Simulating the winter and pre-monsoon aerosol optical depth with new emission inventories over the Indian subcontinent: Implication to dust and anthropogenic contribution

by

Mukul Kumar

MS (by Research)

Prof. Shubha Verma
&
Prof. Amey Pathak

Advanced Technology Development Centre
Indian Institute of Technology Kharagpur
December, 2022

NCAP-COALESCE

Understanding scientific complexities related to carbonaceous aerosols focussing on issues underlying their origin and fate, and their role as drivers of regional climate change over India.

CarbOnaceous AerosoL Emissions, Source apportionment & ClimatE impacts

ACAM

ATMOSPHERIC COMPOSITION & THE ASIAN MONSOON

Ph.D. (PMRF)

Prof. Sagnik Dey
&
Prof. Dilip Ganguly

Centre for Atmospheric Science
Indian Institute of Technology Delhi
June, 2023

Background and Motivation

- **An aerosol is a suspension of solid or liquid particles in a gaseous medium.**
- **Aerosol is emitted from natural sources (desert dust, pollen, sea salt spray, volcanic eruption, etc.) and anthropogenic sources (industries, power plants, and vehicles).**
- **Aerosol impacts human health and the Earth's climatic system.**
- **Air pollution is one of the world's biggest killers, responsible for 4.2 million deaths per year (1 in every 13 deaths) (WHO, 2016).**

Background and Motivation

- An aerosol is a suspension of solid or liquid particles in a gaseous medium.

- Aerosol is emitted from natural sources (desert dust, pollen, sea salt spray, volcanic eruption, etc.) and anthropogenic sources (industries, power plants, and vehicles).

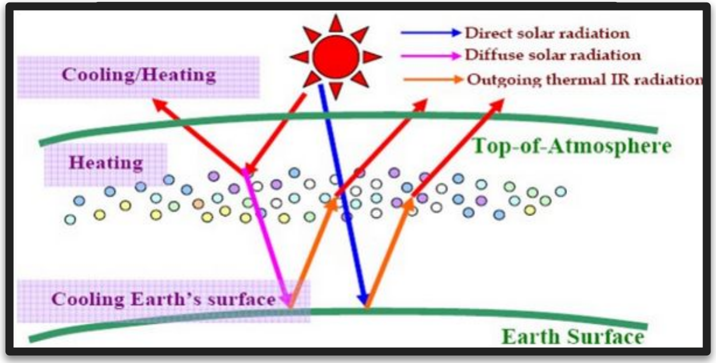
- Aerosol impacts human health and the Earth's climatic system.

- Air pollution is one of the world's biggest killers, responsible for 4.2 million deaths per year (1 in every 13 deaths) (WHO, 2016).

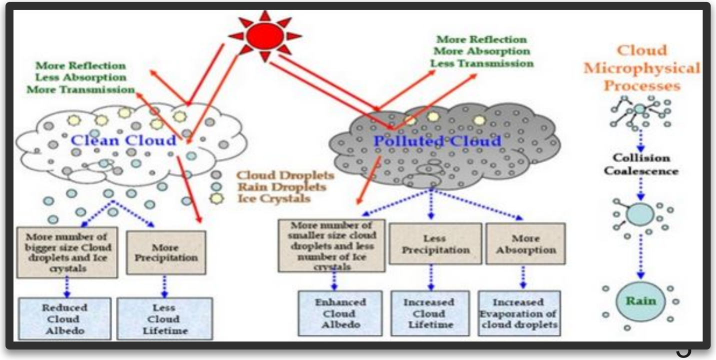
- Aerosol plays one of the leading roles in altering atmospheric radiative balance (Foster, 2007).

- Aerosol affects the Earth's climate through direct and indirect effects (Boucher et al., 2013).

Aerosols direct effect

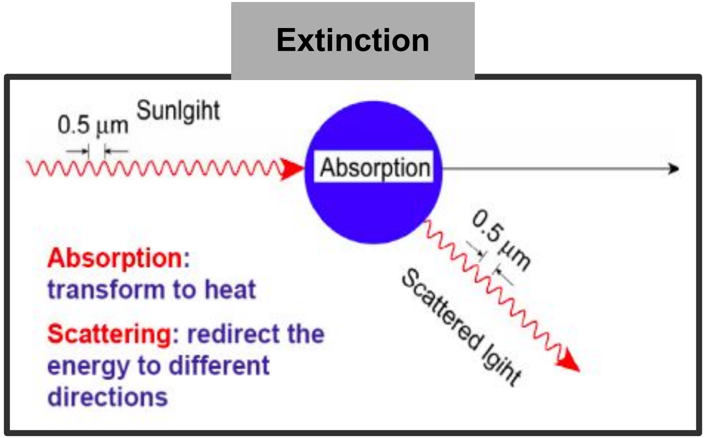


Aerosols indirect effect



Background and Motivation

- **Estimation of aerosol-induced climatic or health impact, requires accurate analysis of aerosol optical properties (aerosol optical depth (AOD), Single scattering albedo (SSA)).**
- **Aerosol has a very short residence time (about a week) in the atmosphere leading to its increased concentration near the source regions, exhibiting a substantial spatial and temporal variation (Ramachandran and Kedia, 2010; Babu et al., 2013) .**



AOD

$$\tau = \int_{surface}^{top\ of\ atmosphere} \sigma^{ext}(z)\, dz.$$

where
τ : Aerosol Optical Depth
σ^{ext} : Extinction Coefficient (m^{-1})
Z: distance (m)

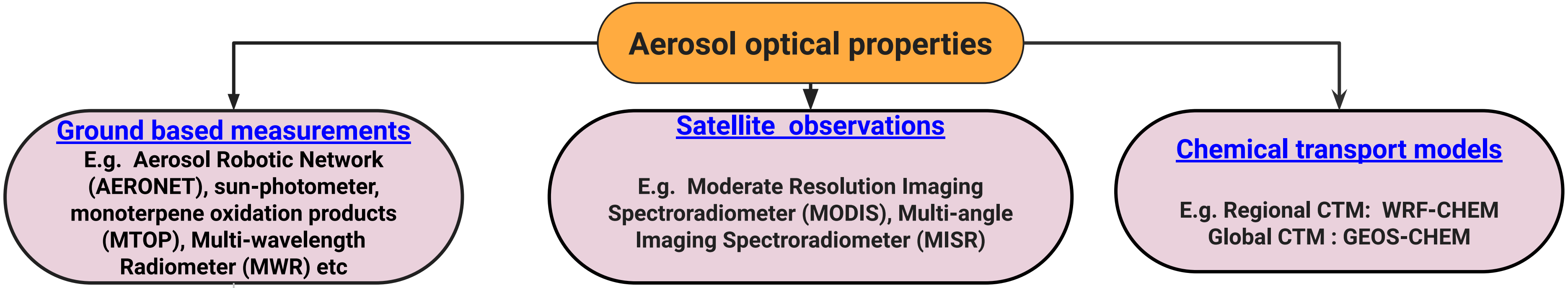
SSA

$$\omega = \frac{Q_{scat}}{Q_{ext}} = \frac{C_{scat}}{C_{ext}}$$

Where
ω : Single scattering albedo
Q_{scat} : Scattering efficiency
Q_{ext}: extinction efficiency

$\sigma^{ext} = N (\pi D^2/4)\, Q_{ext}$
N=Number density
D=hydrodynamic diameter
Q_{ext} **= Extinction efficiency**

Getting Aerosol Optical Properties



- **<u>Ground-based measurements</u>: Valuable insight into the aerosol optical properties but the lack of a robust aerosol measurement network leads to the inconsistent spatial and temporal resolution of the measured aerosol data.**

- **<u>Satellite measurement</u>: provides consistent spatio-temporal information on aerosol but, uncertainties exist due to coarse resolution and several assumptions related to surface reflectance and cloud screening .**

- **<u>Atmospheric chemical transport models (CTM)</u>: provides fine resolved and consistent spatio-temporal information on aerosol, but suffers from different uncertainties related to meteorological fields, emission inventories, boundary conditions, and representation of chemical processes and deposition.**
    - **Providing the necessary framework for integrating individual atmospheric aerosol processes and their interaction.**
    - **Only CTMs has the provision of simulating the specific contribution of aerosol species (e.g. dust and anthropogenic aerosol) to total AOD.**
    - **Aerosol optical properties simulated in a CTM and evaluated against the measurements provide information on the fine resolved spatio-temporal distribution of aerosol.**

Research Gaps: aerosol simulations over the Indian subcontinent

- There is still very high (> 2-times) underestimation in simulated AOD over India (Kumar et. al., 2015a, David et al., 2018).
- The large underestimation of aerosol concentration over the Indian mainland is primarily be due to emission data sets, instead of the model configurations.
- Newly estimated constrained emission inventory has not been fully utilized to simulate AOD over India (Ghosh et. al.,2023).
- Limited understandings are available on seasonal variability of aerosol optical properties from simulation.
- Very limited studies have been done to estimate relative contribution of dust and anthropogenic aerosol on AOD.

Scientific Questions

- Which are the Indian regions that have high/low aerosol loading during winter and pre-monsoon seasons ?
- Is high aerosol loading over a given region is due to anthropogenic emissions or natural (dust) emissions ?
- What are likely sources of emission contributing to the high aerosol loading over a region?

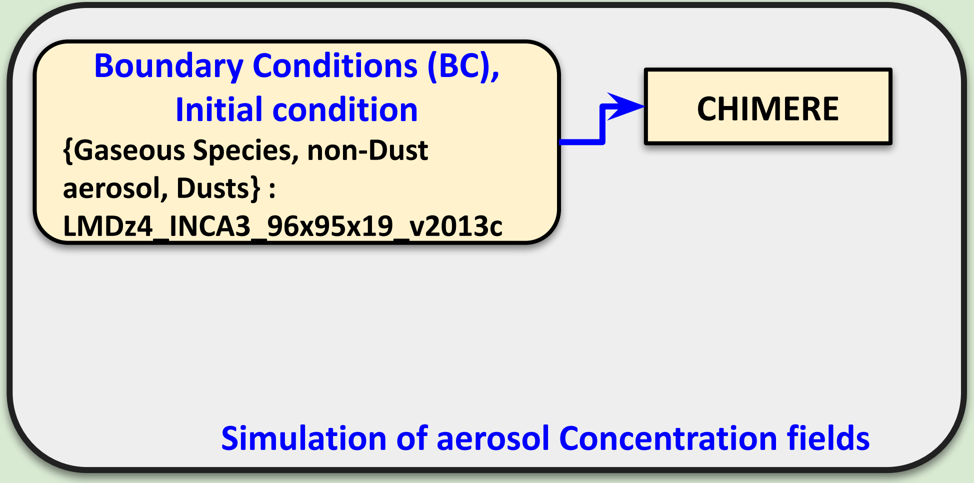
Simulation framework to estimate aerosol optical properties in WRF-CHIMERE-OPTSIM modelling system.

Simulation framework to estimate aerosol optical properties in WRF-CHIMERE-OPTSIM modelling system.

CHIMERE

Simulation of aerosol Concentration fields

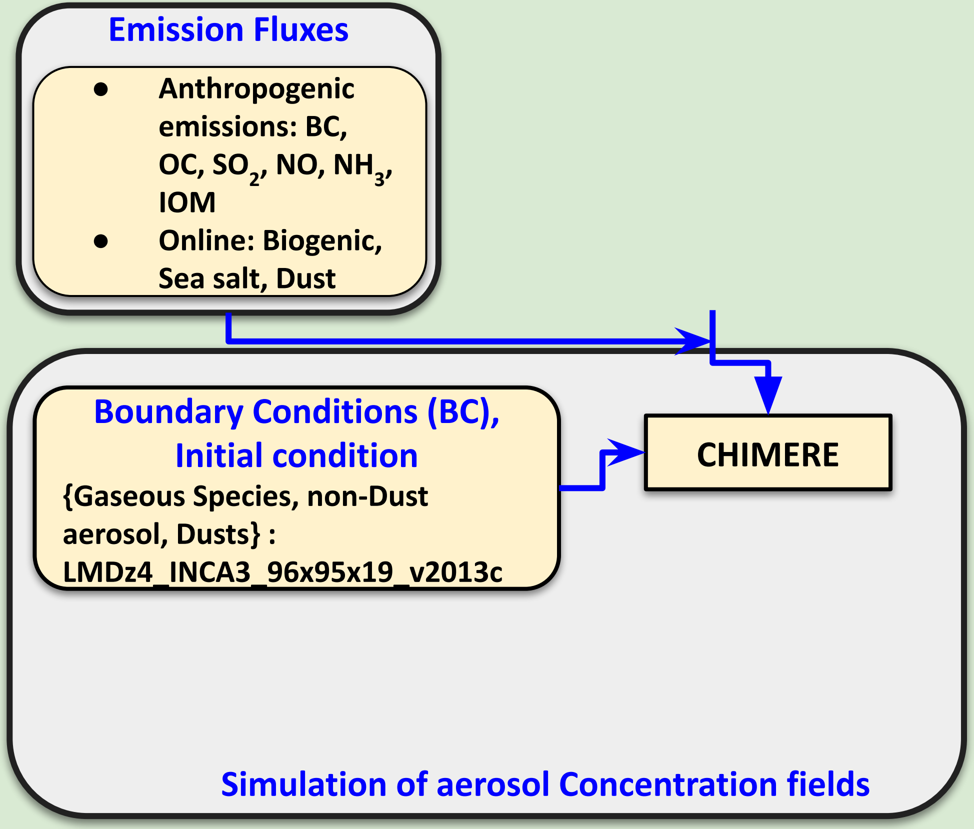
Simulation framework to estimate aerosol optical properties : WRF-CHIMERE-OPTSIM



Laboratoire de Météorologie Dynamique General Circulation Model coupled with Interaction with Chemistry and Aerosols: LMDZ_INCA3

Black Carbon: BC ; Organic Carbon: OC ; Inorganic matter: IOM; Planetary Boundary Layer height: PBLH; National Centers for Environmental Prediction:NCEP

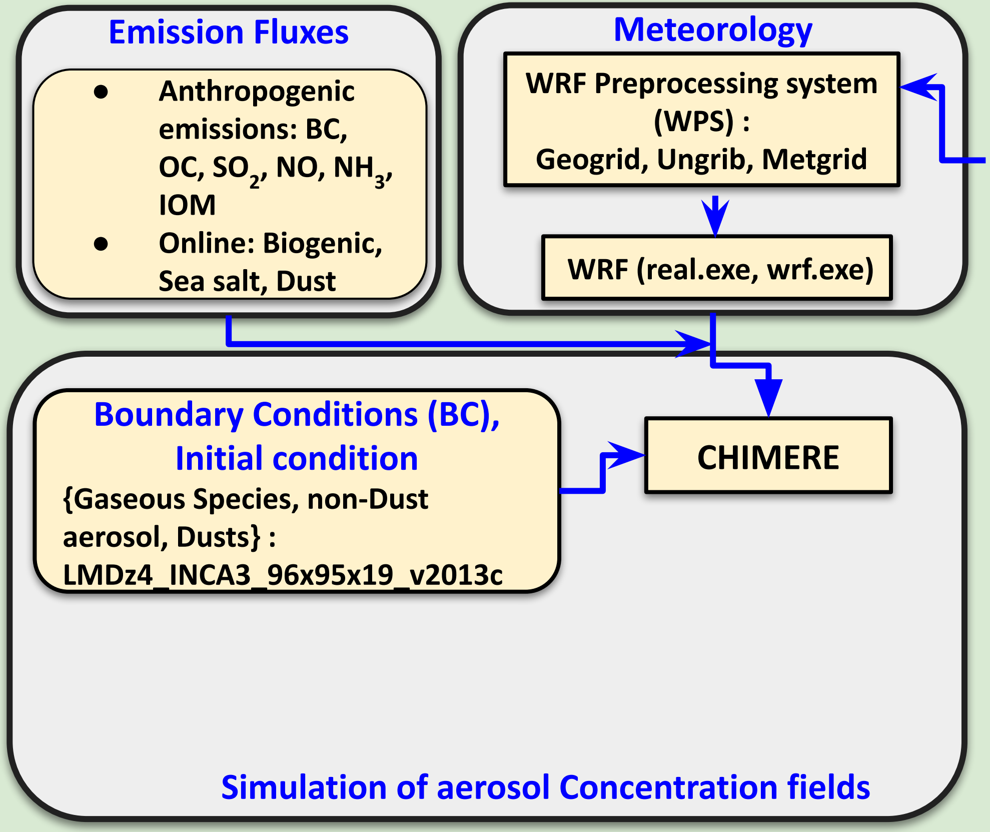
Simulation framework to estimate aerosol optical properties : WRF-CHIMERE-OPTSIM



Laboratoire de Météorologie Dynamique General Circulation Model coupled with Interaction with Chemistry and Aerosols: LMDZ_INCA3

Black Carbon: BC ; Organic Carbon: OC ; Inorganic matter: IOM; Planetary Boundary Layer height: PBLH; National Centers for Environmental Prediction:NCEP

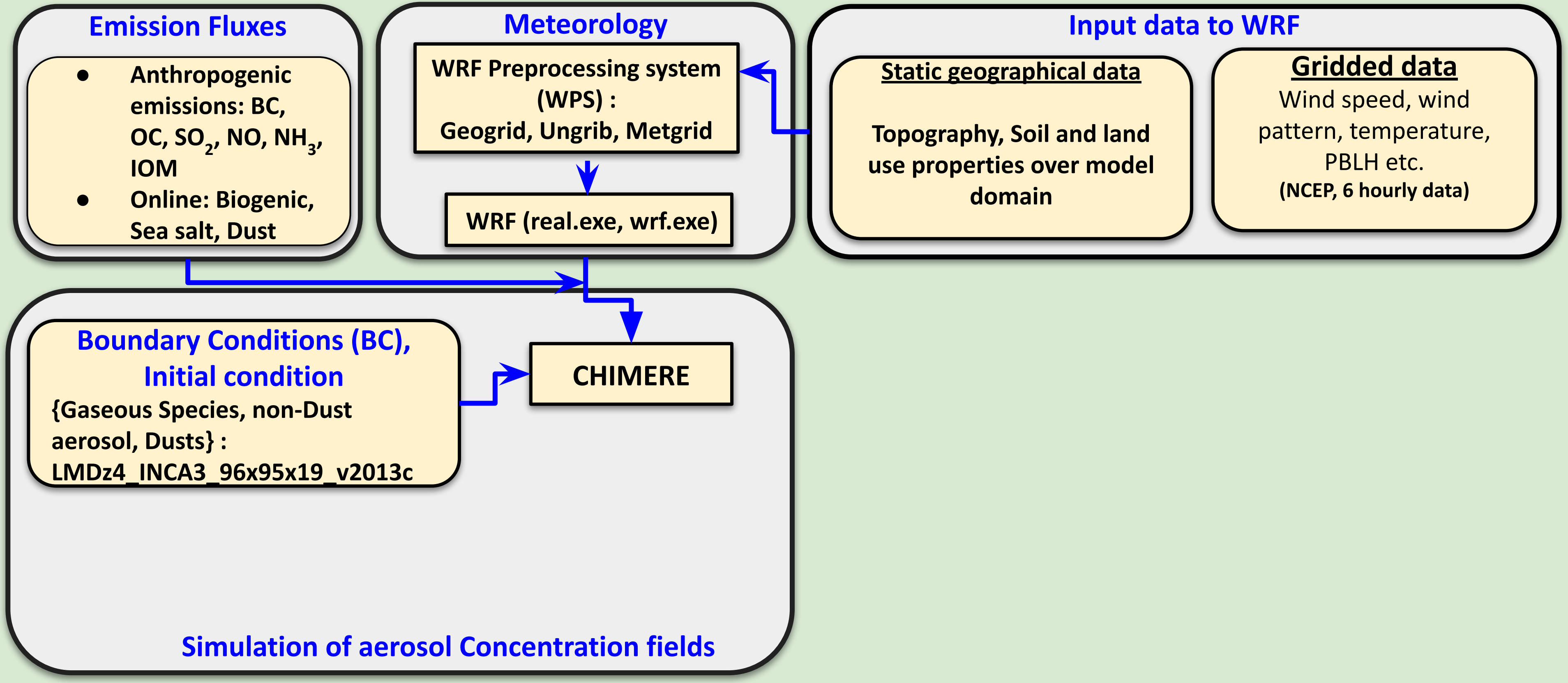
Simulation framework to estimate aerosol optical properties : WRF-CHIMERE-OPTSIM



Laboratoire de Météorologie Dynamique General Circulation Model coupled with Interaction with Chemistry and Aerosols: LMDZ_INCA3

Black Carbon: BC ; Organic Carbon: OC ; Inorganic matter: IOM; Planetary Boundary Layer height: PBLH; National Centers for Environmental Prediction:NCEP

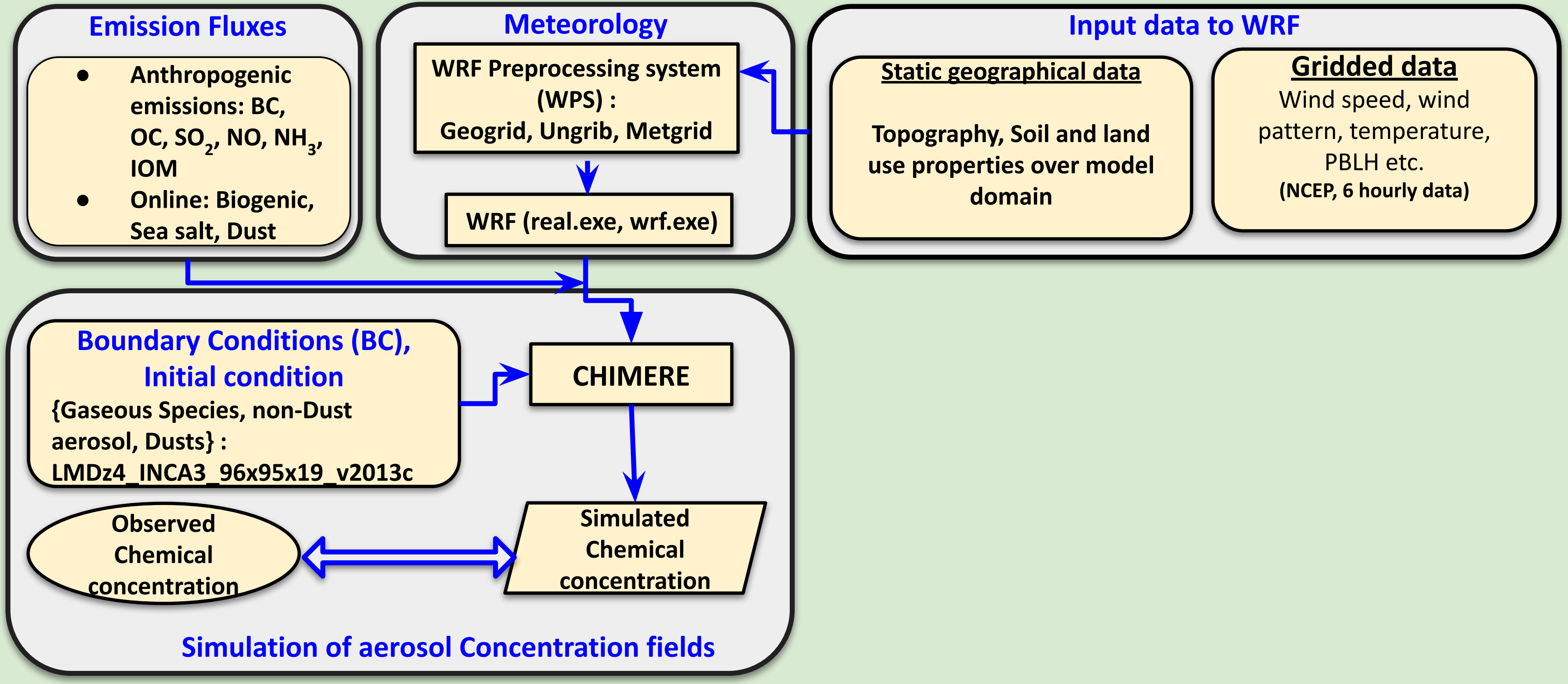
Simulation framework to estimate aerosol optical properties : WRF-CHIMERE-OPTSIM



Laboratoire de Météorologie Dynamique General Circulation Model coupled with Interaction with Chemistry and Aerosols: LMDZ_INCA3

Black Carbon: BC ; Organic Carbon: OC ; Inorganic matter: IOM; Planetary Boundary Layer height: PBLH; National Centers for Environmental Prediction:NCEP

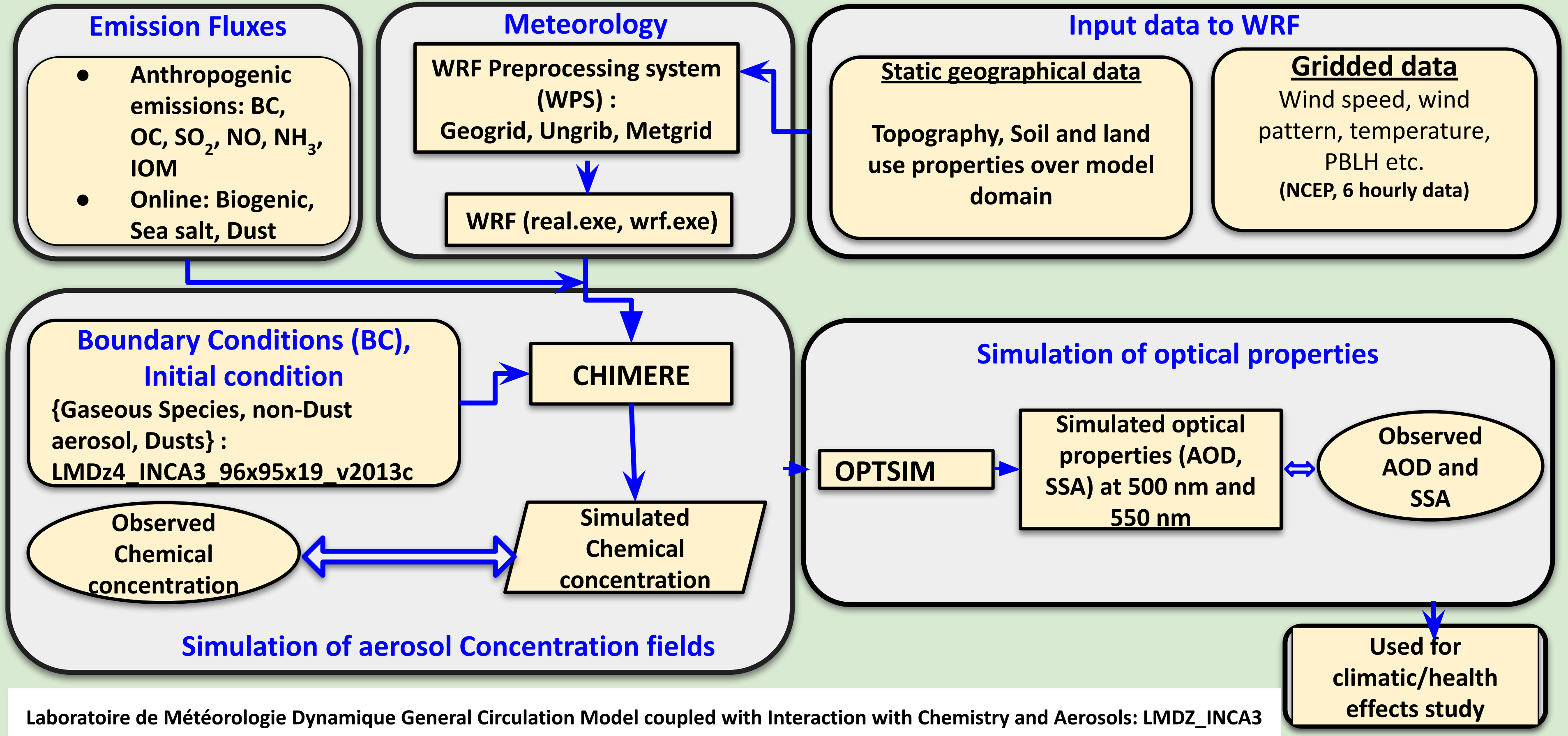
Simulation framework to estimate aerosol optical properties : WRF-CHIMERE-OPTSIM



Laboratoire de Météorologie Dynamique General Circulation Model coupled with Interaction with Chemistry and Aerosols: LMDZ_INCA3

Black Carbon: BC ; Organic Carbon: OC ; Inorganic matter: IOM; Planetary Boundary Layer height: PBLH; National Centers for Environmental Prediction:NCEP

Simulation framework to estimate aerosol optical properties : WRF-CHIMERE-OPTSIM



Laboratoire de Météorologie Dynamique General Circulation Model coupled with Interaction with Chemistry and Aerosols: LMDZ_INCA3

Black Carbon: BC ; Organic Carbon: OC ; Inorganic matter: IOM; Planetary Boundary Layer height: PBLH; National Centers for Environmental Prediction:NCEP

Experimental Setup

Name of Experiment	Emission Database	Aerosol Species	Database Type (Resolution)	References
Smogsimu	SMOG-India	BC, OC, SO2, NOx, NH3, $OPM_{2.5}$	Indian (0.25° ×0.25°)	Sadavarte and Venkataraman, 2014; Pandey et al., 2014
Constrsimu	Constrained, EDGAR	Constrained: (BC, OC, SO_2, IOM) EDGAR : (NOx, NH3)	Indian (0.25° ×0.25°)	Verma et al., 2017, Ghosh et. al., 2023

- Simulations are carried out over India extending for **winter (November- February)** and **pre-monsoon months (April and May)** in continuation mode with spin-up time of 30 days.
- Twenty vertical sigma pressure levels ranging from 997 to 130 hPa are considered in the present study.

- **AOD Dust = AOD with all emissions - AOD with all emission except Dust**
- **AOD anthropogenic = AOD with all emission - AOD with all emission except anthropogenic emissions**

Performance Evaluation Parameters

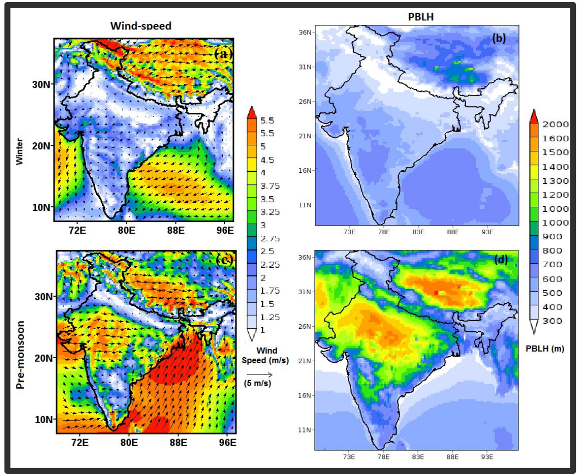
(1) $$Bias = \frac{(X^{modelled} - X^{obs})}{X^{obs}} \times 100\%$$

(2) $$NME = \frac{\sum_1^N |X^{modelled} - X^{obs}|}{\sum_1^N X^{obs}} .100\%$$

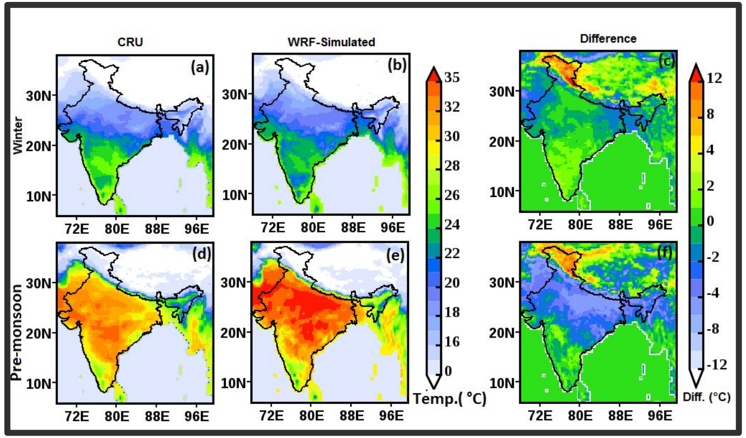
(3) $$RMSE = \left[\frac{1}{N} \sum_1^N (X^{modelled} - X^{obs})^2 \right]^{\frac{1}{2}}$$

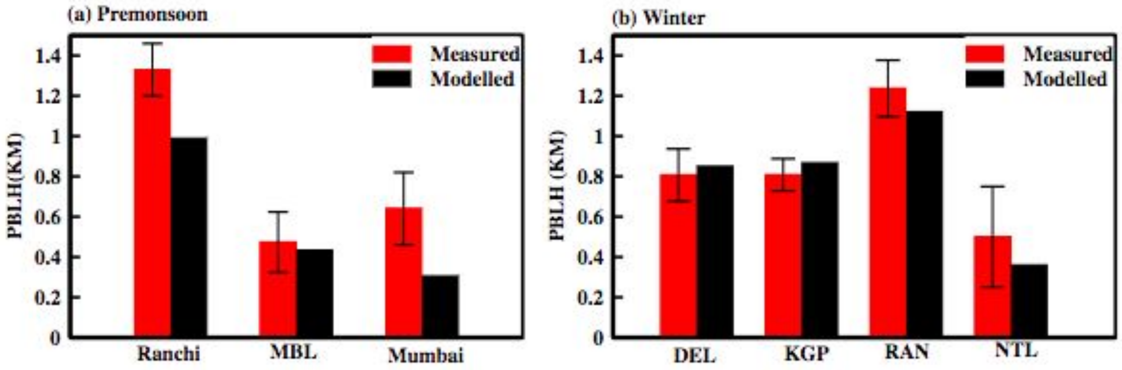
Where, X = AOD, SSA, RH, wind speed, and PBLH.

WRF simulated Meteorological parameters



- Overall, the meteorological parameters, evaluated as seasonal mean are simulated consistently well with the WRF.
- Model is able to capture contrasting features of wind speed, wind direction and PBLH during winter and pre-monsoon seasons.





Comparison of simulated AOD with satellite observation

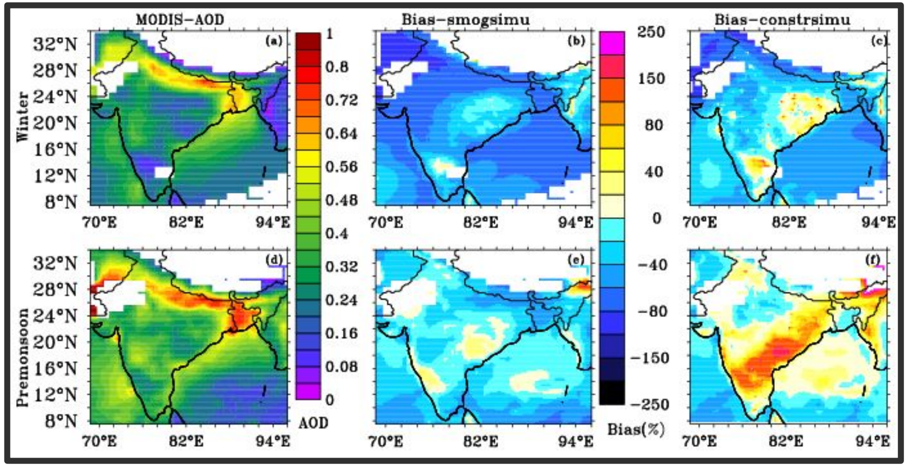


Figure 5 : Spatial distribution of (a-b) AOD at 550 nm for satellite observation (MODIS) during (a) winter and (b) pre-monsoon seasons, (c-f) bias (%) in simulated AOD in case of (c-d) *Constrsimu* during (c) winter and (d) pre-monsoon, (e-f) *Smogsimu* during (e) winter and (f) pre-monsoon.

- Very High overestimation is observed in *CONSTRSIMU* AOD over the eastern IGP and eastern coastal regions.
- Simulated AODs value in the region of high overestimation is coming closer to the ground based measurements.

- During the pre-monsoon season, the spatial pattern of *Constrsimu* AOD showing high value over the IGP, Eastern coastal regions (AOD: 0.6-0.9) is consistent with the observed MODIS AOD.
- High underestimation during winter is observed in *Smogsimu* AOD values with the underestimation being as high as 80% over the parts of IGP and North-Western India.
- Comparatively, the bias (%) value during pre-monsoon season is lower than the winter season. (This pattern is also observed when simulated AOD is compared with ground based measurements.

Pre-monsoon			
Stations	MODIS (AOD)	Aeronet (AOD)	CONSTRSIMU AOD
VSK	0.43	0.86	0.62
KOL	0.5	0.73	0.79
DBG	0.42	0.64	0.56

Comparison of Simulated AOD with ground based measurements

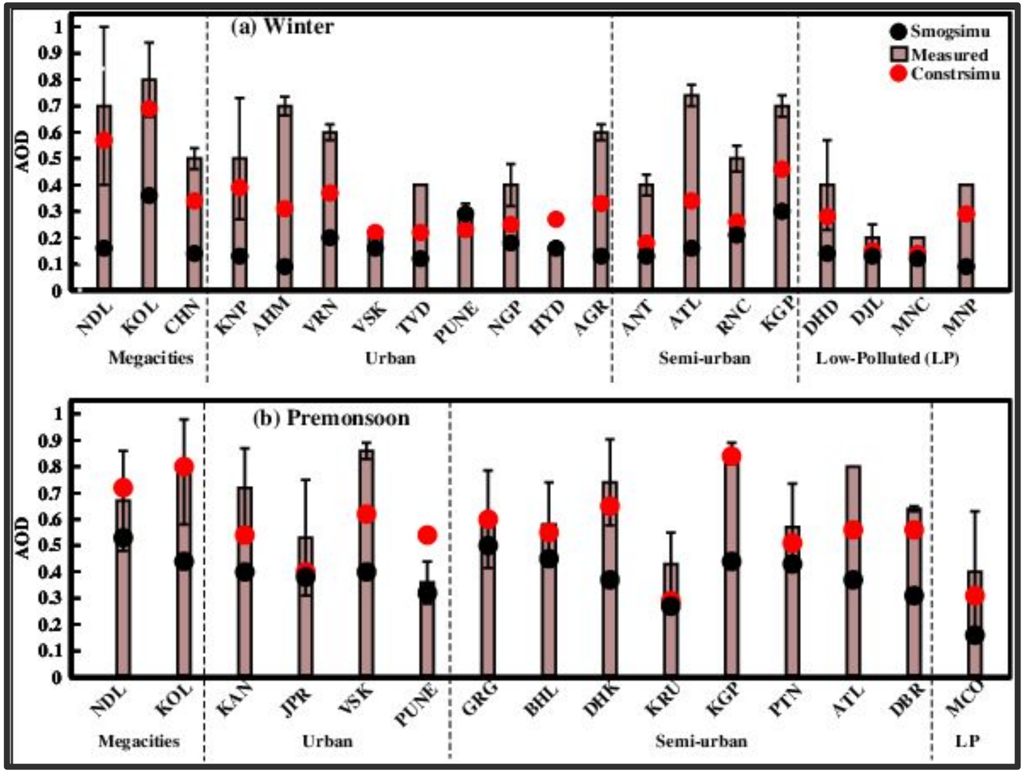


Figure 4: Comparison between the measured and simulated (a) winter (b) pre-monsoon mean AOD at 550 nm for stations under study.

- **During winter, Simulated AODs are underestimated at all the stations for both *Constrsimu* and *Smogsimu* except at Hyderabad where *Constrsimu* AOD is showing overestimation.**
- ***Constrsimu* AODs are showing lesser bias (%) as compared to the *Smogsimu* AOD at all the stations during both winter and pre-monsoon seasons.**

Comparison of Simulated AOD with ground based measurements

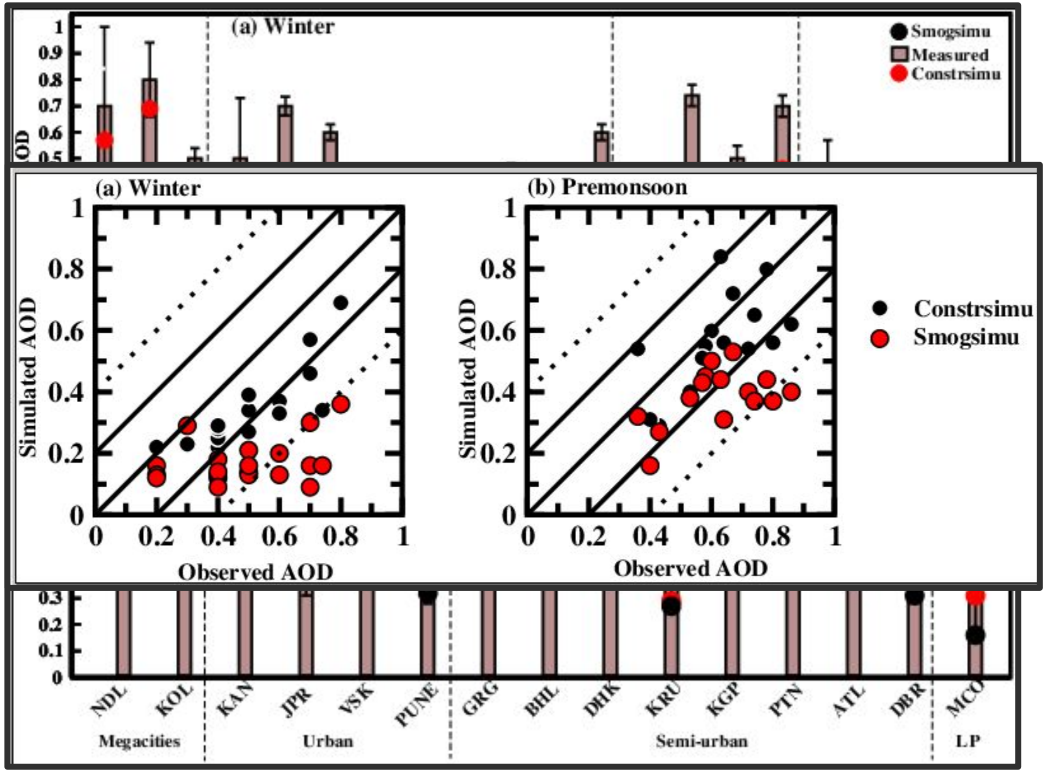


Figure 4: Comparison between the measured and simulated (a) winter (b) pre-monsoon mean AOD at 550 nm for stations under study.

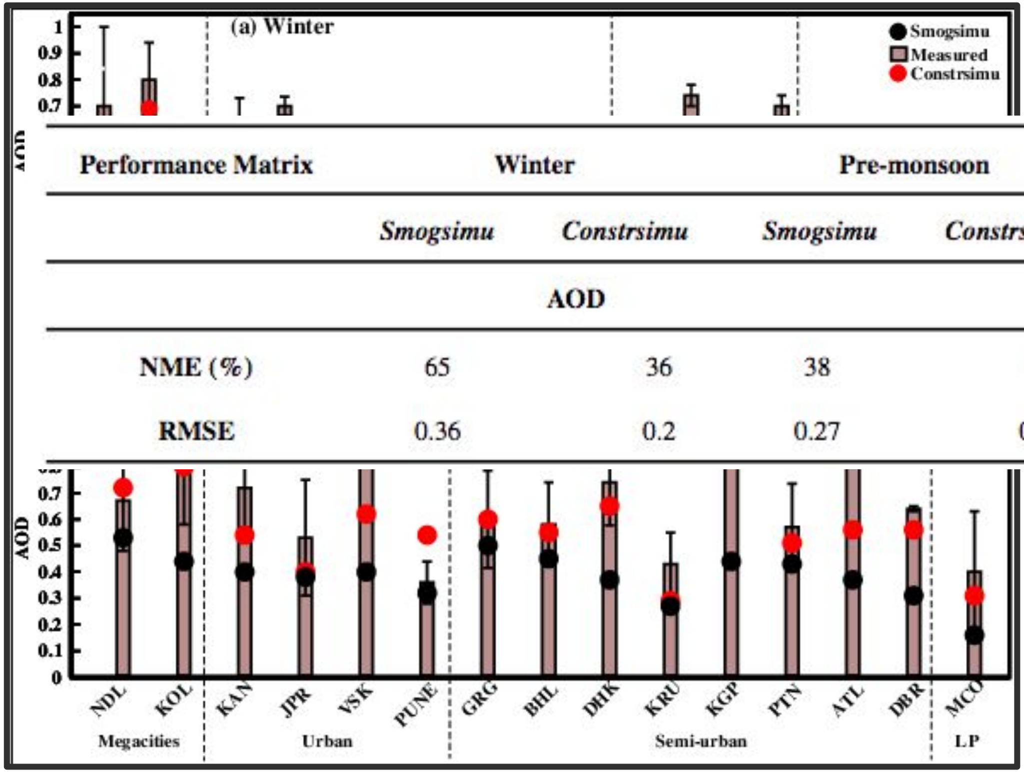
- **During winter, Simulated AODs are underestimated at all the stations for both *Constrsimu* and *Smogsimu* except at Hyderabad where *Constrsimu* AOD is showing overestimation.**

- ***Constrsimu* AODs are showing lesser bias (%) as compared to the *Smogsimu* AOD at all the stations during both winter and pre-monsoon seasons.**

- ***Constrsimu* AODs are confined within ± 40 % Bias during winter and ± 20 % during pre-monsoon.**

- ***Smogsimu* AODs are confined within -70 % Bias during winter and -40 % during pre-monsoon.**

Comparison of Simulated AOD with ground based measurements



Performance Matrix	Winter		Pre-monsoon	
	Smogsimu	*Constrsimu*	*Smogsimu*	*Constrsimu*
AOD				
NME (%)	65	36	38	19
RMSE	0.36	0.2	0.27	0.14

Figure 4: Comparison between the measured and simulated (a) winter (b) pre-monsoon mean AOD at 550 nm for stations under study.

- **During winter, Simulated AODs are underestimated at all the stations for both *Constrsimu* and *Smogsimu* except at Hyderabad where *Constrsimu* AOD is showing overestimation.**

  ***Constrsimu* AODs are showing lesser bias (%) as compared to the *Smogsimu* AOD at all the stations during both winter and pre-monsoon seasons.**

- ***Constrsimu* AODs are confined within ± 40 % Bias during winter and ± 20 % during pre-monsoon.**

- ***Smogsimu* AODs are confined within -70 % Bias during winter and -40 % during pre-monsoon.**

- ***Constrsimu* AODs are having less NME and RMSE than Smogsimu AODs during both winter and pre-monsoon seasons.**

Inter-seasonal variation in AOD from *Constrsimu* and *Smogsimu*

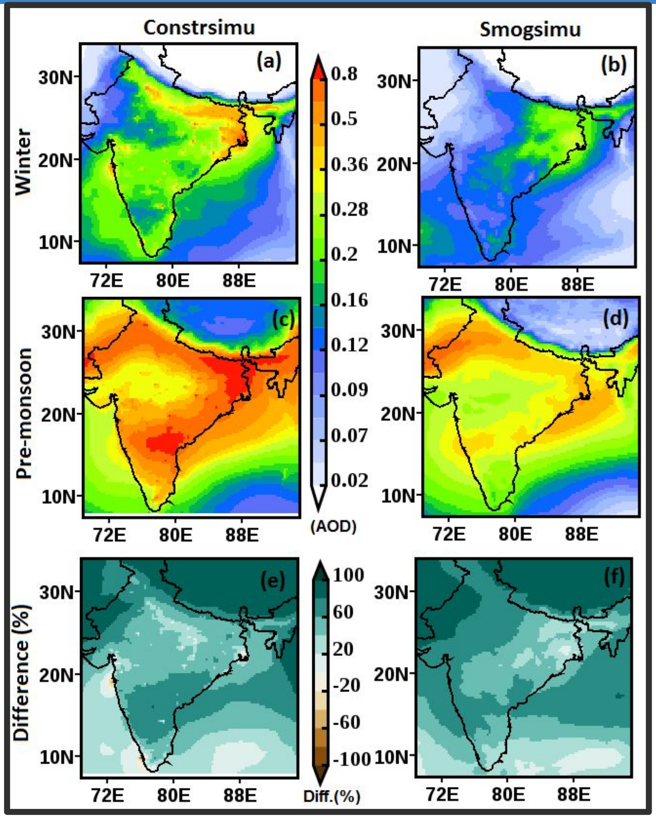


Figure 6: Spatial distribution of (a-b) winter and (c-d) pre-monsoon monthly mean AOD at 550 nm from Constrsimu (a,c) and Smogsimu (b,d), (e-f) percentage increase in AOD from pre-monsoon to winter for (e) *Constrsimu* and (f) *Smogsimu*

- **Simulated AODs exhibit significant seasonal and spatial variation in case of both *Constrsimu* and *Smogsimu*.**
- ***Constrsimu* AOD over the IGP and Eastern coastal regions is higher (2–3 times) than the rest of India during both winter and pre-monsoon seasons, and this is attributed to higher population density, large aerosol emission flux, and favorable advection of aerosols towards these regions.**
- **In general, modeled AOD during pre-monsoon is higher (40%–70%) than winter, and this feature is consistent with the satellite observed MODIS AOD.**
- **Over the upper IGP and Western India, higher AOD during pre-monsoon is found to be associated with the abundance of dust aerosol, while over the lower IGP, Eastern coastal region and Southern peninsular India, it is found to be associated with increased anthropogenic activities (forest fire and open burning over Central india).**
- **The spatial features of high AOD over the IGP region is seen for *Constrsimu* AOD similar to MODIS AOD, however this agreement is absent for *Smogsimu* AOD.**

AOD due to dust and AOD due to anthropogenic aerosol using Constrained emission

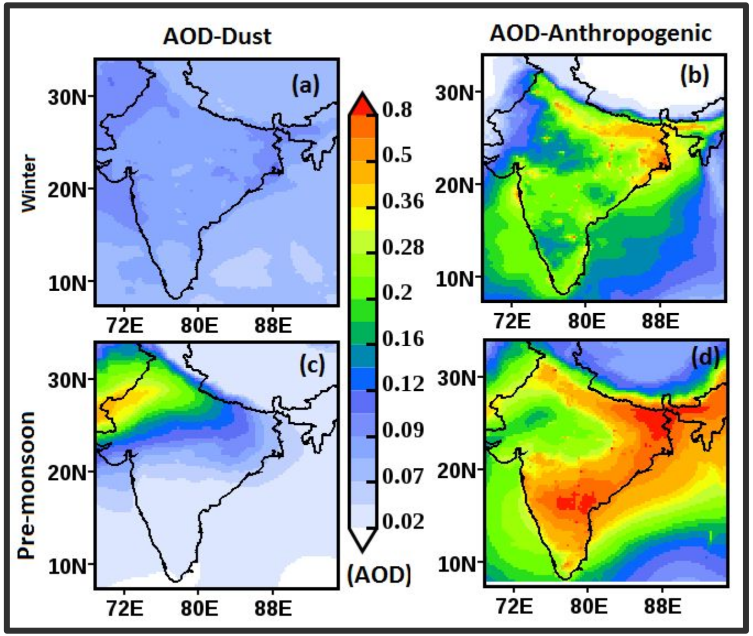


Figure 7: Spatial distribution of seasonal mean aod at 550 nm (a-b) during winter (a) due to dust (b) due to anthropogenic aerosols; (c-d) during pre-monsoon (c) due to dust (d) due to anthropogenic aerosols.

- **Anthropogenic AOD value is found to be higher (2–3 times) over the Eastern IGP than the rest of India during winter and pre-monsoon seasons, while over the Eastern coastal regions, Western coastal regions, and Southern India, it is higher (2–3 times) particularly during pre-monsoon season.**
- **Dust AOD during winter is very low (<0.1) over entire India, while during pre-monsoon, it was high (0.3–0.6) over Western India.**
- **During pre-monsoon, dust AOD was also seen over the upper IGP and Central India.**

Dust Optical Depth: Simulated Vs CALIPSO Derived

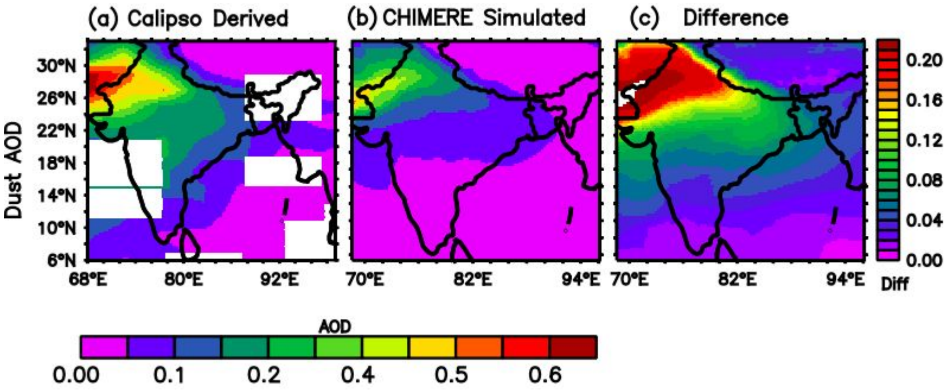


Figure-8: Spatial distribution of pre-monsoon mean aod at 550 nm from (a) Calipso (b) Simulation (c) difference between (a) and (b)

- Spatial variation pattern of dust AOD has been well captured by the model.
- **Underestimation**
  Upper IGP & Western India: 0.15-0.25
  Central India: 0.05-0.15
  Southern India: 0.01-0.05

Song, Q., Zhang, Z., Yu, H., Ginoux, P. and Shen, J., 2021. Global dust optical depth climatology derived from CALIOP and MODIS aerosol retrievals on decadal timescales: regional and interannual variability. *Atmospheric Chemistry and Physics*, *21*(17), pp.13369-13395.

Fractional contribution of dust and anthropogenic aerosol to AOD

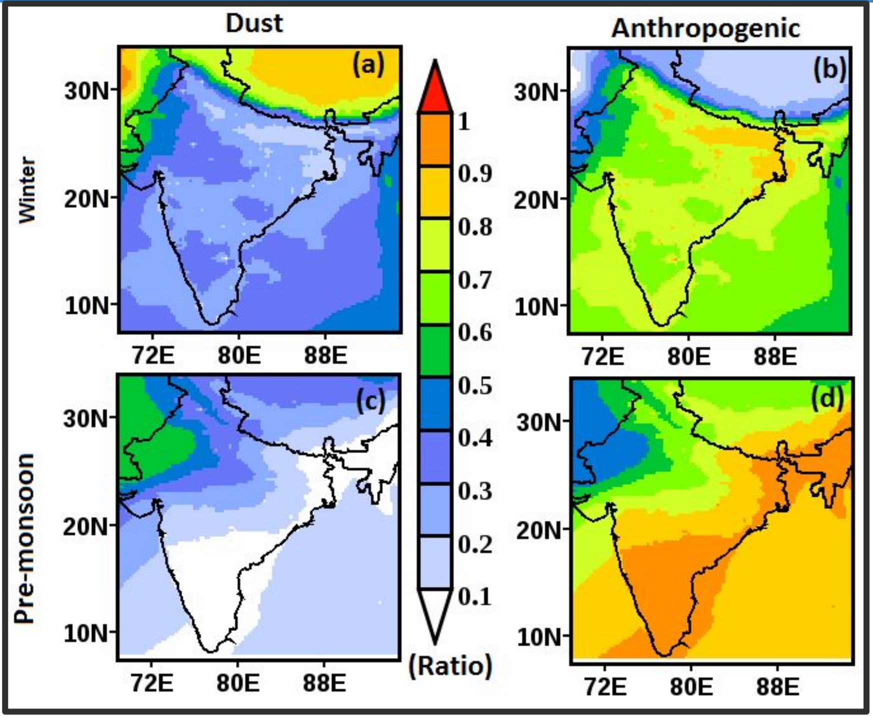


Figure 9: Spatial distribution of seasonal mean fractional contribution of aod at 550 nm (a-b) during winter (a) due to dust (b) due to anthropogenic aerosols; (c-d) during pre-monsoon (c) due to dust (d) due to anthropogenic aerosols

- **In general Western India is dominated by dust contribution while the rest of the India is dominated by anthropogenic contributions.**
- **Over Western India, during pre-monsoon, about 50% – 70% of total AOD is from dust compared to that being 30% to 60% during winter.**
- **Most parts of Central India are having 60% – 70% of total AOD from anthropogenic emission during winter as well as pre-monsoon season.**
- **Over the Eastern IGP, eastern coastal regions and southern India, contribution of anthropogenic aerosol is higher during pre-monsoon (80% – 95%) than during winter (60% – 80%).**

Summary and Conclusion

- We used recently available aerosol emission inventories (SMOG-India and Constrained) in a finely resolved modeling set-up (WRF-CHIMERE-OPTSIM) to estimate the specific contribution of dust and anthropogenic aerosol to total AOD over India during winter and pre-monsoon seasons.

- Chimere model, utilizing constrained emission was consistent in capturing inter-seasonal variation and seasonal mean spatial distribution pattern of satellite observation (MODIS) with a lower bias range (< 40%) compared to previous studies (~ 2-3 times).

- Over Western India, during pre-monsoon, about 50% – 70% of total AOD is from dust compared to that being 30% to 60% during winter.

- Over the Eastern IGP, eastern coastal regions and southern India, contribution of anthropogenic aerosol is higher during pre-monsoon (80% – 95%) than during winter (60% – 80%).

- In general, AOD during pre-monsoon is higher by 40%–70% than winter. Over the IGP and Western India it is associated with the abundance of dust aerosol, while over Southern peninsular India and eastern coast, it is associated with increased anthropogenic activities.

Thank You Everyone!