Response to Reviewer 2

(Response in blue)

Reviewer: In this paper, the authors reported aerosol properties over the Gangetic –Himalayan region, and they estimated aerosol direct forcing values with ground-based measurements and broadband radiative transfer model (RTM) calculations. This is a well written paper, yet it lacks innovative ideas. Aerosol properties of this region have been well studied and reported in numerous papers (e.g. Dey, S., and L. Di Girolamo, 2010, Gautam et al., 2010). Also, estimates of aerosol direct forcing from pyranometer measurements and broadband RTM calculations are not new. I recommend that the authors expand this paper to a review paper that summarizes aerosol climatology over the Gangetic –Himalayan region. Such a review could include ideas from this paper as well as other existing publications. Expanding this paper may require serious effort, and therefore, I recommend that the authors revise and resubmit the paper.

Response: We thank the Reviewer for the constructive comments and recommending revision of the paper. We take this opportunity to address and further improve the paper in light of the comments/suggestions by the Reviewer. Bulk of this paper focuses on ground-radiometric column measurements over Indo-Gangetic Plains (IGP), Himalayan foothills and slopes over the broad domain covering northern India and Nepal during the 2009 pre-monsoon period. Our study region covers both the northwestern region i.e., in the vicinity of Thar Desert and foothill/slope, and the eastern transect in Nepal, in addition to AERONET sites in the IGP. Thus, the paper documents aerosol related observations capturing the zonal gradient (from west to east) and the vertical transects from the IGP to the elevated mountain slopes – which has not been collectively reported previously during the course of pre-monsoon season. This ground-based observational study captures the highly variable aerosol loading, comprised of mineral dust, biomass burning and anthropogenic aerosols, and changes in aerosol optical/radiative properties, strongly influenced by the dynamic meteorological conditions, from the desert/arid climate in northwestern India to the eastern parts of the IGP as well as along the southern slopes of the Himalayas. In the paper, we also highlight the aerosol and water vapor variability and dynamics during the important transition period from dry to monsoon onset conditions over the Gangetic-Himalayan region using column-integrated measurements carried out in a unified and consistent manner from 9 locations in northern India and Nepal.

Previous studies in past reported aerosol measurements mostly over single point locations over northern India and Nepal (cited in the paper) during pre-monsoon period. However, we noted in the paper that coordinated network of simultaneous aerosol related measurements in the Gangetic-Himalayan measurements is important for improved understanding of the aerosol properties and water vapor dynamics and implications to regional radiative forcing. Additionally, information about SSA is of great importance and can assist climate modeling in studying the impact of aerosol absorption on atmospheric circulation related to the investigation of aerosol-monsoon rainfall coupling – as we mention in this paper. The uniqueness of the data collected from the campaign is also an important aspect of the paper as the comprehensive dataset follows similar instrumentation and calibration protocols across the AERONET sunphotometer, Microtops and pyranometer measurements over northern India and Nepal during the pre-monsoon season. Such unified distributed network of column-integrated aerosol measurements also aid in the better understanding of local-to-regional aerosol characteristics in relation with validation and potential improvement of satellite-retrieved aerosol products (e.g., from MODIS, MISR) that have been shown to have relative biases over northern India and Nepal region (Kahn et al., 2009; Kahn et al., 2010).

In summary, the paper reports regional aerosol distribution coupled to the dynamical background from ground-based column observations at 9 locations in the complex environment of the Gangetic-Himalayan region during pre-monsoon period, with support from satellite and reanalysis datasets. With coordinated ground measurements limited to one pre-monsoon season, we highlight the aerosol solar absorption from IGP to Nepal Himalayas foothill/slope region, together with the moisture-laden airmass impact on the aerosol radiative forcing.

Regarding the viewpoint of Reviewer on pyranometer measurements and broadband RTM calculations, we would like to mention here that majority of the prior publications related to aerosol radiative forcing, in the Gangetic-Himalayan region during pre-monsoon season, are based on RTM calculations that do not show or constrain the calculations with pyranometer measurements (please refer to Table 2 of this document). Additionally, column-integrated AERONET SSA over northern India and Nepal as shown in this paper, provides insight into the regional distribution of absorbing aerosols in a consistent and coherent manner. Furthermore, some previous studies show the SSA to be quite low (~0.7 at 500nm) at few locations in northern India/IGP (Table 2) and it is not clear whether those estimates reflect aerosol absorption at the surface level or represent column-integrated values. Given the lack of in situ chemical composition data, we therefore show the SSA estimates from AERONET and model calculations (constrained by surface flux measurements) and thus provide a consistent picture of the regional aerosol solar absorption characteristics, in terms of SSA variations, in the complex environment of the Gangetic-Himalayan region (from west to east and from south to north). Therefore, we believe the scope of the current study justifies its potential for publication.

With that said and the reasons outlined below in this rebuttal, we do not entirely agree with the Reviewer that the current manuscript should be transformed into a Review paper. The purpose of the paper is to highlight the findings from the 2009 pre-monsoon RAJO-MEGHA campaign. A 100% review paper needs to be an independent work and is beyond the scope of the current manuscript. As the Reviewer may note, we in fact do provide sufficient background information about the existing aerosol measurements in northern India and Nepal focused during pre-monsoon season. We tried to capture in the paper what has been done before, what is new with this paper and how our results compare to previous published studies – as given by the 70 published studies cited in the paper (with the inclusion of other recent works in our revised submission).

However, per Reviewer's suggestion, the paper can be improved by including a more robust comparative analysis with published literature in the revised manuscript and therefore we will list results from previous published studies on AOD, SSA and radiative forcing estimates (Table 2). We will also refer to (and place in context) some recent relevant publications in the revised manuscript.

Per the Reviewer's recommendation and our own additions, revisions to the paper will include:

- Improved readability of comparative review of published results based on aerosol loading, SSA and radiative forcing estimates in N. India and Nepal (Table 2).
- Details of RTM calculations and discussion related to uncertainties (Table 1).
- Expansion of the section related to the coupling of aerosol and water vapor radiative forcing.
- Diurnal variability of aerosol and water vapor loading over the Nepal transect consisting of the three locations i.e., from foothill to higher elevation mountain slope (3670 masl), in order to show the accumulation of aerosols over elevated regions along the southern slopes associated with the enhanced convection and upslope transport of pollutants – indicating significant accumulation of aerosols in the free troposphere at elevated mountain regions.

Reviewer: Other suggestions: (1) The authors mentioned two MODIS aerosol products: the Darktarget and Deep Blue products. In the last part of section 2.2 and in Figure 3, the authors mentioned a term called "MODIS AOD data" without further explanation. Were "MODIS AOD data" derived from both the Dark-target and Deep Blue products, or was only one of the products used? This needs to be specifically stated.
Response: Yes, the MODIS AOD data were obtained from both the Dark-Target and Deep Blue products in order to show, in a qualitative sense, the progression of the pre-monsoon aerosol loading. The Level-2 Aqua MODIS AOD from both products were averaged over each pixel in our spatial domain and the composite AOD is shown to cover the aerosol loading over bright surfaces in the region in addition to the dark-target AOD. This point was not as clear, as the Reviewer pointed out, and we will clarify it in the revised manuscript.

Reviewer: (2) Figure 3 and Figures 11a and b look similar to figures from Gautam et al., 2010 (Gautam, R., N. C. Hsu, and K.M. Lau (2010), Premonsoon aerosol characterization and radiative effects over the Indo-Gangetic Plains: Implications for regional climate warming, J. Geophys. Res., 115, D17208, doi:10.1029/2010JD013819.) In fact, the topics of these two papers are very similar. The authors need to highlight the significant contributions from this paper that differ from Gautam et al., 2010.
Response: Figure 3 is included to show the regional distribution of aerosol loading. Since we cover a number of locations in the Gangetic-Himalayan region in this paper and discuss their optical properties, we thought it was important to show the spatial coverage of AOD from satellite, specifically for 2009 pre-monsoon season, that maybe helpful for the readers to comprehend the spatial variability observed from ground, with background information provided by satellite AOD and prevailing meteorology figures. Figures 11a, b are the instantaneous

forcing efficiency and comparison between observed and modeled fluxes, respectively, at Jaipur. This site is different from the Kanpur plots in Gautam et al., 2010. Fig. 11a, b is shown to emphasize the usage of pyranometer measurements and to constrain our model calculations as reported in the paper. The comparison plot also brings greater confidence to our model calculations. However, as the Reviewer suggests the figure looks similar tone to that from Gautam et al. 2010, we will move Fig. 11a, b to supplementary material. Thus, we would like to keep the figure associated with the paper for the reasons stated above.

In addition, as the Reviewer says the topics of the current paper are similar to that of Gautam et al., 2010 that focused only over Kanpur. We argue that the topics of the two papers are only partially similar. The current paper expands and advances the knowledge of aerosol loading in the Gangetic-Himalayan region from a coordinated network of aerosol and water vapor measurements over northern India and Nepal at 9 strategically selected locations encompassing the near-source region of Thar Desert, Indo-Gangetic Plains and the foothill and slopes of the Himalayas. The paper shows in a given pre-monsoon season how the aerosol properties and water vapor dynamics vary among the various sites in the three sub-regions of the Gangetic-Himalayan region.

We strongly believe this coordinated observational analysis covering such a complex environment itself significantly adds to the current state of knowledge about the regional aerosol distribution. It should be noted that mostly single point aerosol related studies were published in the past and such dense coordinated network of aerosol measurements as reported by us have not been carried out during pre-monsoon season previously in northern India and Nepal. Additionally, we highlight the spatial gradients in aerosol solar absorption from west to east and also provide estimates of aerosol radiative forcing and comparison with previous studies among different regions. Furthermore, the role of the dynamical background on the regional aerosol distribution and its impact of radiative forcing is also a key aspect of the paper that was not well understood previously either in Gautam et al., 2010 or other publications.

In contrast, results from Gautam et al., 2010 were based on aerosol radiative forcing estimates and focused only over the Kanpur AERONET site in the IGP. Gautam et al., 2010 had three main points:

- MODIS AOD climatology of aerosol loading over South Asia and AERONET aerosol loading climatology over Kanpur,
- Aerosol radiative forcing over Kanpur,
- Aerosol vertical distribution from CALIPSO focusing over northern India,
- Three-decade long annual mean tropospheric warming over the Gangetic-Himalayan region, possibly amplified by aerosol solar absorption effects in northern India.

Reviewer: (3) Section 2, water vapor data. Water vapor data from the MERRA dataset were used in this study. However, no details about this dataset were included, and it is necessary that the authors discuss the bias and uncertainties of these water vapor data.

Response: MERRA water vapor is shown in Fig. 4. Please note that the MERRA water vapor is only shown in Fig. 4. The water vapor data over all the ground sites are used from sunphotometer measurements as well as for aerosol radiative forcing analysis. Total precipitable water from MERRA was used to demonstrate the spatial and temporal variation of aerosols over India and adjacent oceanic regions associated with seasonal migration of atmospheric water vapor. Water vapor from MERRA was not used for actual calculation shown in this paper.

MERRA is a new reanalysis product for the satellite era based on GEOS-5 GCM and data assimilation system, developed with a goal to improve the hydrological cycle (Rienecker et al. 2011). For atmospheric water vapor, the major sources of data assimilated are radiosondes. The assimilation system also includes instantaneous rain rate estimates from SSM/I and the TRMM TMI, and moisture-sensitive radiance data from SSM/I and AMSU-B (Rienecker et al. 2008, 2011). MERRA water vapor has been compared/validated with other reanalysis (Rienecker et al. 2011), SSM/I (Rienecker et al. 2011), AIRS (Wong et al. 2011) and in situ observations (Kennedy et al. 2011).

Reviewer: (4) Section 2.3, radiative transfer model (RTM). Broadband surface reflectance values are needed for the RTM calculations. However, the method of obtaining the broadband surface reflectance values, the uncertainties of the broadband surface reflectance values, and sensitivity studies related to this parameter were not discussed. The authors need to expand their discussion of these topics in their next version of the paper. Also, the overall uncertainties of their RTM calculations need to be reported.

Response: We agree with the Reviewer that details of the RTM calculations were not entirely provided. We will provide details related to surface albedo for surface solar flux calculations (in the current manuscript, results are presented and discussed for surface forcing estimates and NOT for TOA forcing). We obtain the broadband surface albedo from CERES data (Rutan et al., 2009). However, the sensitivity of surface reflectance to surface solar flux is quite small with a maximum value of ±1.5% in the broadband surface albedo range of 0.15-0.25. We will also include discussion related to sensitivity studies to various input parameters and overall uncertainties as follows (briefly presented here, but more detailed in the revised manuscript):

Several variables factor into the uncertainty in estimating shortwave aerosol radiative forcing at surface as listed in Table 1. Uncertainties are estimated from perturbing input variables from radiative forcing calculations with only one variable perturbed with others fixed. Table 1 lists the various sensitivity parameters namely, aerosol optical model, aerosol height, broadband surface albedo, AERONET water vapor retrieval uncertainty (Schmid et al., 2001; Smirnov et al., 2004) and AERONET AOD retrieval uncertainty. The overall uncertainty combining various scenarios, as listed in Table 1 as well as assuming uncertainties are not correlated, thus becomes ±25% based on RMSE of the uncertainties arising from individual variables.

Table 1. Uncertainty associated with radiative forcing calculations.

Sensitivity Variable	Type/Range	Uncertainty in Surface Forcing Estimate
Aerosol Optical Model	Dust 0.5µm / Dust 1.0µm / Mineral Accumulation mode / Mineral Transported mode / ±1% change in soot	±23%
Aerosol Height	Gaussian aerosol profile within 1 and 5km	±1%
Surface Albedo	0.15-25	±1.5%
AERONET Water Vapor retrieval	±10%	±3%
AERONET AOD retrieval	±0.01±0.02	±8%

Reviewer: (5) The separation of WRF and ARF is interesting. However, the results from both WRF and ARF need to be validated before any conclusions can be drawn from this study. I recommend that the authors to expand this part of their study as well.

Response: We are happy to note that the Reviewer found this section interesting related to aerosol and water vapor radiative effect. As the Reviewer suggested, we explain the separation of aerosol and water vapor radiative effect in more detail here and likewise will incorporate the revisions in the re-submission. The goal of this section is to show the leading role of the coupled aerosol- and moisture-laden airmass in influencing the overall observed aerosol radiative forcing impact. In general terms, aerosol radiative forcing refers to the difference between aerosol-laden and aerosol-free flux in cloud-free atmosphere. The forcing thus signifies the absorption (or scattering) associated with the aerosol loading given other parameters are not subject to large variations. In this paper, the shortwave aerosol radiative effect is derived from broadband solar flux measurements as well as obtained from RTM calculations. In an environment, where aerosol and water vapor loading co-occur and systematically vary, it is reasonable to anticipate a measurable contribution of the water vapor radiative effect such that the two exert forcing in tandem. Since water vapor has strong absorption bands in the near- and shortwave- IR wavelengths, it acts as an absorbing layer and thus would induce reduction in downward solar flux.

This paper deals with aspects related to aerosol-induced reduction (atmospheric absorption) in downward solar flux. Over northwestern (NW) India, we noted in the observations during pre-monsoon period that the westerly airmass causing mineral dust influx is enriched with moisture as it moves over the northern Arabian Sea, thus resulting in a systematic and simultaneous increase in both column-integrated AOD and water vapor, during the course of the pre-monsoon period. From Fig. 7 in the paper, aerosol and water vapor loading are found to be strongly correlated in NW India (over Jaipur and Chitkara) with a large range observed for both AOD (from 0.2 to 1.5) and water vapor (from 0.4 to 4cm). The noted observations led us to infer that the regional aerosol radiative effect is convoluted with the water vapor forcing signal since it varies systematically (significantly increases). The water vapor radiative effect becomes more important because it is not constant and/or randomly distributed in the measurement time period. Few previous studies also noted correlations between aerosol and water vapor loading (Smirnov et al., 2002; Prasad and Singh, 2007) but have not explored beyond the correlations and not explained the coupling from a dynamical perspective. In this paper, we discuss in detail the physical mechanism underlying the coupled aerosol-water vapor airmass and also their relative/combined effects on net radiative effect.

First, we show the instantaneous pyranometer observations indicating the observed forcing efficiency (F_e) to be ~-274Wm^{-2}/AOD at 25°-35° solar zenith angle (Fig. 1a). The cloud-screening procedure was discussed in the paper before the forcing analysis is carried out. This observed F_e is associated with the regional aerosol solar absorption; however, since the aerosol and water vapor radiative effects are convoluted in the data, we attempt to separate their relative impacts as opposed to the net observed aerosol-water vapor effect.

The relative impact assessment is carried out by turning on and off the observed aerosol and water vapor inputs in the RTM calculations, with all other variables fixed, and investigate the corresponding reduction (solar absorption) in downward solar flux. We have noted in the paper that since the relative humidity is generally less than 50% during the dust-dominant dry pre-monsoon season, we therefore do not include aerosol humidification effect by turning off the RH dependency factor in the RTM and thus focus on the coupled aerosol-water vapor airmass effect. Aerosol optical model (external mixture of dust, water soluble and soot components) inputs are discussed in the paper and are fixed for all computation cases.

We analyze three scenarios as follows:

- COMBINED AEROSOL AND WATER VAPOR (both aerosol and water vapor ON),
- AEROSOL ONLY (no water vapor input),
- WATER VAPOR ONLY (no aerosol input)

The COMBINED aerosol and water vapor run yields a F_e of ~-277Wm^{-2}/AOD (in close agreement with observed F_e as discussed in the paper) associated with aerosol and water vapor absorption (Fig. 1b). In the case of AEROSOL only with no water vapor input, the F_e is estimated to be about -208 Wm^{-2}/AOD, largely associated with absorption from mineral dust and soot components, and is a large fraction (~75%) of the combined F_e (Fig. 1b). Whereas, the WATER VAPOR F_e (as a function of water vapor) due to absorption of solar radiation by water vapor only is ~-28 Wm^{-2}/AOD (Fig. 1c) and is an order of magnitude smaller compared to the aerosol absorption effect, but is certainly a non-negligible fraction of the observed surface F_e (~10%). In addition to the instantaneous forcing, diurnally averaged F_e also suggests ~8% contribution from water vapor to the combined F_e (Fig. 2). Thus, we clearly see the amplification of aerosol absorption leading to enhanced surface forcing (cooling) due to water vapor radiative effect which is associated with the systematically co-varying aerosol and water vapor over NW

India. In addition, it is also noted that the modeled net F_e is not a linear combination of the respective aerosol and water vapor F_e which is an indication of the enhanced solar absorption especially at higher values of AOD and water vapor.

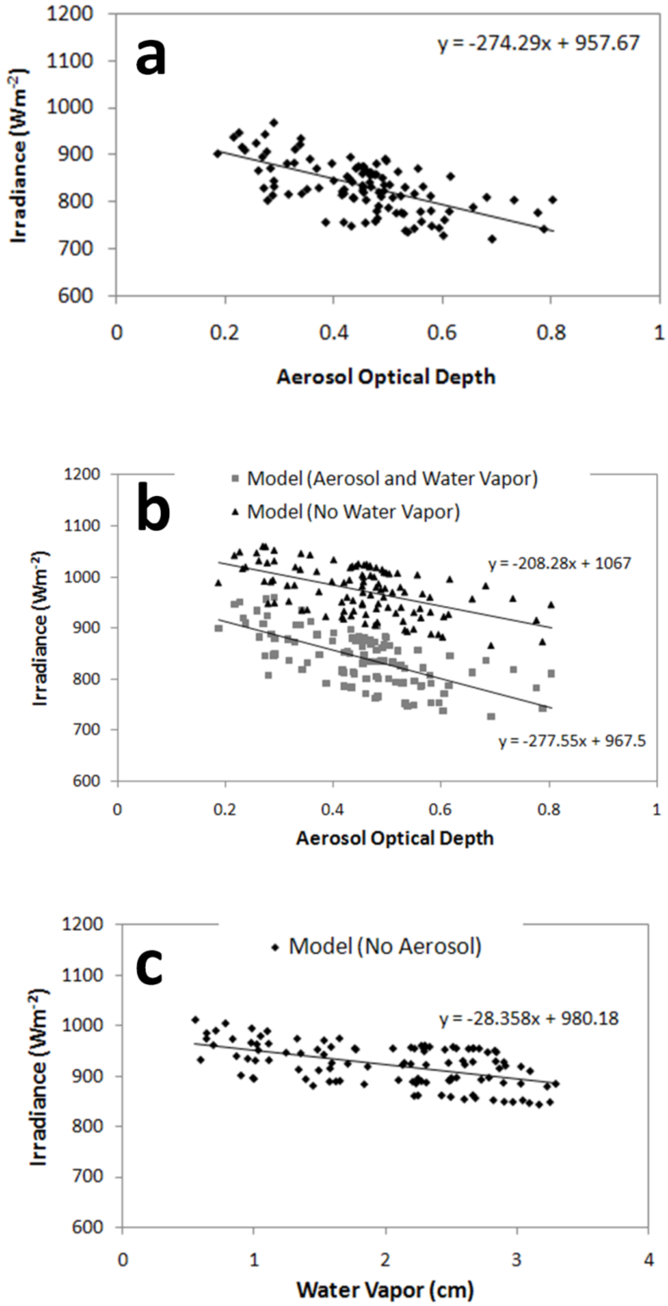

Fig. 1(a) Instantaneous forcing efficiency (F_e) observed from pyranometer surface flux measurements over Jaipur at 25°-35° solar zenith angle, (b) model calculated F_e due to combined aerosol and water vapor radiative effect (black) and aerosol only with no water vapor input (grey), and (c) model calculated water vapor F_e. Aerosol and water vapor inputs to model calculations are obtained from CIMEL sunphotometer measurements.

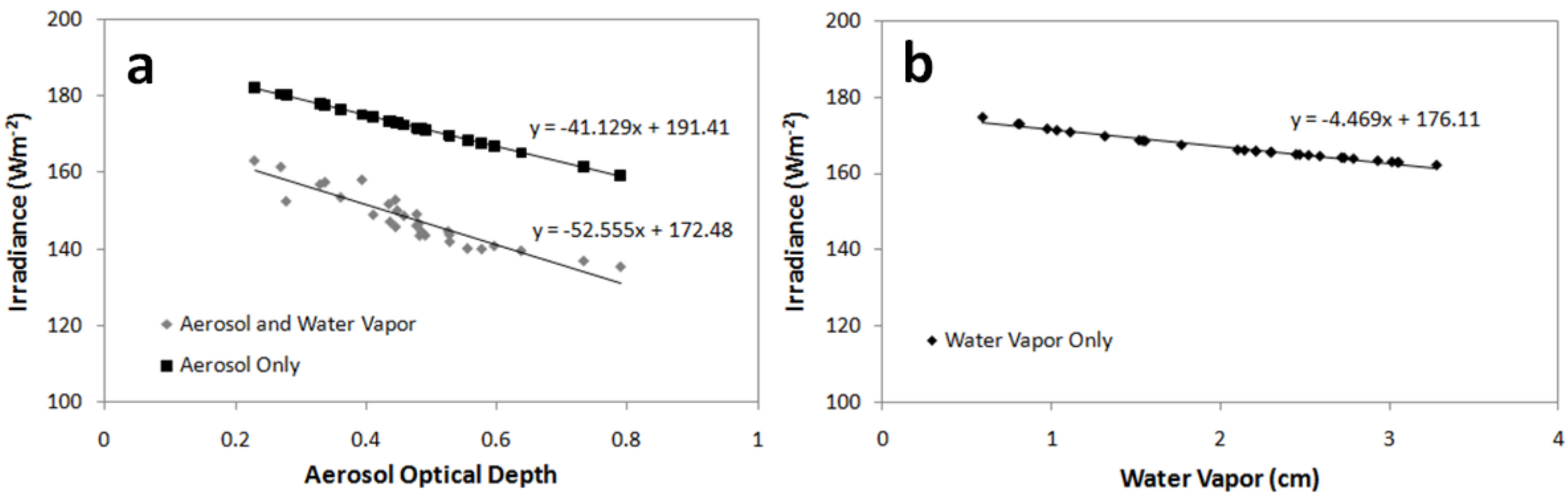

Fig. 2 Diurnally averaged forcing efficiency (F_e) obtained from model calculations for (a) combined aerosol and water vapor (grey) and aerosol only (black); (b) water vapor only with no aerosol input.

We also found indication of the relative impact of water vapor radiative effect in the co-located pyranometer-sunphotometer data over Jaipur. To determine the water vapor effect, solar flux data were grouped based on low and high water vapor conditions given that the aerosol loading was small and representative of the background AOD. First, the solar flux data were only selected corresponding to low AODs (< 0.3) and were further separated in low (< 1cm) and high (> 2.5 cm) water vapor. Thus two groups were formed and the corresponding fluxes were averaged, as shown in Fig. 3. Blue bars represent mean solar flux for the low AOD (0.25±0.03) and low water vapor (0.78±0.16cm) group; and red bars correspond to the low AOD (0.27±0.01) and higher water vapor (2.73±0.07cm) group. The irradiance values (y-axis) indicate the instantaneous surface flux of 915±37Wm^{-2} and 843±34Wm^{-2} corresponding to low and high water vapor observations (first set of bars on extreme left of the x-axis), with similar background aerosol loading conditions at 25°-35° solar zenith angle over Jaipur, suggesting enhanced absorption associated with higher water vapor. Similarly, corresponding to the two groups, model calculations show a comparable difference in the surface fluxes between low and high water vapor conditions with both aerosol and water vapor inputs turned on in RTM calculations as indicated by the Aerosol and Water Vapor label on the x-axis of Fig. 3. Further, separating the impacts of water vapor (no aerosol) and aerosol (no water vapor) solar absorption clearly shows the large difference in fluxes associated with the water vapor radiative effect compared to the aerosol (only)-induced fluxes. It is to be noted that since the aerosol and water vapor loading co-occurs, therefore the sample size is limited with relatively few observations in the aforementioned groups. However, the detailed model calculations (instantaneous and diurnal) of separating aerosol and water vapor radiative effect and their combined role in enhancing the overall net radiative impact as well as indication of the enhancement in instantaneous observations suggest that the two exert forcing in tandem leading to enhanced solar absorption/surface cooling.

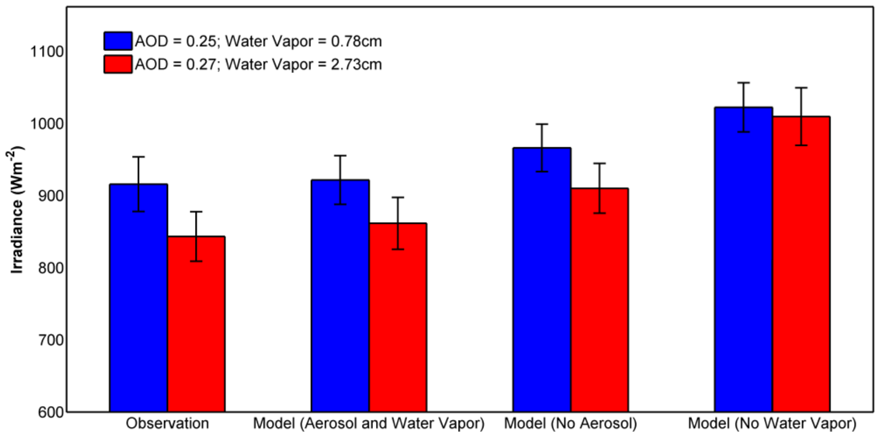

Fig. 3 Irradiance (downward shortwave flux) plotted for two groups: low AOD and low water vapor group (blue bars), and low AOD and higher water vapor (red bars). Fluxes are obtained from observations and model calculations for three cases namely, combined aerosol and water vapor, water vapor only (no aerosol) and aerosol only (no water vapor).

Table 2. Aerosol radiative forcing estimates over northern India and Nepal (North of 20°N) during pre-monsoon season.

Site	Location	Surface Forcing	SSA	Period	Measurement/Method	Reference
Jaipur	26.90° N, 75.80° E 450 masl	−23.3 Wm^{-2}	0.91±0.018 (~550nm)	Apr-May-Jun	AERONET sunphotometer, pyranometer, RTM	This study
Chitkara University	30.86° N, 76.86° E 520 masl	-19.6 Wm^{-2}	0.93±0.012 (~550nm)	Apr-May-Jun	Microtops, pyranometer, RTM	This study
Ahmedabad (I)	23.05°N, 72.55°E 55 masl	-46 Wm^{-2}	-	Apr	Microtops, aerosol insitu, RTM	Das and Jayaraman, 2011
Ahmedabad (II)	23.05°N, 72.55°E 55 masl	-44.7 Wm^{-2}	0.69 (550nm)	Mar-Apr-May	Microtops, aerosol insitu, RTM	Ramachandran and Kedia, 2011
Udaipur	24.58°N, 73.70° E 500 masl	-35 Wm^{-2}	-	Apr	Microtops, aerosol insitu, RTM	Das and Jayaraman, 2011
Mt. Abu (I)	24.65° N, 72.78°E 1700 masl	-31 Wm^{-2}	-	Apr	Microtops, RTM	Das and Jayaraman, 2011
Mt. Abu (II)	24.65° N, 72.78°E 1700 masl	-14 Wm^{-2}	0.93	Mar-Apr-May	Microtops, aerosol insitu, RTM	Das and Jayaraman, 2011
Delhi (I)	28.38°N, 77.17°E 240 masl	-64 – -106 Wm^{-2}	0.74 - 0.84 (~500nm)	Apr-May	PREDE sunphotometer, RTM	Pandithurai et al. 2008
Delhi (II)	28.38°N, 77.17°E 240 masl	-65 – -110 Wm^{-2}	0.77 - 0.82 (~500nm)	Mar, May	Microtops, RTM	Singh et al., 2010
Kanpur	26.51° N, 80.23° E 123 masl	-44 Wm^{-2}	0.89±0.01 (~550nm)	Apr-May-Jun	AERONET sunphotometer, pyranometer, RTM	Gautam et al., 2010
Dibrugarh	27.3° N, 94.6° E 111 masl	-37.1 Wm^{-2}	0.8 (500nm)	Mar-May	Microtops sunphotometer, RTM	Pathak et al., 2010
Nainital	25.25°N, 81.58°E 1970 masl	-26 – -53 Wm^{-2}	-	Mar-May	Microtops sunphotometer, RTM	Kumar et al., 2011
NCO-P	27.95° N, 86.82° E, 5079 masl	-1.6 - -19 Wm^{-2}	0.82-0.89 (500nm)	Mar-May	AERONET sunphotometer, aerosol insitu, RTM	Marcq et al., 2010

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