Supplement of Atmos. Chem. Phys., 26, 13189–13211, 2026
https://doi.org/10.5194/acp-26-13189-2026-supplement
© Author(s) 2026. CC BY 4.0 License.

Atmospheric Chemistry and Physics
Open Access
EGU

Supplement of

Improving aerosol–radiation interactions in the operational forecasting system – AIRWISE

Sumit Kumar et al.

Correspondence to: Sumit Kumar (sr.sumit50@gmail.com) and Gaurav Govardhan (gaurav.govardhan@tropmet.res.in)

The copyright of individual parts of the supplement might differ from the article licence.

Supplementary Figures:

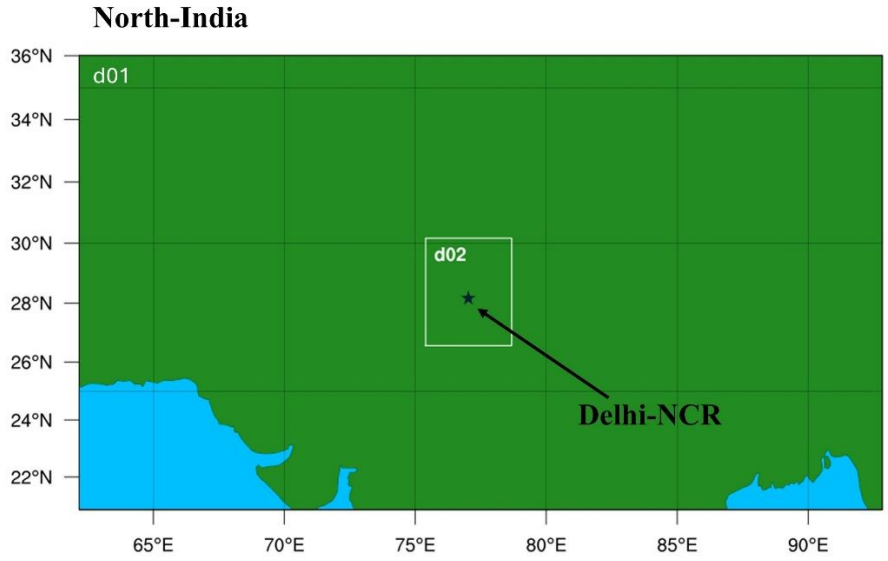

Fig. S1. Schematic representation of the study area: box outlining Delhi-NCR and the star indicating the location of Delhi.

35

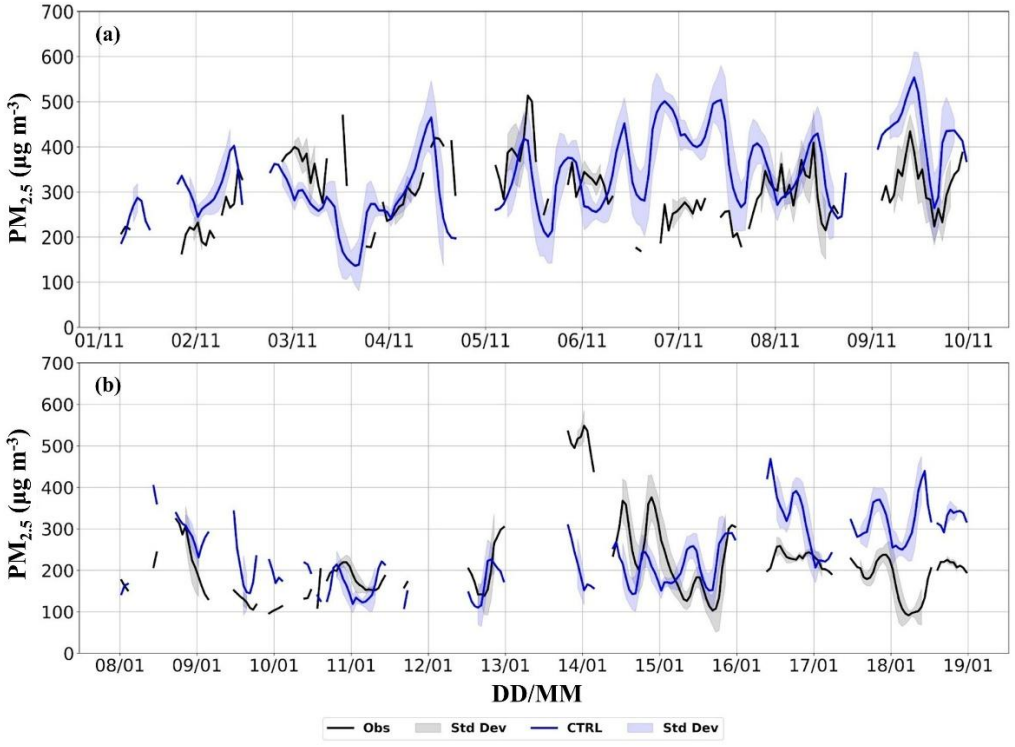

Fig. S2. $PM_{2.5}$ mass concentrations in CTRL and observations averaged over Delhi under clear-sky conditions during (a) Event-I and (b) Event-II. Shading denotes ±1 standard deviation across monitoring stations for the observations and across Delhi grid cells for CTRL.

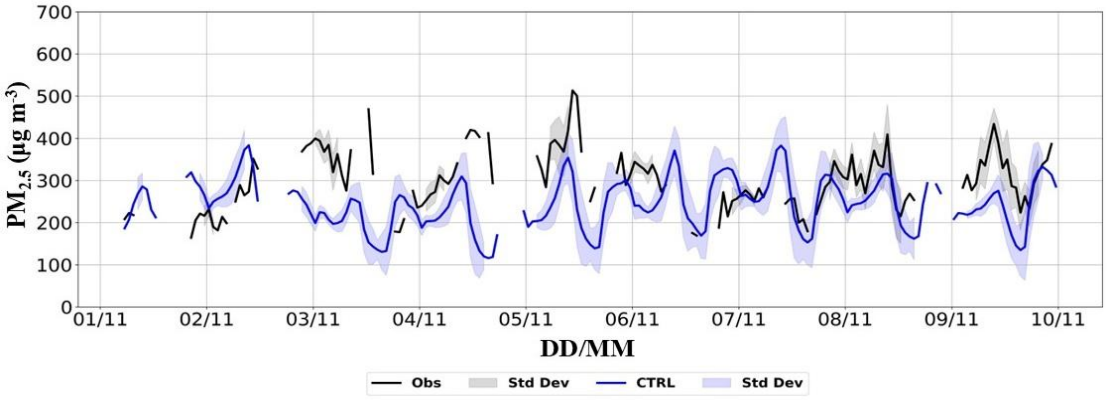

Fig. S3. $PM_{2.5}$ mass concentrations in CTRL without fire emissions and observations averaged over Delhi under clear-sky conditions during Event-I. Shading denotes ±1 standard deviation across monitoring stations for the observations and across Delhi grid cells for CTRL.

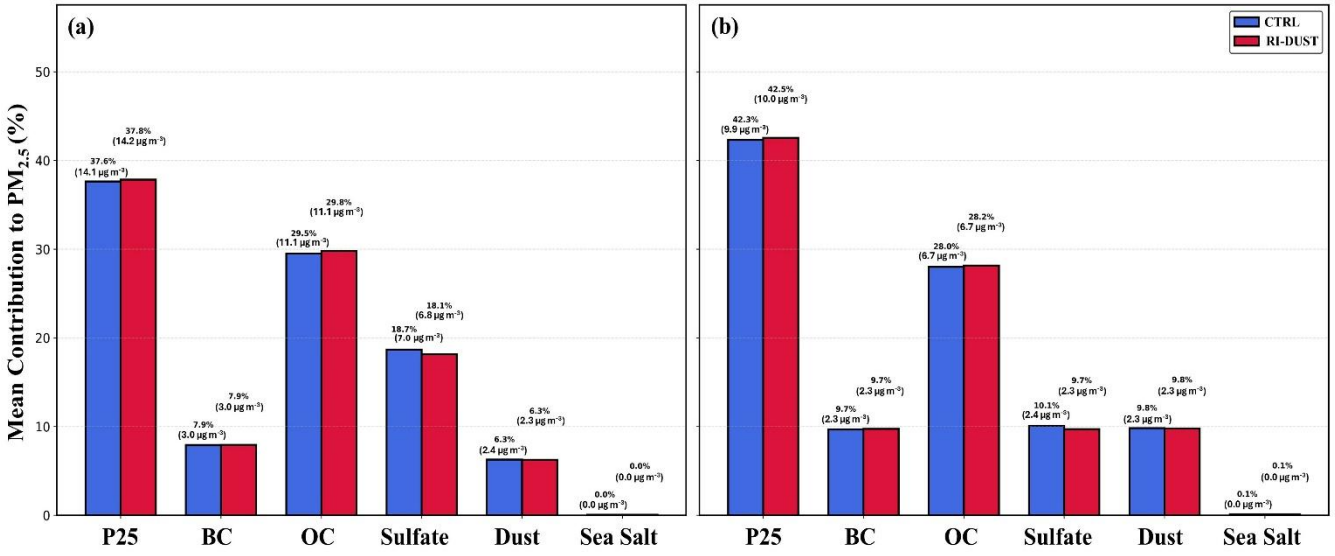

Fig. S4. Mean percentage contribution of $PM_{2.5}$ components (P25, BC, OC, Sulfate, Dust, and Sea Salt) in CTRL and RI-DUST configurations over Delhi for (a) Event-I and (b) Event-II. Values above the bars indicate the mean contribution (%) and mean concentrations (µg m^{-3}).

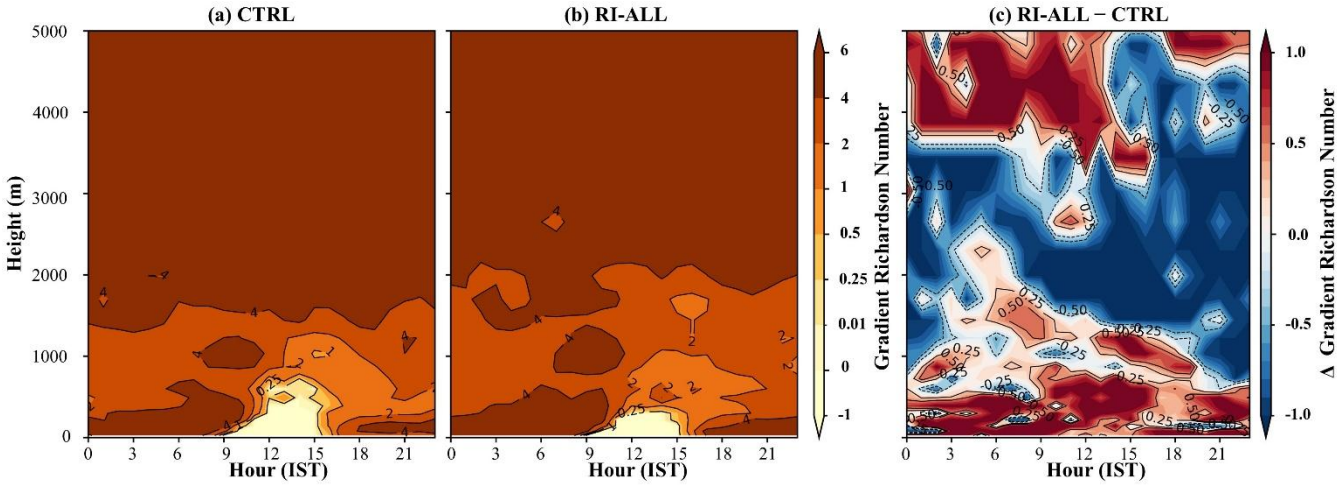

Fig. S5. Mean diurnal time–height cross-sections over Delhi showing the gradient Richardson number (R) for (a) CTRL and (b) RI-ALL simulations, and (c) their difference (RI-ALL − CTRL) during Event-I. Filled contours represent R (or R differences in panel c), while black contours denote selected R values. Positive (negative) differences indicate enhanced (reduced) atmospheric stability in the RI-ALL simulation relative to CTRL.

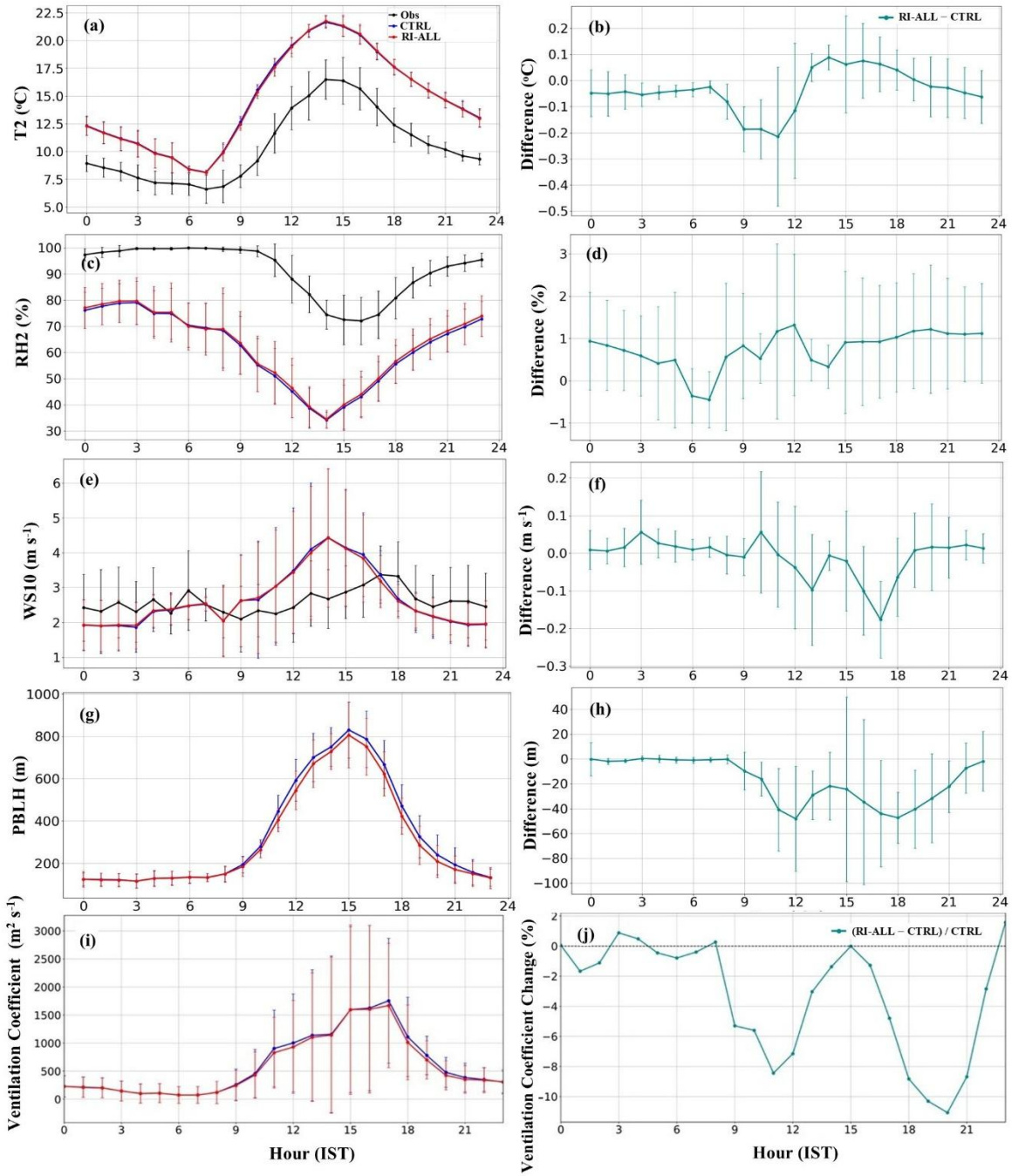

Fig. S6. Diurnal cycle of simulated meteorological parameters in CTRL and RI-ALL along with observations, and changes in RI-ALL with respect to CTRL for Event-II under clear-sky: (a) and (b) for T2, (c) and (d) for RH2, (e) and (f) for WS10, (g) and (h) for PBLH, and (i) and (j) for ventilation coefficient.

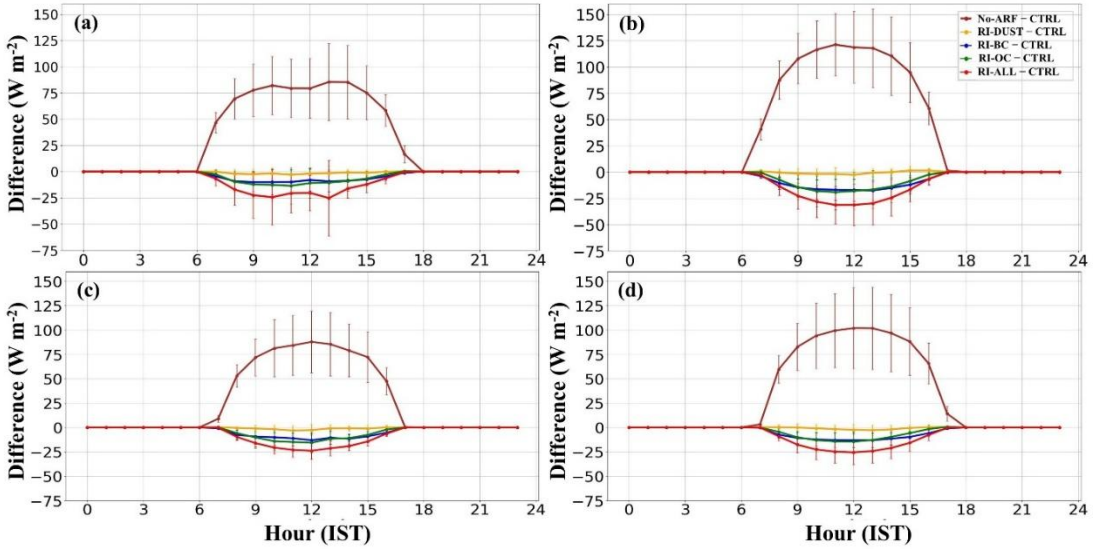

Fig. S7. Diurnal cycle of changes in averaged SWDOWN for No-ARF, RI-DUST, RI-BC, RI-OC, and RI-ALL with respect to CTRL in d01 simulations under clear-sky over Delhi: (a) October 2023, (b) November 2023, (c) December 2023, and (d) January 2024.

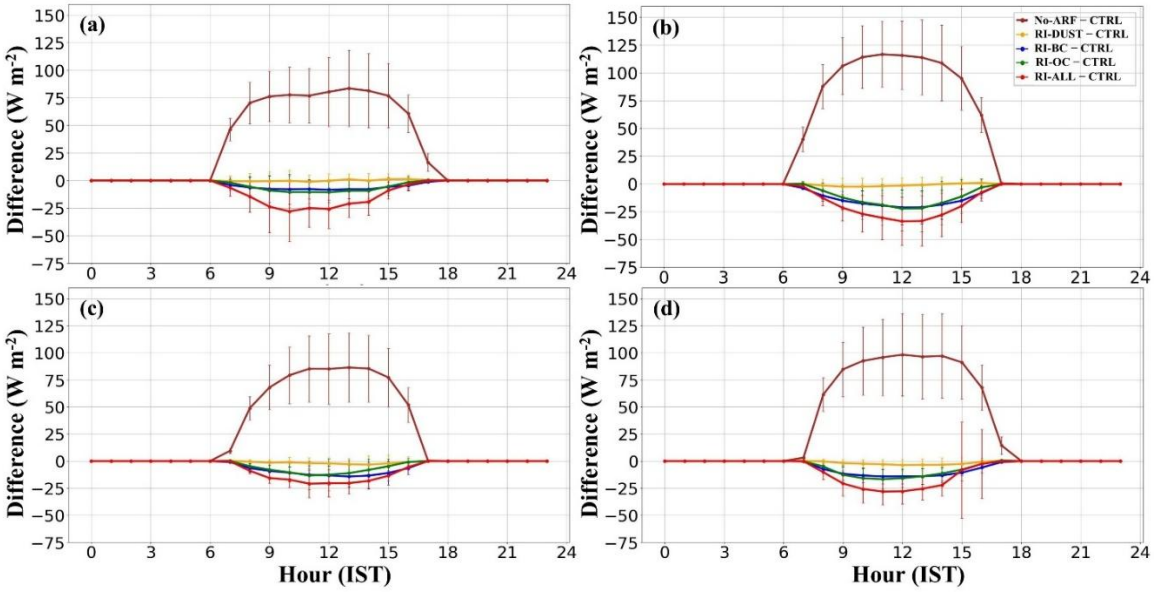

Fig. S8. Diurnal cycle of changes in averaged SWDOWN for No-ARF, RI-DUST, RI-BC, RI-OC, and RI-ALL with respect to CTRL in d02 simulations under clear-sky over Delhi: (a) October 2023, (b) November 2023, (c) December 2023, and (d) January 2024.

Supplementary Tables:

Table S1. Model configuration and physics schemes used in the study.

Physics	Schemes
Microphysics	WSM6
Longwave radiation	RRTMG longwave
Shortwave radiation	RRTMG shortwave
Boundary-layer physics	MYNN2.5
Convective parameterization	Grell-Freitas Ensemble
Land-surface interaction	Unified Noah Land-Surface model
Surface layer	Eta Similarity

75

Table S2. Statistical parameters used to evaluate the model performance.

Performance Metric	Formula	Description
Mean Bias (MB)	$MB = \text{mean}(X_M - X_O)$	Indicates the average systematic difference between model (X_M) and observed (X_O) values. Positive (negative) values represent overestimation (underestimation). MB = 0 indicates a perfect model.
Root Mean Square Error (RMSE)	$RMSE = \sqrt{\text{mean}[(X_O - X_M)^2]}$	Represents the overall magnitude of model error, giving more weight to larger errors. Lower RMSE values indicate better model performance; RMSE = 0 denotes a perfect model.
Normalized Mean Square Error (NMSE)	$NMSE = \text{mean}[(X_O - X_M)^2] / (\text{mean}(X_O) \times \text{mean}(X_M))$	A normalized measure of total error accounting for both variance and magnitude. Smaller NMSE values indicate improved model performance; NMSE = 0 represents a perfect model.
Fractional Bias (FB)	$FB = 2 \times (\text{mean}(X_M - X_M) / \text{mean}(X_M + X_O))$	A dimensionless bias metric normalized by the mean of model and observed values. FB ranges from −2 to +2, with FB = 0 indicating no bias. Positive (negative) values indicate overprediction (underprediction).

Note:

X_O and X_M represent observed and model values, respectively; σ_o and σ_M denote their standard deviations and *mean* indicates temporal averaging.

Table S3. Hourly means SWDOWN differences (Model − Observations) for RRTMG, Goddard, and CAM radiation schemes for sunlit hours. Positive values indicate model overestimation, while negative values indicate underestimation.

Hour (IST)	**RRTMG (Wm^{-2})**	**Goddard (Wm^{-2})**	**CAM (Wm^{-2})**
7	19.07	30.87	30.81
8	74.49	134.80	136.80
9	81.99	157.57	160.05
10	73.85	153.68	156.60
11	58.37	144.94	146.82
12	26.32	115.70	118.07
13	0.02	85.66	88.71
14	14.34	95.73	98.84
15	-19.65	53.79	58.30
16	-35.17	15.25	17.30
17	-3.22	-3.19	-3.12

Table S4. Statistical evaluation of meteorological parameters under clear-sky for Event-I over Delhi.

S. No.	**Met. variables**	**MB**		**RMSE**		**NMSE**		**FB**	
		CTRL	**RI-ALL**	**CTRL**	**RI-ALL**	**CTRL**	**RI-ALL**	**CTRL**	**RI-ALL**
1.	**T2 (°C)**	-0.49	-0.41	1.43	1.59	0.003	0.004	-0.021	-0.017
2.	**RH2 (%)**	-29.68	-27.42	30.56	28.43	0.286	0.236	-0.503	-0.456
3.	**WS10 (ms^{-1})**	0.20	0.01	0.83	0.75	0.283	0.262	0.115	-0.01

Table S5. Statistical evaluation of meteorological parameters under clear-sky for Event-II over Delhi.

S. No.	Met. variables	MB		RMSE		NMSE		FB	
		CTRL	RI-ALL	CTRL	RI-ALL	CTRL	RI-ALL	CTRL	RI-ALL
1.	SWDOWN (Wm^{-2})	4.58	0.86	22.45	21.61	0.043	0.042	0.042	0.008
2.	T2 (°C)	4.40	4.37	4.74	4.72	0.135	0.134	0.337	0.334
3.	RH2 (%)	-29.55	-28.70	31.79	31.29	0.184	0.176	-0.391	-0.378
4.	WS10 (ms^{-1})	0.07	0.05	1.28	1.29	0.236	0.239	0.023	0.019

Table S6. Mean values of SWDOWN (Wm^{-2}) during sunlit hours under clear-sky and percentage change in Event-I and Event-II over Delhi.

S. No.	Sensitivity Experiments (Exp)	SWDOWN Event-I (Wm^{-2})	SWDOWN Event-II (Wm^{-2})
1.	**Control run (CTRL)**	348.18	384.11
2.	**No-ARF**	503.17 **Δ** = 154.99 **δ** = 44.51 %	463.04 **Δ** = 78.93 **δ** = 20.54 %
3.	**RI-DUST**	349.58 **Δ** = +1.4 **δ** = 0.41 %	383.38 **Δ** = -0.73 **δ** = -0.19 %
4.	**RI-BC**	325.72 **Δ** = -22.46 **δ** = -6.45 %	374.77 **Δ** = -9.34 **δ** = -2.43 %
5.	**RI-OC**	336.83 **Δ** = -11.35 **δ** = -3.26 %	378.42 **Δ** = -5.69 **δ** = -1.48 %
6.	**RI-ALL**	320.66 **Δ** = -27.52 **δ** = -7.90 %	370.72 **Δ** = -13.39 **δ** = -3.48 %

here, $\mathbf{\Delta} = (Exp - CTRL)$

$$\mathbf{\delta} = \frac{\mathbf{\Delta} \times 100}{CTRL} \%$$

Table S7. Mean values of SWDOWN (Wm^{-2}) from domain d01 during sunlit hours under clear-sky and percentage change in each month over Delhi.

S. No.	Sensitivity Experiments (Exp)	SWDOWN October (Wm^{-2})	SWDOWN November (Wm^{-2})	SWDOWN December (Wm^{-2})	SWDOWN January (Wm^{-2})
1.	**Control run (CTRL)**	455.93	374.38	366.12	358.52
2.	**No-ARF**	523.66 **Δ** = 67.73 **δ** = 14.85 %	467.87 **Δ** = 93.49 **δ** = 24.97 %	432.09 **Δ** = 65.97 **δ** = 18.02 %	433.05 **Δ** = 74.53 **δ** = 20.79 %
3.	**RI-DUST**	454.59 **Δ** = -1.39 **δ** = -0.29 %	373.75 **Δ** = -0.63 **δ** = -0.16 %	364.87 **Δ** = -1.25 **δ** = -0.34 %	357.62 **Δ** = -0.90 **δ** = -0.25 %
4.	**RI-BC**	448.40 **Δ** = -7.53 **δ** = -1.65 %	361.86 **Δ** = -12.52 **δ** = -3.34 %	357.34 **Δ** = -8.78 **δ** = -2.40 %	349.45 **Δ** = -9.07 **δ** = -2.53 %
5.	**RI-OC**	447.67 **Δ** = -8.26 **δ** = -1.81 %	362.87 **Δ** = -11.51 **δ** = -3.07 %	356.76 **Δ** = -9.36 **δ** = -2.55 %	350.54 **Δ** = -7.98 **δ** = -2.22 %
6.	**RI-ALL**	440.19 **Δ** = -15.74 **δ** = -3.45 %	354.42 **Δ** = -19.96 **δ** = -5.33 %	350.63 **Δ** = -15.49 **δ** = -4.23 %	342.82 **Δ** = -15.70 **δ** = -4.38 %

Table S8. Mean values of SWDOWN (Wm^{-2}) from domain d02 during sunlit hours under clear-sky and percentage change in each month over Delhi.

S. No.	Sensitivity Experiments (Exp)	SWDOWN October (Wm^{-2})	SWDOWN November (Wm^{-2})	SWDOWN December (Wm^{-2})	SWDOWN January (Wm^{-2})
1.	**Control run (CTRL)**	458.21	372.39	364.27	352.41
2.	**No-ARF**	525.22 **Δ** = 67.01 **δ** = 14.62 %	464.16 **Δ** = 91.77 **δ** = 24.64 %	431.31 **Δ** = 67.04 **δ** = 18.40 %	425.58 **Δ** = 73.17 **δ** = 20.76 %
3.	**RI-DUST**	458.18 **Δ** = -0.03 **δ** = -0.01 %	371.51 **Δ** = -0.88 **δ** = -0.24 %	362.59 **Δ** = -1.68 **δ** = -0.46 %	350.46 **Δ** = -1.95 **δ** = -0.55 %
4.	**RI-BC**	451.89 **Δ** = -6.32 **δ** = -1.38 %	358.19 **Δ** = -14.20 **δ** = -3.81 %	354.42 **Δ** = -9.85 **δ** = -2.70 %	342.74 **Δ** = -9.67 **δ** = -2.74 %
5.	**RI-OC**	451.52 **Δ** = -6.69 **δ** = -1.46 %	360.26 **Δ** = -12.13 **δ** = -3.26 %	356.91 **Δ** = -7.36 **δ** = -2.02 %	343.18 **Δ** = -9.23 **δ** = -2.62 %
6.	**RI-ALL**	441.95 **Δ** = -16.26 **δ** = -3.55 %	351.96 **Δ** = -20.43 **δ** = -5.49 %	350.18 **Δ** = -14.09 **δ** = -3.87 %	336.84 **Δ** = -15.57 **δ** = -4.42 %

Table S9. Statistical evaluation of SWDOWN (Wm^{-2}) from d01 simulations in December 2023 and January 2024 under clear-sky (non-foggy) conditions over Delhi.

S. No.	Month	MB (Wm^{-2})		RMSE (Wm^{-2})		NMSE		FB	
		CTRL	RI-ALL	CTRL	RI-ALL	CTRL	RI-ALL	CTRL	RI-ALL
1.	December	10.53	3.96	37.54	34.01	0.06	0.05	0.07	0.02
2.	January	23.63	15.26	44.94	39.35	0.08	0.06	0.15	0.10

Table S10. Monthly averaged changes in meteorological variables (SWDOWN, T2, RH2, WS10, PBLH) and $PM_{2.5}$ mass concentrations from October 2023 to January 2024 in d01 simulations under clear sky over Delhi.

Month	October 2023		November 2023		December 2023		January 2024	
	CTRL	RI-ALL	CTRL	RI-ALL	CTRL	RI-ALL	CTRL	RI-ALL
SWDOWN ($W\ m^{-2}$)	461.15	445.23	376.58	356.50	368.18	352.61	358.52	342.82
T2 (°C)	31.55	31.72	25.81	25.99	19.71	19.42	19.29	18.85
RH2 (%)	36.03	38.05	40.60	42.27	44.42	48.04	37.18	47.40
WS10 ($m\ s^{-1}$)	3.78	3.76	1.89	1.85	2.45	2.37	2.63	2.62
PBLH (m)	1058.23	1047.27	835.16	809.50	619.95	565.10	776.12	688.45
$PM_{2.5}$ ($\mu g\ m^{-3}$)	128.68	127.02	207.87	213.41	169.10	173.95	188.94	192.64