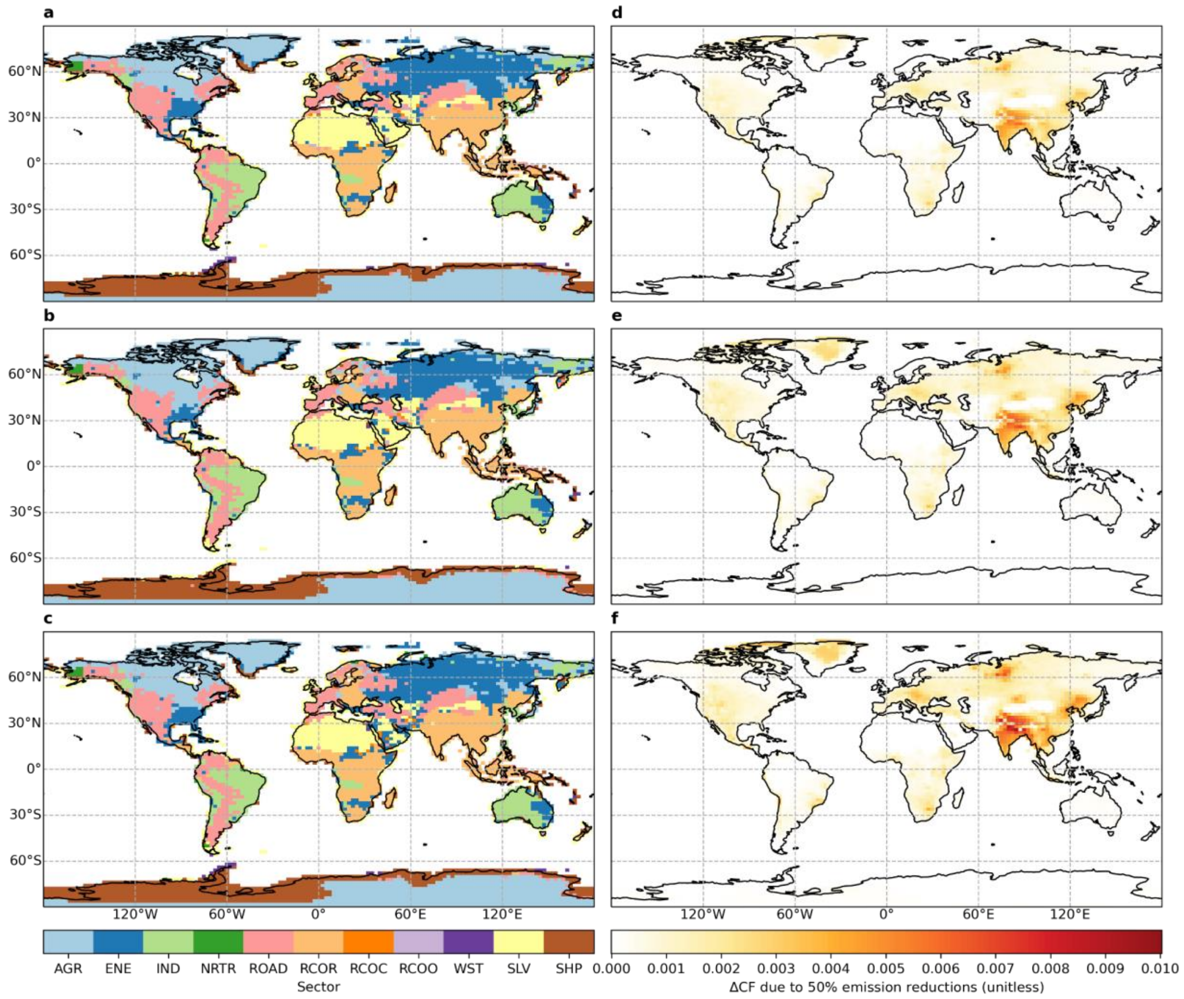
- The brightening benefits for the three panels of halving residential emissions are 8%, 9%, and 9% and identically 12% over East and South Asia, respectively.
- The corresponding values are equally 8% and equally 13% of halving agricultural emissions over East Asia and West & Central Europe, respectively.



Cleaning benefits of reducing emissions

Halving residential emissions result in widespread decreases in PM soiling.

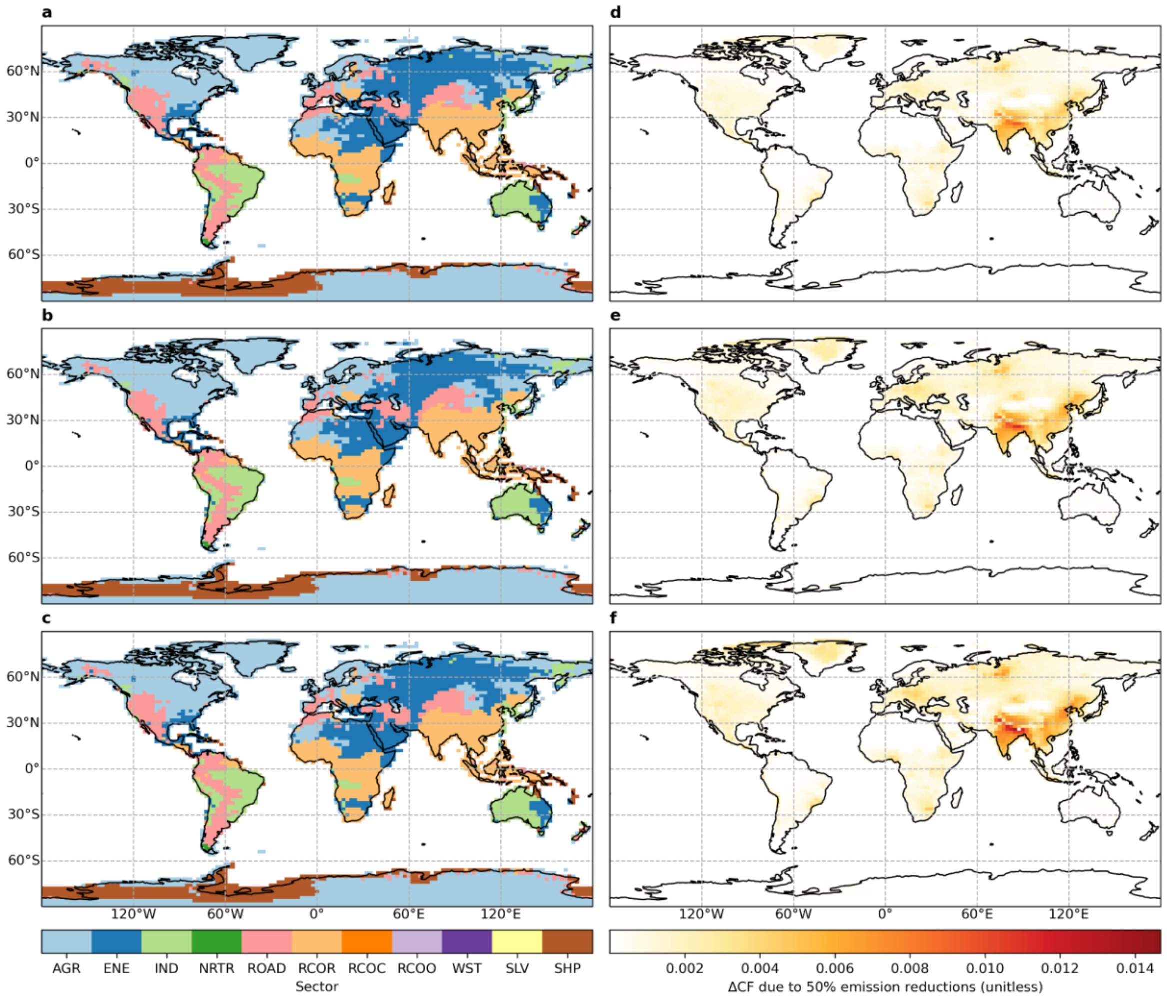
- The cleaning benefits for the three panels of halving residential emissions are uniformly 3% over East and South Asia.
- The corresponding value is slightly higher at 4-5% over the Tibetan-Plateau.



Total benefits of reducing emissions

The combined benefits from brightening and cleaning mainly follow the pattern of cleaning.

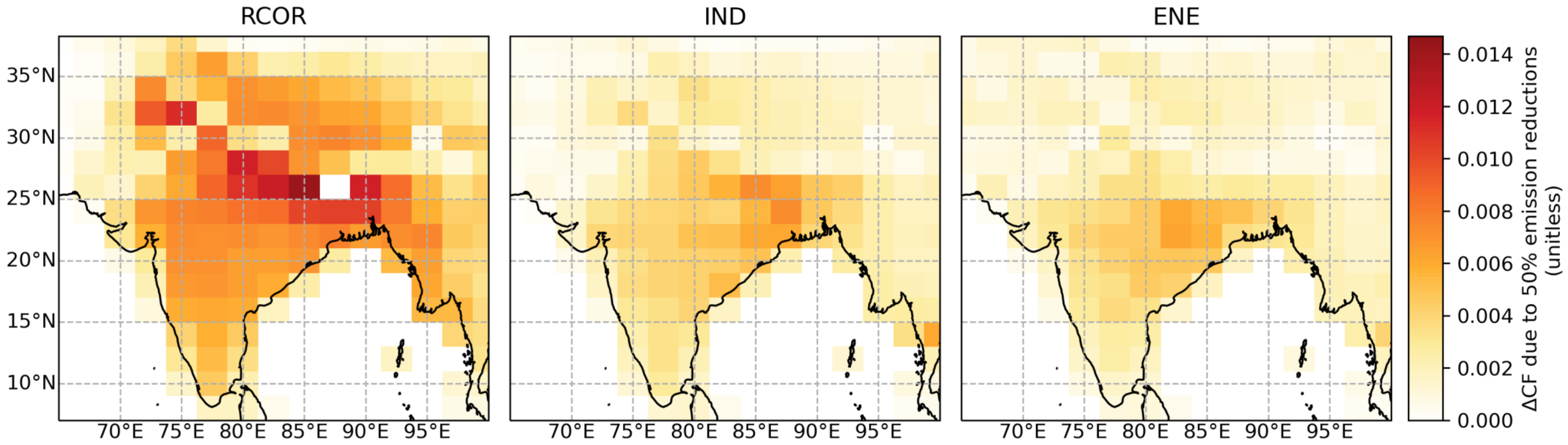
- Halving residential emissions uniformly results in total benefits of 4-5% for the three panels over East and South Asia, and the Tibetan-Plateau.
- Halving industrial emissions results in total benefits of 3% for the three panels over East Asia.



A clear priority of sectors to target in South Asia

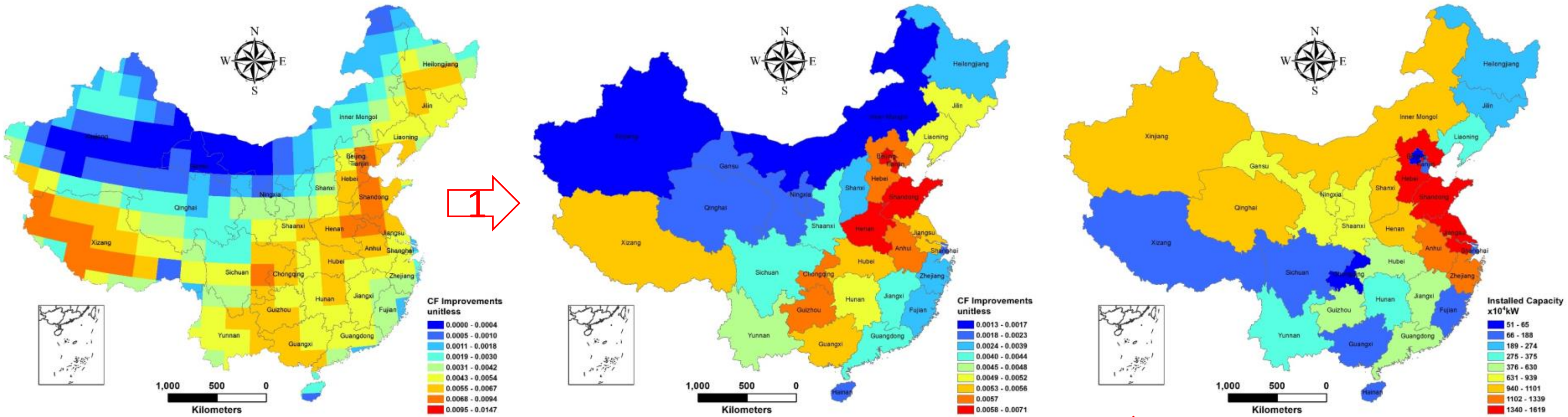
The industrial and energy sectors are the next two important places to target.

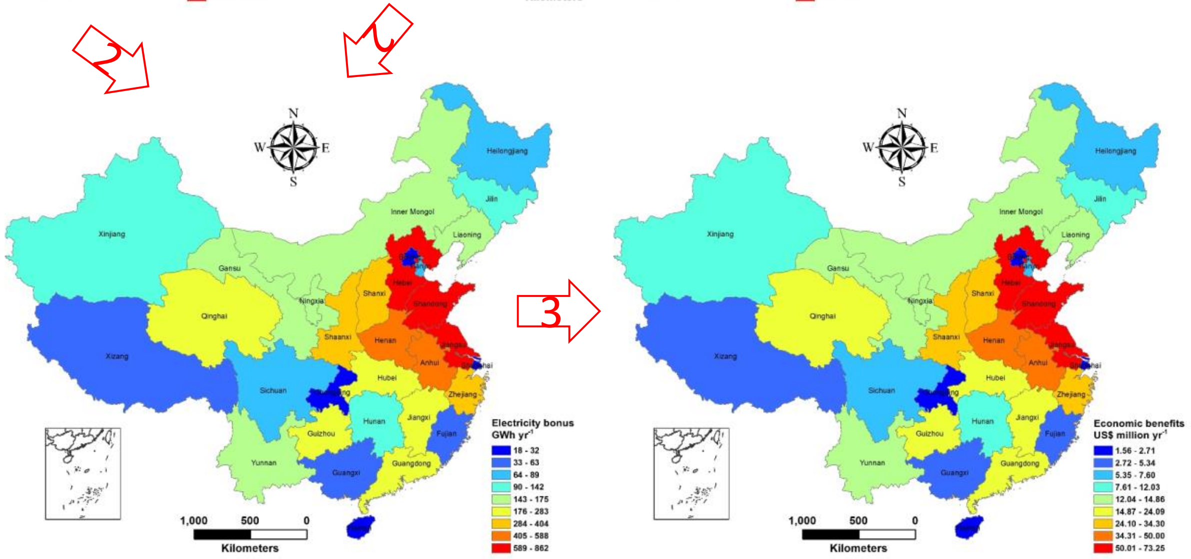
- Halving industrial and energy emissions uniformly provide total benefits of 2% and 1-3% for the three panels on the decadal and corresponding seasonal scales, respectively.
- Similar results for brightening and cleaning benefits.



Total benefits for the OAT panel as an illustration here

Impact on energy sector





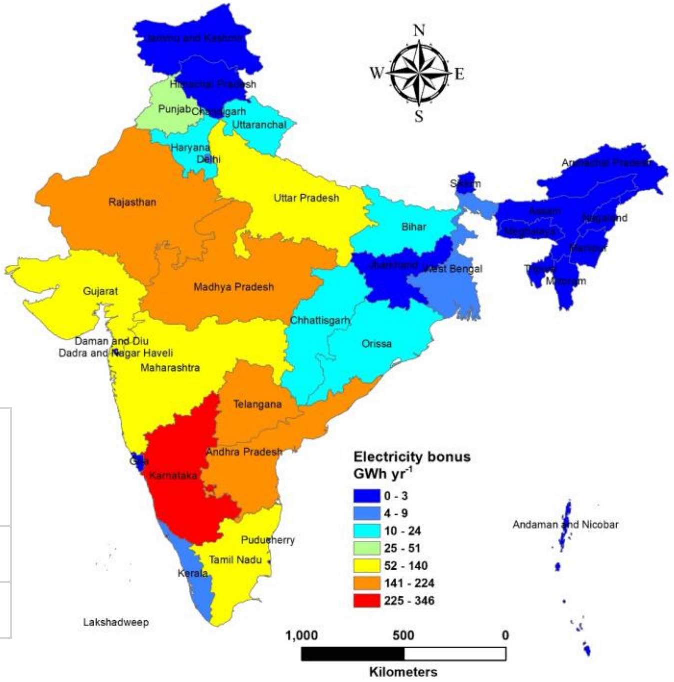
1. Gridded ΔCF aggregated to provincial ΔCF
2. Electricity bonus = ΔCF * installed capacity * 1 year
3. Economic bonus = electricity bonus * electricity price

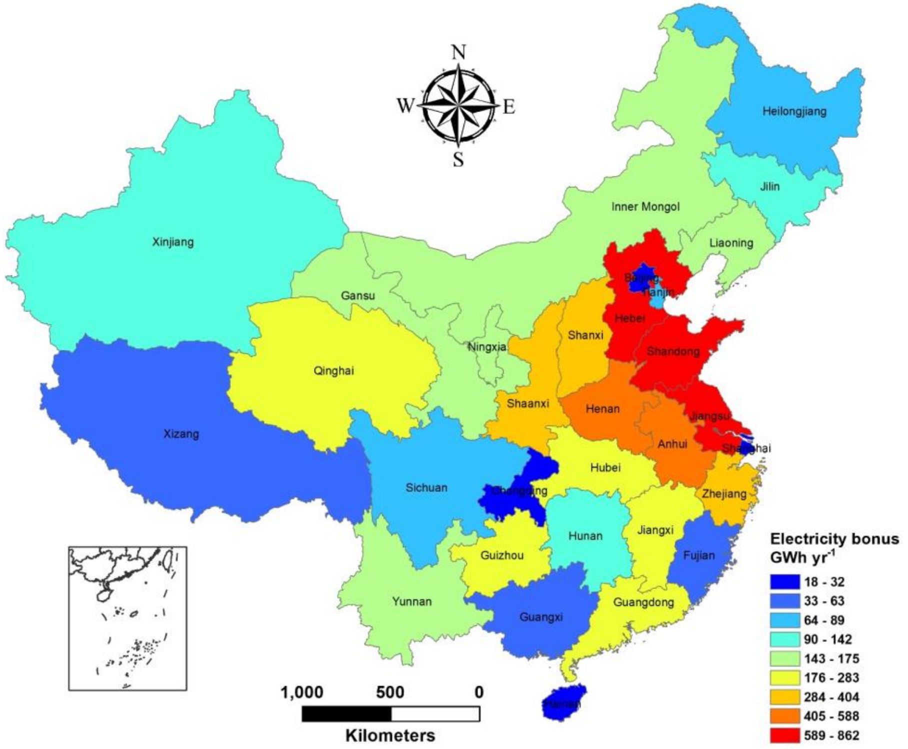
N.B. Tilt and OAT ΔCFs are assumed for distributed and utility-scale PV installations; ΔCFs across provincial boundaries are properly split with a geographical information system program.

Impact on energy sector

- Regions where there are larger established PV installations will generally benefit more from reducing residential emissions.
- Regions with moderate PV installations will also benefit from larger ΔCF due to reducing residential emissions, e.g. Henan province in China and Madhya Pradesh state in India.

	Electricity bonus ($GWh\ yr^{-1}$)	Economic benefits ($US\$million\ yr^{-1}$)
China	**7355**	**1721**
India	**625**	**136**





Consistent benefits throughout years

South Asia:

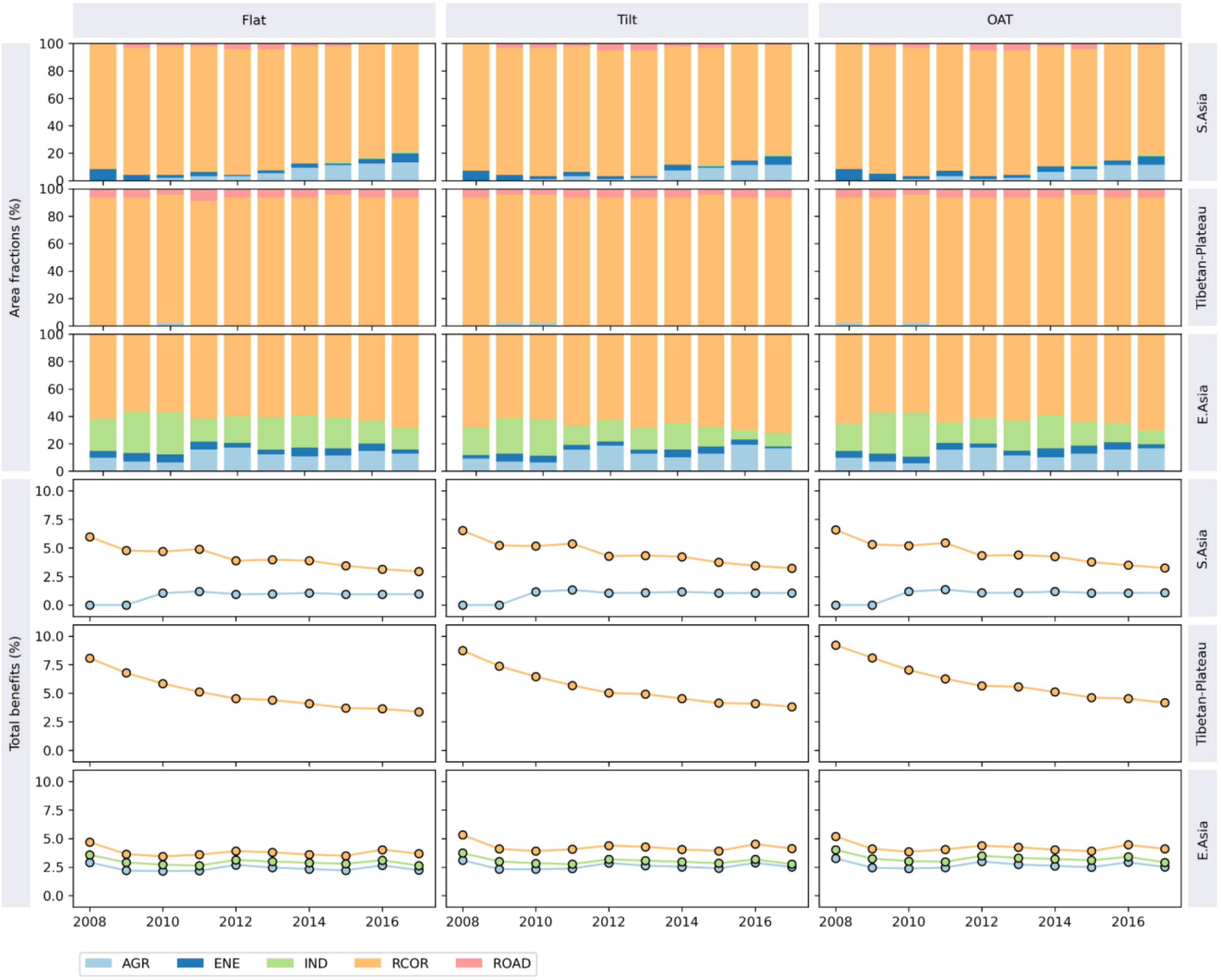
- While the agricultural sector slowly steals more area fractions from the residential sector, its percent benefits are tiny throughout the period.

Tibetan-Plateau:

- The residential sector shows invariant dominant area fractions over years.

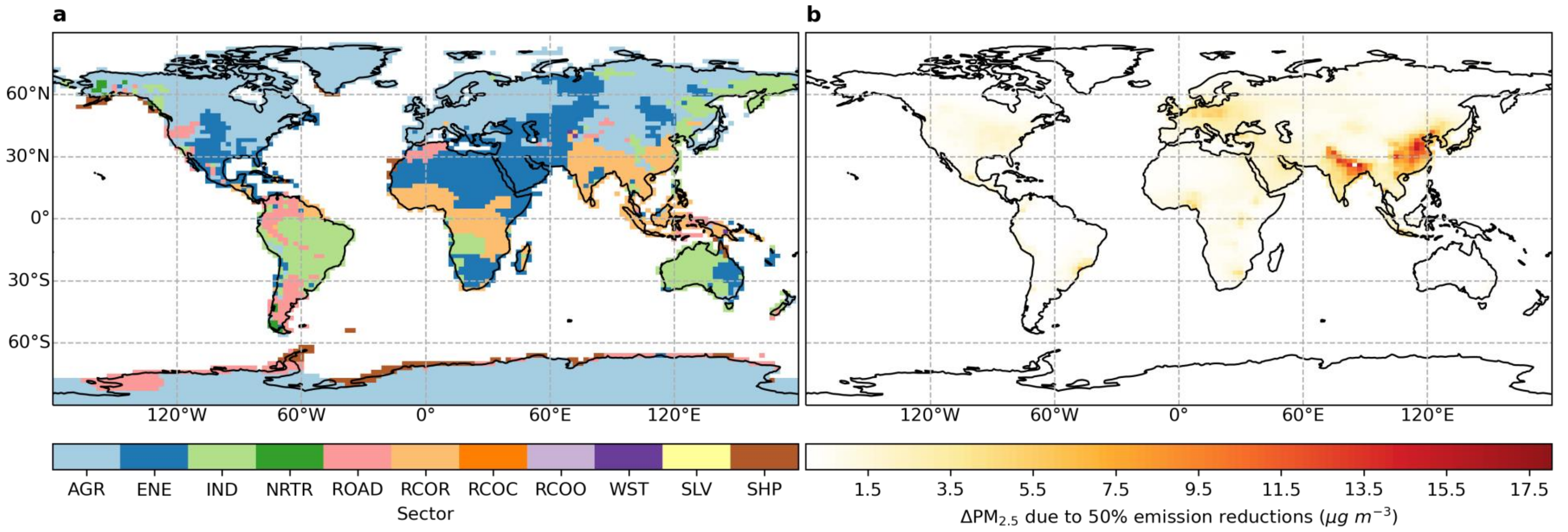
East Asia:

- Relatively constant relationships between the residential, agricultural, and industrial sectors.



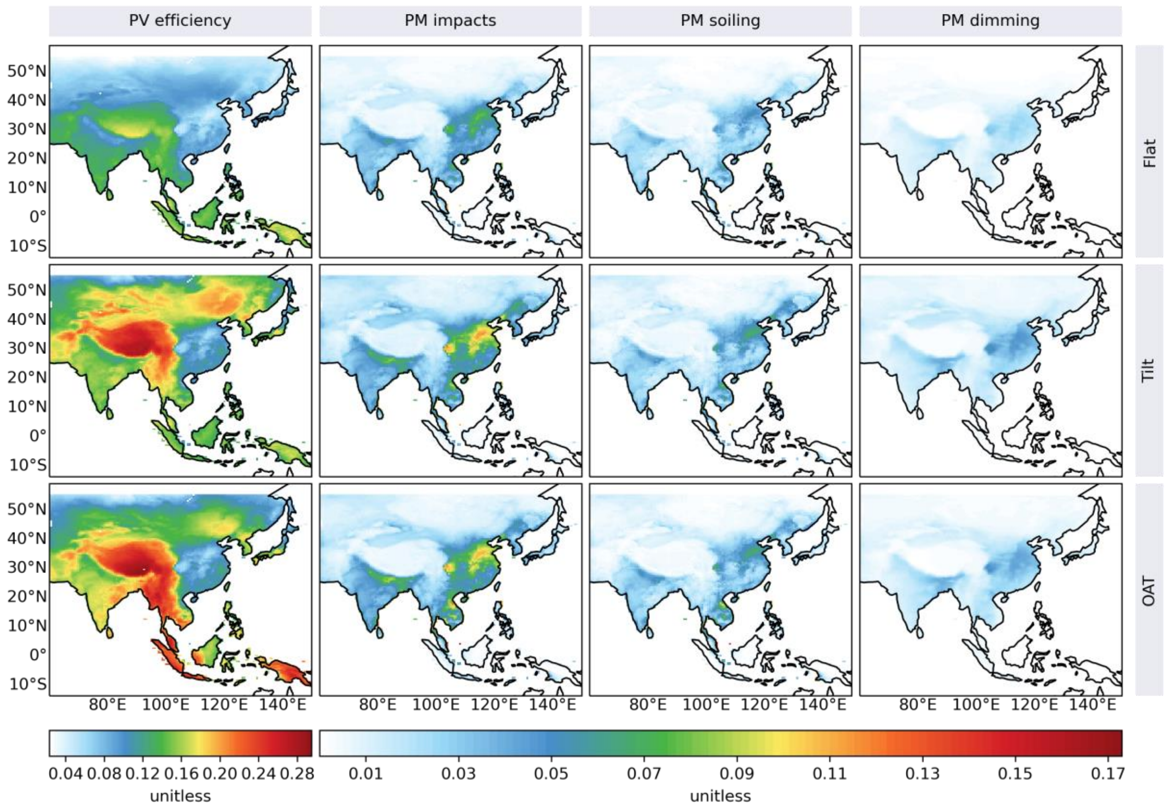
Co-benefits to surface air quality

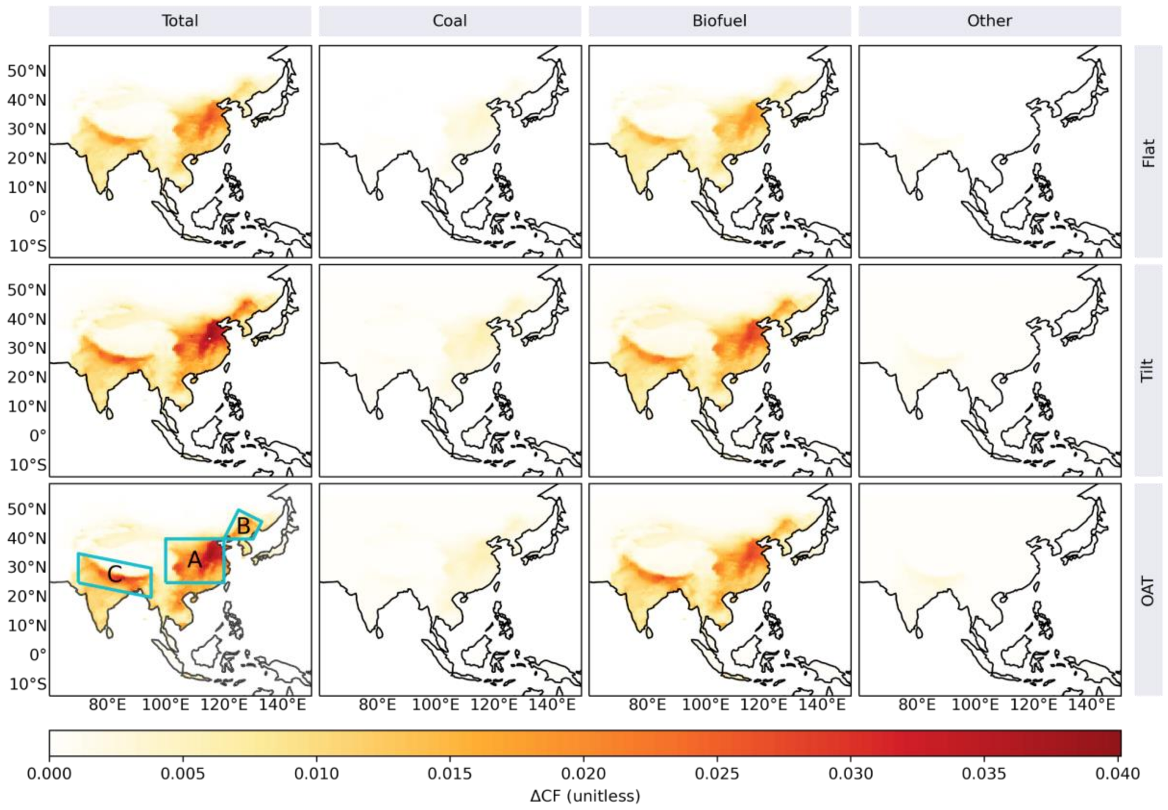
- Stringent reductions in residential emissions also lead to noticeable improvements in surface air quality with respect to $PM_{2.5}$.
- The uncontrolled and inefficient combustion of solid fuels in residential devices is likely the prime culprit.



Zoom into Asia focusing on Jan-Feb 2008

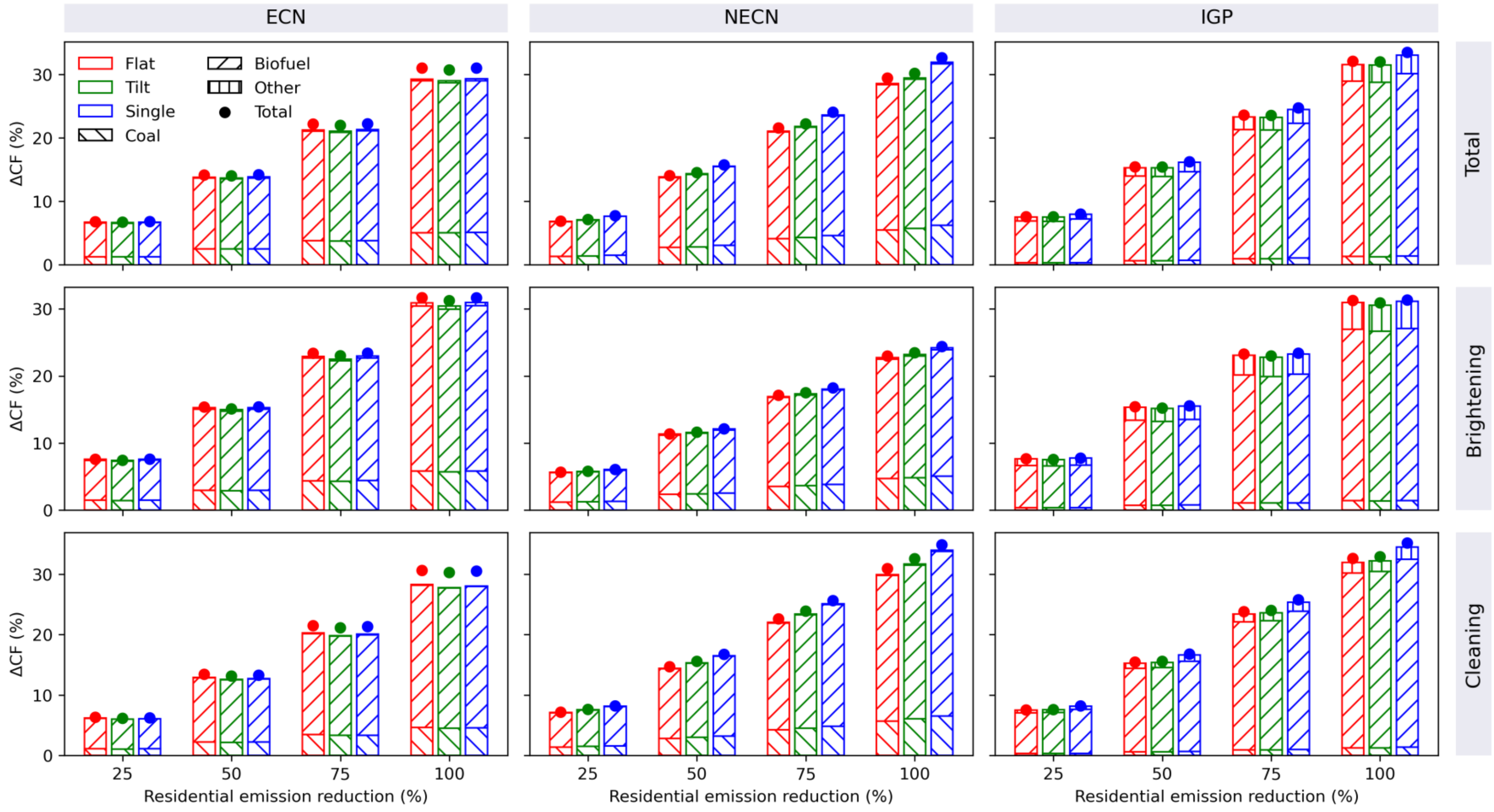
Eastern (A) and North-eastern (B) China, and the Indo-Gangetic Plain (C) are the three key regions where removing residential particularly solid biofuel emissions greatly alleviates PM-induce PV efficiency losses.





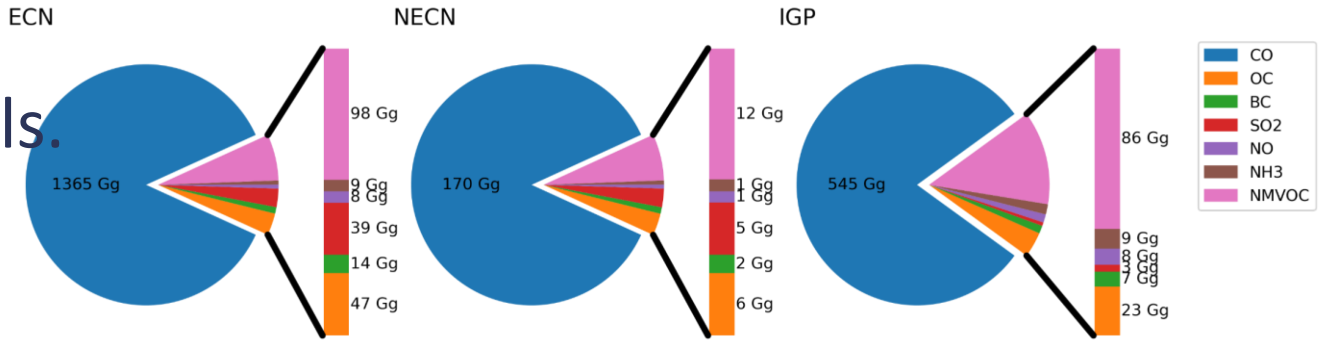
Zoom into Asia focusing on Jan-Feb 2008

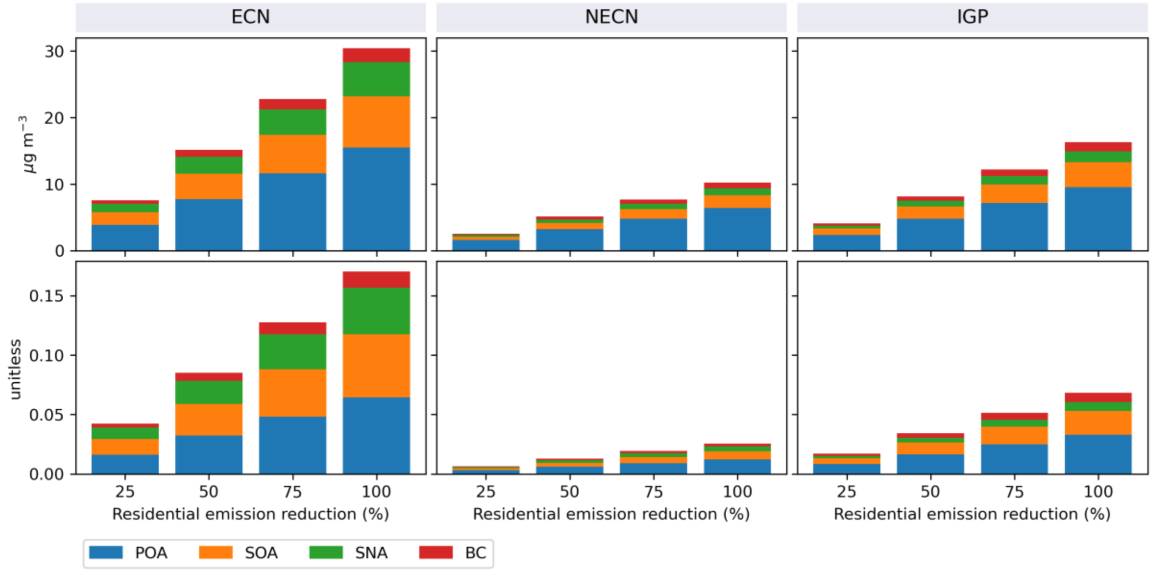
Such alleviations change approximately linearly with the extent to which residential fuel emissions are reduced.



Zoom into Asia focusing on Jan-Feb 2008

- Large volume of carbon emissions generally form into carbon aerosols.
- Reducing these carbon emissions leads approximately linearly to reductions in PM species levels and these linear reductions finally extend to linear improvements in PV efficiency.

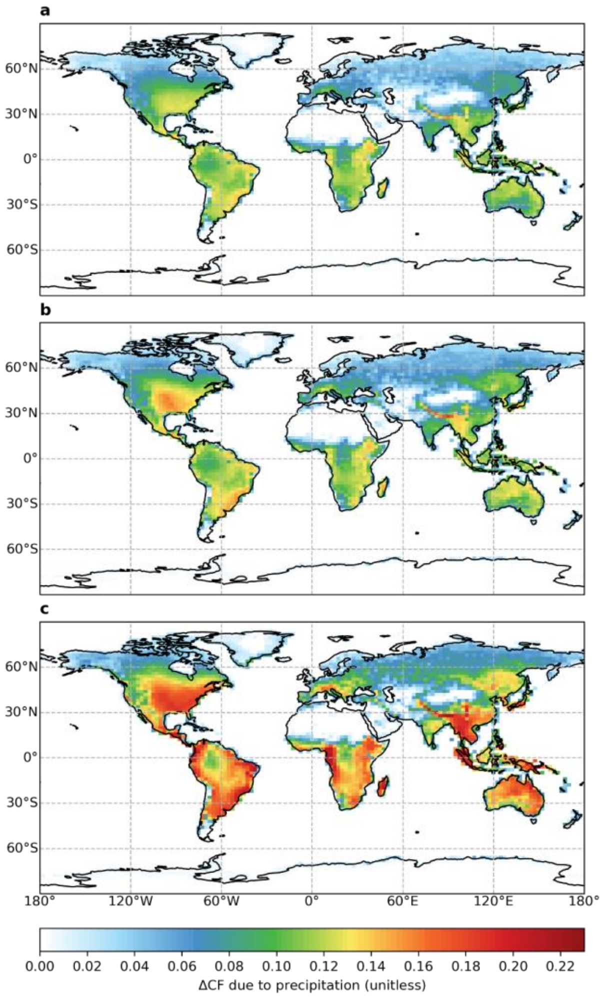


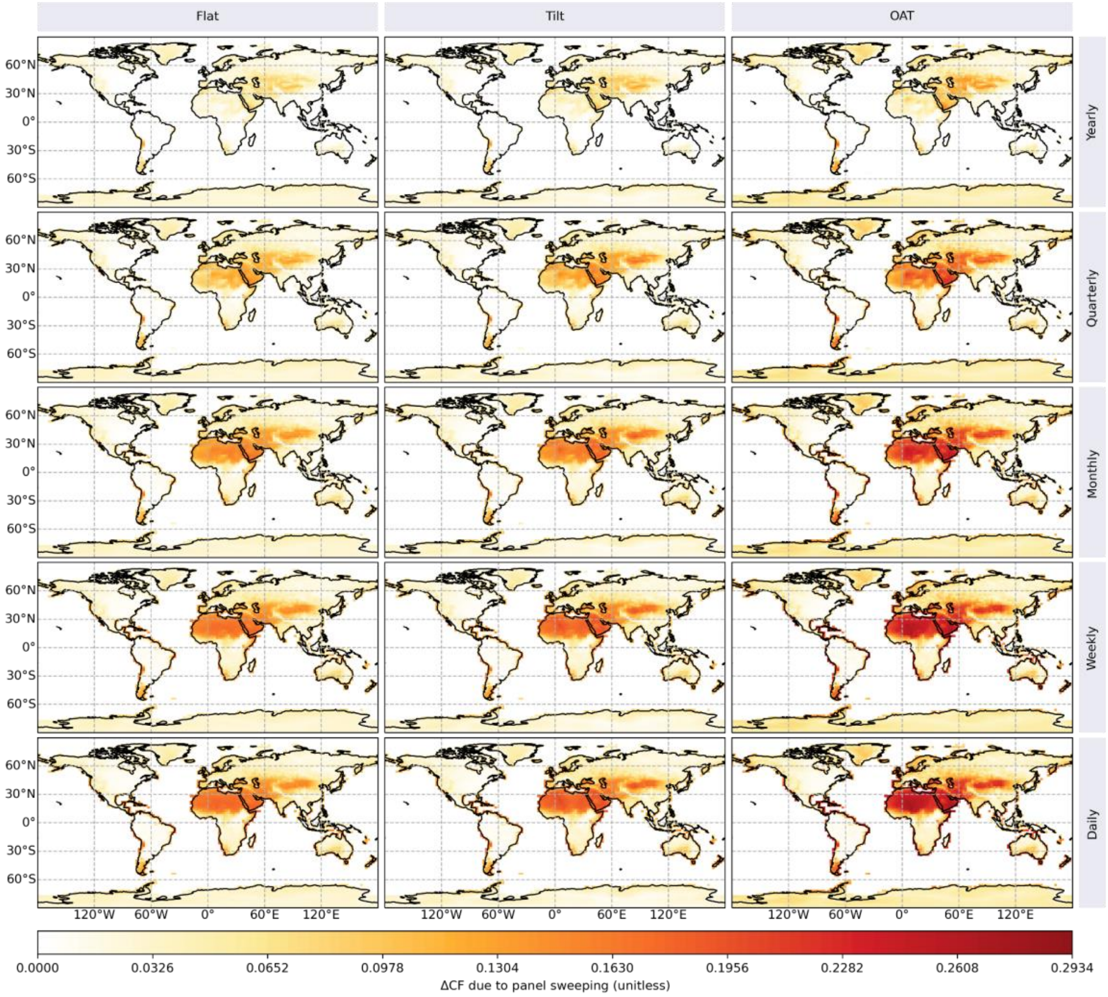


N.B. CO is not a direct precursor of OA, but it is feasible that GEOS-Chem calculates anthropogenic contribution to SOA using CO emissions as a proxy, i.e. 6.9% scaled co-emission of SOA precursor from fossil fuel CO.

Role of precipitation and panel cleaning

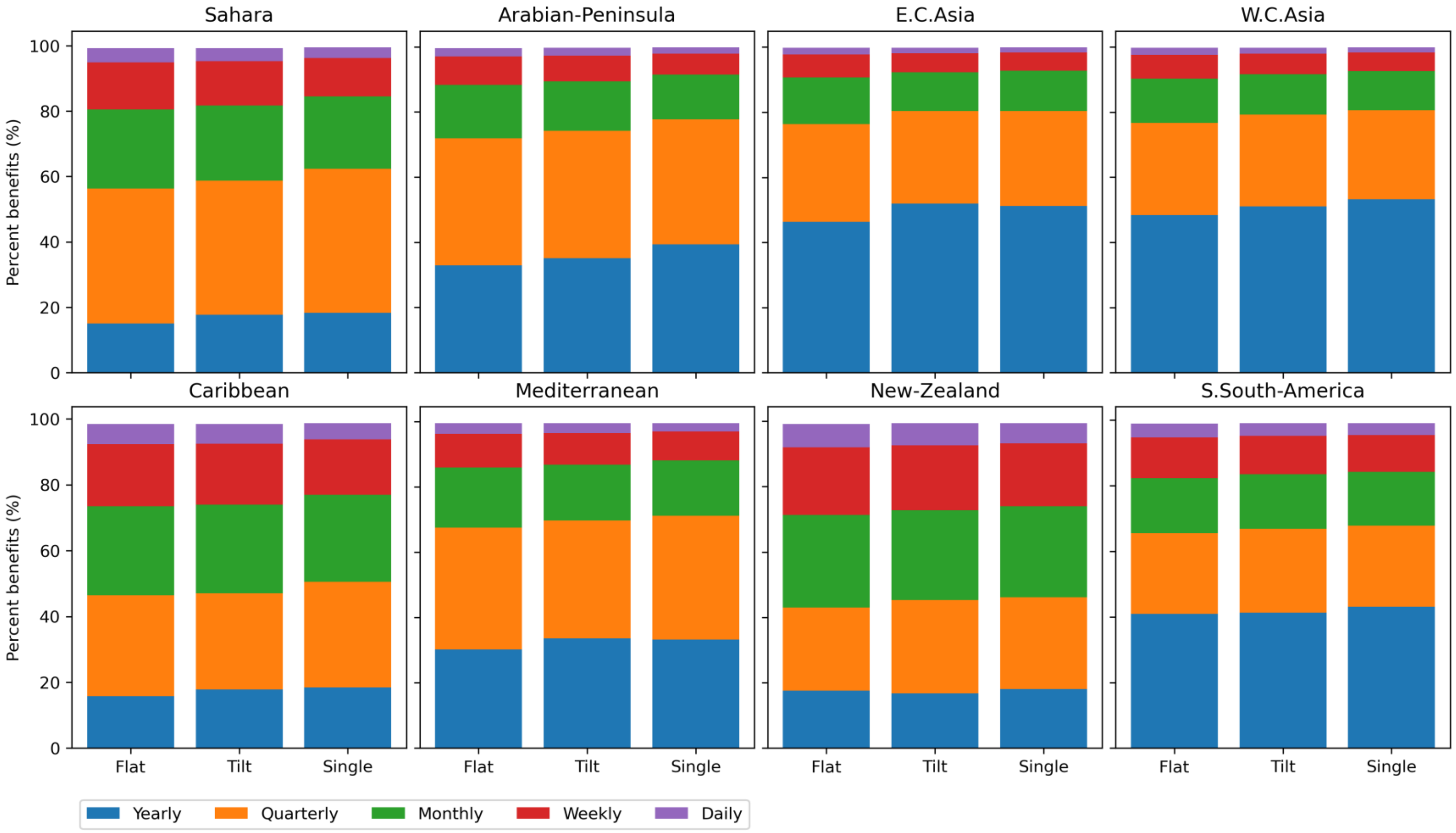
- Precipitation plays an important role in shaping the spatial pattern of current-level PV efficiency.
- Routine sweeping of panels could overcome the majority of PM soiling impacts.





Regional-mean benefits of panel cleaning

Even an annual sweeping routine will remove around 40% of PM soiling impacts in Central Asia and Southern South America.



Concluding remarks

- The extent to which PM pollution damages PV efficiency can be comparable to the maximum PV efficiency that can be achieved. The damage caused by deposited PM far exceeds that by atmospheric PM.
- Deep cuts in residential emissions substantially benefit PV efficiency over East and South Asia. The industrial and energy sectors are the next two important places to target in South Asia.
- Eastern and North-eastern China, and the Indo-Gangetic Plain are the three key regions where reducing residential particularly solid biofuel emissions leads approximately to improvements in PV efficiency.
- Routine sweeping of deposited PM is effective at decreasing PM soiling. Precipitation plays an important role in shaping the spatial pattern of current-level PV efficiency.

Future research avenues

- Continuous advancing model developments may slightly modify but will undoubtedly refine the findings presented in this work.
- Accurately projecting future PV power output and stability in the context of climate change and attributing its changes to individual drivers will offer valuable implications for solar grid planning and operations.
- A virtuous versus vicious cycle.