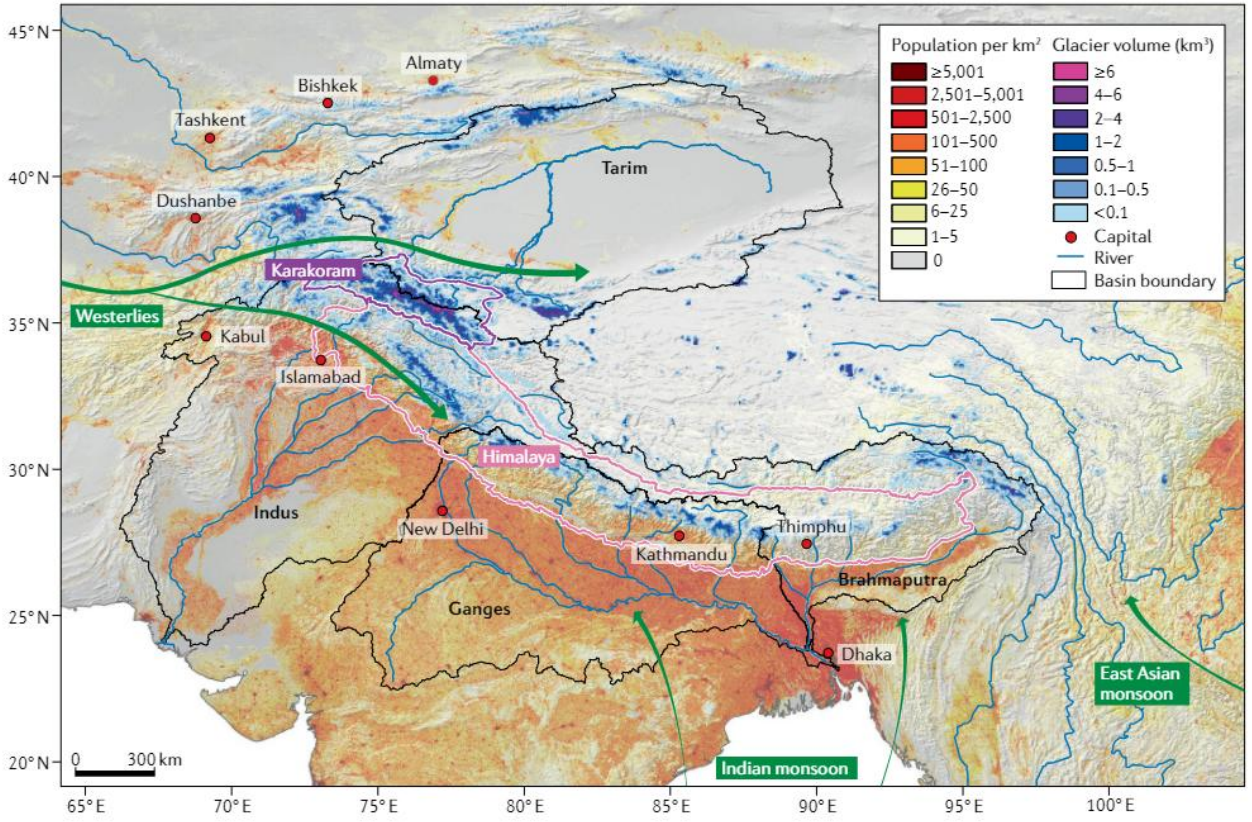
Tracing black carbon's footprint on the Hindu Kush Himalaya: an assessment of emissions, deposition and albedo trends using multimodal, gridded, and satellite datasets

Praveen Kumar Singh[1], Arshini Saikia[2], Tenzing Chogyal Sherpa[2], Ajanta Goswami[1], Siva Praveen Puppala[3]

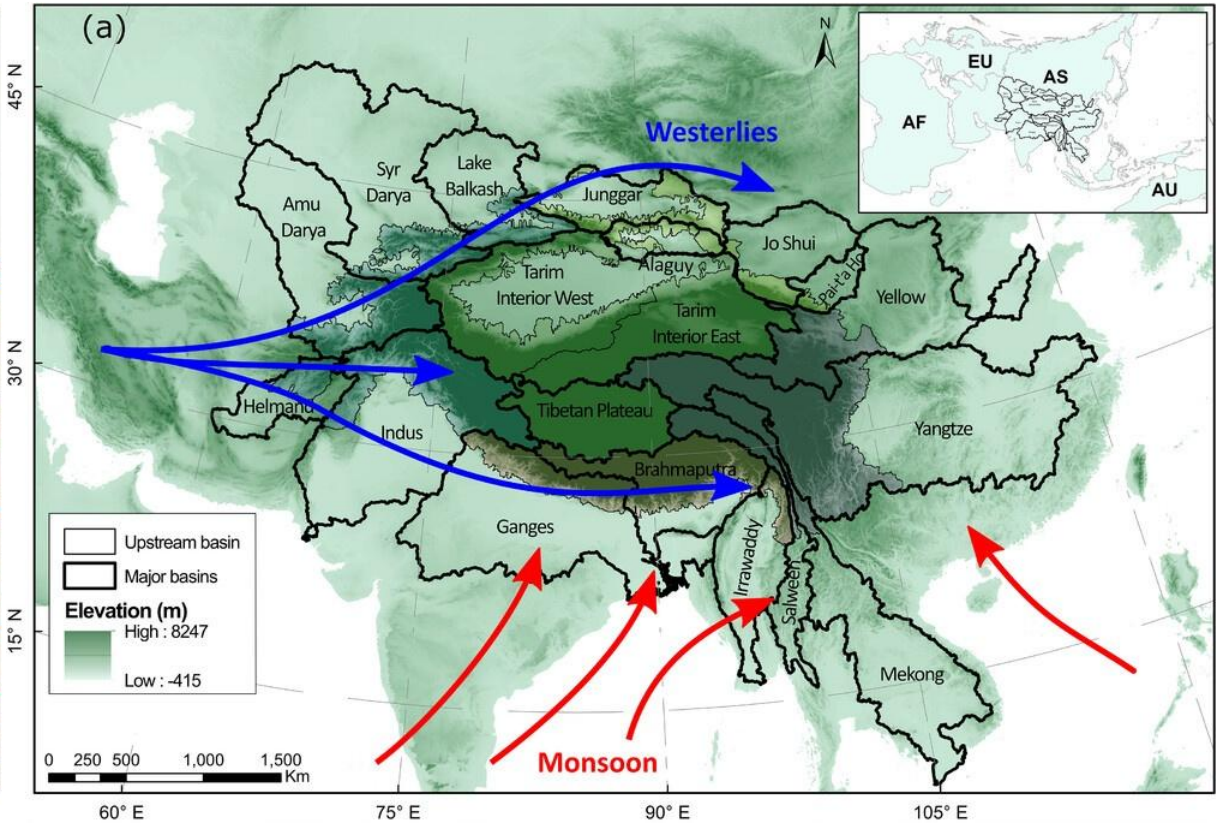
[1]CoEDMM, IIT Roorkee, India
[2]ICIMOD, Nepal
[3]DCCEEW, NSW, Australia

Second Inter-Polar Conference
3 – 5 September 2025
Kathmandu, Nepal

The third pole



High-mountain Asia population and glacier volume (Nie et al., 2021)

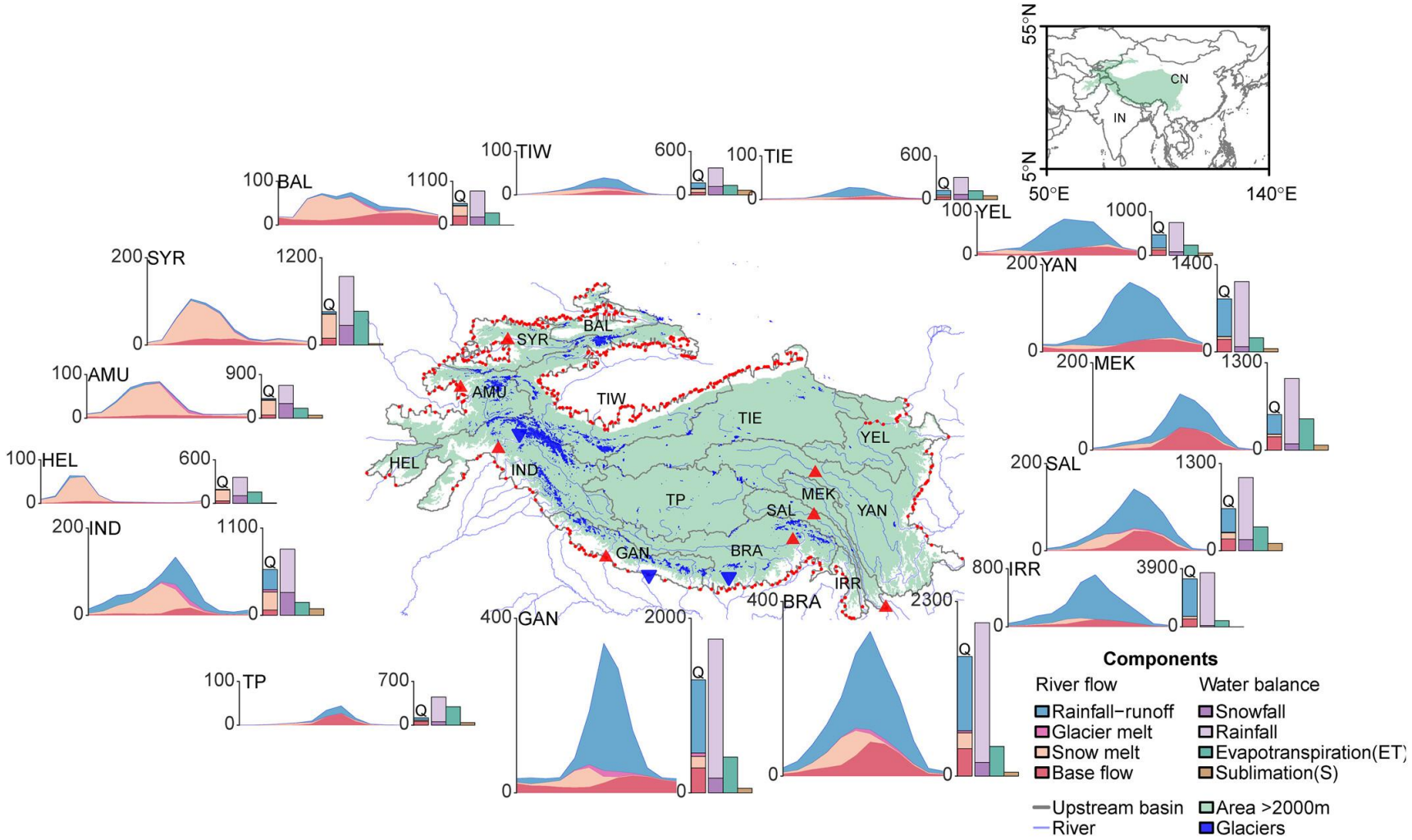


The river basins and their important moisture source (Khanal et al., 2023)

- High Mountain Asia consists of the Qinghai–Tibet Plateau and its surrounding regions, including the Karakoram, Pamir, Himalayas, and Tien Shan
- HMA hosts 131819 glaciers, covering a total area of ~99,817 km^2 (Sakai, 2019)

The water resources in the region

Contribution of snow melt is more in the total runoff

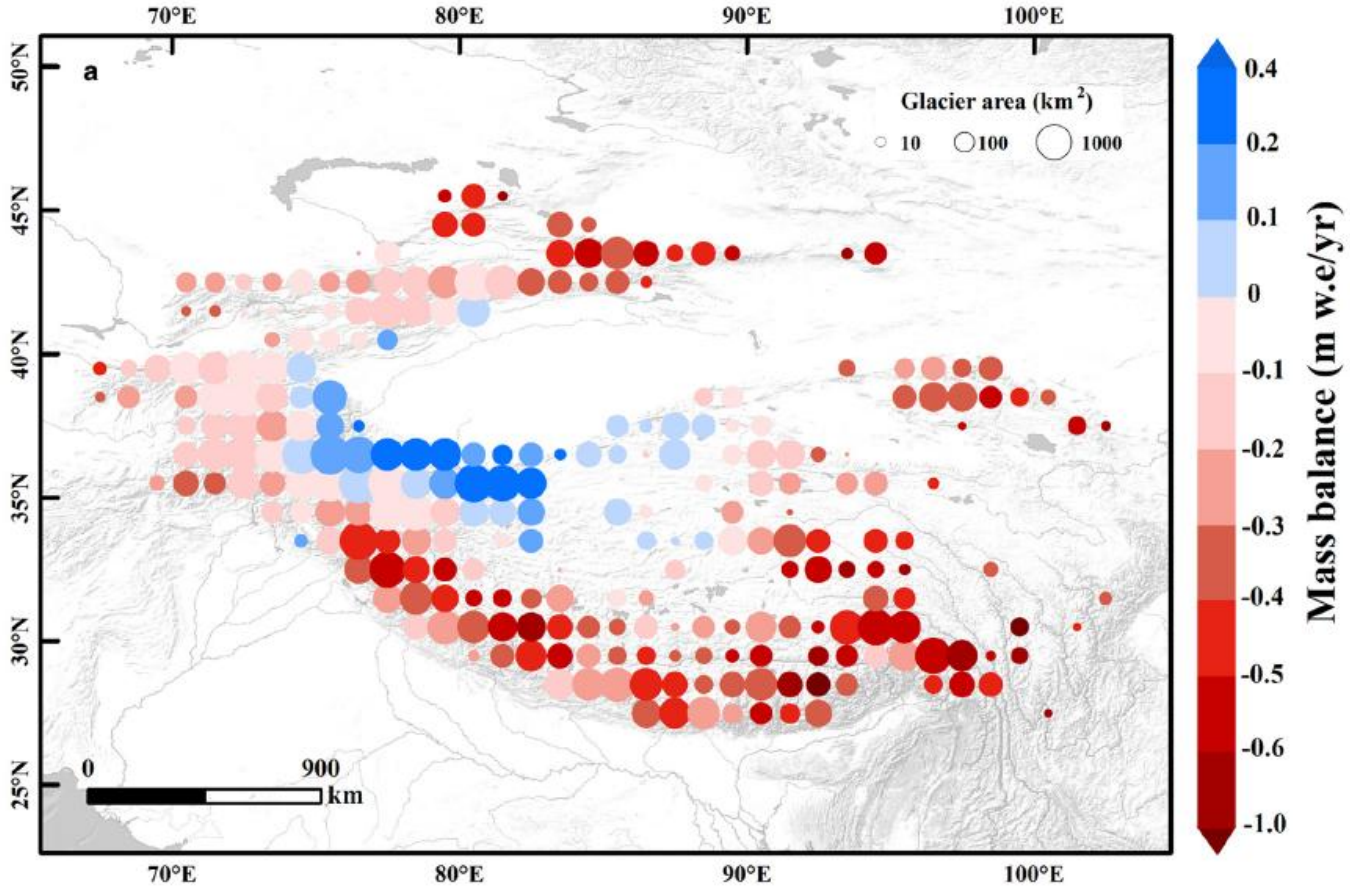


Contribution of rainfall is more in the total runoff

1985 – 2014 mean seasonal cycles of discharge and contribution of baseflow, snowmelt, glacier melt, and rainfall-runoff (Khanal et al., 2021)

Present status of glaciers

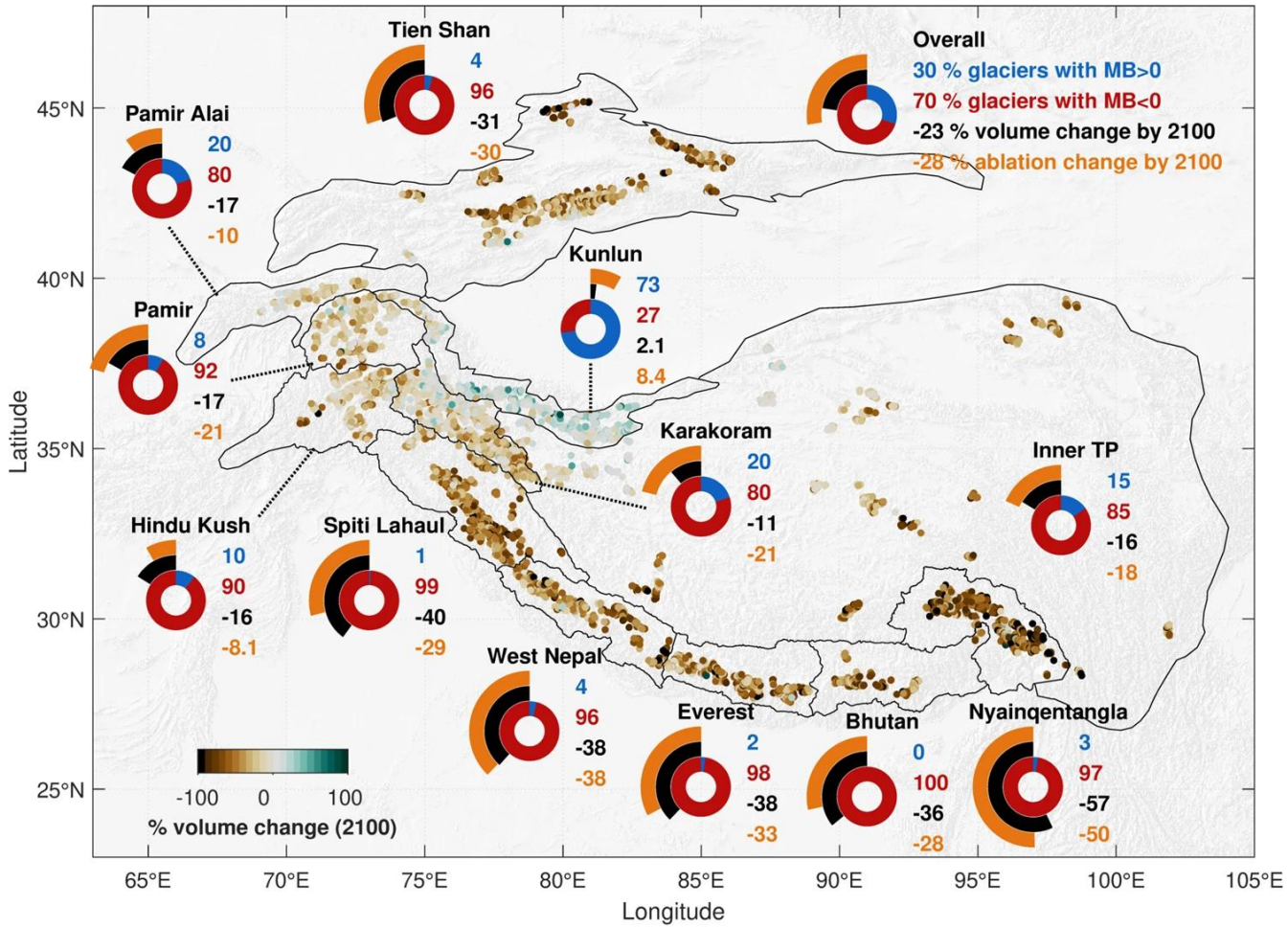
- ~−0.18 ± 0.12 m w.e. a^{-1} (−17.53 ± 11.36 Gt a^{-1}) from 2000 to 2021
- South-eastern: up to −1m w.e. a^{-1}, southern and north-eastern: ~−0.6m w.e. a^{-1}
- Hissar Alay, Pamir and West Tien Shan Mountains: −0.1m w.e. a^{-1}
- Positive trend: ~0.2–0.4 m w.e. a^{-1}



Glacier mass balance change between 2000 – 2021 (Fan et al., 2023)

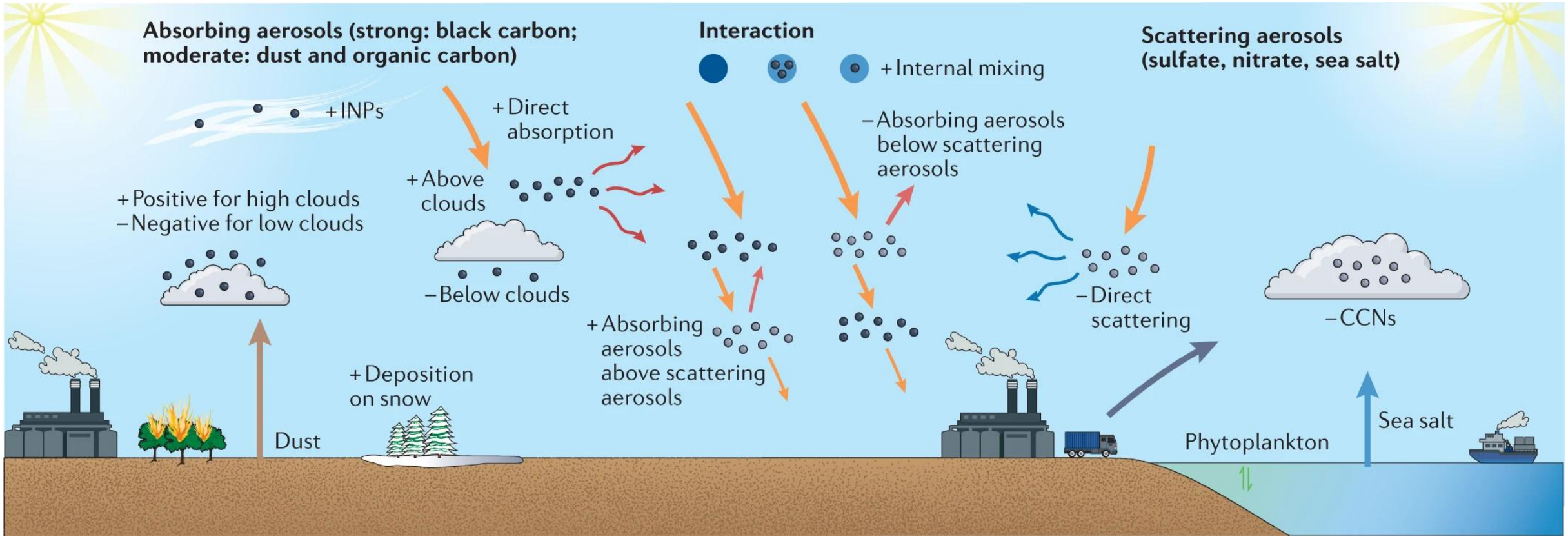
Future changes

- All subregions along the Himalaya lose at least 35% of their present-day volume by 2100.
- 10-20% for the Karakoram, Pamir Alai, Pamir, and Hindu Kush
- A volume gain of 2.1% for the Kunlun Shan



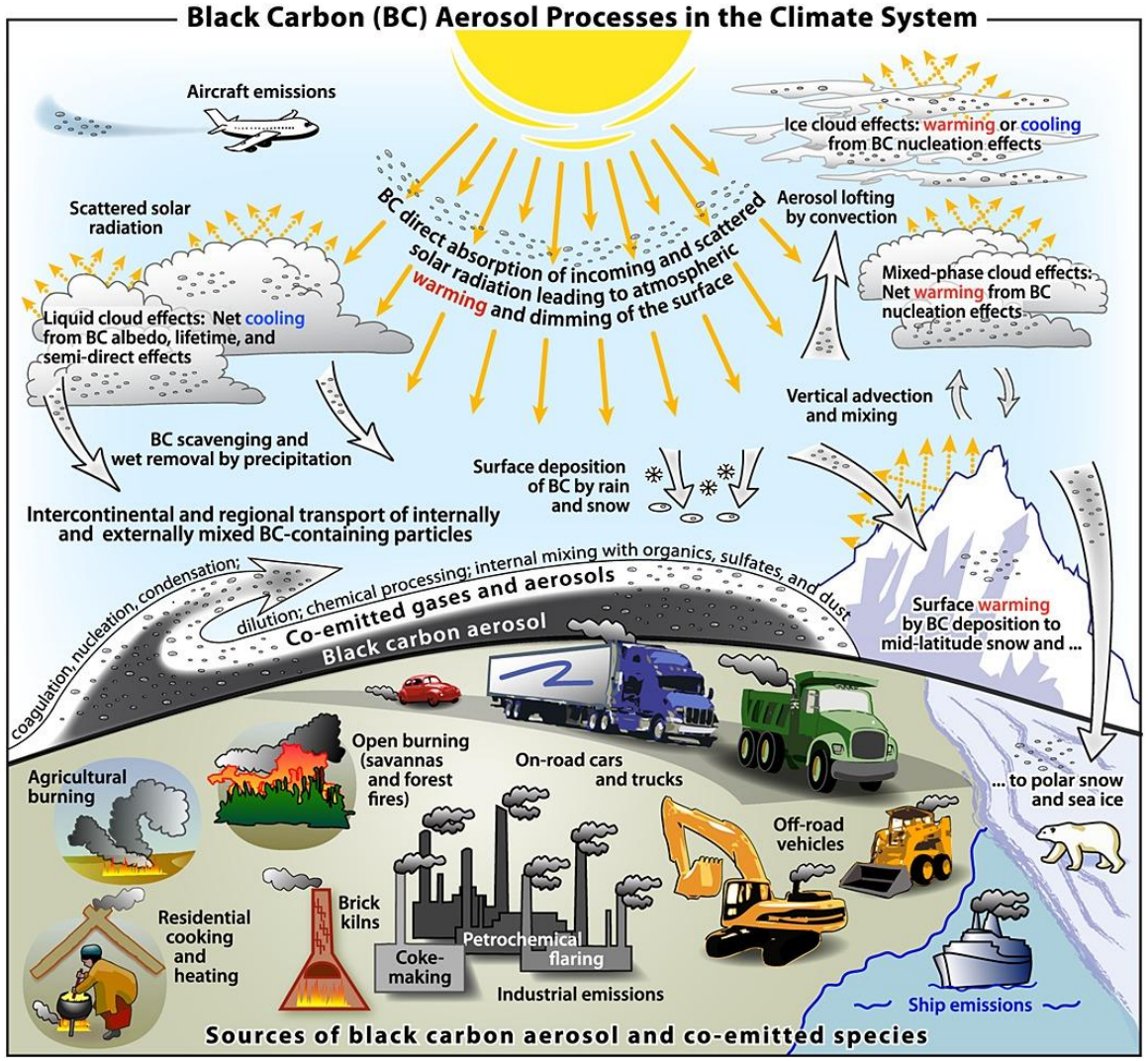
Changes in glacier volume and total ablation by 2100 implied by 2000-2016 mass balance regime (Miles et al., 2021)

Absorbing vs scattering aerosols

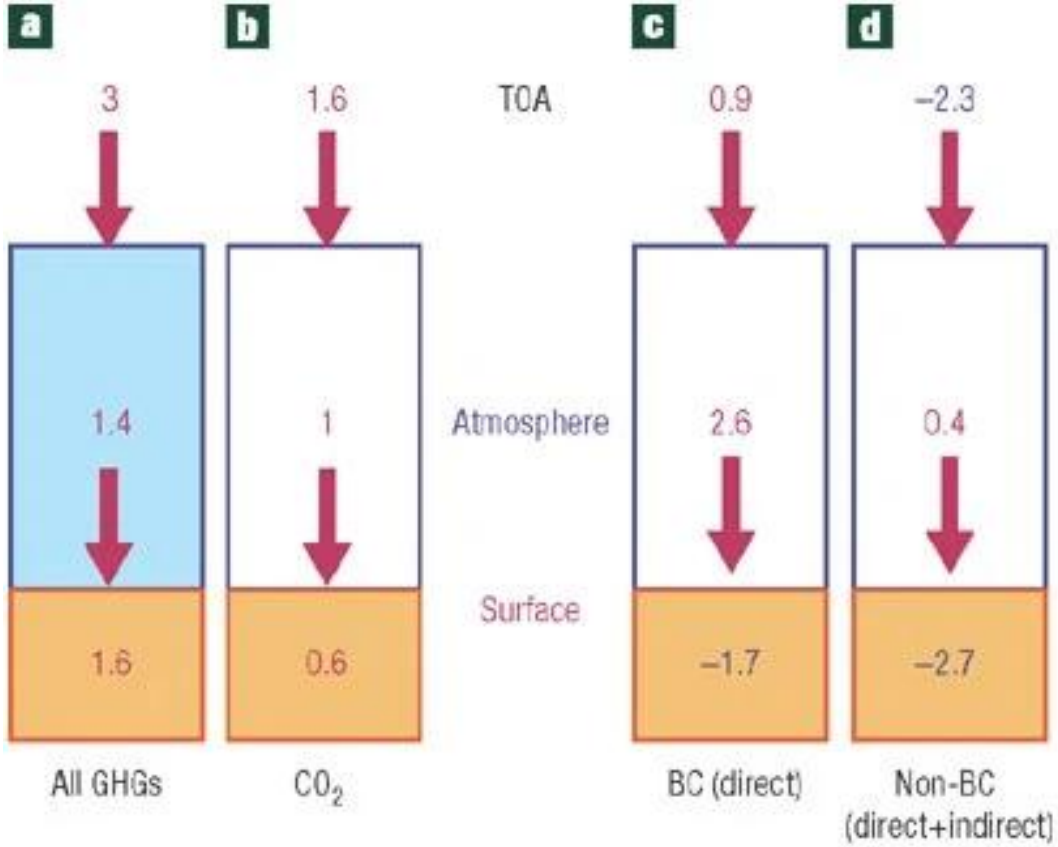


(Li et al., 2022)

Black carbon in the climate system

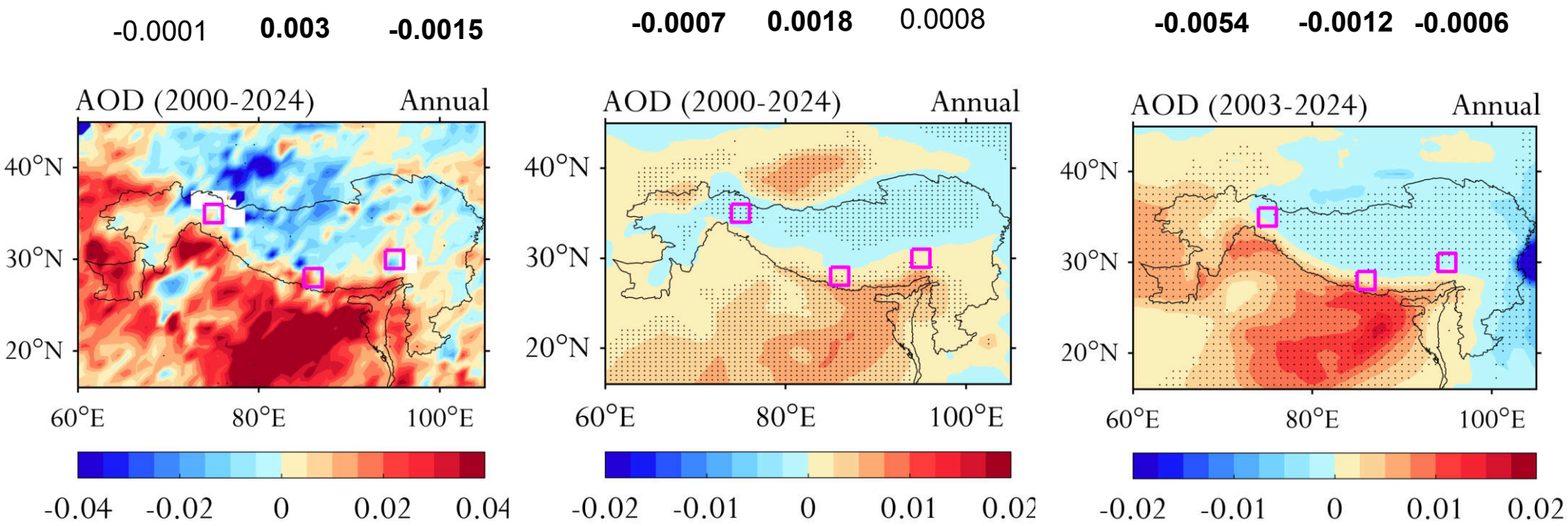


(Bond et al., 2013)



(Ramanathan & Carmichael, 2008)

Aerosol optical depth



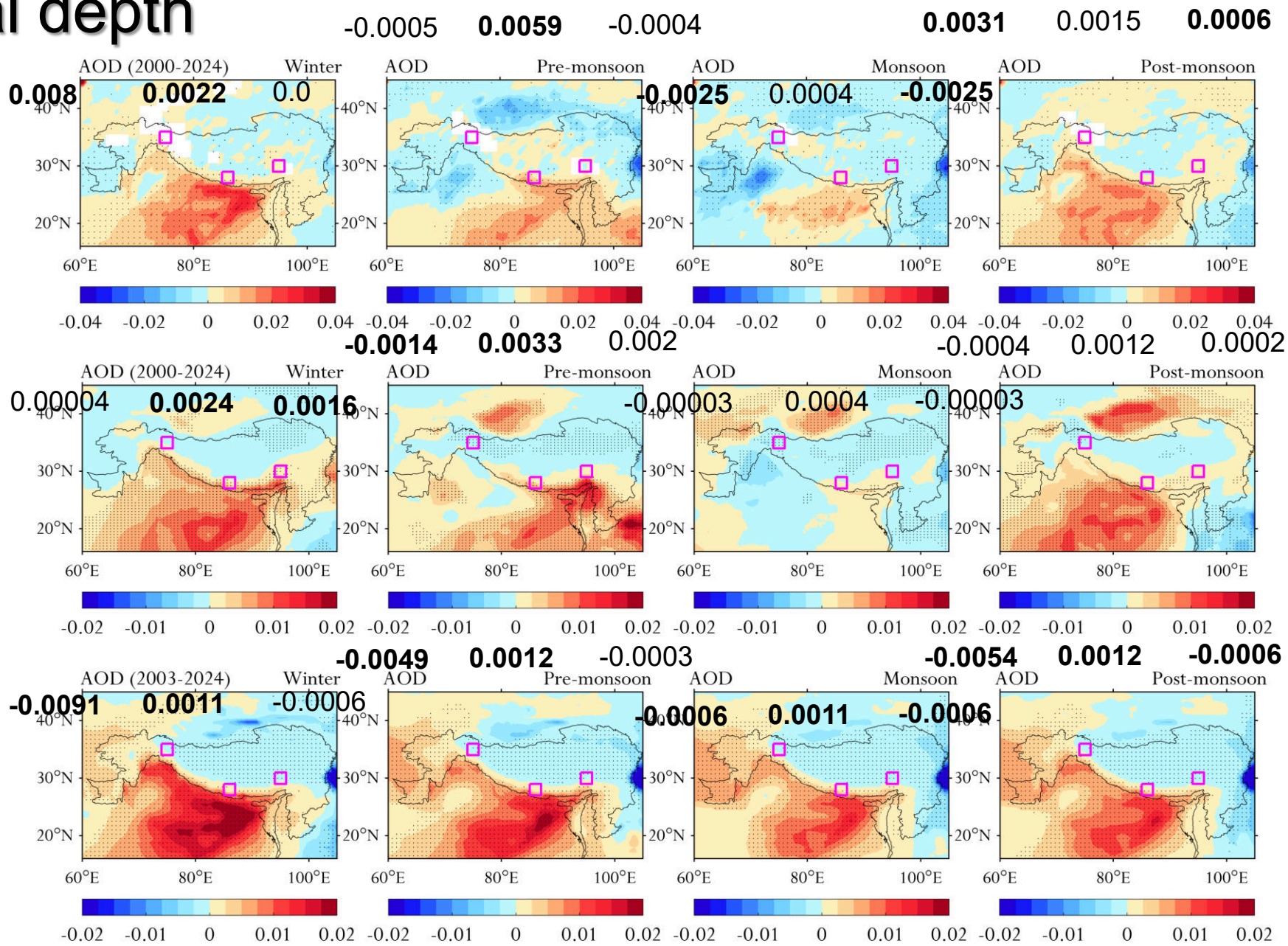
Trends of Annual AOD from MODIS, MERRA2, CAMS data

Aerosol optical depth

MODIS
1º × 1º

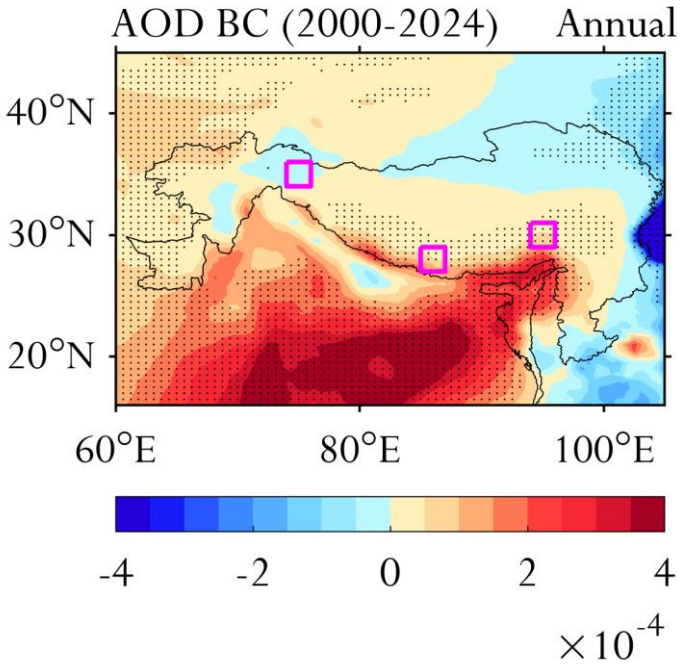
MERRA2
0.5º × 0.625º

CAMS
0.75º × 0.75º

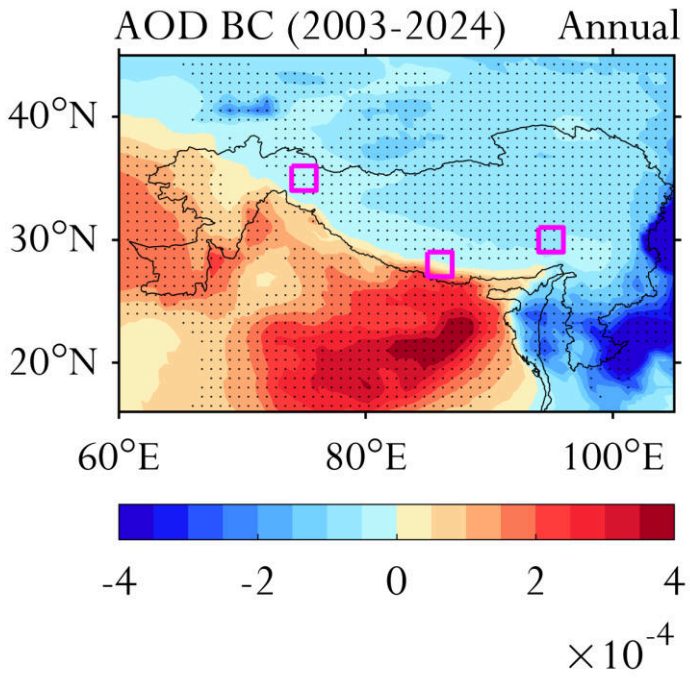


BC Aerosol optical depth

-0.000008 **0.00007** **0.00005**



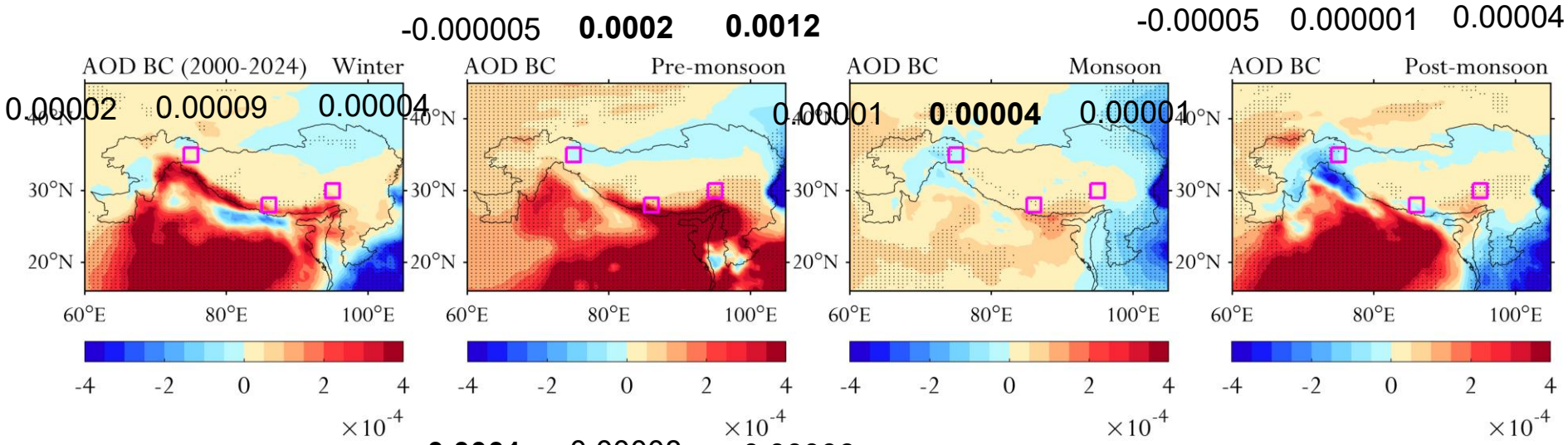
-0.00012 **0.00006** **0.00006**



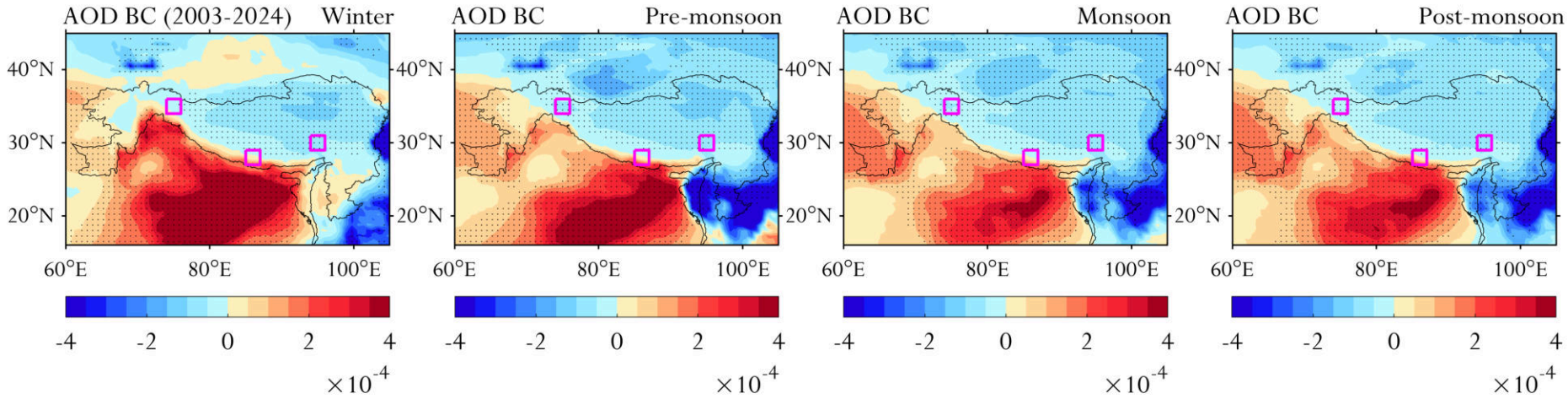
Trends of Annual BC AOD from MERRA2, and CAMS data

BC Aerosol optical depth

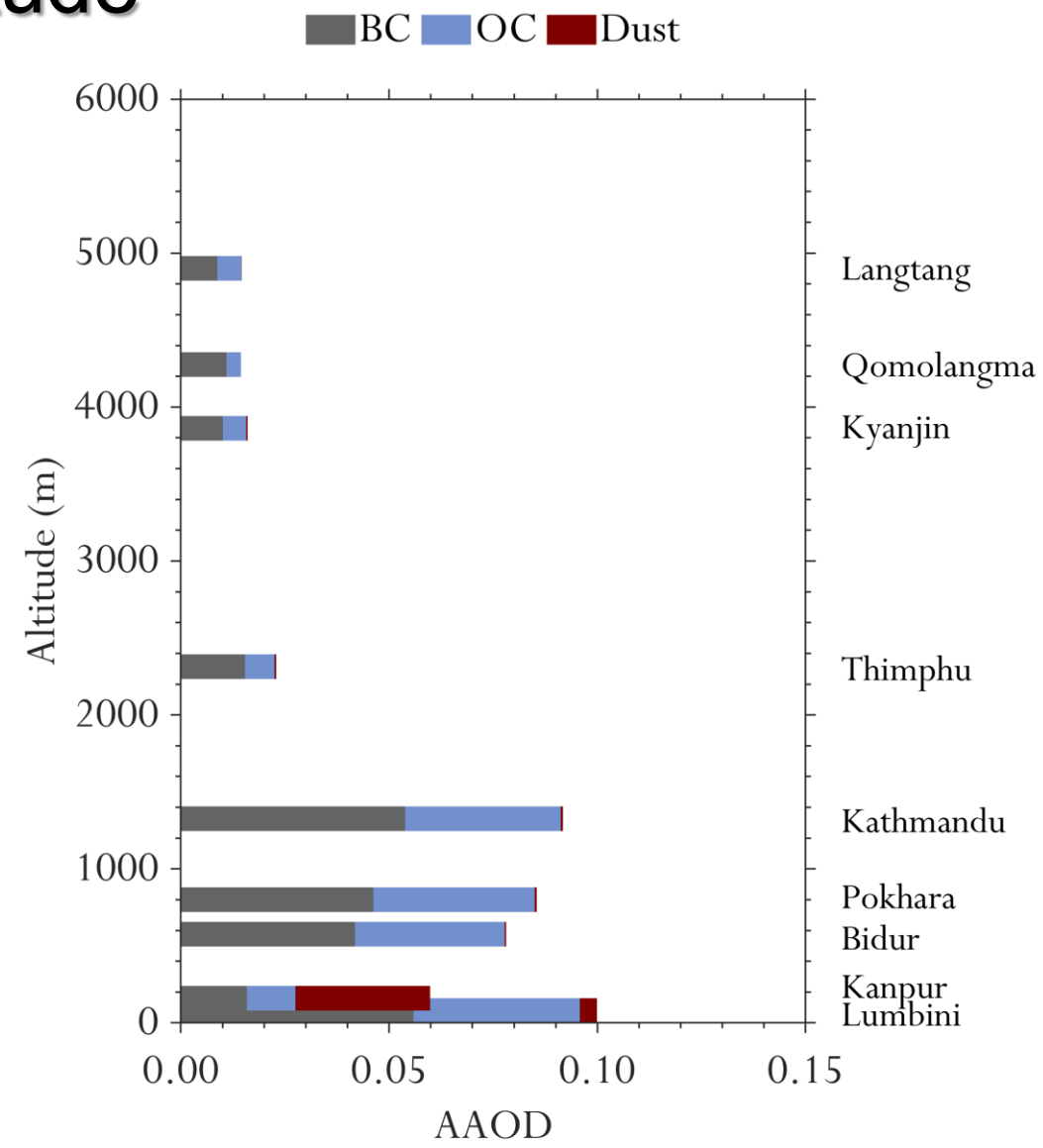
MERRA2



CAMS

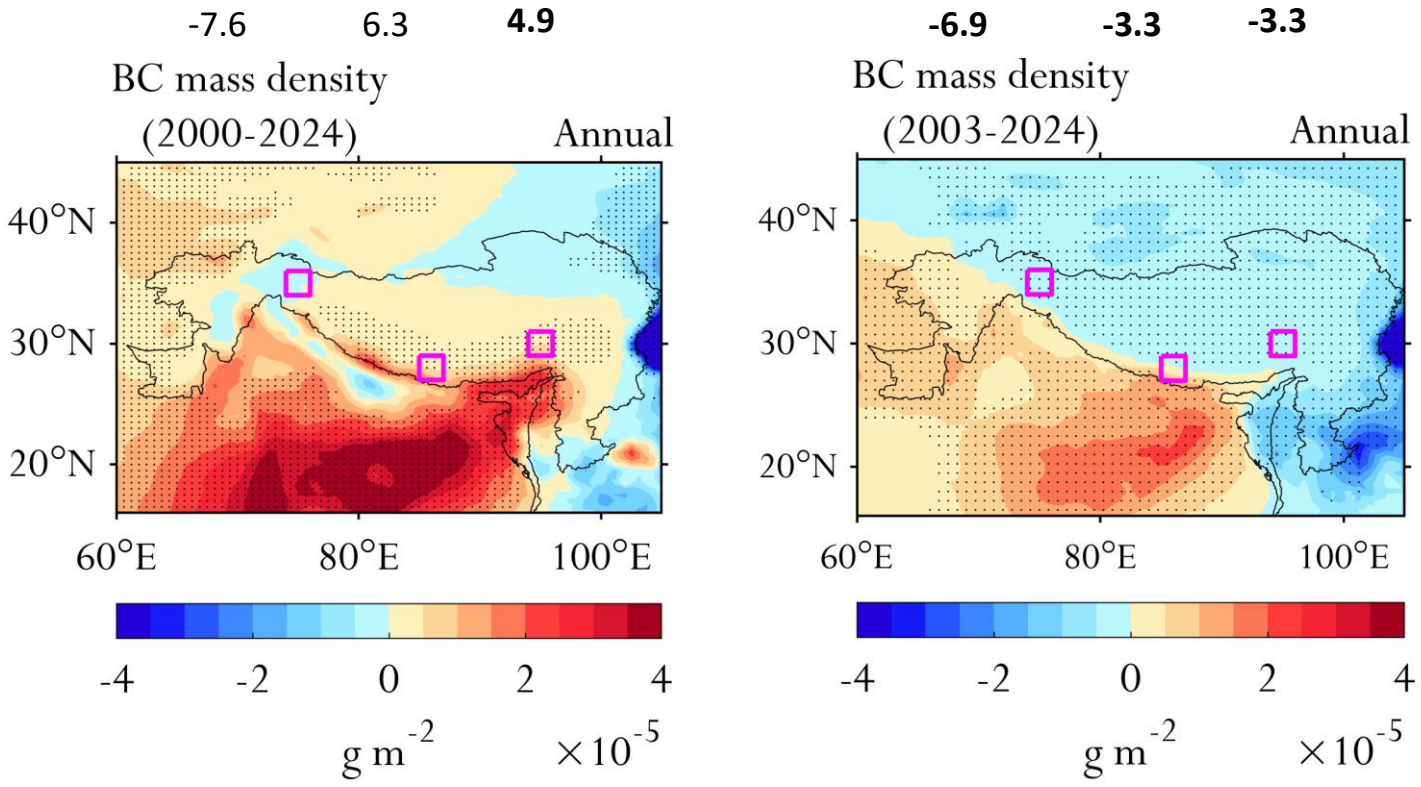


Variability with altitude



(Singh et al., 2025 (under review in STOTEN))

BC columnar density

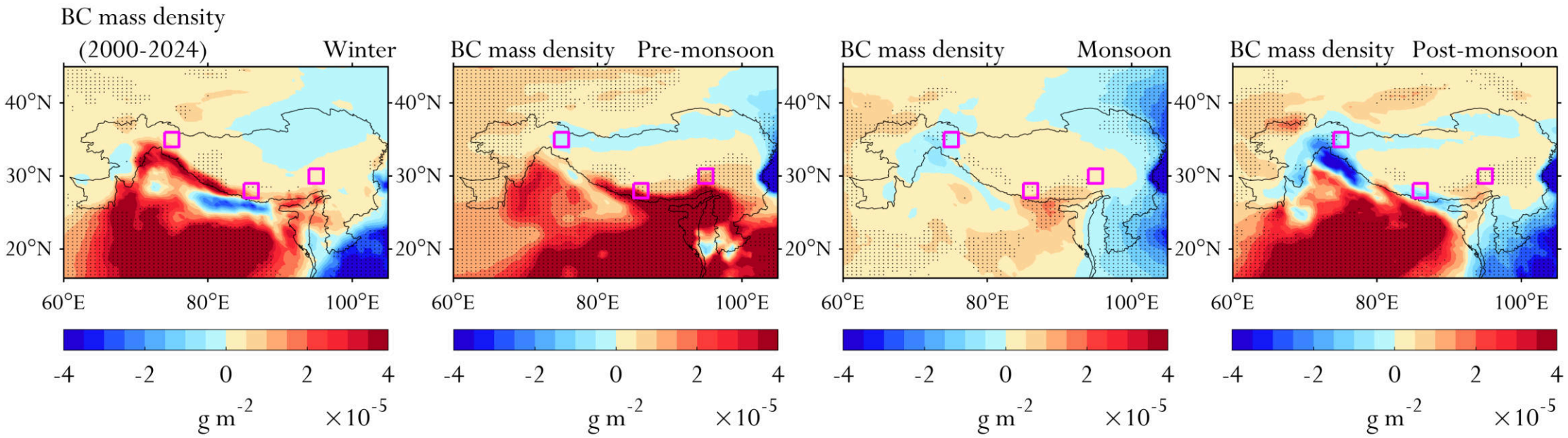


Trends of Annual BC mass density from MERRA2, and CAMS data

Trends are presented in the multiple of 10^{-9}

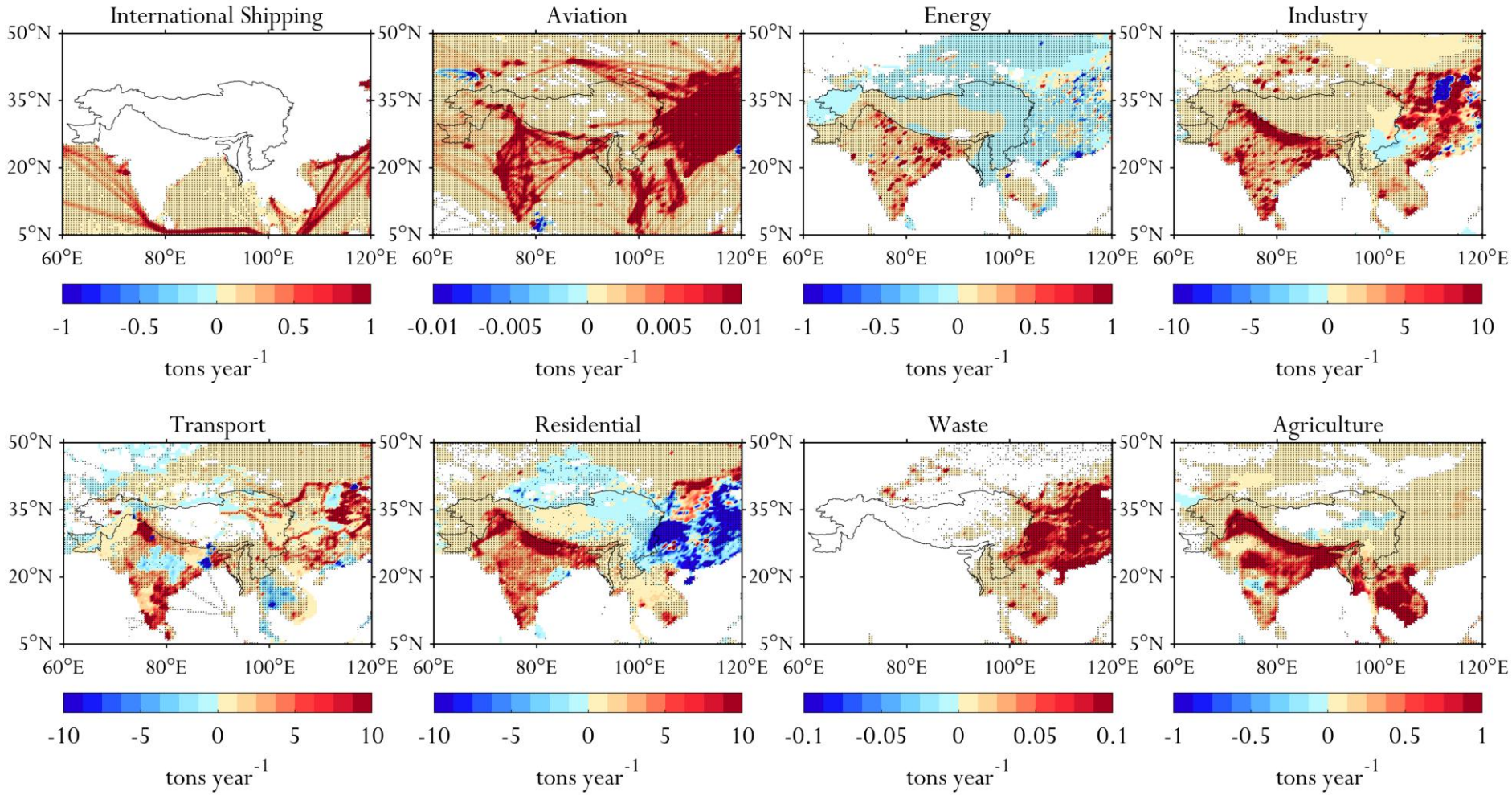
BC columnar density

3.7 6.3 0.86 -89 **22** **120** 1.6 **3.7** 1.6 **-5.8** -3.1 **3.8**



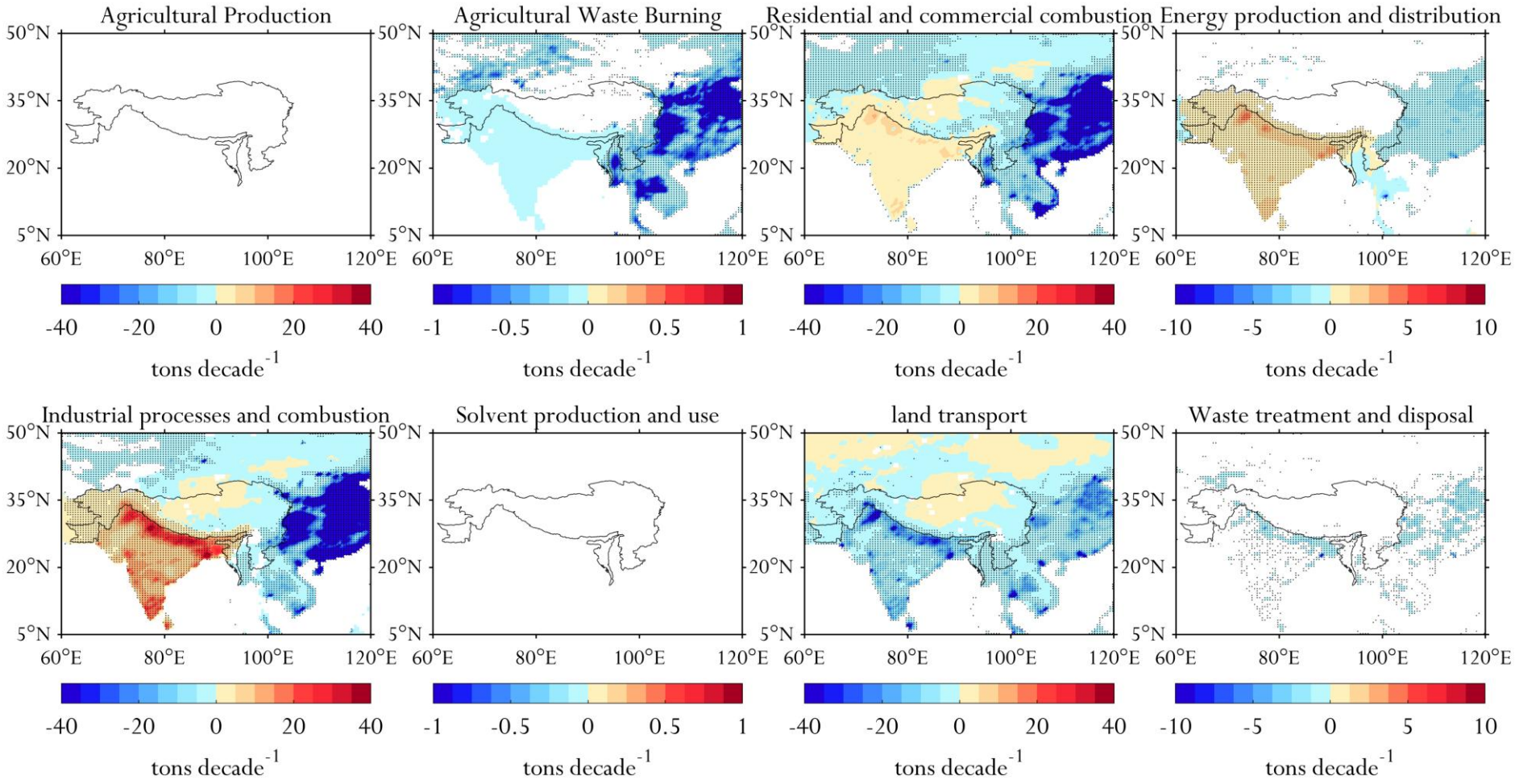
Trends are presented in the multiple of 10^{-9}

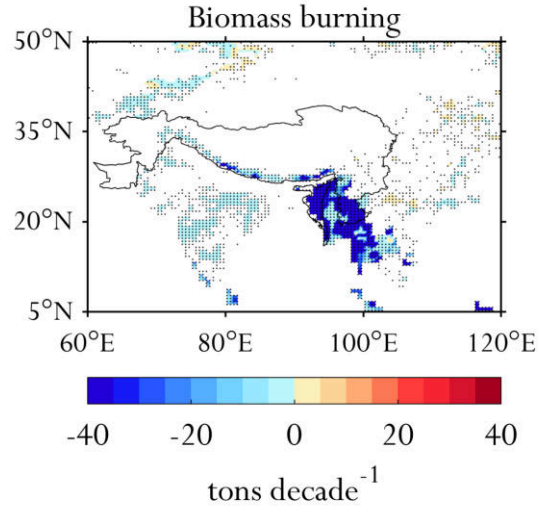
BC sectoral emission



BC sectoral emissions from EDGAR HTAPv3 data from 2000 to 2018

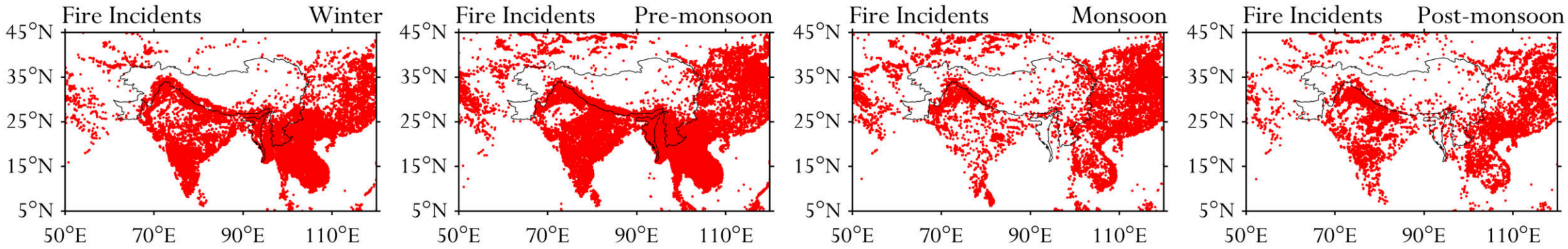
BC sectoral emission

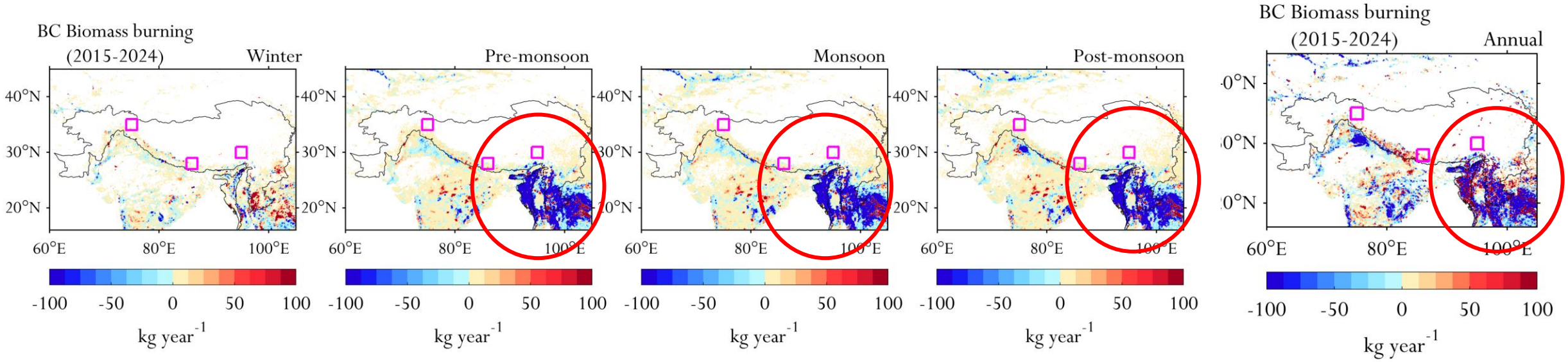




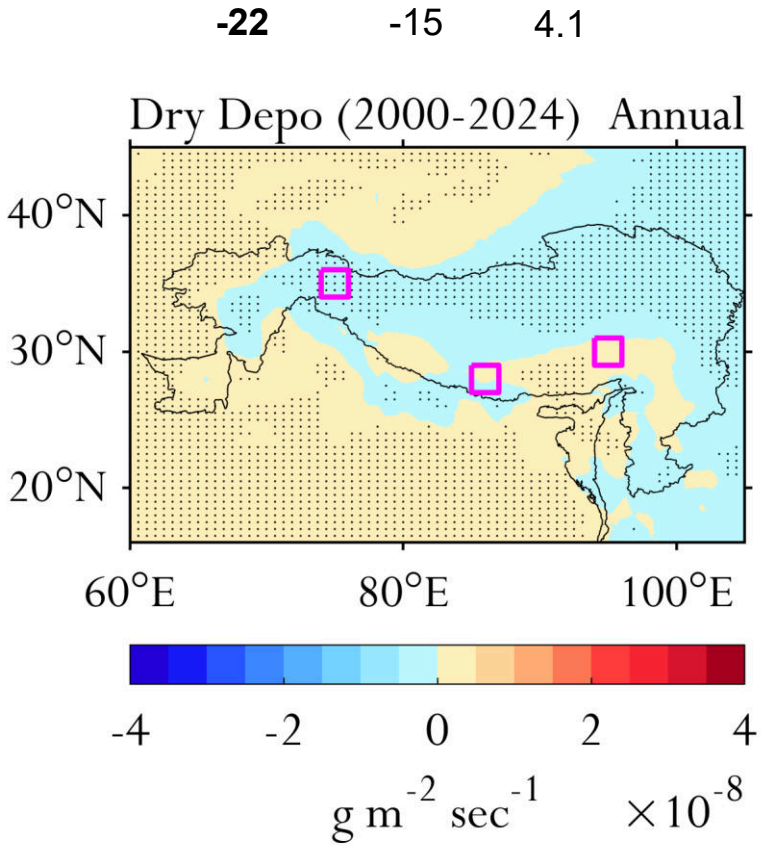
BC sectoral emissions from RCP 8.5 data from 2020 to 2050

BC from biomass burning



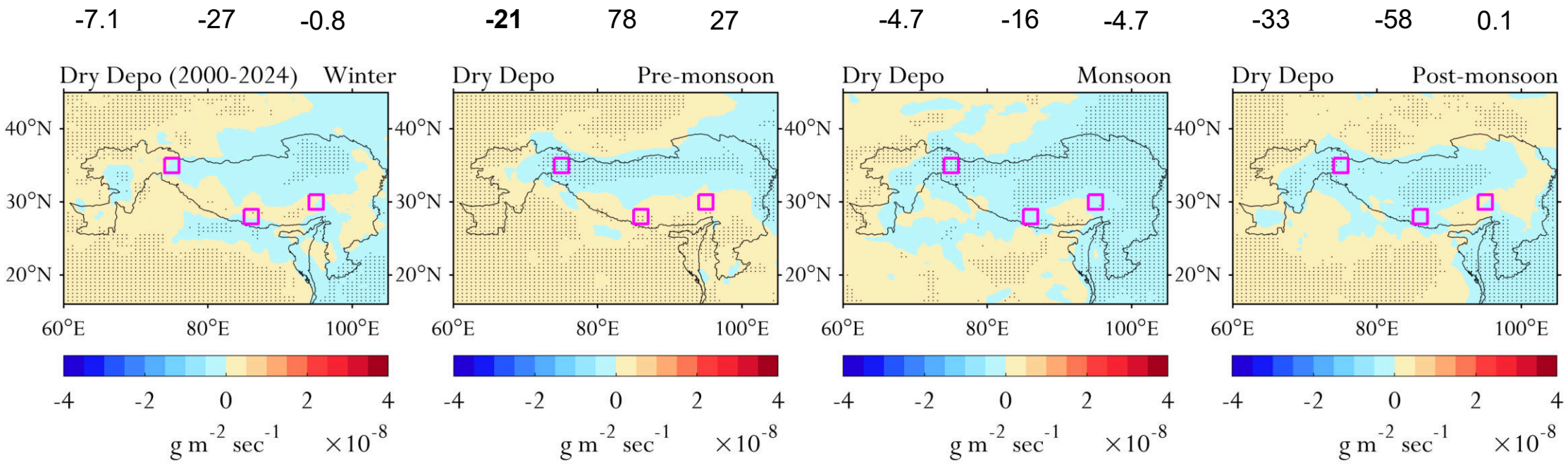


BC dry deposition



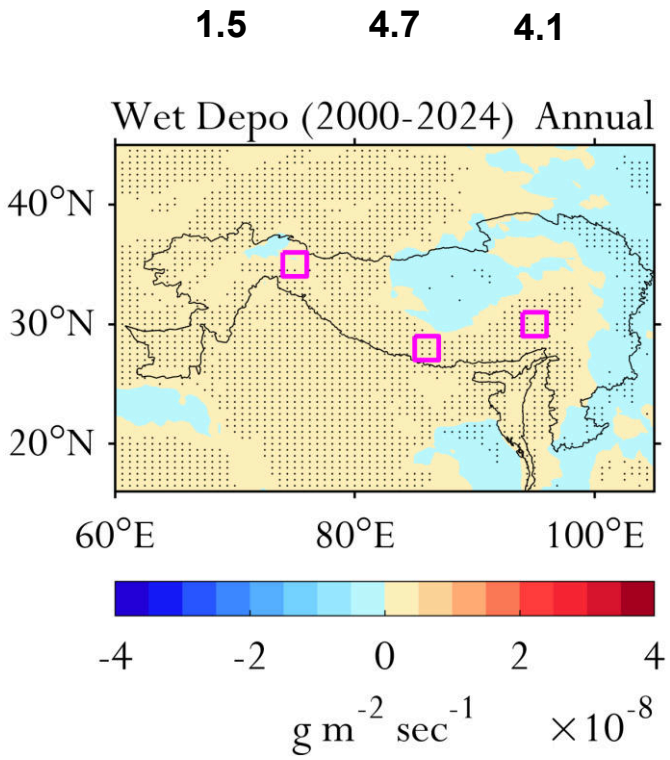
Trends are presented in multiple of 10^{-16}

BC dry deposition



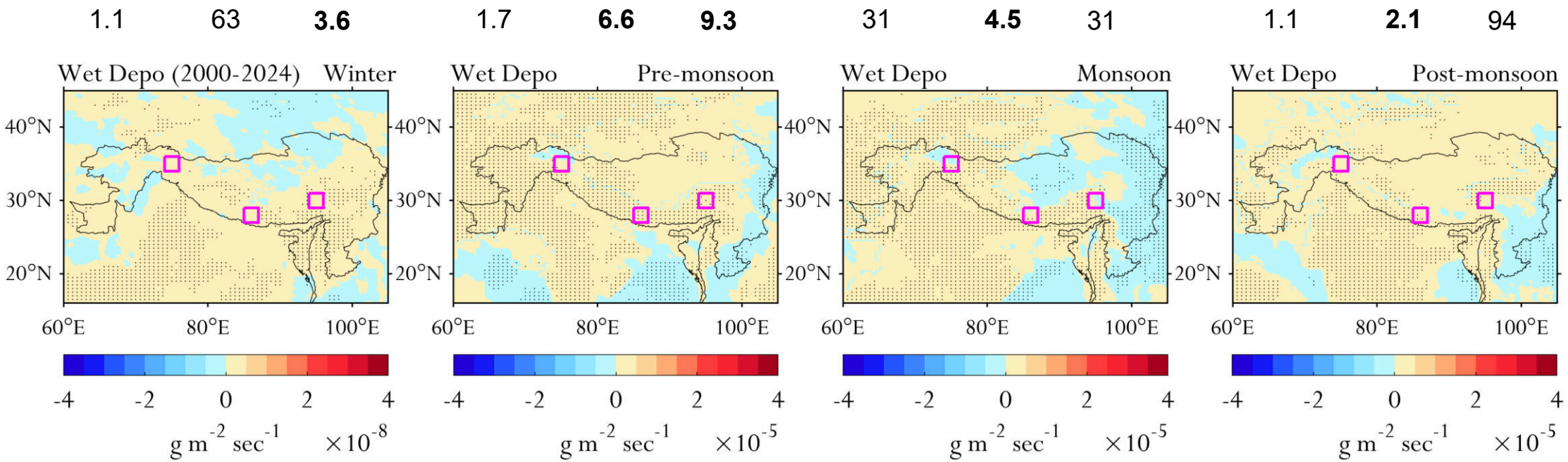
Trends are presented in 10^{-16}

BC wet deposition



Trends are presented in multiple of 10^{-14}

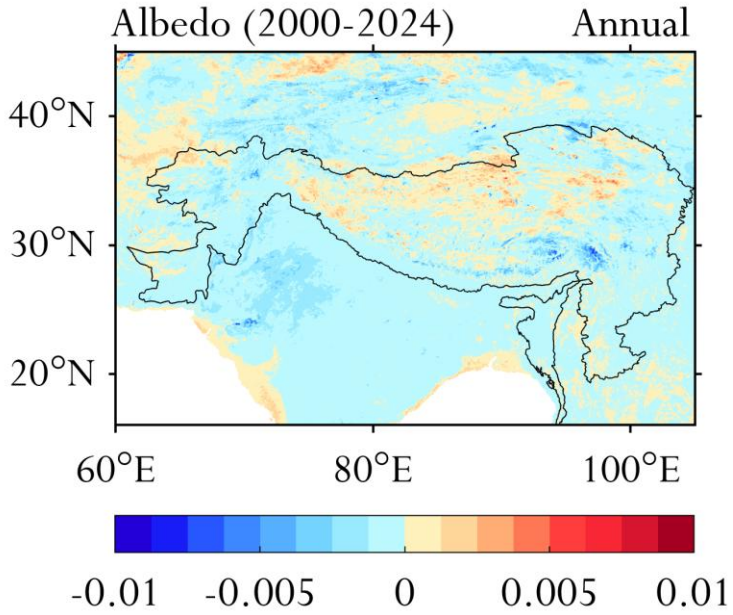
BC wet deposition

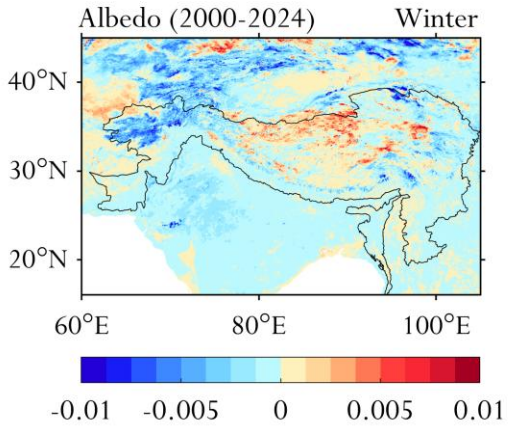


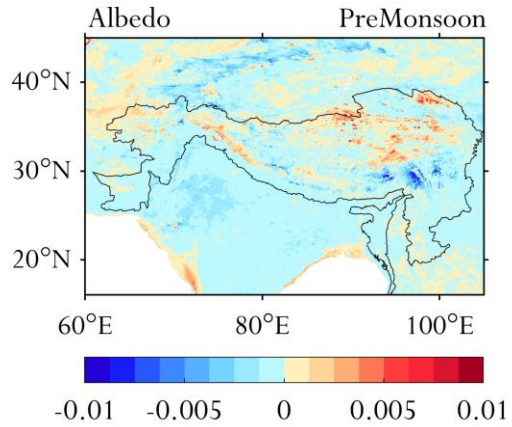
Trends are presented in multiple of 10^{-14}

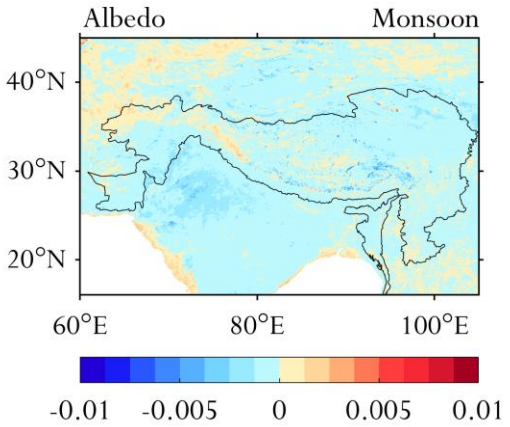
Albedo

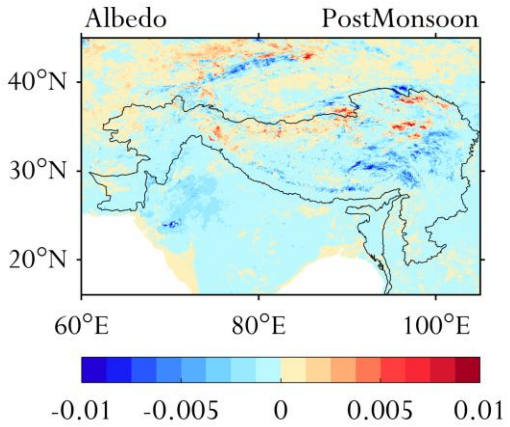
MODIS
0.05º × 0.05º



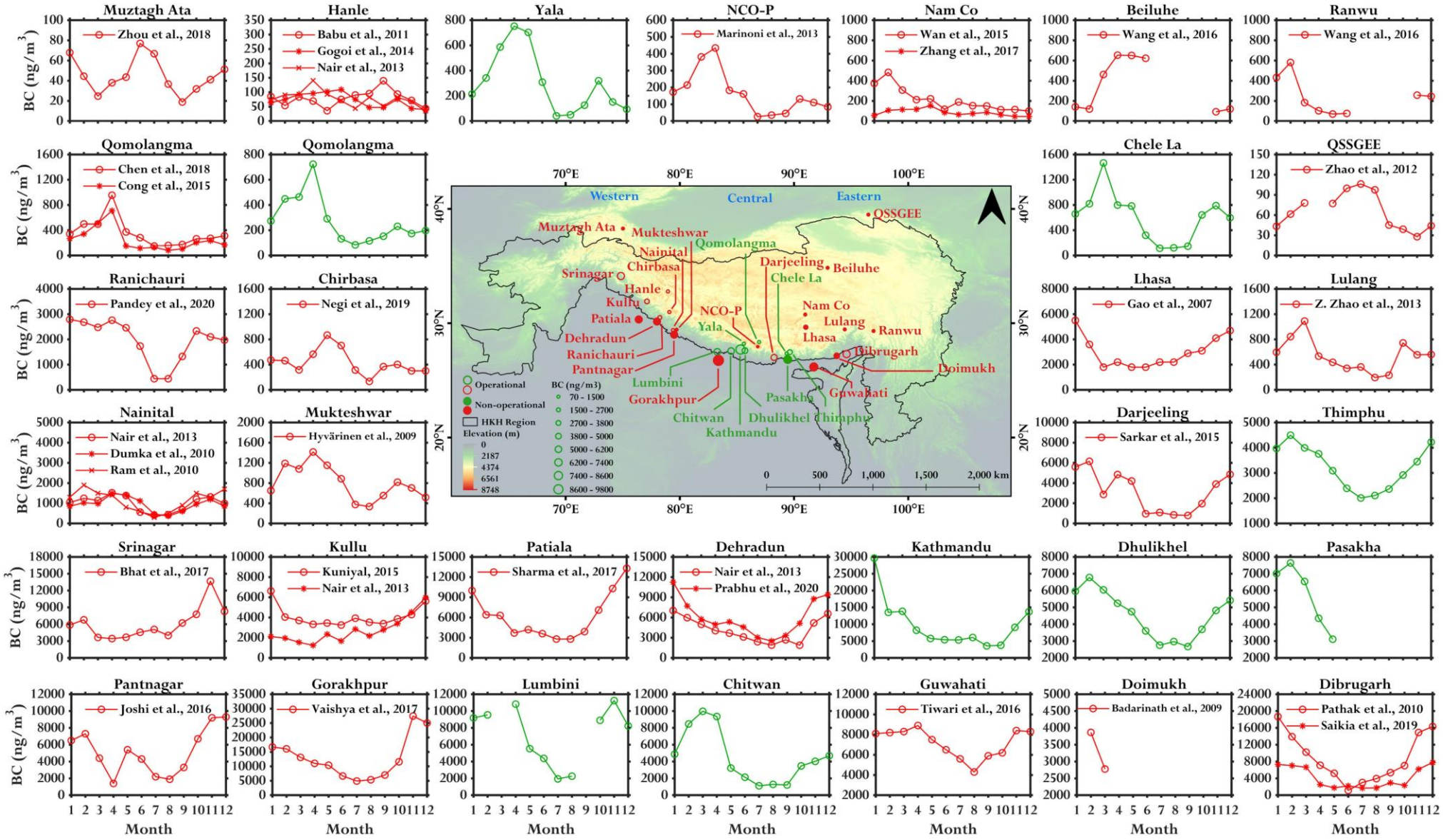






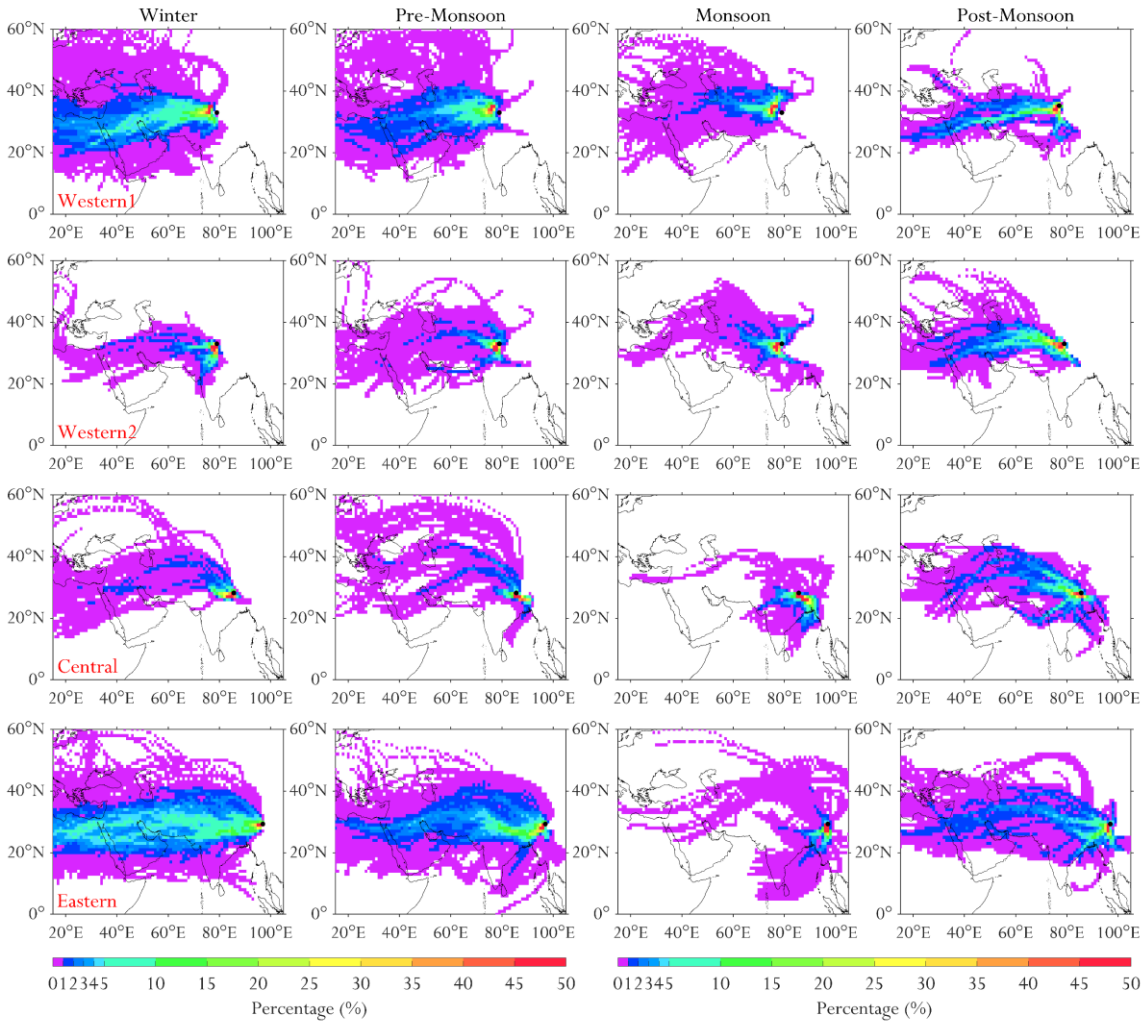


Status of BC monitoring and its seasonal variability over HKH

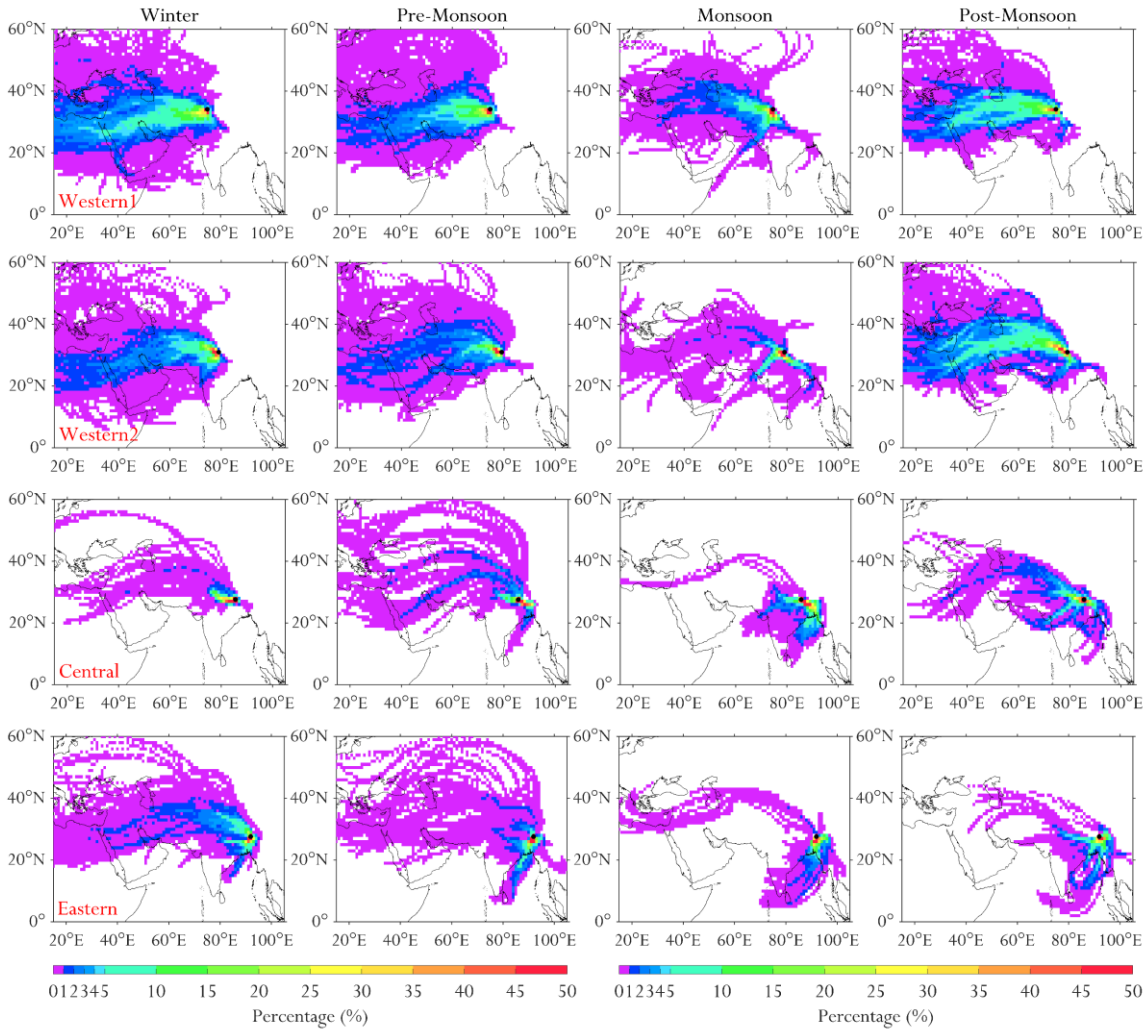


(Singh et al., 2023)

Transportation of BC over the HKH

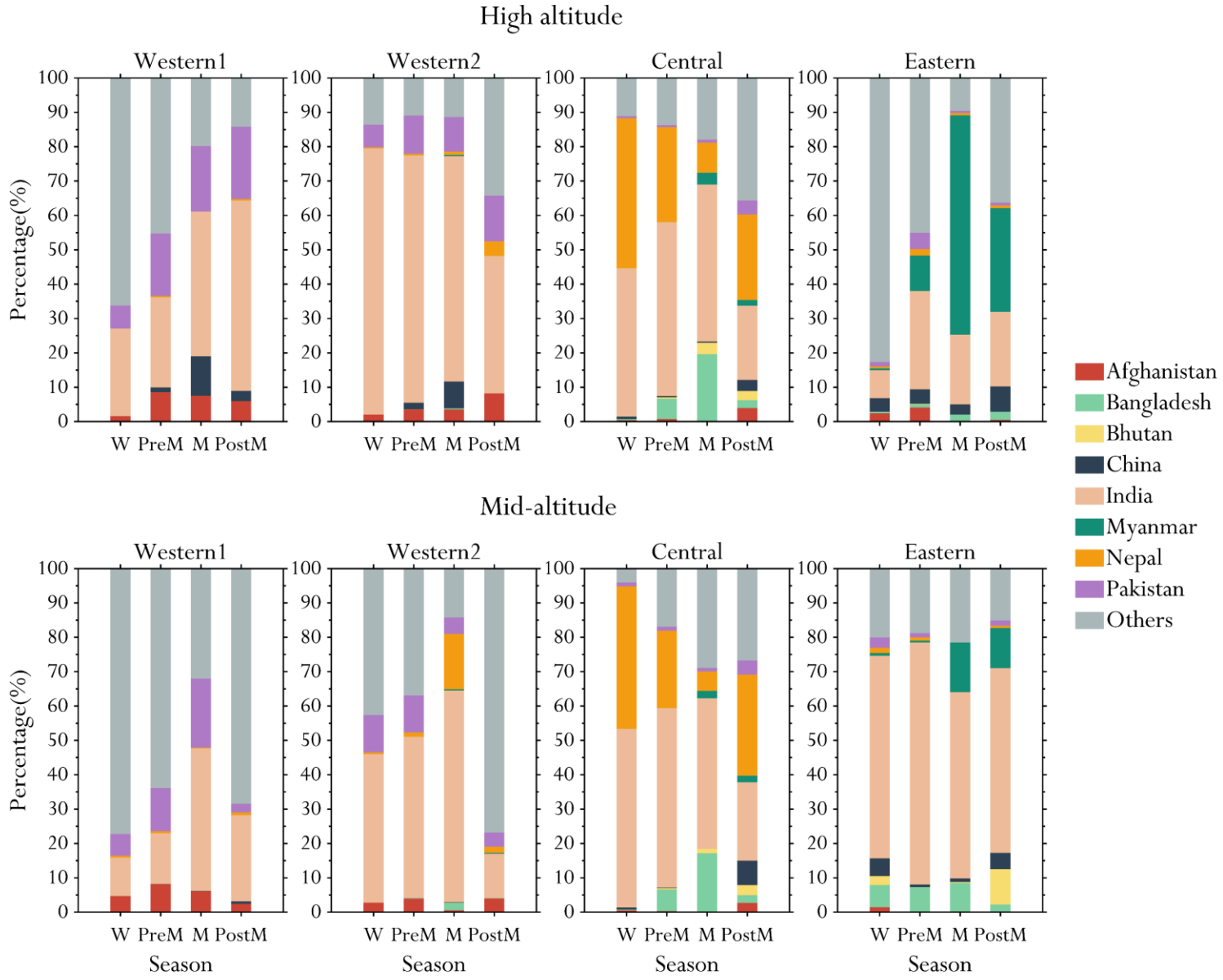


Transport patterns over the high-altitude sites



Transport patterns over the mid-altitude sites

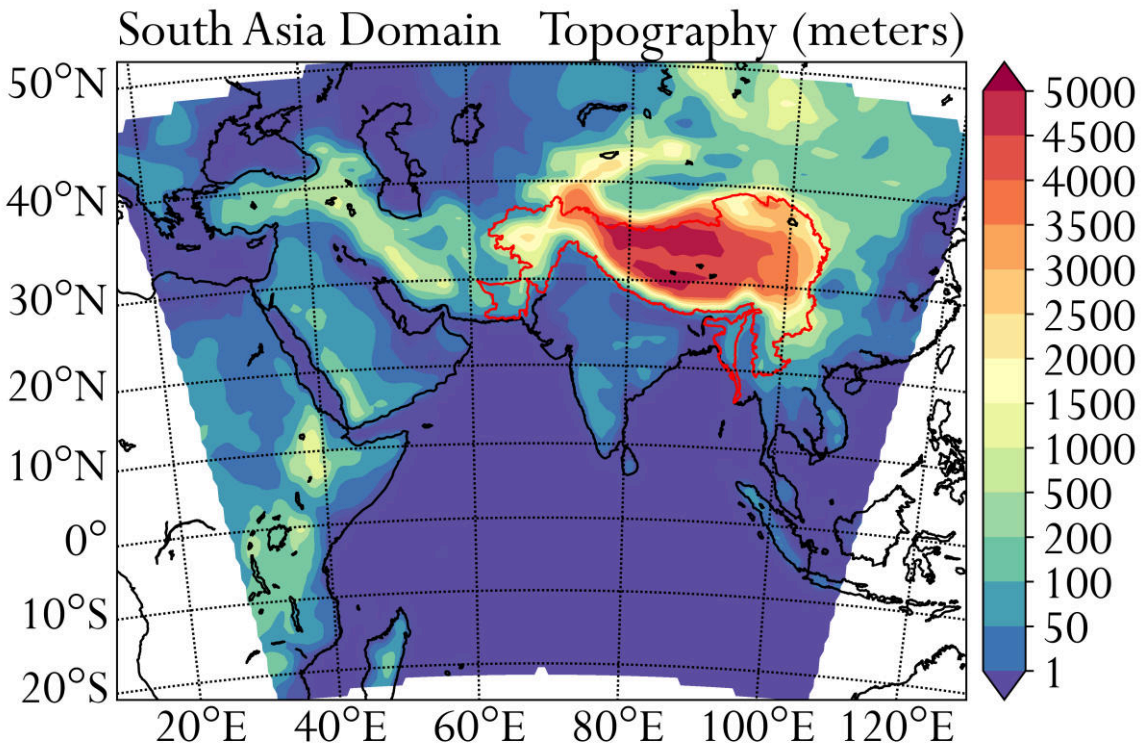
(Singh et al., 2023)



Analysis of the origin of air mass trajectories

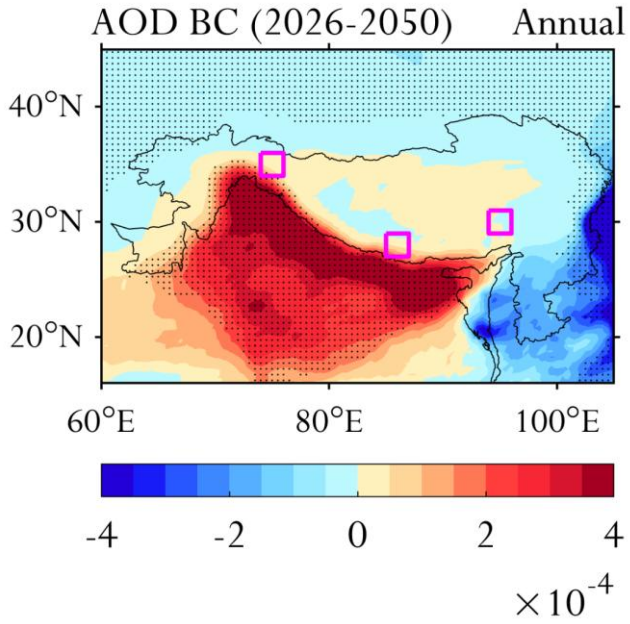
(Singh et al., 2023)

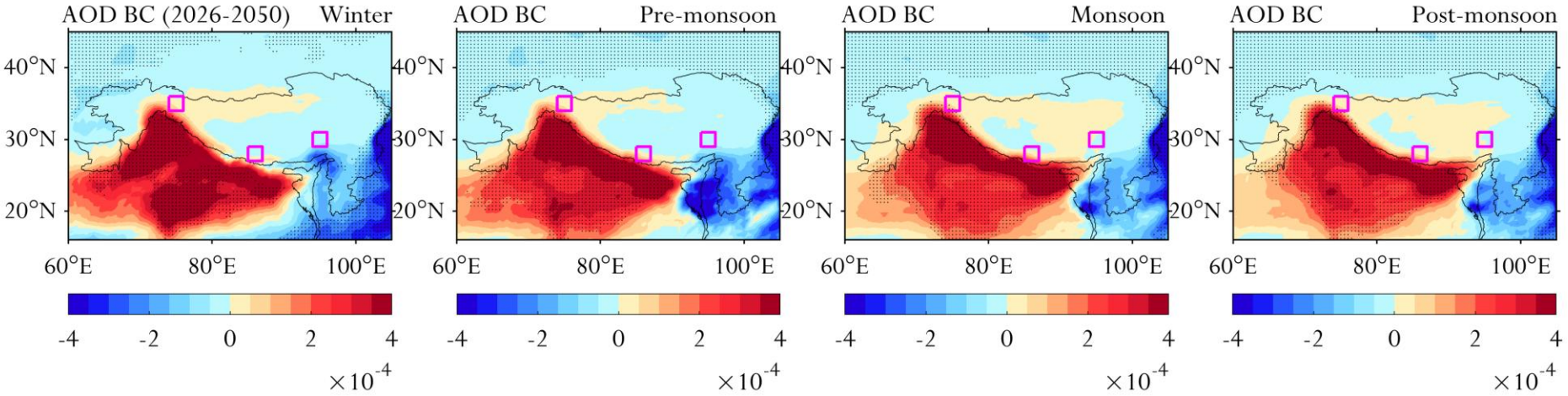
RegCM model Domain used for simulation



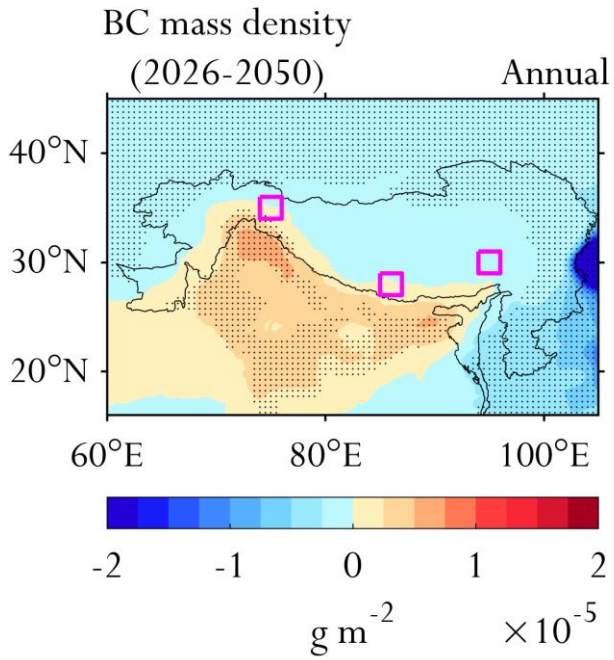
CORDEX domain	180*162 grid point and 23 vertical levels (top at 50 hPa)
lateral boundary conditions	GFDL-ESM2M
LULC	USGS at 30-sec resolution
Aerosol boundary conditions and emissions	RCP database
Boundary layer scheme	UW PBL (Bretherton and McCaa, 2004)
convection	• MIT convection scheme (Emanuel and Živković-Rothman, 1999) over land • Tiedtke scheme (Tiedtke, 1993, 1989) over the ocean
Radiation	RRTM radiation scheme
Moisture	Subgrid Explicit Moisture Scheme (Pal et al., 2000)
Land surface	CLM4.5

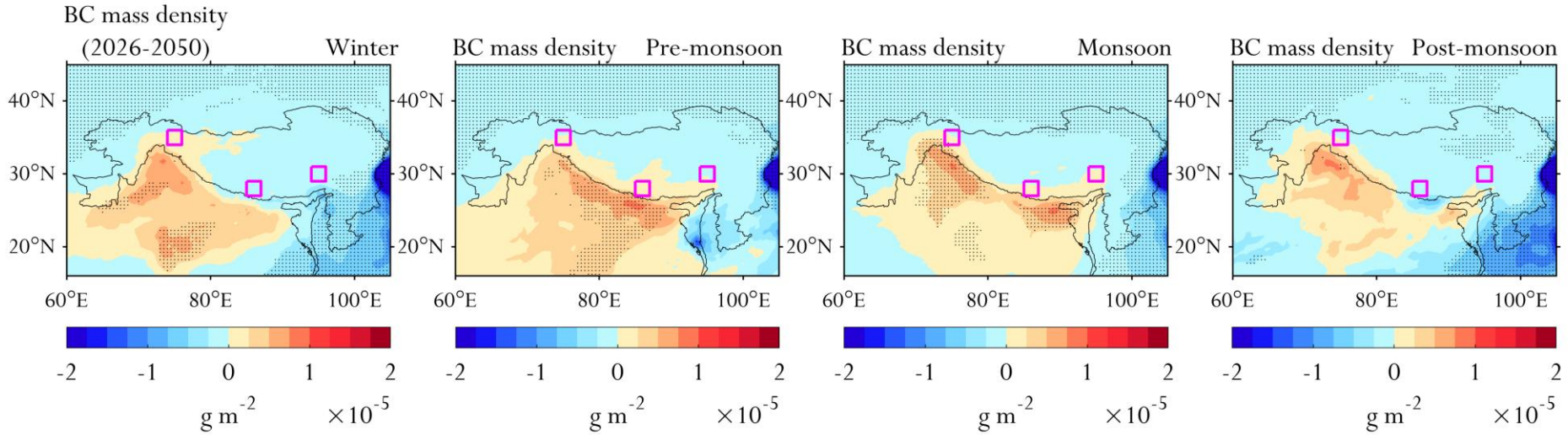
BC Aerosol optical depth



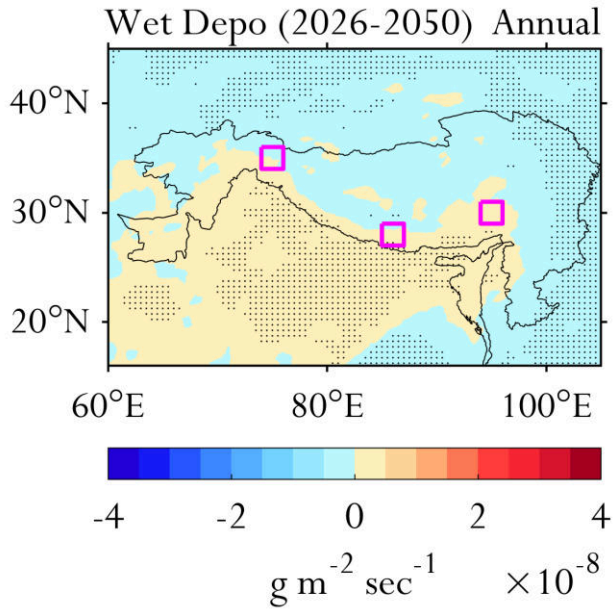


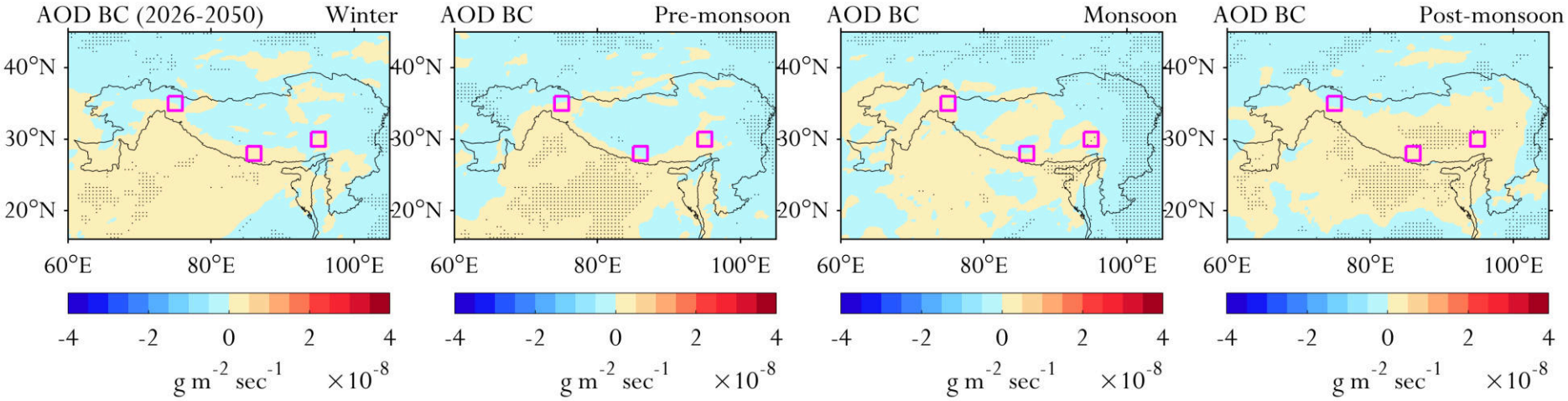
BC mass density



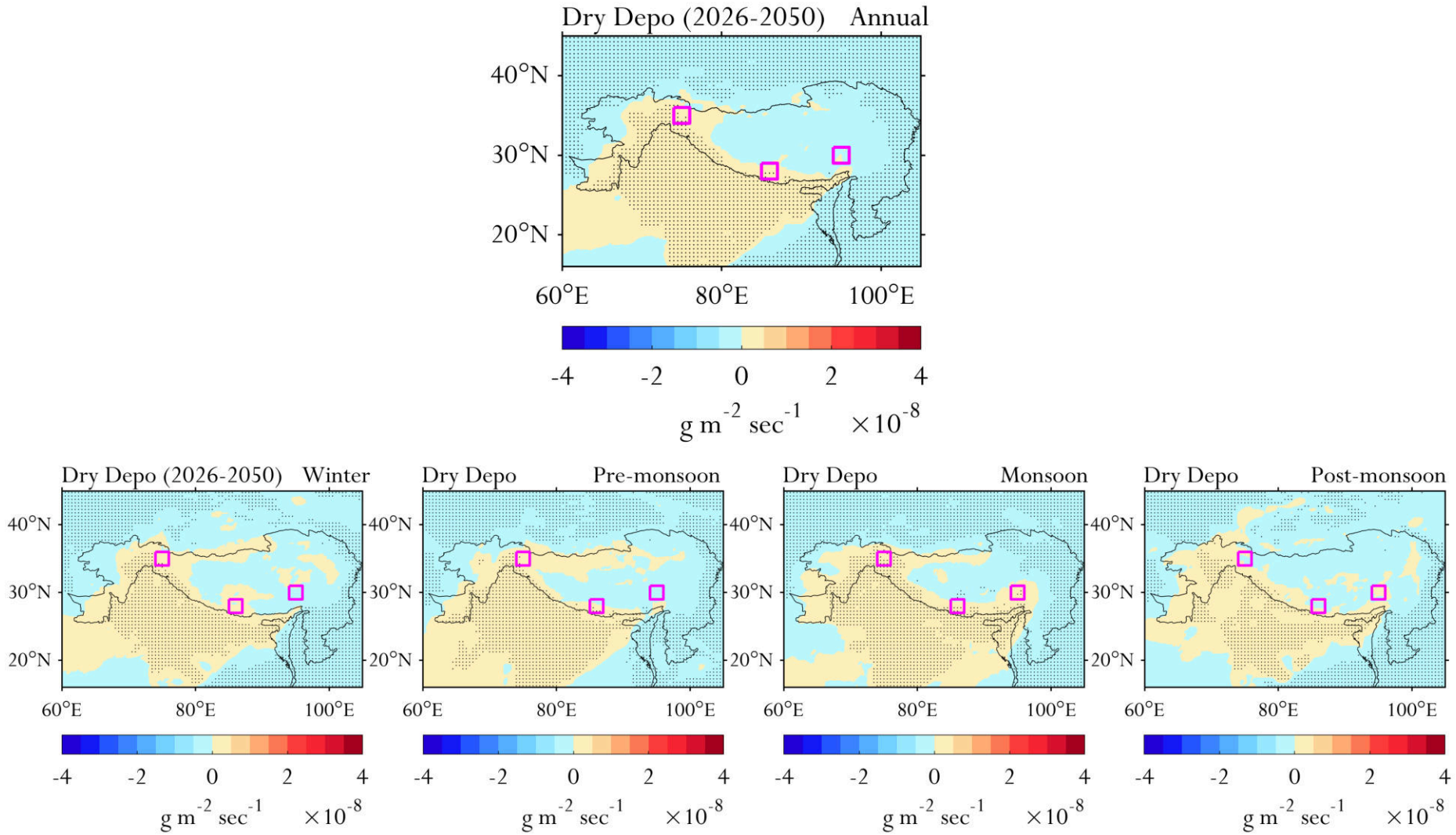


BC wet deposition

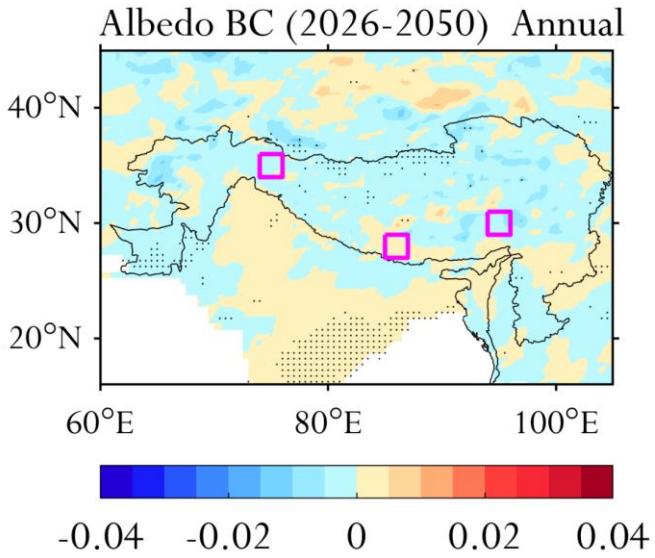


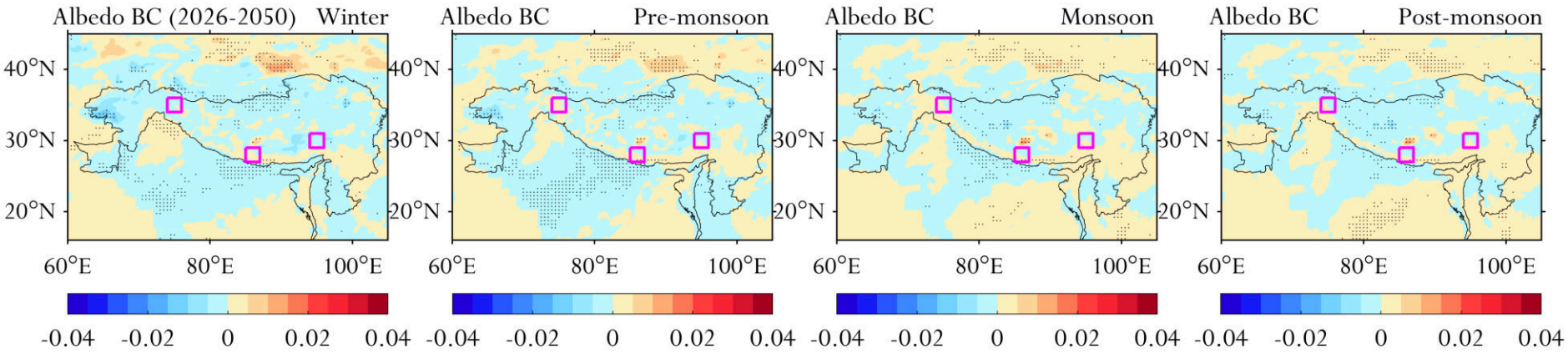


BC dry deposition



Albedo


Albedo BC (2026-2050) Annual
40°N
30°N
20°N
60°E
80°E
100°E
-0.04
-0.02
0
0.02
0.04


Albedo BC (2026-2050) Winter
Albedo BC Pre-monsoon
Albedo BC Monsoon
Albedo BC Post-monsoon
40°N
30°N
20°N
60°E
80°E
100°E
-0.04
-0.02
0
0.02
0.04

Key takeaways

- Apart from climate change BC is a significant driver for glacial changes in the HKH region
- Problem is transboundary and regional cooperation is essential
- Investment in clean technologies is the need of hour
- Systemic interventions are required targeting one sector at a time

Acknowledgements

- Different data teams for proving open access data
- RegCM model development team
- IIT Roorkee for providing infrastructure to carry out this work
- ICIMOD for hosting me during my Ph.D. and providing this platform to show this work

For questions, collaborations, and further discussions

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