Source Sector Mitigation of Solar Energy Generation Losses Attributable to Particulate Matter Pollution

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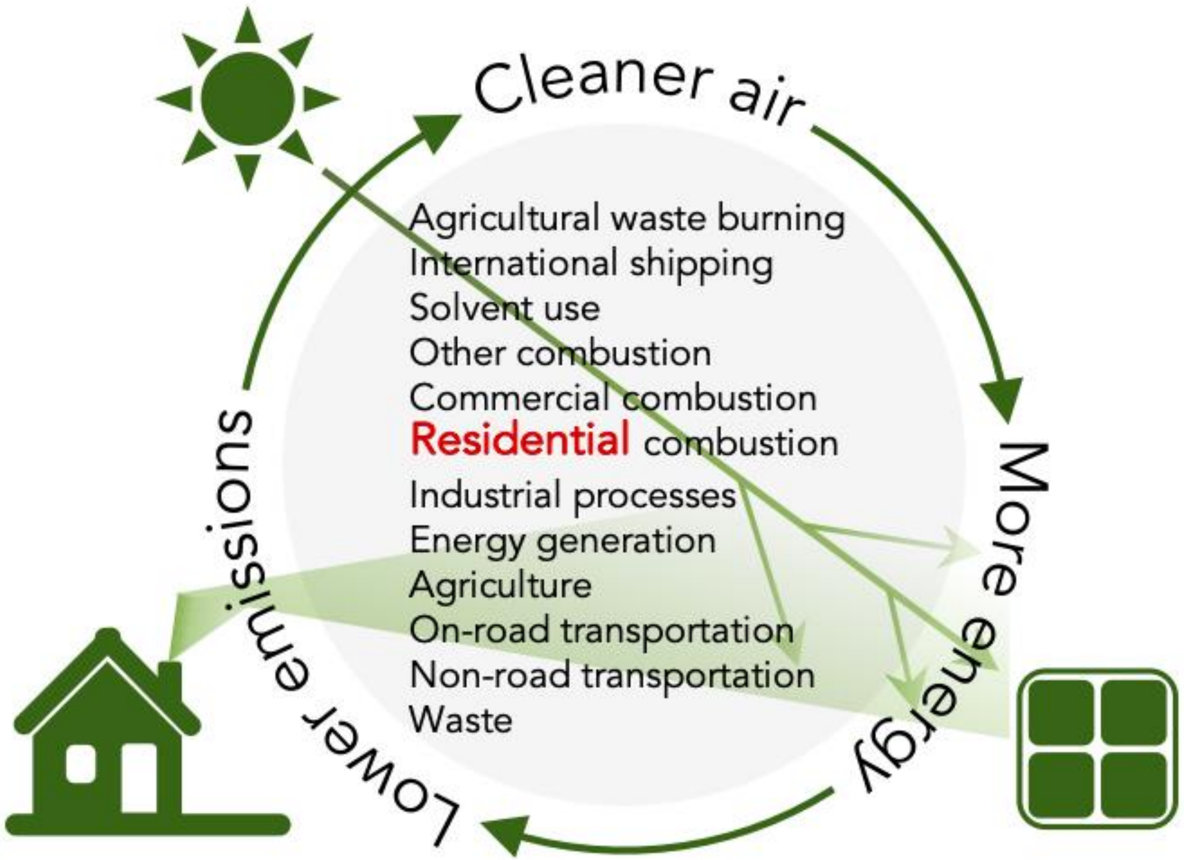
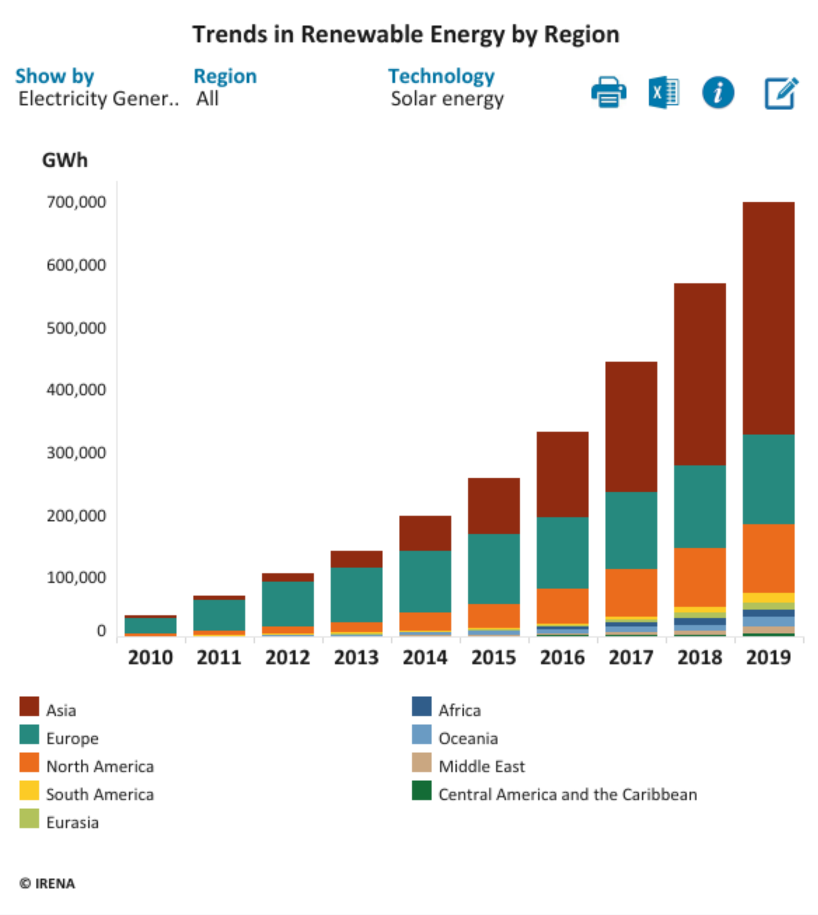
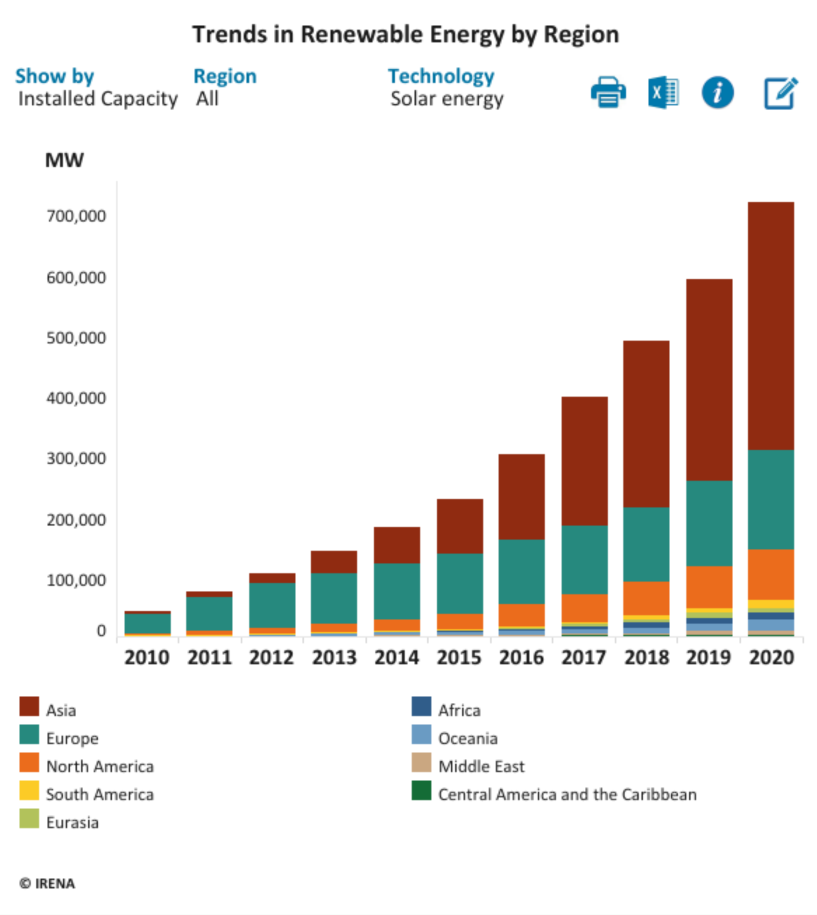


@北京大学蔚蓝空间大气科学论坛第51期
2022年7月

Solar energy helps to mitigate climate change

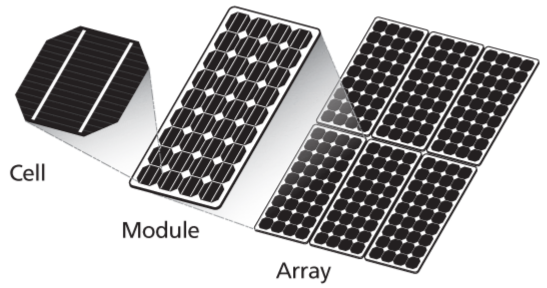
- $\text{Electricity Generation} = \int(\text{Installed Capacity} \times \text{Capacity Factor})dt$





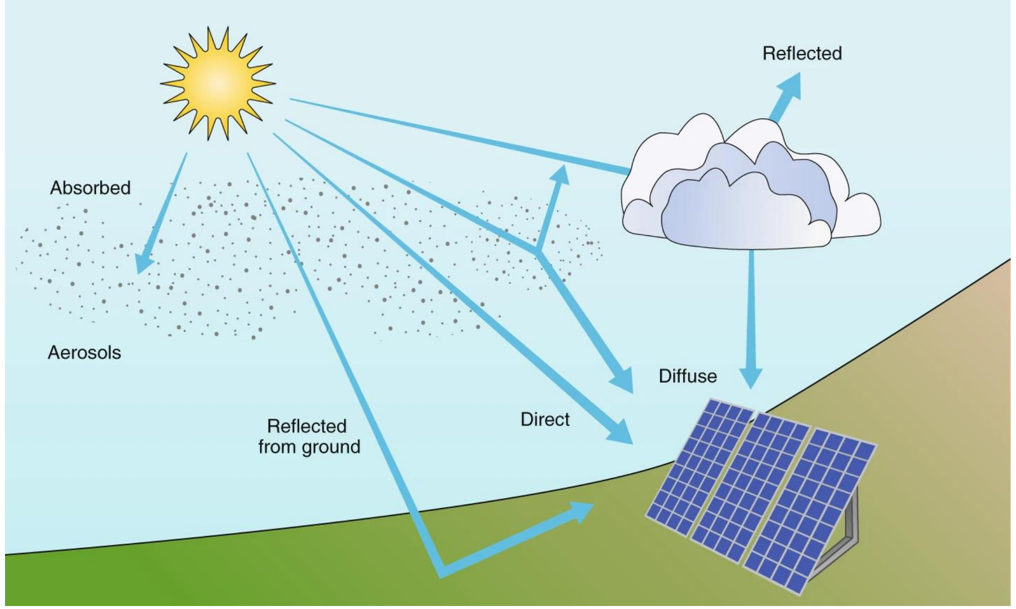
Weather conditions: irradiance, temperature, and wind speed.

Properties and configurations of Photovoltaic (PV) materials.

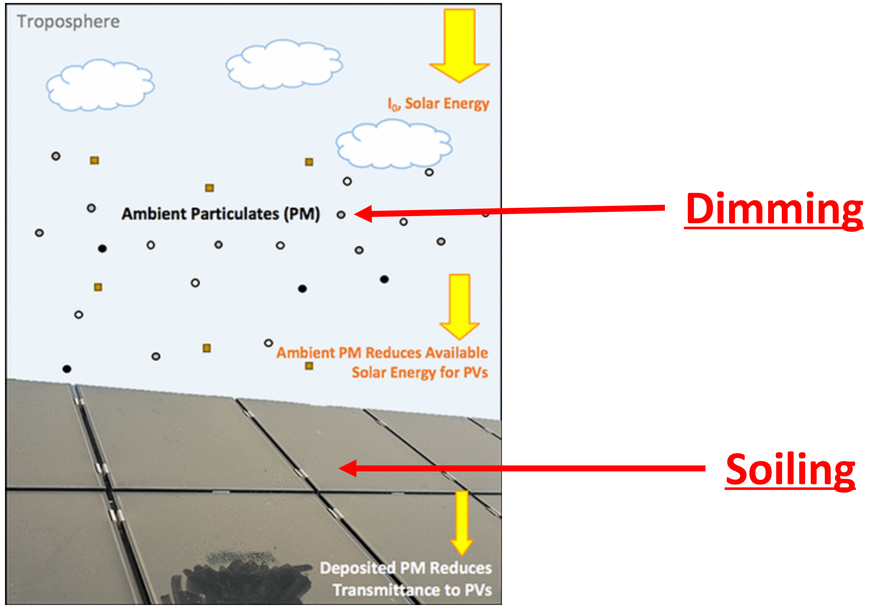


Air pollution reduces solar energy generation

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).



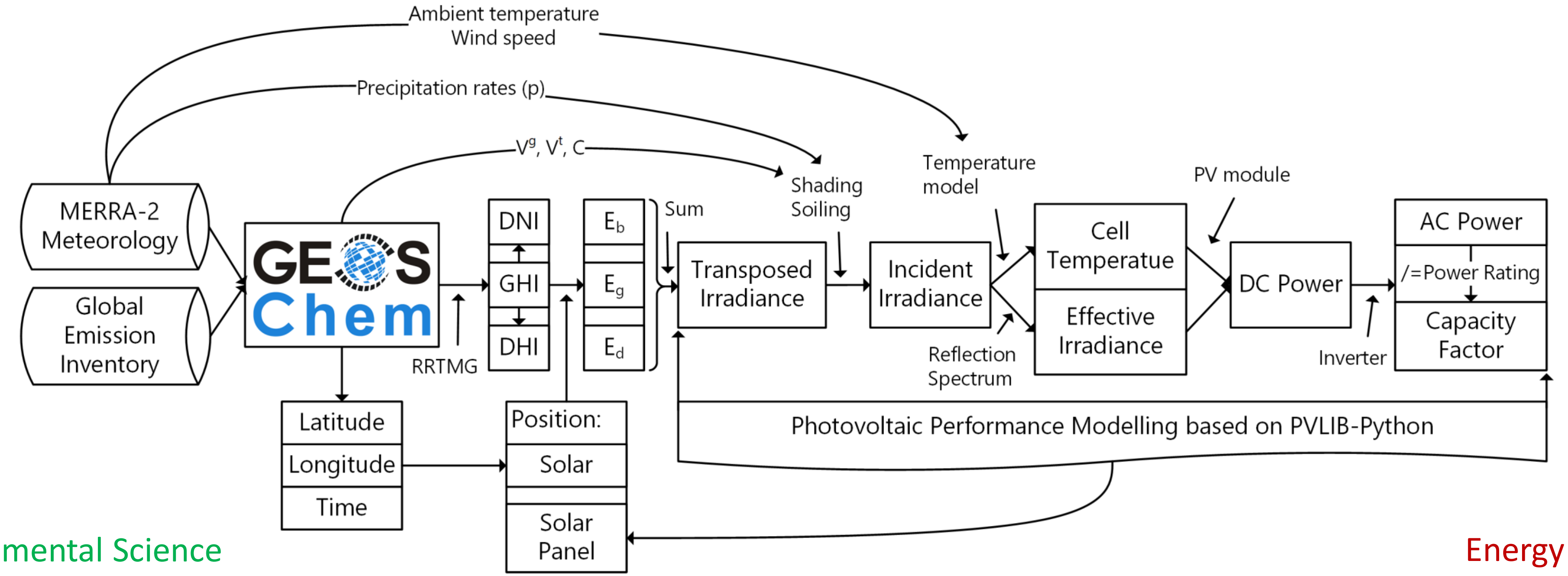
Ekins-Daukes, N. and Kay, M., Nat. Energy., 2019



Bergin et al., Environ. Sci. Technol. Lett., 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.



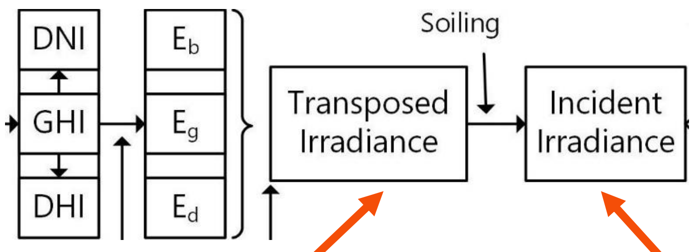
Environmental Science

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: CEDS$_{GBD\text{-}MAPS}$ (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.



$$\tau = \sum_{i=1}^{17}((E_{abs,i} + \beta_i E_{scat,i}) \times PM_i)$$

Species	E_{abs} (m^2g^{-1})	β	E_{scat}(m^2g^{-1})
Dust	0.02	0.02	1.00
Organic carbon	0.00	0.30	4.00
Black carbon	8.00	0.30	0.00
Inorganic aerosols	0.00	0.30	4.00

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

$$PM_i = PM_i^{Accum} - PM_i^{Removal}$$

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.

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

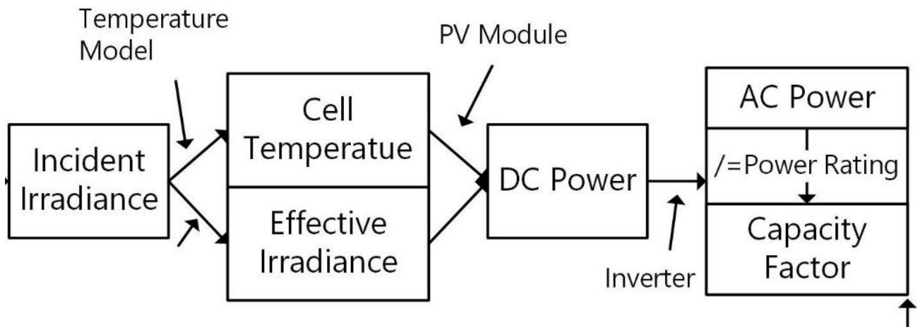
$PM_i^{Removal}$ is a function of precipitation rates (p) and aerosol properties:

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

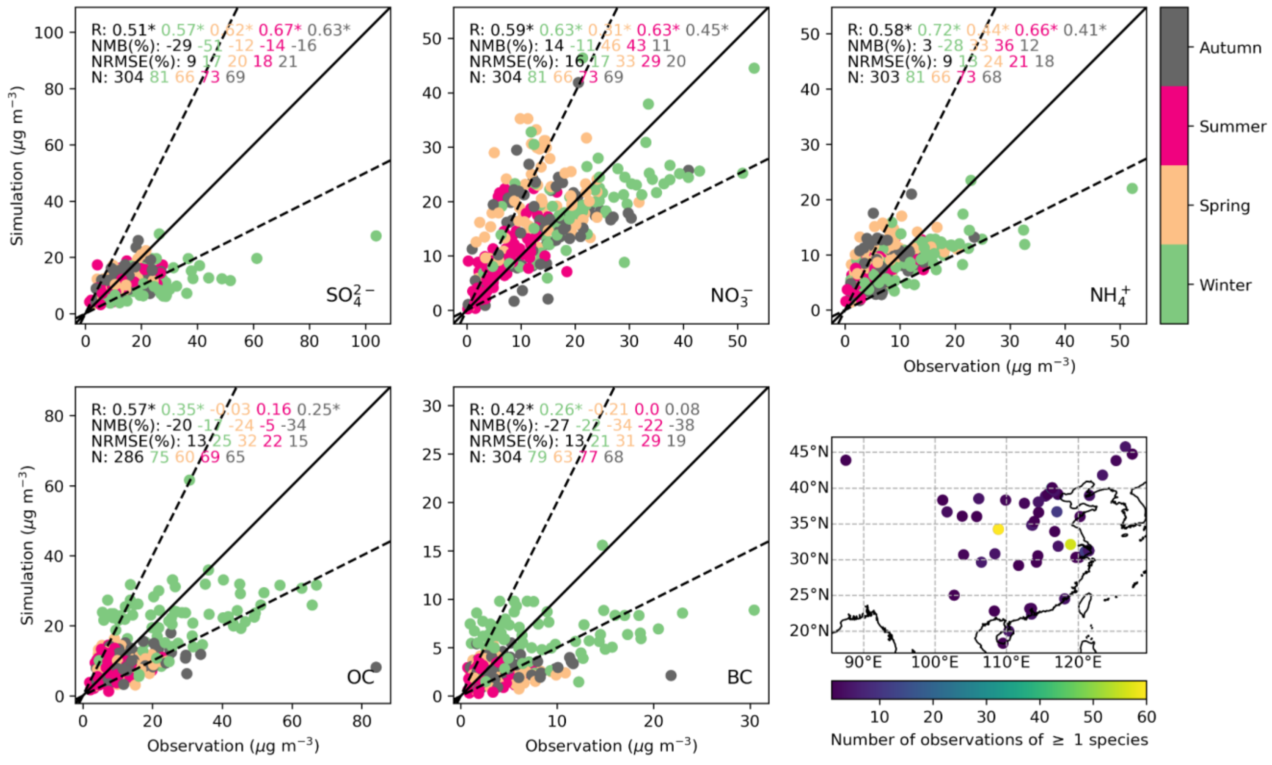


Name	Abbreviation	Descriptions
Flat solar panels	Flat	Solar panels are fixed mounted and horizontal
Latitude-tilt solar panels	Tilt	Solar panels are fixed mounted, tilted at the latitude tilt, and oriented to the equator
Single axis tracking solar panels	OAT	Solar panels rotate around one axis from east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

Model evaluations

The integrated model can generally reproduce the observed variations in GHI and levels of atmospheric and deposited PM during both high and low solar insolation.

- Note that uncertainties in dry deposition velocities (won't be altered in revising emissions) have been well evaluated in previous studies (Zhang et al., Atmos. Environ., 2021) and used to determine measured dry deposition fluxes (Xu et al., Sci. Data, 2019).



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

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: $(CF3\text{-}CF1)_{CTRL}-(CF3\text{-}CF1)_{0.5SECTOR}$

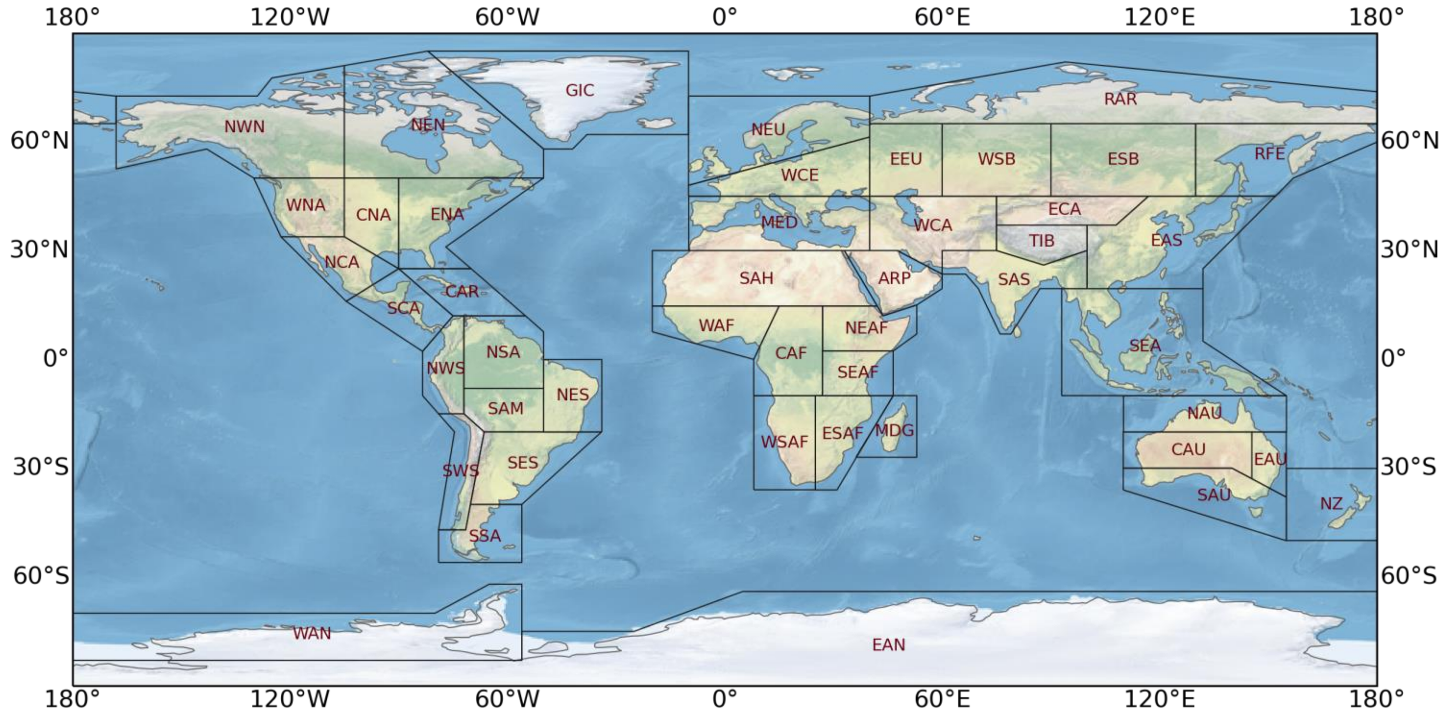
	AGR	ENE	IND	ROAD	NRTR	RCOR	RCOC	RCOO	SLV	WST	SHP	AWB
CTRL	Leave them as they are											
0.5SECTOR	Halve them one by one											
CTRL+NOPrecip	Same as CTRL but without precipitation											
CTRL+SWEEPING	Same as CTRL with solar panels cleaned periodically											

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

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

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

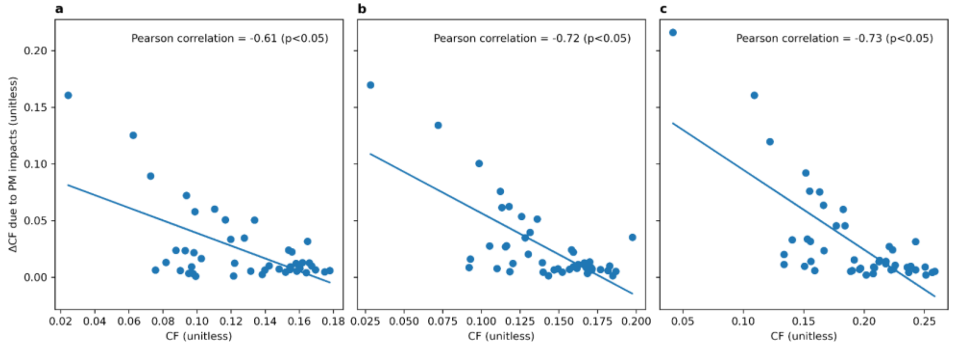
PV efficiency and PM impacts

High PV efficiency found over:

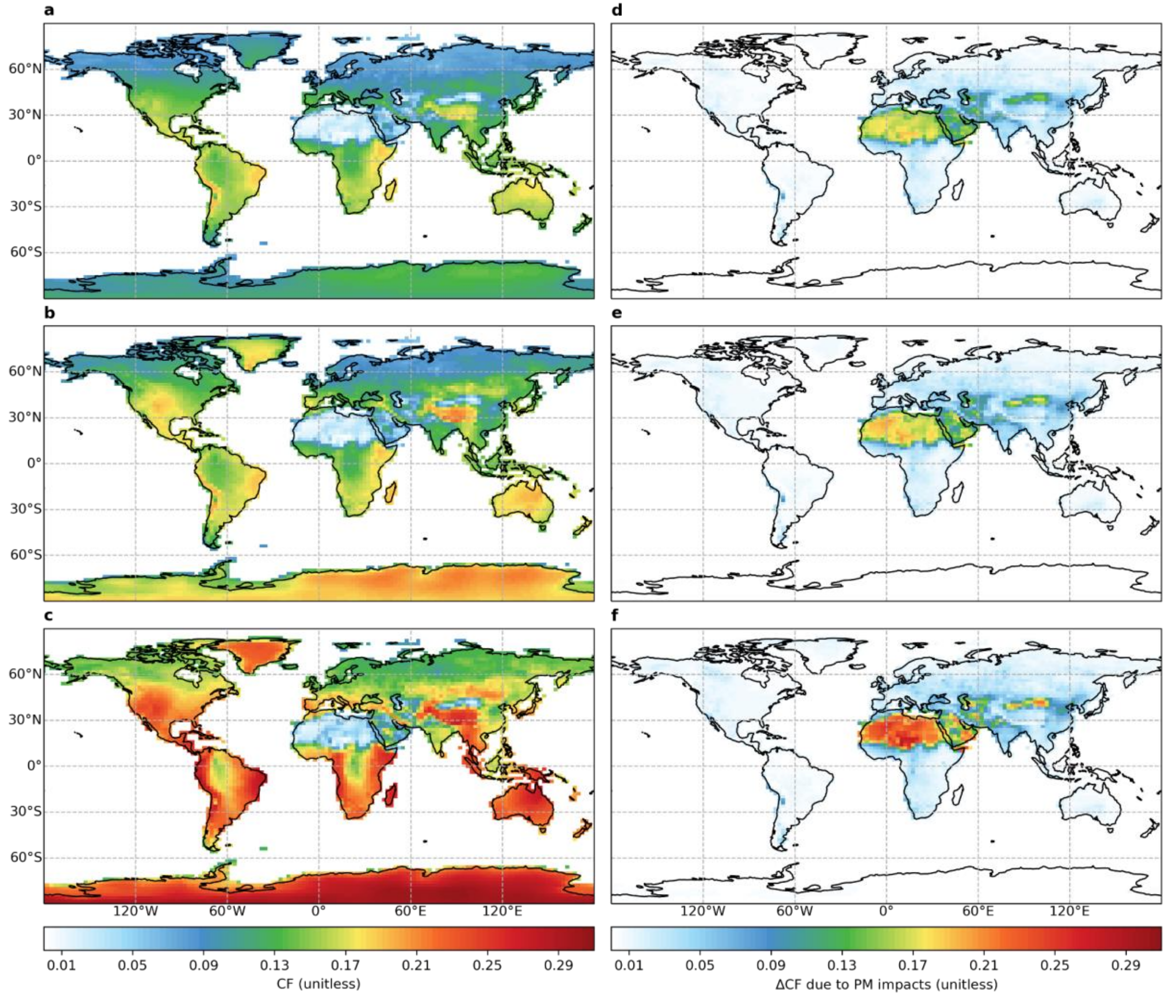
- North and South America, Eastern and Southern Africa, the Tibetan-Plateau, Southeast Asia, Australia, Madagascar, and (tilt and OAT panels) high-latitude regions including Greenland and Antarctica.

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

PM Impacts



PV efficiency



Flat

Tilt

OAT

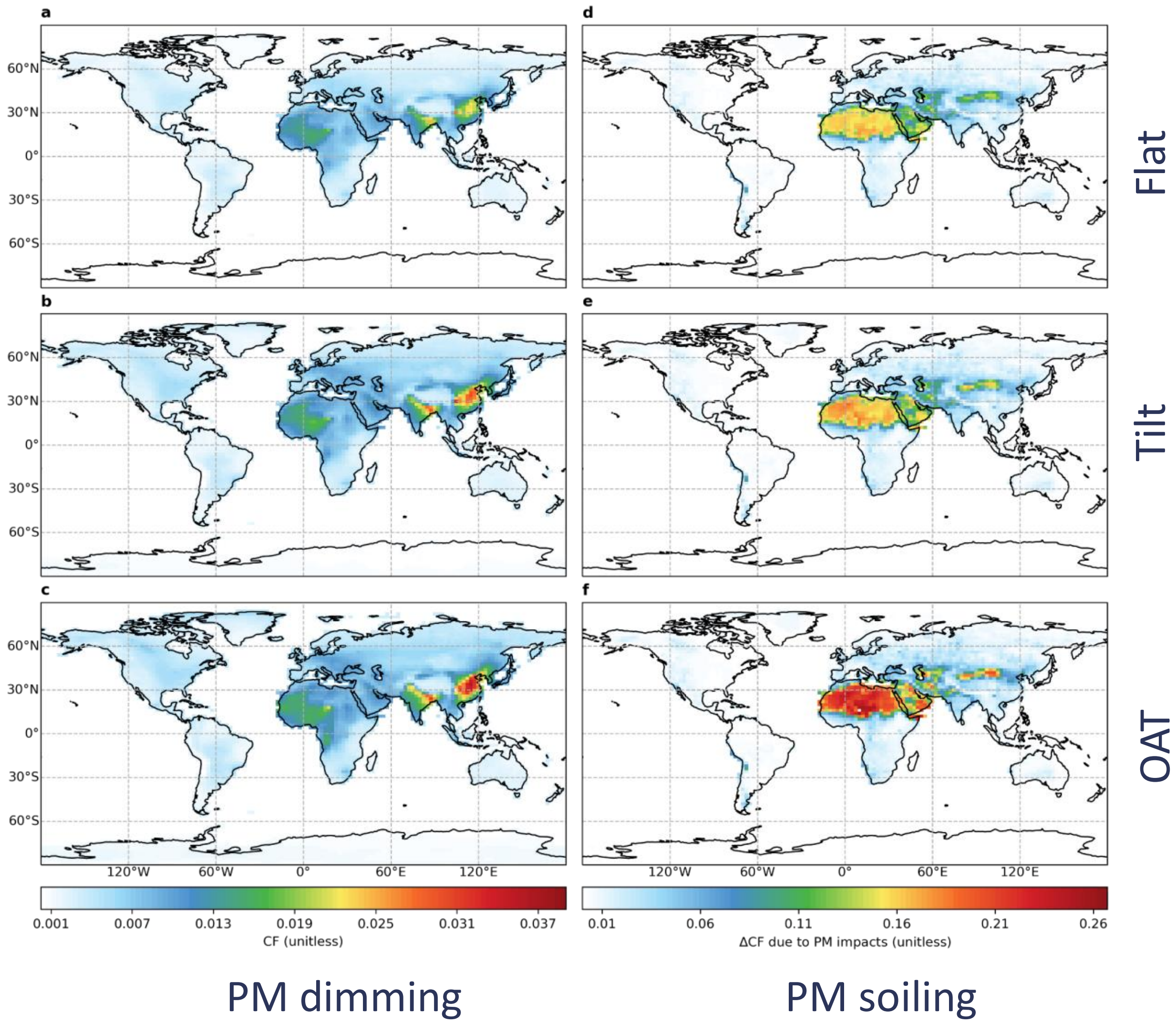
PV efficiency

PM Impacts

PV dimming versus soiling

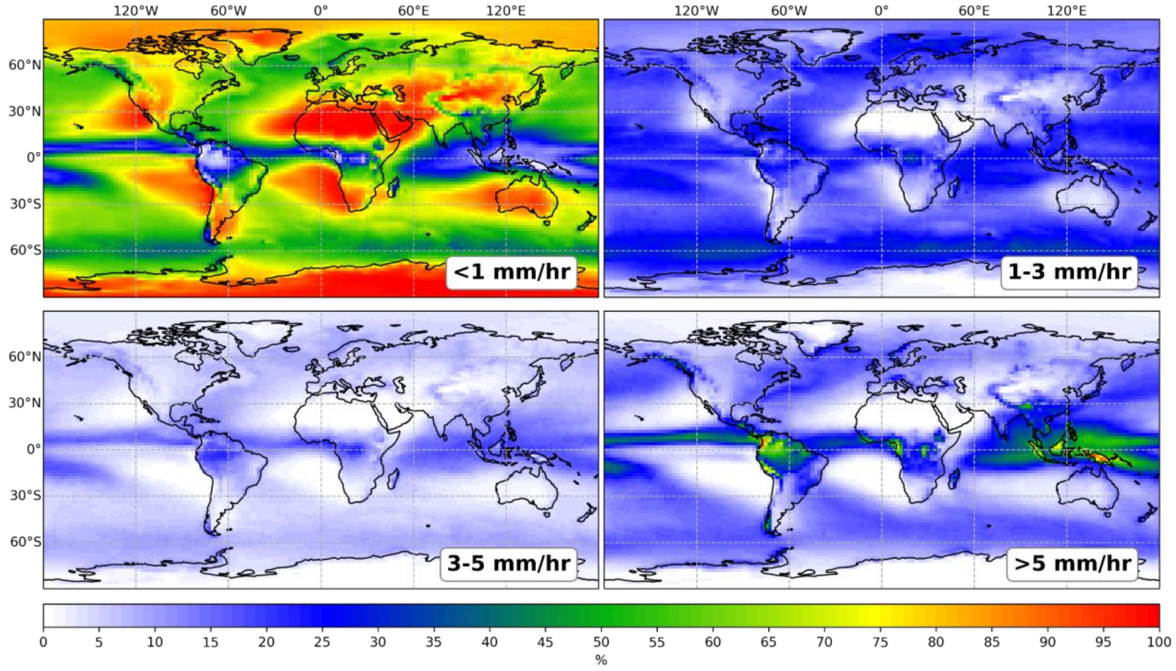
The magnitude and distribution of PM impacts is almost exclusively determined by soiling.

- East and South Asia feature high PM dimming impacts of up to 0.04.
- Desert regions including the Sahara, Arabian-Peninsula, and Central Asia feature high PM soiling impacts.

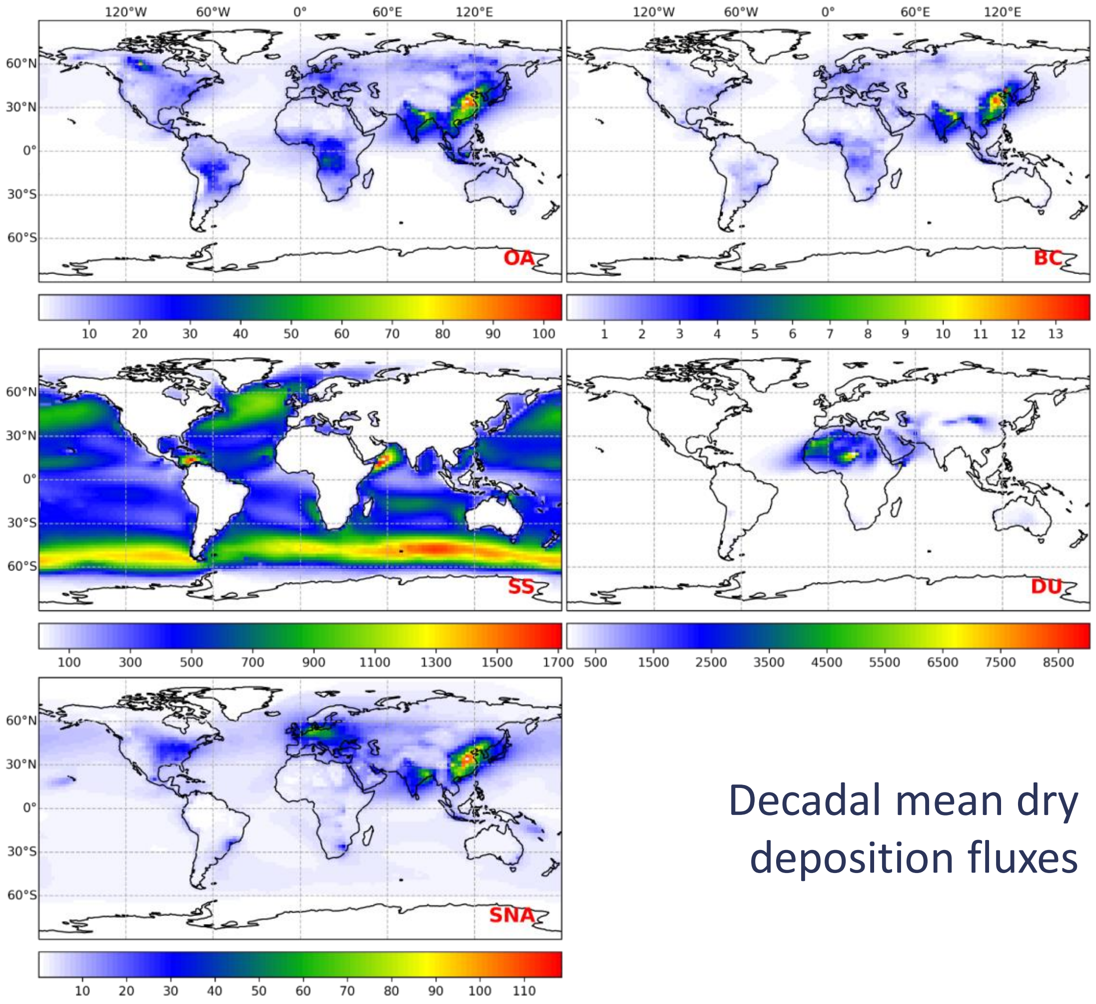


PV dimming versus soiling

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.



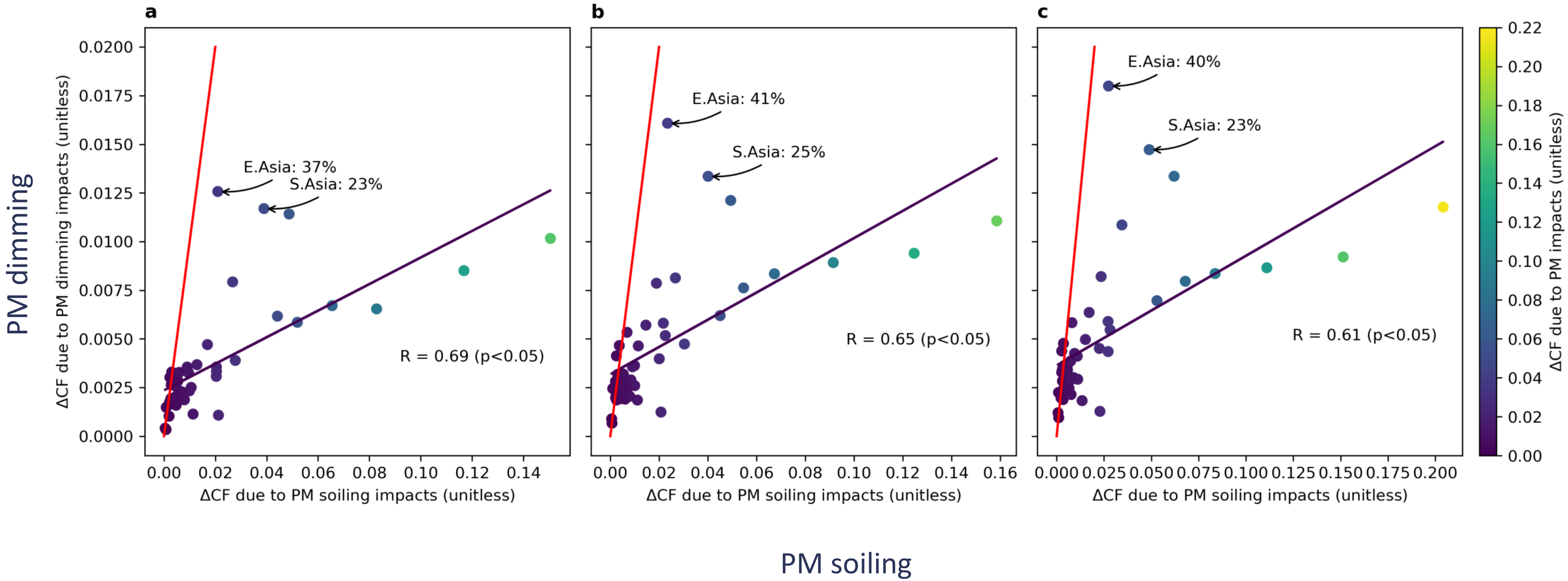
Frequency of precipitation rates



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

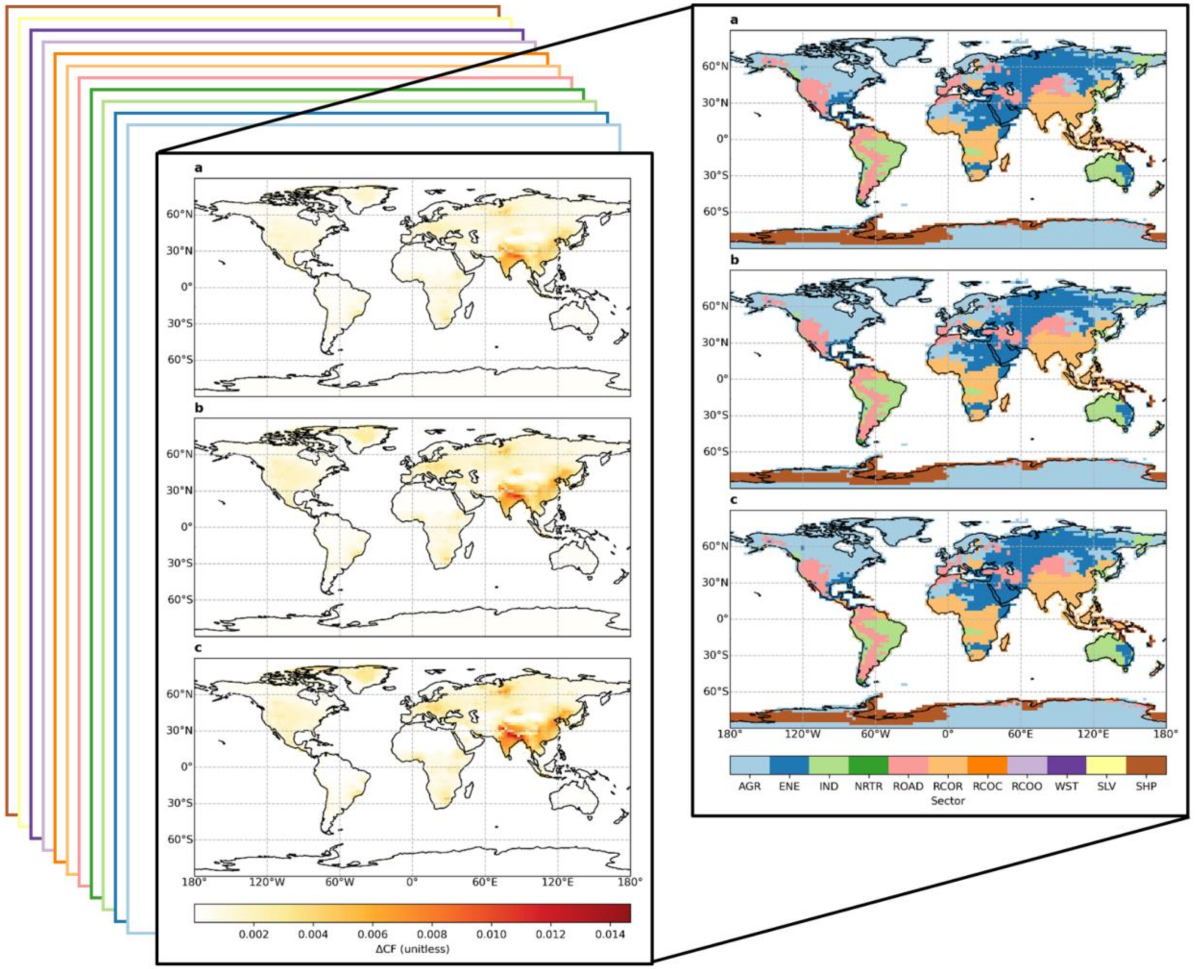
GEOS Chem

+

aer RRTMG
Atmospheric and Environmental Research

+

pvlib



Flat

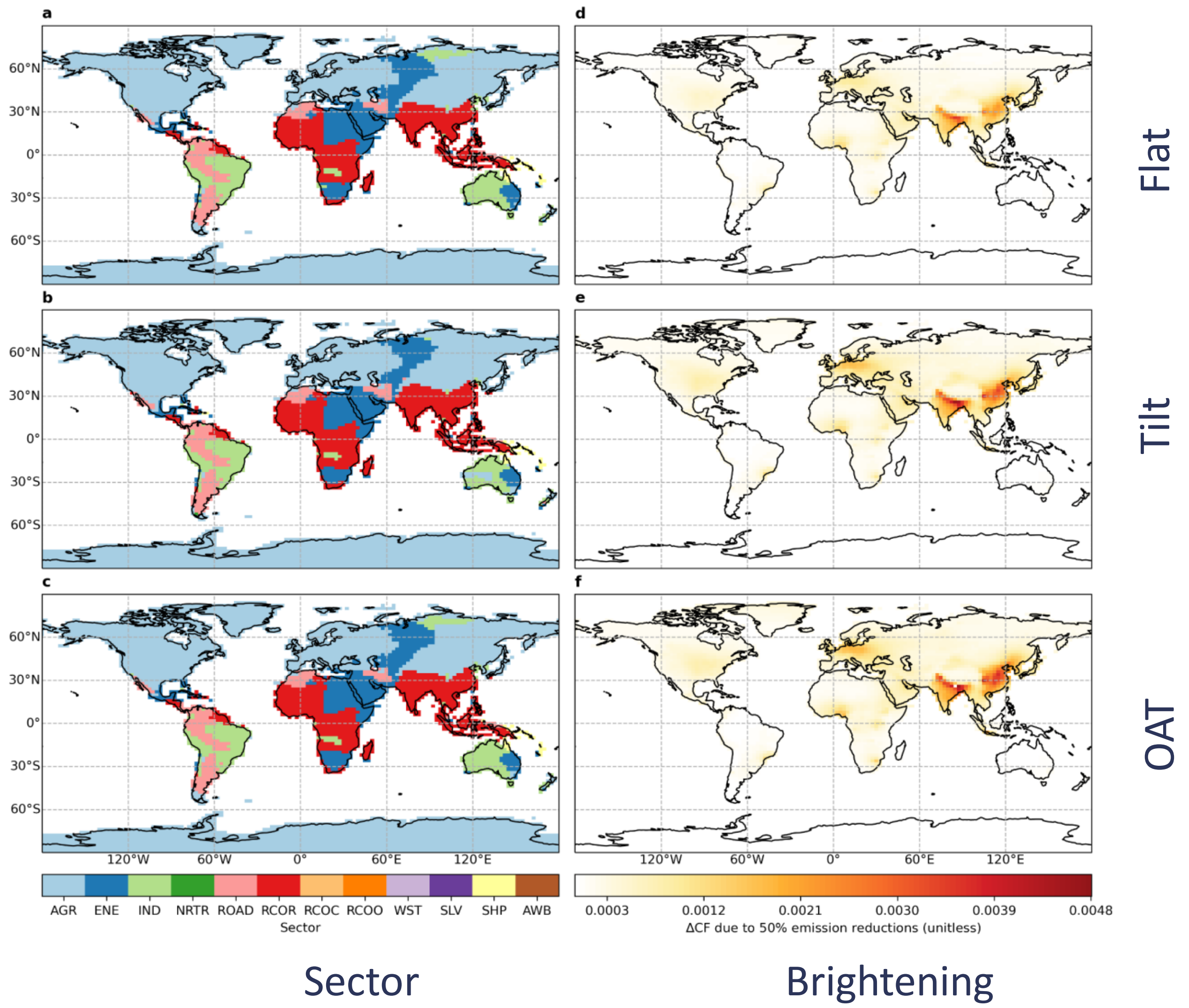
Tilt

OAT

Brightening benefits of reducing emissions

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

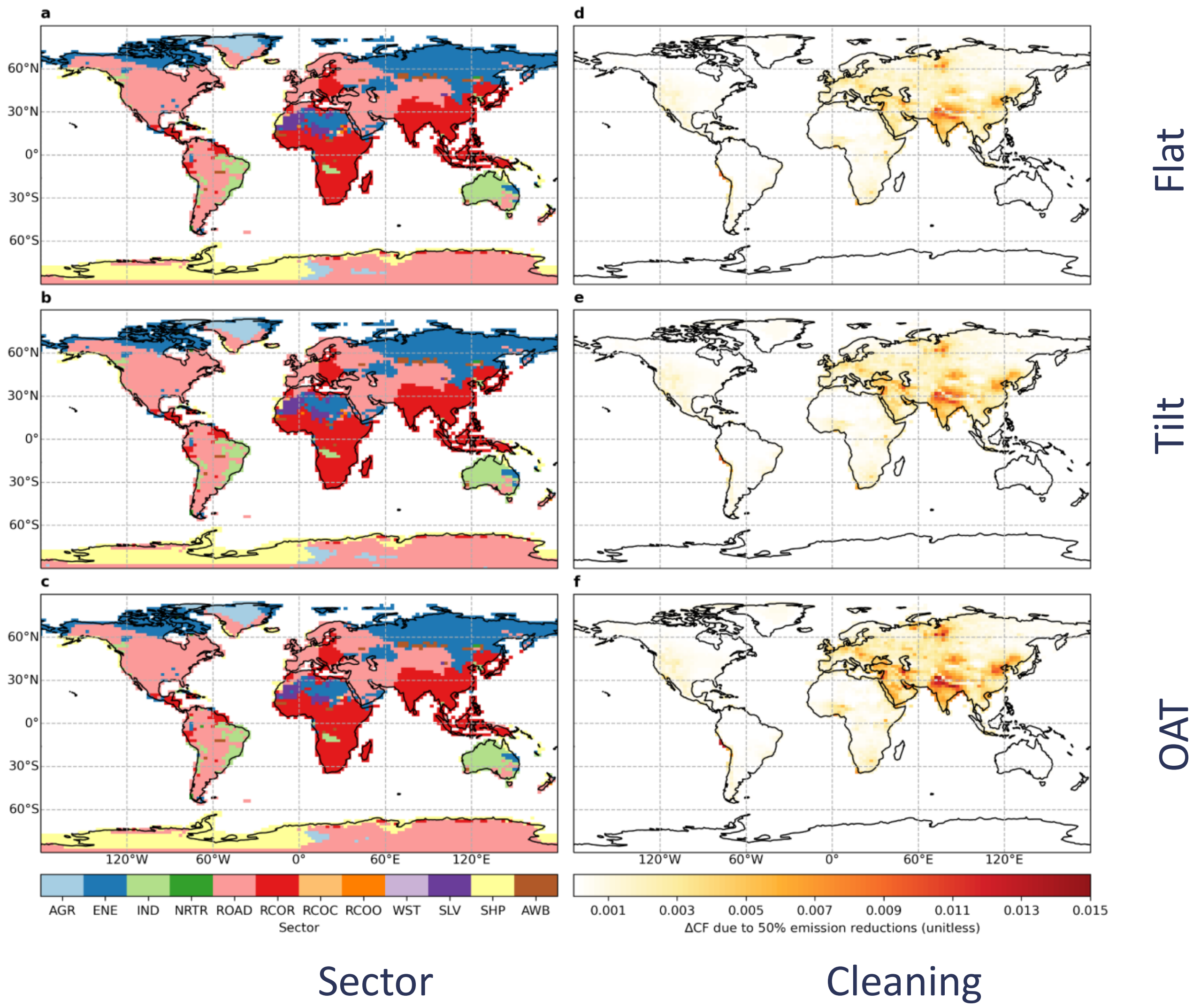
- The brightening benefits for the three panels of halving residential emissions are 8%, 9%, and 9% and equally 12% over East and South Asia, respectively.
- The corresponding values are equally 8% and equally 13% of halving agricultural emissions over East Asia and West & Central Europe, respectively.



Cleaning benefits of reducing emissions

Halving residential, on-road, and energy emissions result in widespread decreases in PM soiling.

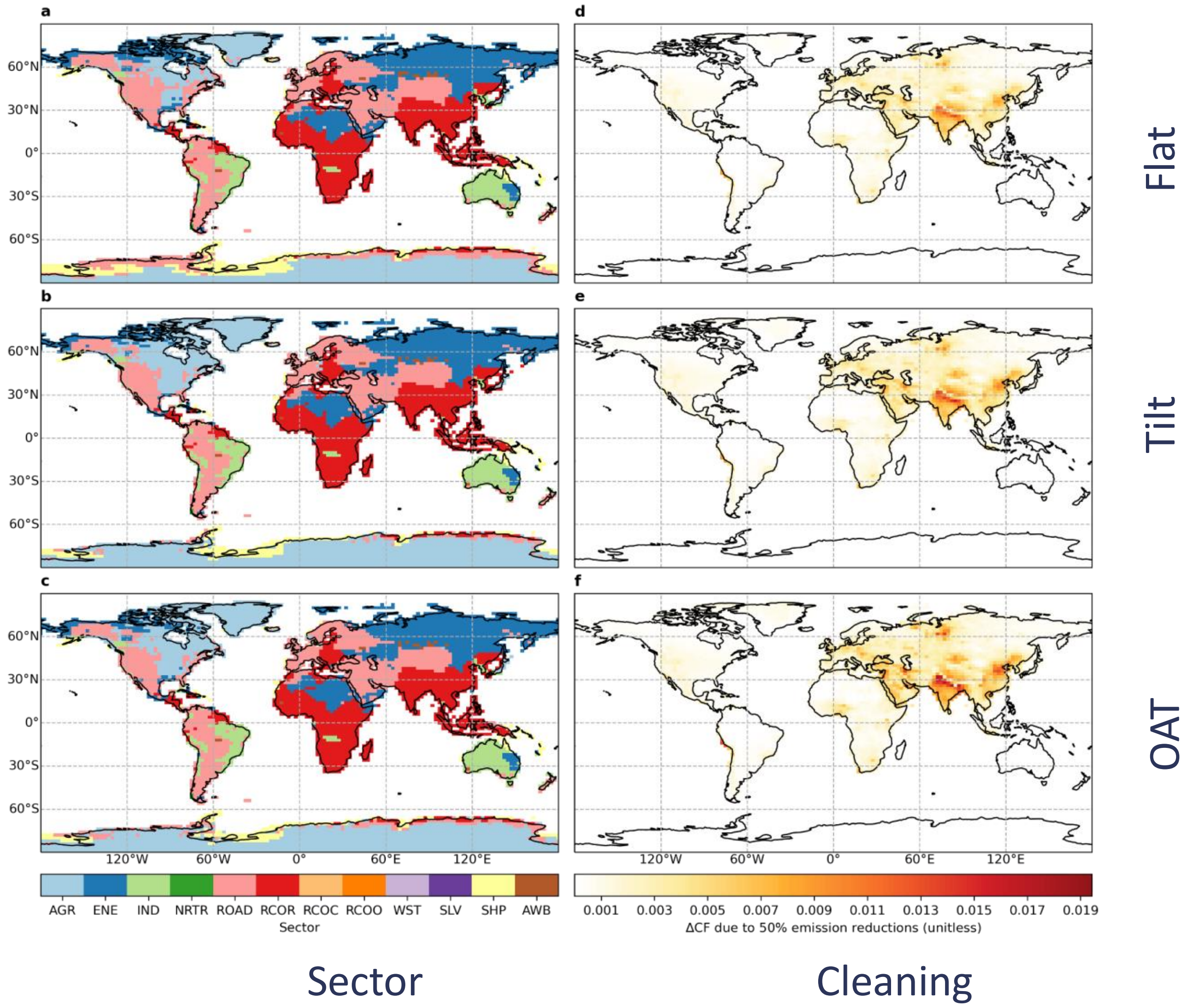
- The cleaning benefits for the three panels of halving residential emissions are equally 12-13% over East and South Asia. The corresponding values are slightly higher at 15-17% over the Tibetan-Plateau.
- The cleaning benefits for the three panels of halving on-road emissions are equally 2-4% over Central Asia and the Arabian Peninsula, and they are equally 10% of halving energy emissions over Western Siberia.



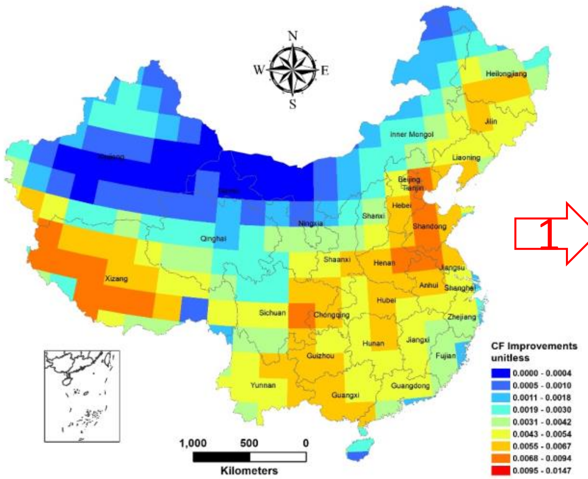
Total benefits of reducing emissions

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

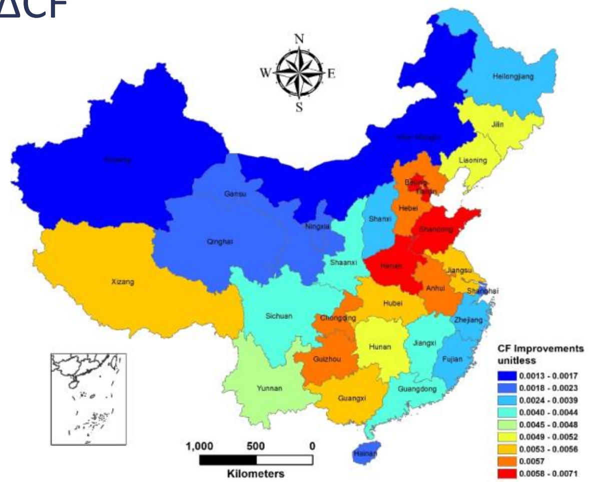
- The total benefits for the three panels of halving residential emissions are equally 10-12% over East and South Asia. The corresponding values are slightly higher at 15-16% over the Tibetan-Plateau.
- The total benefits for the three panels of halving on-road emissions are equally 2-4% over Central Asia and the Arabian Peninsula, and they are equally 9-10% of halving energy emissions over Western Siberia.



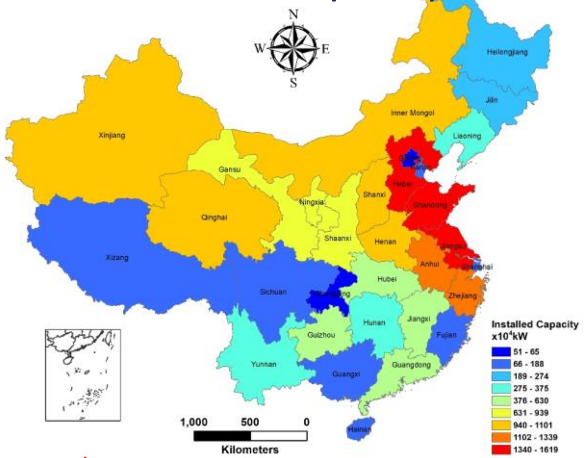
Impact on energy sector



ΔCF

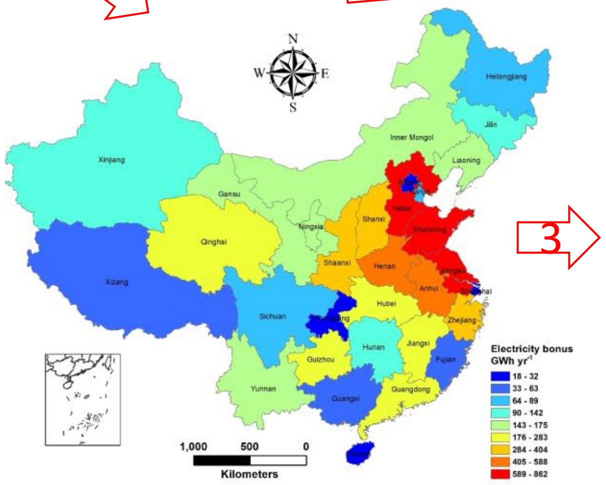


Installed capacity

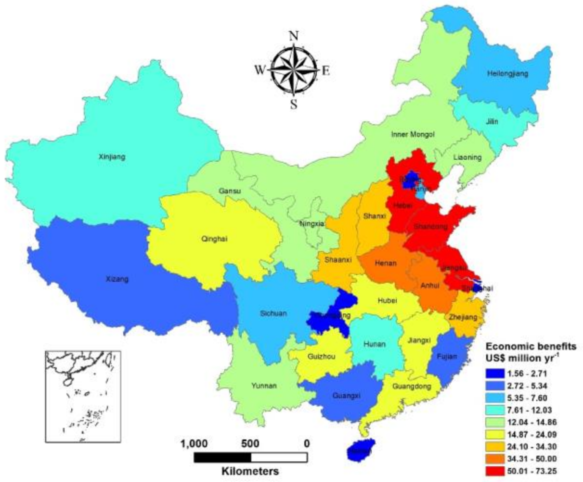


1. Gridded ΔCF aggregated to provincial ΔCF
2. Electricity bonus = ΔCF * installed capacity * 1 year
3. Economic bonus = electricity bonus * electricity price

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.



Electricity bonus

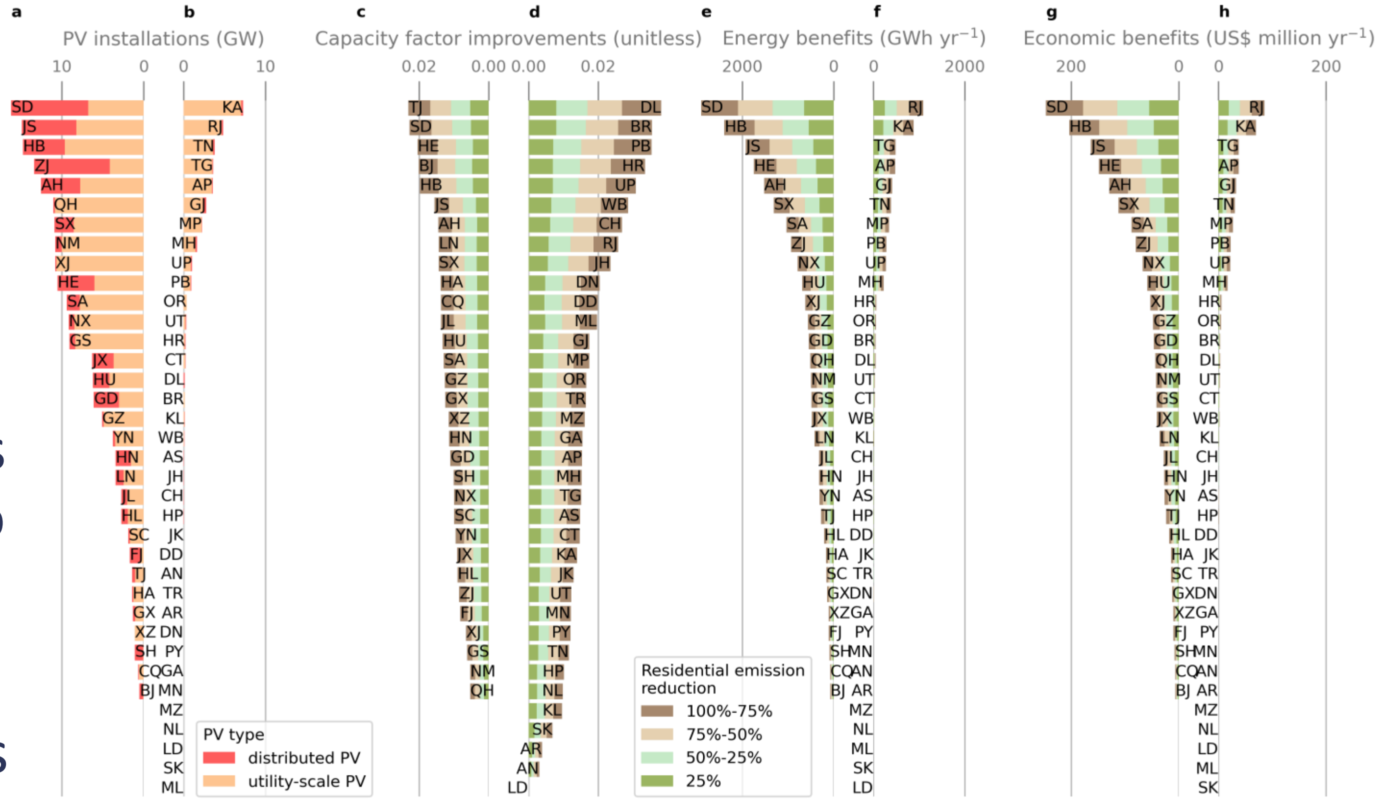


Economic benefits

Impact on energy sector

Three highlights:

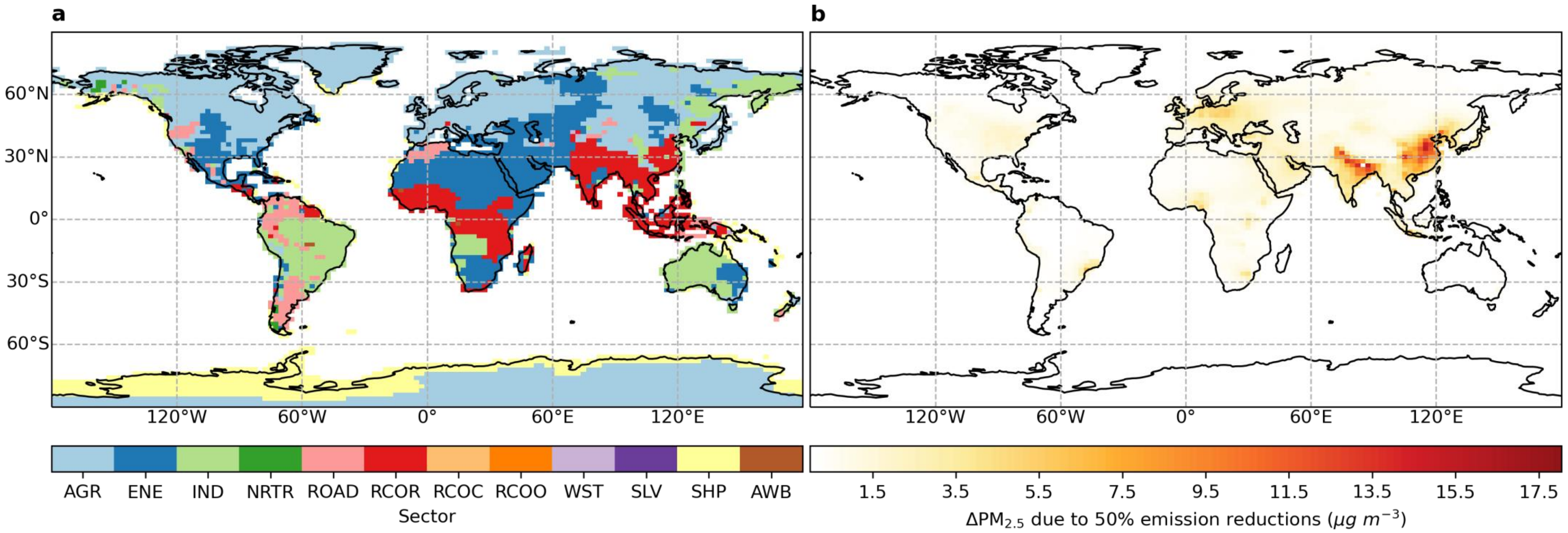
- Regions where there are larger established PV installations will generally benefit more from reducing residential emissions.
- Regions with moderate PV installations will also benefit from larger ΔCF due to reducing residential emissions, e.g. Henan province in China.
- Policies to reduce residential emissions will likely lead approximately linearly to improvements in PV efficiency and the associated energy and economic benefits.



	Electricity bonus (TWh yr^{-1})	Economic benefits (US$million yr^{-1})
China	10.3	878
India	2.5	196

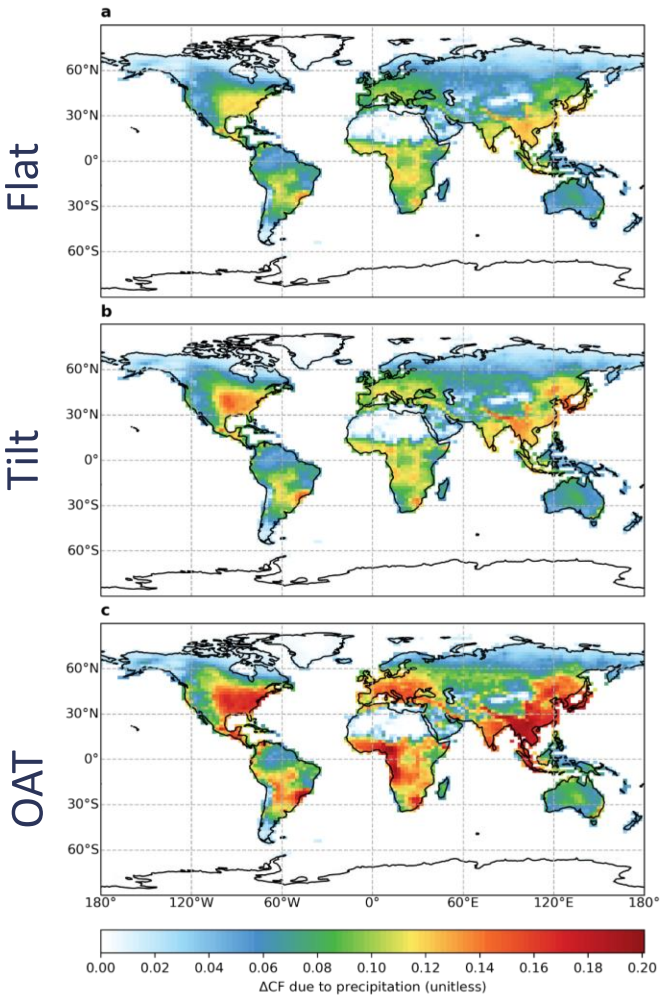
Co-benefits to surface air quality

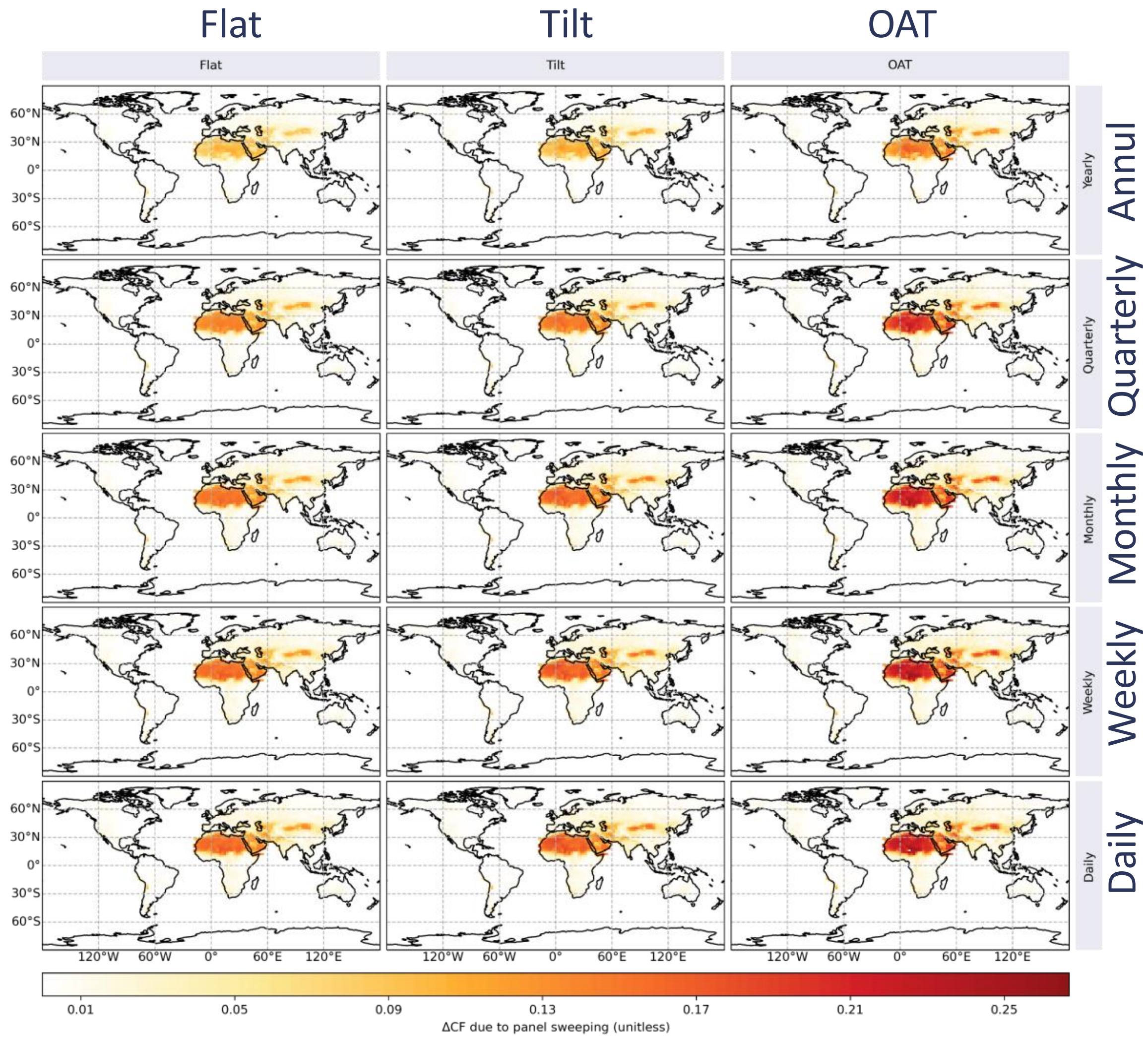
- Stringent reductions in residential emissions also lead to noticeable improvements in surface air quality with respect to $PM_{2.5}$.
- The uncontrolled and inefficient combustion of solid fuels in residential devices is likely the prime culprit.



Role of precipitation and panel cleaning

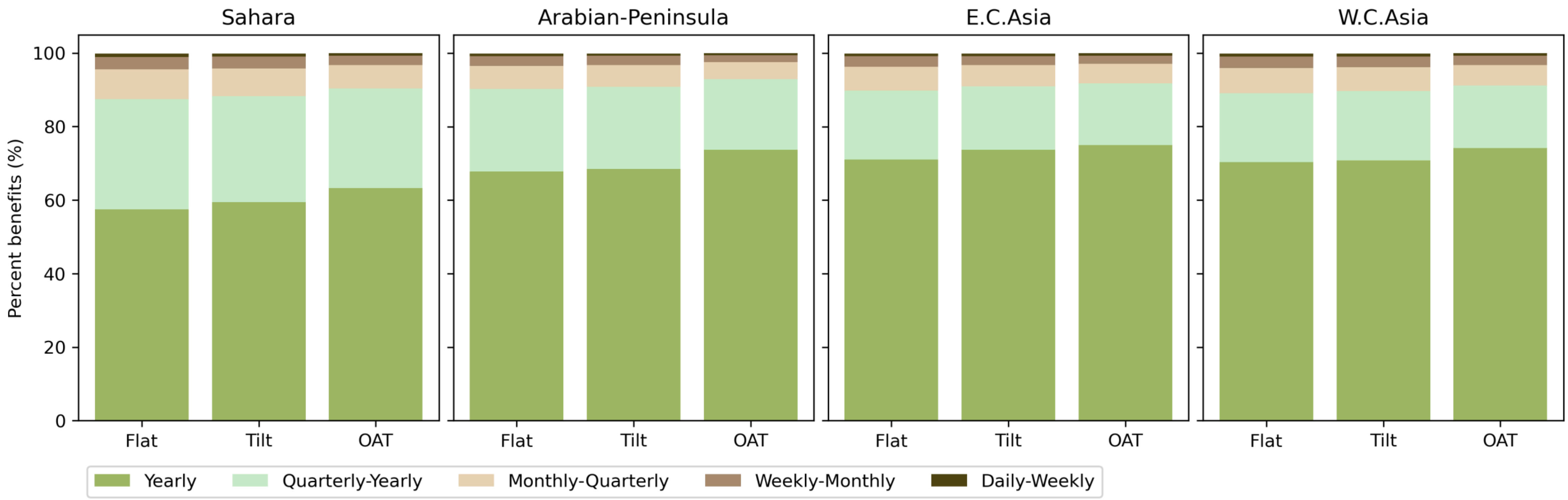
- Precipitation plays an important role in shaping the spatial pattern of current-level PV efficiency.
- Routine sweeping of panels could overcome the majority of PM soiling impacts.





Regional-mean benefits of panel cleaning

Even an annual sweeping routine will remove around 60% of PM soiling impacts in desert regions.



Concluding remarks

Deep cuts in air pollutant emissions from the residential, on-road, and energy emissions are the most effective approaches to mitigate PM-induced PV energy losses over East and South Asia, and the Tibetan Plateau, Central Asia, and the Arabian Peninsula, and Western Siberia, respectively.