ARIES, Nainital: a strategically important location for climate change studies in the Central Gangetic Himalayan region

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ARIES, acronym for Aryabhatta Research Institute of Observational Sciences, located in the Central Gangetic Himalayan (CGH) region is emerging as one of the unique sites for climate change studies. The long-term, *in situ*, precise measurements of aerosols and trace gases obtained from this region provide valuable inputs for climate studies. Atmospheric scientists from ARIES are actively involved in near-surface measurements for meteorology, aerosols and trace gases as well as vertical profiling. The Institute is also providing the observational infrastructure and research support to three major projects of the Indian Space Research Organization, Geosphere Biosphere Programme, which basically deals with the measurement of aerosols, trace gases and boundary-layer experiments. The upcoming stratosphere–troposphere radar and high-power micro-pulse lidar observational facilities will be utilized for the continuous vertical profiling of winds, aerosol and cloud properties at a very fine resolution in time and space. Apart from this, atmospheric scientists of ARIES also have active national and international research collaborations. The important results obtained from these research activities are highlighted and upcoming major observational facilities in the field of atmospheric sciences are discussed. They clearly demonstrate the importance of the unique geographical location of ARIES for climate change studies in the CGH region. These measurements and routine meteorological observations provide the necessary atmospheric corrections to the astrophysical observations taken using optical telescopes located at the site.

Keywords: Aerosols, air pollution, climate change, trace gases, wind profiler.

THE Aryabhatta Research Institute of Observational Sciences (acronym ARIES) is an autonomous research institute under the Department of Science and Technology (DST), Government of India. It came into existence in 2004, when the 50-year-old State Observatory was transferred to the Central Government of India by a Cabinet decision taken on 7 January 2004. A detailed description of this is given elsewhere[1–3]. On the outskirts of Nainital city, Uttarakhand, ARIES is located on a hilly terrain called Manora Peak (Figure 1) in the Central Gangetic Himalayan (CGH) region. The Institute carries out fundamental research in the fields of atmospheric science, astronomy and astrophysics, and solar physics[2,3]. Taking advantage of its geographical location, atmospheric scientists from ARIES aim to understand the various aspects of aerosols and gases and meteorology of the mountain region using the existing modern and upcoming major facilities at the Institute, which are essential for climate change studies. These measurements along with routine meteorological observations also provide estimates of attenuation and blurring of a point-like source due to the Earth's atmosphere, which are essential for most observations of celestial bodies made with the 104-cm Sampurnanand and other optical telescopes located at Manora Peak[2,3].

It is a well-known fact that climate system is strongly influenced by the manner in which the incoming solar and outgoing longwave radiations are scattered, absorbed and re-radiated by the aerosols, trace species and gases present in the lower atmosphere. Apart from natural sources, there are diverse anthropogenic sources of aerosols and gases that perturb the climate system and are a real issue for climate change. Global warming is now real and its effects are being observed world over, notwithstanding the expected cooling. It is clearly reflected over

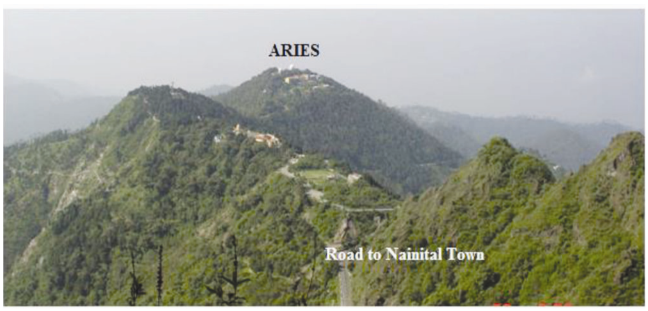

Figure 1. The ARIES at Manora Peak, Nainital.

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India in surface air temperature, surrounding marine regions, melting of Himalayan glaciers, etc. Increasing levels of anthropogenic aerosols and gases also have a deleterious effect on human health, as well as those other living organisms, and vegetation. *In situ* measurements of aerosols and gases are therefore being made from several sites in different parts of the world. They show large spatial and temporal variability that leads to significant uncertainty in quantifying their radiative forcing and hence making climate change predictions more difficult[4]. Additionally, processes in the lower atmosphere become more complex in the tropical regions due to more water vapour (~80% of the global budget) and intense solar radiation, leading to more active photochemistry. Study of different atmospheric processes, like physical, chemical, dynamical, etc. in these regions is therefore important. Despite this, the required *in situ* measurements are limited in the developing world and in tropical Asian regions, particularly India.

It has been shown that the anthropogenic emissions of some of the pollutants (e.g. NO_x, CO, volatile organic compounds (VOCs)) are significantly decreasing or almost constant over Europe and USA; however, they are increasing in the regions dominated by the developing countries[5–7] (see also the Intergovernmental Panel on Climate Change (IPCC) 2007 report). In this context, the South Asian, particularly the Indo-Gangetic Plains (IGP) region assumes great importance as both ground-based and space-borne observations have shown higher levels of anthropogenic emissions here[8–15]. Additionally, the model studies have shown that the strong convection during the summer/monsoon is transporting the South Asian pollutants to the Mediterranean Sea[16]. The reverse trend also happens; when intense convection persists over South Asia, especially over the IGP as the synoptic winds during summer are mostly from the western direction, bringing in pollutants from the West Asian and African regions to South Asia. Also, the satellite imagery shows a thick hazy layer over the Himalaya with significant light absorption due to large black carbon (BC) concentration[14,17–19]. *In situ* measurements of aerosols and trace gases have already been obtained at different urban[8,9,20], rural[21,22] and remote sites[7,23] under the Indian Space Research Organization (ISRO) Geosphere Biosphere Programme (GBP). However, such measurements from a high-altitude site in Northern India are lacking while they are essential for climate change studies as the contributions from higher altitude regions need to be quantified. Such studies are therefore recently initiated at ARIES, Nainital[24], Kullu (G.B. Pant Institute of Himalayan Environment and Development)[25], and Hanle (Indian Institute of Astrophysics, Bengaluru)[18,26]. Under this initiative, in 2002 scientists from ARIES began *in situ* measurements of aerosols optical depths (AOD)[24]. Considering the importance of the high-altitude Nainital site in the CGH region, modern observational facilities for measurements of aerosol number concentration, BC, radiation and meteorological parameters were established in 2004, while surface ozone measurements were initiated during late 2006. Realizing the importance of this pristine site as the representative observational site in the North Indian region and also better located to study the influence of intercontinental transport, mainly from southern Europe and northern Africa, more modern observational facilities for the measurement of other aerosols properties (nephelometer, particle sizer and OC/EC), trace gases, including greenhouse gases were added here. The technical details of these instruments are given elsewhere[3]. Vertical distribution of aerosols and ozone are also being studied here using lidar and balloons respectively. To improve knowledge about radiative properties of aerosols, their origin and spatial-temporal distribution over the CGH region, *in situ* measurements of a number of their physical and chemical parameters were carried out during June 2011 to March 2012 using the state-of-the-art instruments from the Atmospheric Radiation Measurement Mobile Facility under the Indo-US joint collaborative programme called Regional Aerosol Warming Experiment (RAWEX)–Ganges Valley Aerosol Experiment (GVAX)[27]. In addition to *in situ* measurements of aerosols and trace gases, a wind profiler stratosphere–troposphere (ST) radar is being set up with funding from DST, so that the dynamical atmospheric processes taking place in the CGH region can be studied. The present article is focused on the frontline research activities, providing an overview of the existing observational facilities as well as the new initiatives taken up during recent years in the field of atmospheric sciences at ARIES.

Geographical location of ARIES

ARIES, Manora Peak (29.4°N, 79.5°E, 1958 m amsl), Nainital (~225 km northeast of New Delhi) located in the CGH region is far away from any major pollution sources with a total population of 0.5 million (according to census 2011) and having a population density of ~50 people per km^2. The nearby towns Haldwani and Rudrapur, about 20–40 km south, have small-scale industries. Below the site lies the densely populated, polluted IGP region toward the south and west. Mountains are located towards the north and east of ARIES. The northeastern sector of the study region encompasses the higher altitude (>1000 m amsl) Himalayan mountain ranges, while the rest are low-altitude (<1000 m amsl) areas. Figure 2 *a* and *b* shows the topography map of the observational site along with a map of population density. Presence of thick vegetation cover around the site can be noted in Figure 2 *c*. Croplands (~43%) and shrub lands (~23%) are the most common land-use categories in the study region[28]. This region is largely affected by the agricultural fires. The synoptic-scale wind patterns are generally westerly

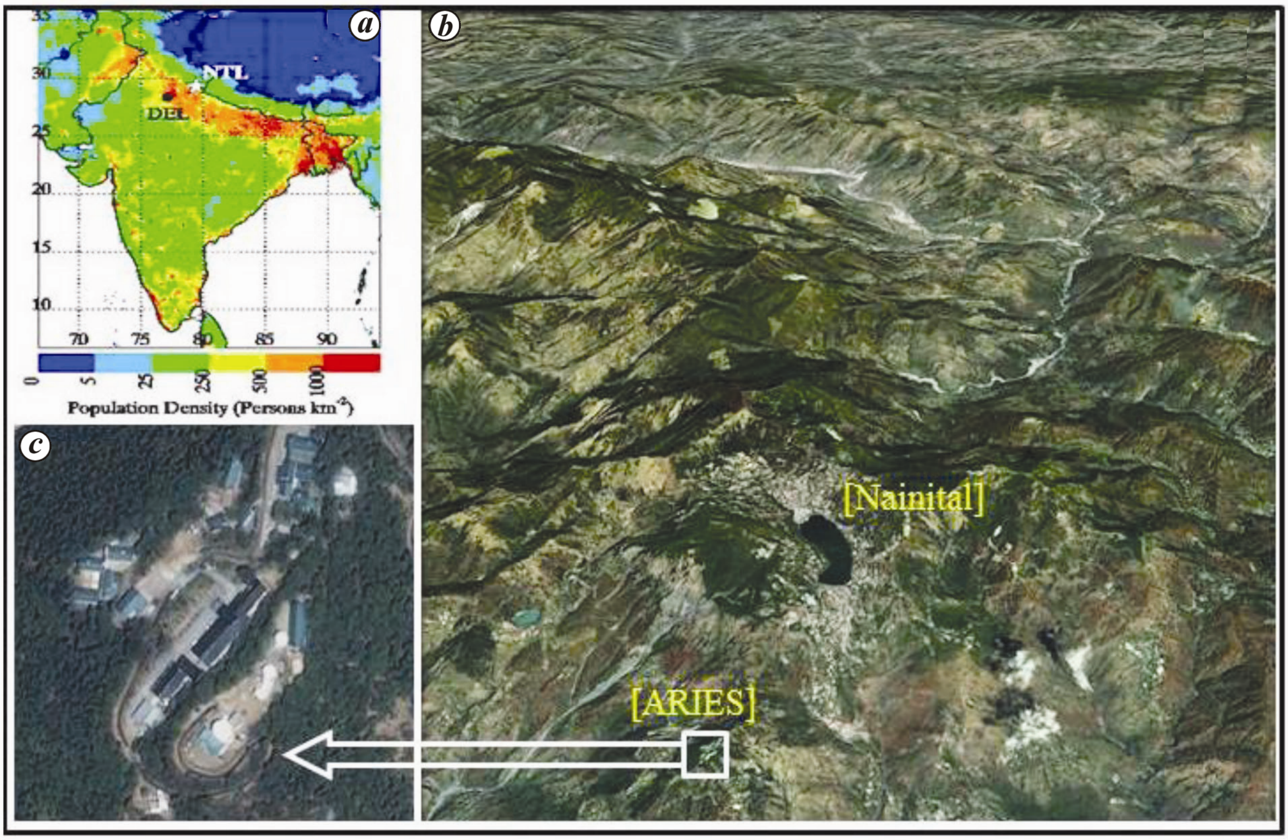

Figure 2. ***a***, Map of population density; ***b***, Topography map around ARIES and Nainital town; ***c***, ARIES and its surroundings. Source: *Google* map.

or northwesterly during winter. In contrast to the summer monsoon season (June–August), the air masses generally circulate over the North Indian region during spring and autumn (May and September), and it is worth noting that such changes in synoptic wind patterns repeat every year[29]. The observations from high-altitude locations just above the IGP region, allow estimation of upslope wind influence and long-range transport of pollutants[15,30–32]. The existing observational facilities, related measurements and main scientific results are briefly described in the following sections.

Aerosol, trace gases and balloon-borne measurements

A multi-wavelength solar radiometer (MWR), designed and developed by the Space Physics Laboratory, ISRO at Thiruvananthapuram was installed in 2002 for the continuous spectral extinction measurements of directly transmitted ground-reaching solar radiation[8,10,24]. The microtops sun photometer and ozonometer are also being used for the measurement of columnar AOD, water vapour content and ozone since 2004. Recently (November 2012), a three-wavelength TSI integrated nephlometer (model 3563; TSI) has been installed for the measurement of total scattering and back scattering coefficients. An aerodynamic particle sizer (APS, model 3321) has been in use since June 2013 for measurement of total and size-segregated aerosol number concentration near the surface. In order to study the possible effects of meteorology on aerosol properties, the surface meteorological parameters (such as ambient temperature, relative humidity and solar radiation, etc.) were also collected using automatic weather station. Figure 3 shows the monthly variations of major surface meteorological parameters.

Furthermore, bulk aerosol samples were also collected during February 2005 to July 2008 on pre-combusted (650°C for ~6 h) quartz filter (PALLFLEXTM, 2500QAT-UP; size: 20.0×25.4 cm^2) using a high-volume air sampler with a constant flow rate of 1.0 ± 0.1 m^3 min^{-1}. The aerosol samples were collected for about 15–20 h to get adequate aerosol mass on the filters[33,34]. The total suspended particulate (TSP) mass was obtained gravimetrically by weighing the filters (before and after sampling) on a very high precision (0.1 mg) analytical balance at equilibration condition (temperature: 22 ± 1°C, and relative humidity: 40 ± 5%). A part of each filter was analysed for carbonaceous aerosols such as elemental carbon (EC; equivalent to BC) and organic

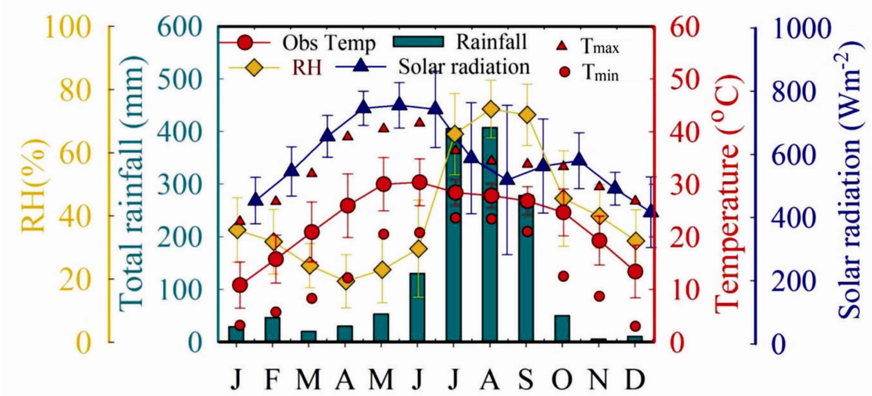

Figure 3. Meteorological parameters observed at ARIES.

carbon (OC) by thermal-optical carbon aerosol analyser (Sunset Laboratory) using the National Institute of Occupational Safety and Health, USA protocol based on thermal-optical transmittance (TOT) and inorganic anions and cations[33,34].

Surface measurements of ozone were initiated at ARIES in October 2006 in collaboration with Physical Research Laboratory, Ahmedabad. Later, other related gases (CO, NO–NO_y, SO_2) along with the various meteorological parameters (e.g. solar radiation, ambient temperature, relative humidity, rainfall, etc.) were also added under the ISRO-ATCTM project. Continuous measurements of surface ozone are being made using UV absorption[28] and the CO instrument operates on non-dispersive infrared (NDIR) absorption technique. The NO–NO_y analyser utilizes chemical luminescence reaction between NO and ozone[15], whereas the SO_2 analyser operates on the pulsed fluorescence technique[35]. It is important to note that the pristine environment of this region requires ultrasensitive instruments having very low detection limits (in pptv range) and therefore NO–NO_y and SO_2 instruments of very low detection limits (50 pptv) have been installed at this site. In addition to the surface ozone measurements, the balloon-borne observations of ozone and meteorological parameters such as relative humidity, temperature, and wind speed and wind direction were made every week since January 2011 using ECC-type ozonesonde (EN-SCI 2ZV7 ECC). Further details on this are given elsewhere[36–38]. The balloon ascent rate was ~5 m/s with burst altitude ~30 km and vertical resolution was ~10 m in the lower atmosphere. The sensors had a response time of 1–2 sec and accuracy of observed parameters was 5–10%.

To gain information on the source region, observations of ozone and BC were also initiated at Pantnagar (29.0°N, 79.5°E, 231 m amsl), a semi-urban site in the IGP region[13]. The observational site is in the campus of G.B. Pant University of Agriculture and Technology that has a perimeter of about 30 km, encompassing a large area of about 16,000 acres and used primarily for the agricultural research. There is no major source of emissions close to the observational site, except vehicular movement in the university campus. Few small-scale industries (mainly non-combustible units) are located around 12 km to the southwest, except a paper manufacturing unit to the northeast of Pantnagar. Delhi is the nearest megacity, about 225 km southwest of Pantnagar[13,30,38]. Apart from these observations, a chemistry model (WRF-Chem) has been used for simulation of meteorological parameters and trace gases over the South Asian region[12]. Analysis of measurements along with the model simulation is useful in understanding the various physical, chemical and dynamical processes over the IGP region.

Important scientific results

Results based on analysis of the above-mentioned extensive measurements have been published recently[10,24,39,40] and some of the important findings are presented here. Figure 4 shows the average picture of AOD over Nainital as a contour plot of monthly mean AOD values in temporal–spectral representation. The spectral variation of AOD is important, as it is indicative of changes in the aerosol size characteristics in the vertical column. During the winter months (October to February), very low AOD values (<0.1 at 0.50 μm) are encountered[10]. These are comparable to those reported for the Antarctic environment and are indicative of the prevailing pristine environment during that part of the year[10], when the peak is isolated from the valley by low-level inversions and shallow boundary layer. However, remarkably high AOD values (with AOD > 0.5 at 0.50 μm) typical to continental regions are not uncommon during the summer months (March to June), when the convective activities lift the local boundary layer above the peak, favouring mixing of the valley-based pollutants with pristine air. In general, the AOD values are higher at shorter wavelengths, decreasing to lower values at longer wavelengths. The higher AODs value for shorter wavelengths shows the dominance of the smaller-sized particles in the number density spectra. Besides the temporal feature, Figure 4 also shows a change in the spectral dependency of AOD with season, from relatively steeper spectra during winter to shallower ones in summer, suggesting seasonal changes in the size distribution of aerosols.

In addition, the monthly variation of columnar AOD values for both forenoon (FN) and afternoon (AN) along with their differences (i.e. AN – FN) are presented in Figure 5 as a function of wavelength at the Manora Peak site. They yield an interesting differences between AOD values of the FN and AN hours. The differences in the measured AOD values are observed to be insignificant in the morning hours, but significant in the afternoon hours (Figure 5). Similar to the differences in columnar AOD values, the near-surface aerosol measurements such as aerosol BC mass concentration and aerosol number concentration are also found to be lower in the FN hours but higher in the AN hours (Figure 6). All these observed differences are attributed to the growth of the planetary boundary layer (PBL), which brings the aerosols and pollutions from the Ganges Valley below the mountain peak during the night and early morning hours to the observational site (i.e. Manora Peak) by later afternoon hours. Beside this, the role of long-range transport, mountain valley wind cell and related dynamics also assumes importance in understanding the high aerosol loading over Manora Peak, in the AN hours. The above-mentioned observed diurnal variability of 50% and more in aerosols can provide a unique opportunity to estimate the direct radiative forcing impact of aerosols on radiative transfer, which can lead to a better understanding of everyday cloud–aerosol interactions in a predictable manner.

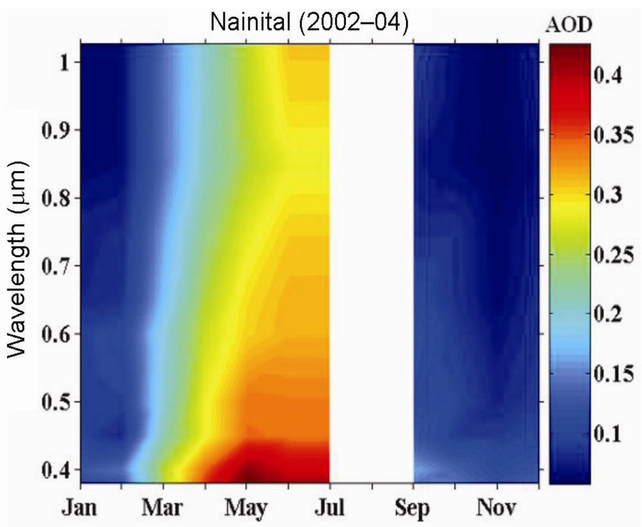

Figure 4. Monthly variation of spectral aerosol optical depth (AOD) at ARIES showing distinctive changes in each month. Gap in the plot represents absence of data due to extensive rainfall over the site during the study period[41].

In addition to the optical and physical properties, the chemical composition of atmospheric aerosols was also studied. Multi-year observations[33,34] have shown that the TSP mass concentration ranged from 13 to 272 $\mu g\, m^{-3}$ during February 2005 to July 2008. The mass concentration of OC and EC varied from 0.4 (2% of TSP) to 22.3 $\mu g\, m^{-3}$ (~40% of TSP) with an average value of 8.2 ± 5.2 $\mu g\, m^{-3}$, and from 0.14 (0.1% of TSP) to 7.6 $\mu g\, m^{-3}$ (8% of TSP) with a mean value of 1.3 ± 1.2 $\mu g\, m^{-3}$ respectively. High values of OC (10.8 ± 5.5 $\mu g\, m^{-3}$) and EC (1.4 ± 0.7 $\mu g\, m^{-3}$) concentration were obtained during the post-monsoon season. The OC/EC ratio varied from 4.0 to 27.2 with an average of 7.7 ± 3.4. The high OC/EC value suggests the dominance of scattering OC over the absorbing EC aerosols, derived from the primary emission source (such as biomass burning) and contribution from secondary organic aerosols. These results can be used for the assessment of single-scattering albedo and aerosol radiative forcing on a regional scale.

Surface ozone observations at ARIES show that the role of *in situ* photochemical ozone production is not significant in this region, dynamical processes seem to dominate. Figure 7 shows the temporal variation of hourly average ozone values and monthly mean statistics of ozone mixing ratios at Manora Peak during October 2006 to December 2008. A systematic increase in ozone is observed from January to early June and afterwards its levels show a dramatic decrease with lower mixing ratios continuing until August. Ozone then increases and shows a secondary maximum during October and November[28]. The first ever observations of NO_y from the Indian region clearly showed incomplete *in situ* photochemistry and confirmed the role of dynamical processes in controlling the levels of ozone and other pollutant in the CGH region[15]. The higher CO/NO_y value also confirms minimal influence of fresh emissions at the site. Increase in ozone, CO and NO_y during high fire activity period was estimated to be 4–18%, 15–76% and 35–51% respectively. Despite higher CO and NO_y concentrations at the site, ozone levels were nearly similar to those at other global high-altitude sites.

Unlike at Manora Peak, surface ozone observations made at a semi-urban site (i.e. Pantnagar) in the IGP region showed daytime photochemical build-up with ozone levels[13] sometimes as high as 100 ppbv. Seasonal variation in 24-h average ozone showed a distinct spring maximum (39.3 ± 18.9 ppbv in May), while daytime (1130–1630 h) average ozone showed an additional peak during autumn. The daytime observed ozone seasonality at Pantnagar is in good agreement with the space-borne observations of OMI tropospheric column NO_2, TES CO (681 hPa), surface ozone observations at a nearby high-altitude site (Manora Peak, Nainital) in the CGH region and with model results. It is suggested that spring maximum is mainly due to photochemistry, involving local pollutants, and small-scale dynamical processes, while secondary

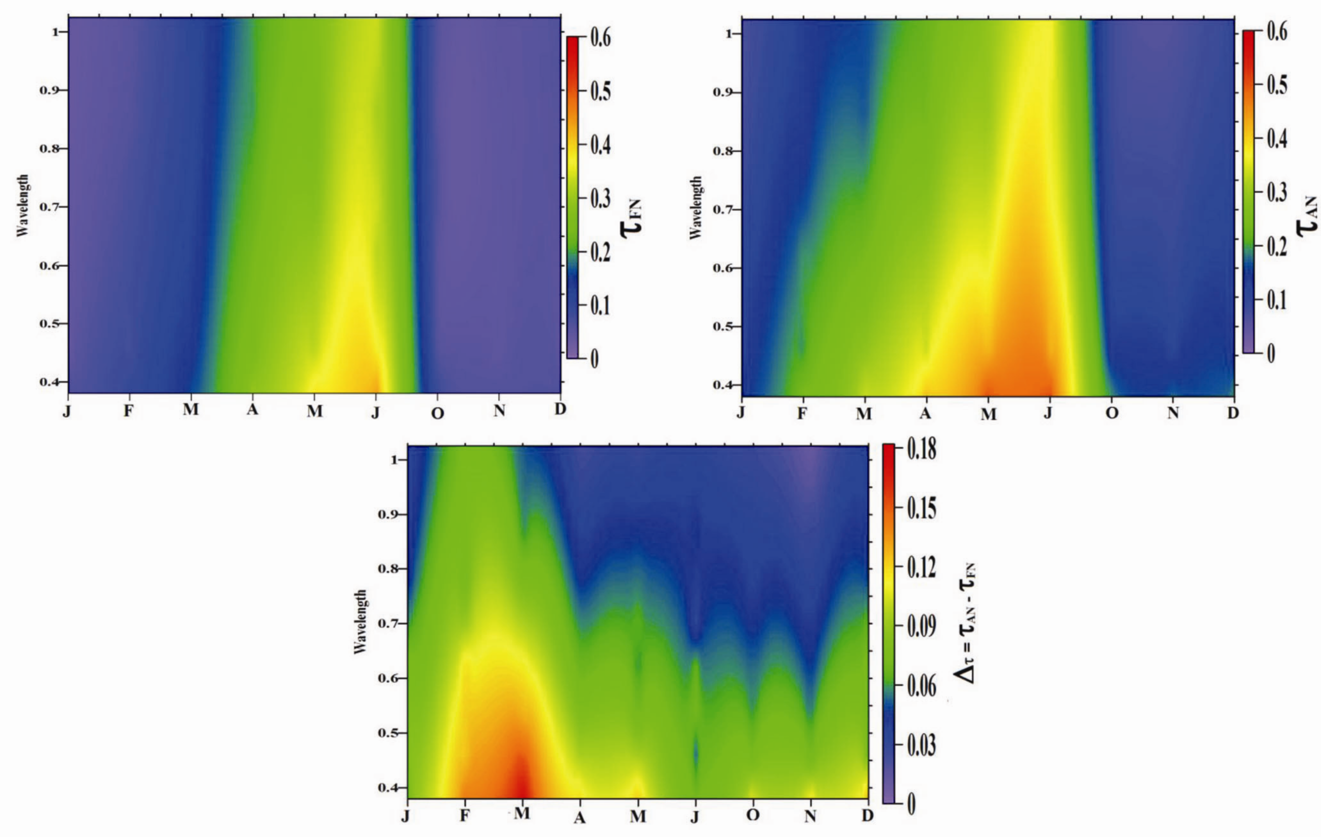

Figure 5. Forenoon and afternoon asymmetry in spectral aerosol optical depth as a function of wavelength[10,41].

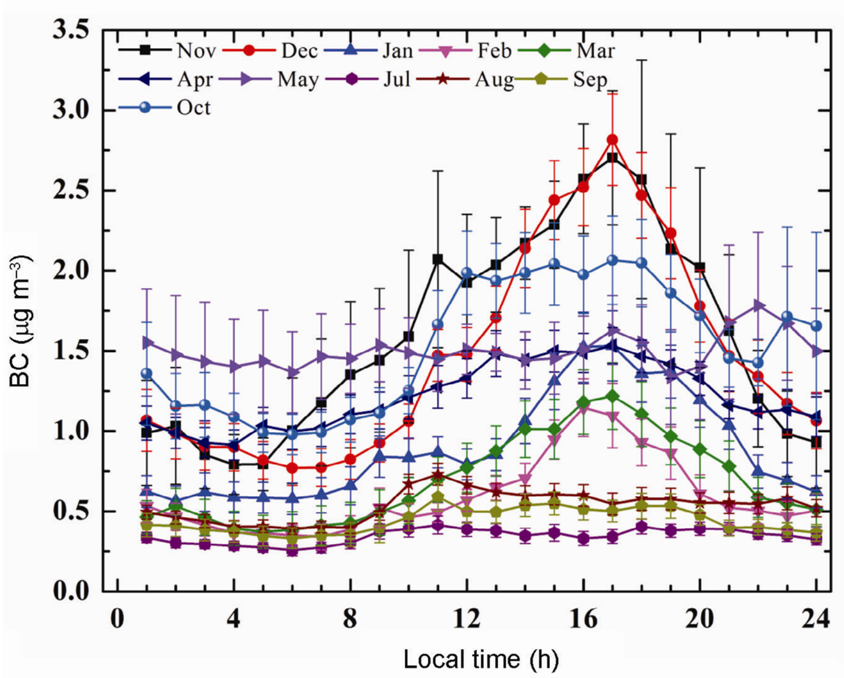

Figure 6. Temporal variation of black carbon (BC) mass concentration at diurnal and monthly timescales[39].

maximum during autumn is due to large-scale processes. It is also shown that maximum possible influence of the IGP region to the CGH region could be 3–10 ppbv. Ozone seasonality over the IGP region is different from that over southern India. Result from a global chemistry transport model captures observed ozone seasonality, but

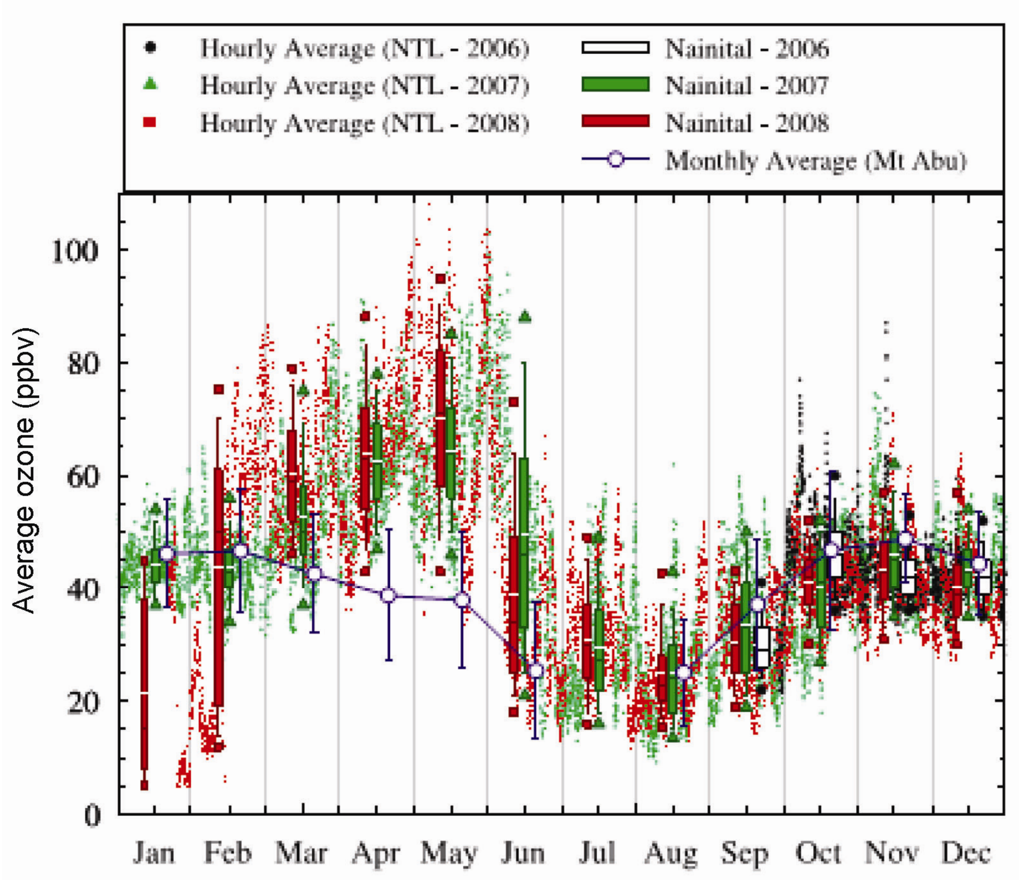

Figure 7. Temporal variations in ozone mixing ratios during October 2006–December 2008 at Manora Peak, Nainital. In box plots, the lower and upper edges of the boxes represent the 25th and 75th percentile respectively. The whiskers below and above are the 10th and 90th percentile respectively. The solid white line inside the box represents the mean of the data[28].

overestimates ozone levels. The chemical box model simulation indicates that ozone chemistry is in NO_x-limited regime. The AOT40 index in this region is significantly high, indicating threat to vegetation in the IGP region.

Vertical ozone profiling was made in the CGH region (Figure 8). The lower tropospheric ozone shows a prominent seasonality with highest levels during spring (~110 ppbv in May) and lowest levels during summer monsoon (~50 ppbv). Influences of subtropical jets are observed (wind speed ~80 m/s) in the middle upper troposphere, particularly during winter. A stratospheric intrusion event is also observed during winter, which enhances the ozone levels by ~180% in the middle–upper troposphere. A noticeable feature of the secondary ozone peaks (~250 ppbv) is in the middle troposphere (~12 km). Ozone levels in 2–4 km altitude range are higher by about 20 ppbv during the spring-time high-fire activity period over Northern India. Moreover, the lower tropospheric ozone levels over ARIES, during spring are found to be considerably (~30 ppbv) higher than those observed over Ahmedabad in western India. This ozone enhancement is attributed mainly to the regional pollution of IGP supplemented with the North Indian biomass burning. It is suggested that regional photochemistry and biomass burning processes play a controlling role in the lower troposphere, while the middle–upper tropospheric variations are driven by dynamical processes, including advection and stratospheric intrusion[38].

Annual simulations of tropospheric ozone and related species were made using the WRF-Chem model over South Asia. The model-simulated ozone, CO, and NO_x were evaluated against ground-based, balloon-borne and satellite-borne (TES, OMI and MOPITT) observations. Comparison of model results with surface ozone observations from seven sites, and CO and NO_x observations from three sites, indicates the ability of the model in reproducing seasonal variations of ozone and CO, but shows some differences in NO_x. The modelled vertical ozone distribution agrees well with the ozone soundings data from two Indian sites. The vertical distributions of TES ozone and MOPITT CO are generally well reproduced, but the model underestimates TES ozone, OMI tropospheric column NO_2 and MOPITT total column CO retrievals during all months, except MOPITT retrievals during August–January and OMI retrievals during winter. Largest

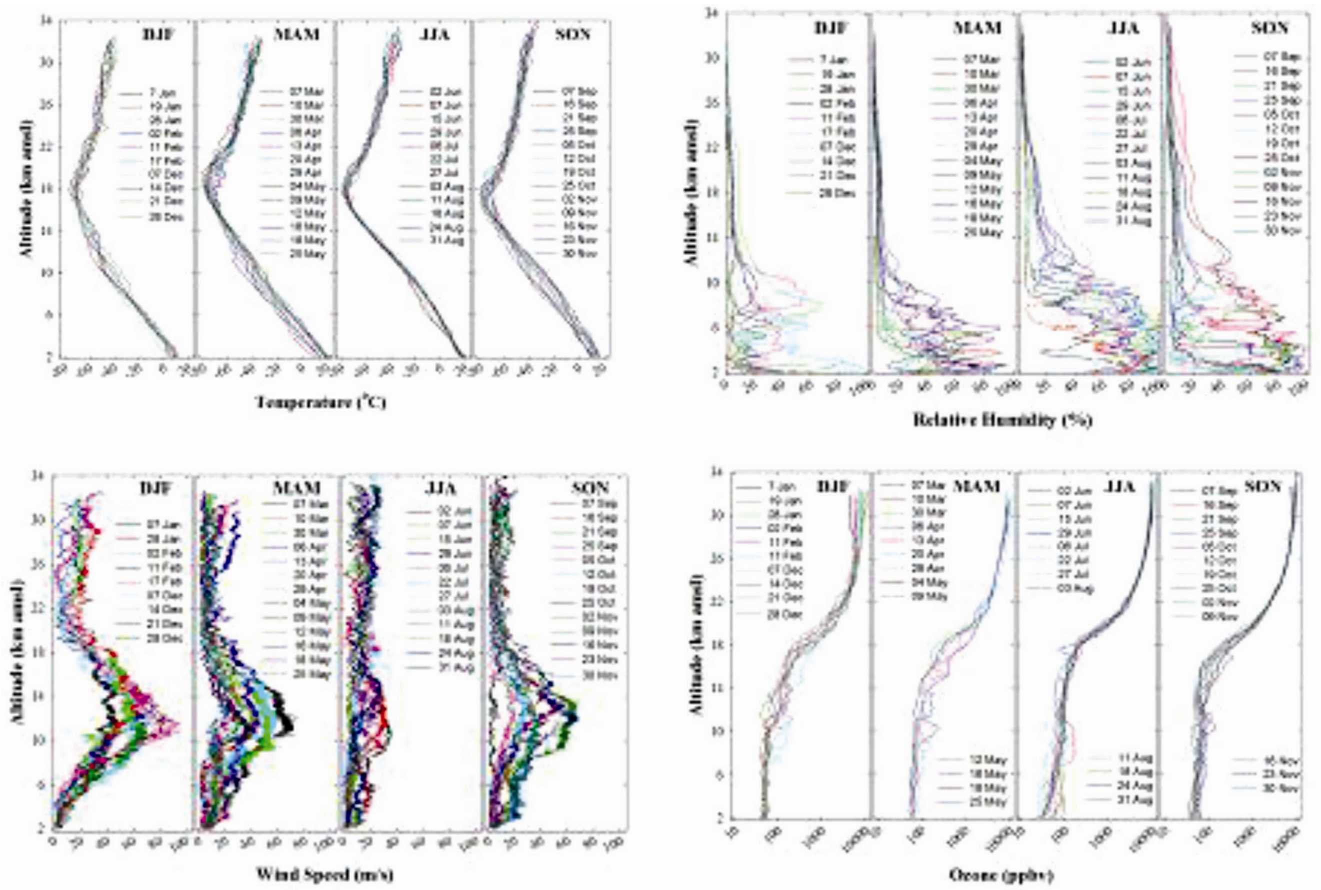

Figure 8. Vertical distribution of ozone and meteorological parameters at ARIES[38].

differences between modelled and satellite-retrieved values are found during spring, when intense biomass burning activity occurs in this region. The evaluation results indicate large uncertainties in anthropogenic and biomass burning emission estimates, especially for NO_x. The model results indicate clear regional differences in the seasonality of surface ozone over South Asia with estimated net ozone production during daytime (1130–1530 h) over inland regions of 0–5 ppbv h^{-1} during all seasons and of 0–2 ppbv h^{-1} over marine regions during outflow periods. The model results indicate that ozone production in this region is mostly NO_x-limited. This study shows that the WRF-Chem model captures many important features of the observations and gives confidence to use the model for understanding the spatio-temporal variability of ozone over South Asia. However, improvements of South Asian emission inventories and simulations at finer model resolution, especially over the complex Himalayan terrain in North India, are also essential for accurately simulating ozone in this region.

High-power micro-pulse lidar

A high-power micro-pulse lidar has been set up at ARIES for studying the vertical profile of aerosols, with the provision of Mie and Rayleigh telescopes used for the lower and upper atmospheric measurements of aerosols and temperature profiles. The Mie lidar system is operational since January 2010 and the Rayleigh lidar is currently being set up. Figure 9 shows a block diagram of the ARIES high-power micro-pulse lidar. Campaign-based observations made by this lidar identified thin and thick cloud layers around 10 and 7 km respectively. AOD of both these types of cloud was about 0.1. Mean value of AOD at Manora Peak was ~0.003 km^{-1}. Observations from the Mie lidar were also compared with data from space-borne sensor (MODIS). AOD data from Terra and Aqua satellite were found to be in good agreement[41–43].

In situ measurements of aerosol properties using AMF-1

In order to improve our knowledge of radiative properties of atmospheric aerosols, their origin and spatial-temporal distribution over the CGH region, observations of aerosol optical and microphysical properties were carried out on daily basis using state-of-the-art but commercially not available instruments mounted on the Atmospheric Radiation Measurement Mobile Facility-1 (AMF-1) during

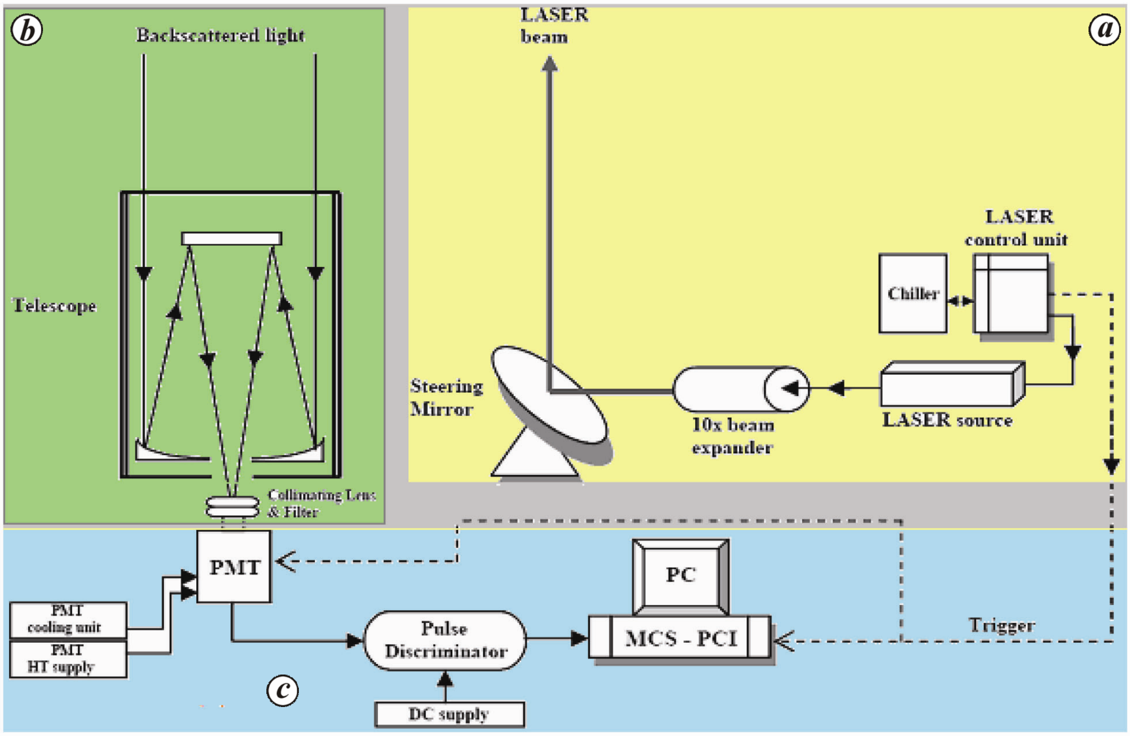

Figure 9. Schematic diagram of monostatic bi-axial pulsed Mie lidar system at ARIES: ***a***, transmitter, ***b***, optical receiver; ***c***, detector and data acquisition system[43,44].

June 2011 to March 2012 under a joint Indo-US research project called RAWEX–GVAX[27,31,32]. The campaign was also aimed to study the impact of aerosol on regional climate, contribution of Ganges Valley to aerosol plumes over Himalaya and to understand physical processes of aerosol–cloud interactions as the site of measurement, located at a relatively pristine high-altitude area in the CGH region, is an ideal location for such studies. During the campaign, the aerosol observing system consisting of a three-wavelength (470, 528, and 660 nm) particle soot absorption photometer and three-wavelength (450, 550, and 700 nm) integrating nephelometer, measured valuable *in situ* optical and physical parameters of aerosols such as aerosol light absorption (σ_{ap}) and scattering (σ_{sp}) coefficients, number concentration of condensation nuclei (N_{CN}) and cloud condensation nuclei (N_{CCN}) for two different size fractions ($D_{1\ \mu m}$ and $D_{10\ \mu m}$). During the campaign, other instruments used for observations were radiosonde launched every 6 h, atmospheric emitted radiance interferometer (AERI), multi-filter rotating shadow band radiometer, Doppler lidar (DL), laser ceilometer (CM) and a micro-pulse lidar (MPL). Huge amounts of extremely valuable data have been obtained during the campaign. A few preliminary results based on these unique data have been recently published[31,32,43–45]. Manoharan *et al.*[35] have reported the higher absorption of the super-micron (1–10 µm) aerosol particles during October and November accounting for 44% of the total aerosol radiative forcing, while Dumka and Kaskaoutis[46] have studied the variation of the single scattering albedo (SSA) and its contribution to the aerosol radiative forcing efficiency along with some preliminary results on the monthly variation of scattering and absorption coefficients. The results show enhanced values of σ_{ap} and σ_{sp} along with high N_{CCN} and N_{CN} during November to March due to transported plumes from agricultural fires in northwestern India, uplift of urban-anthropogenic aerosols from the Ganges Valley and local biofuel burning in winter. In contrast, during monsoon, the aerosol concentrations are significantly lower due to rainy washout. SSA varies from 0.90 to 0.95 for $D_{10\ \mu m}$ and from 0.87 to 0.93 for $D_{1\ \mu m}$ aerosol particles[46], while N_{CN}, N_{CCN} and activation ratio (AR = N_{CCN}/N_{CN}) range from 1606 to 4124 cm^{-3}, 684 to 2065 cm^{-3} and 0.38 to 0.60 respectively, suggesting large heterogeneity in aerosol properties, types and sources[31]. All these results clearly demonstrate that the transported aerosol from the Ganges Valley (below the mountain peak) and abroad, the boundary-layer dynamics and atmospheric modification processes play an important role in the aerosol optical–physical properties and aerosol–cloud interactions over the CGH region. Further details of these studies have been reported by Dumka *et al.*[31,32]. Shukla *et al.*[47] estimated mixing layer height for the CGH region using vertical velocity variance as a basic measurement parameter for the period September–November 2011 and found that it is located ~0.577 ± 0.1 and 0.457 ± 0.05 km above ground level during day-time and night-time respectively.

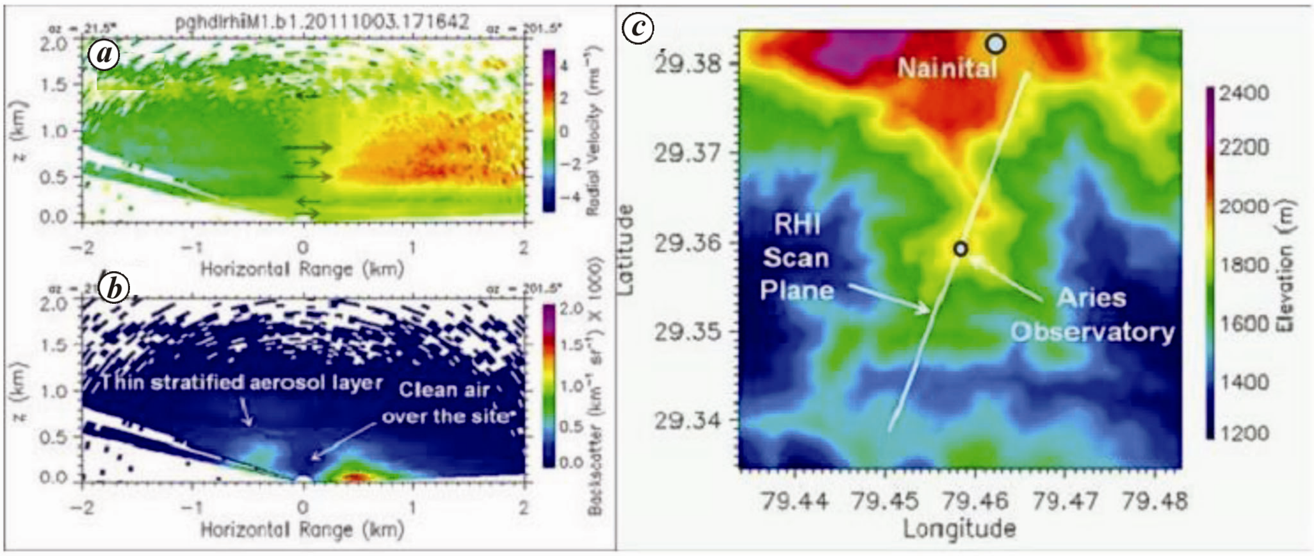

Figure 10. (***a***) Radial velocity, (***b***) attenuated backscatter data from a range height indicator (RHI) scan acquired by AMFDL during GVAX campaign at ~1717 UTC on 3 October 2011 and (***c***) orientation of RHI relative to the local terrain and the town of Nainital[50].

Figure 10 *a* and *b* shows typical examples of radial velocity and backscattered coefficient measurements respectively from the AMF DL on 3 October 2011. Figure 10 *c* shows the orientation of the range height indicator (RHI) scan relative to the local terrain and the town of Nainital. The particular example shows a fairly complex vertical structure characterized by thin layers with distinct shifts in either wind speed or wind direction. Figure 10 clearly shows the location of thick aerosol layers above the ground. The top left panel of Figure 10 shows how the air is flowing over the top of the mountain while the bottom left panel of Figure 10 shows the complex distribution of aerosols above the surface with distinct layers. This indicates aerosol distribution is more localized and confined to thin layers, rather than evenly distributed as assumed by most atmospheric models.

Stratosphere–troposphere radar

Realizing the importance of vertical winds observations, a ST radar wind profiler is being set-up at ARIES. The continuous monitoring of vertical structure in the wind is necessary to understand the total meteorology of any region. In this perspective, ST radar has great potential to provide the profiles of vertical velocities and also the vertical structure of the horizontal velocities of different types of monsoon clouds with very high temporal and elevation resolution. Further, this region is also dominated by western disturbances during winter and spring. Measurements from the ST radar can be made in all weather conditions. Finally, ST radar offers an unparalleled opportunity to study not only gross features of the total wind field, but also small-scale, time-varying structures such as gravity waves, exchange process between stratosphere and troposphere, and turbulence through the middle atmosphere.

Considering the above-mentioned importance of the continuous measurements of vertical winds in the CGH region, which is one of the essential components of day-to-day weather, the ST radar is being set up at ARIES with funding from DST. Figure 11 shows a concept of design of ST radar building and antenna array system. This 206.5 MHz ST radar system uses three-element Yagi–Uda antennae (588 in number) array (circular aperture with dia about 27 m) and equilateral triangle grid. Two most popular techniques, viz. Doppler beam swinging (DBS) and spaced antenna drift (SAD) are being used. The ST radar is configured as an active aperture distributed phased array using state-of-the-art solid-state TR module and digital signal processing techniques to cover a height region beyond the tropo-pause.

Summary and conclusion

Studies related to aerosols and trace gases in the lower atmosphere have been the prime focus globally during recent time. Both, gases and aerosols are recognized to be a threat to human health/vegetation and creating radiative imbalance. India is shown to be among the top ten countries where pollution-related deaths could take place[48]. Ghude *et al.*[49] have estimated a loss of about 9% to the total production of cereals in India due to higher ozone levels. Considering the global importance of climate change studies, atmospheric scientists at ARIES, taking advantage of the unique geographical location of the Institute, have not only made valuable observations in the

Figure 11. Antennae array of stratosphere–troposphere radar on the rooftop of the building at ARIES.

field of atmospheric science, but also published several internationally recognized and interesting scientific results. A few key results obtained are mentioned below:

(1) Long-duration (>5 years) observations of aerosols show that during winter, fine aerosols (radius <0.1 μm), comparable with those over the Antarctic, dominate over the CGH region, confirming its pristine environment. In contrast, during summer there is larger aerosol loading comparable to those over urban regions. This is due to the dominating contribution of coarse aerosols (radius >0.5 μm) from at least two diverse and prominent sources of aerosols. Aerosols radiative forcing over the CGH region is estimated to be very low (+4.9 W m^{-2}) in comparison to that over urban sites (+71 W m^{-2}).
(2) Using state-of-the-art instruments, *in situ* observations of aerosol optical and microphysical properties have been carried out. They have provided valuable and unique scientific information about atmospheric aerosols over the CGH region, such as higher absorption of the supermicron (1–10 μm) aerosol particles accounting for 44% of the total aerosol radiative forcing during October and November.
(3) The extended lidar observations over Manora Peak substantiate the presence of elevated aerosol layers and clouds, which are important in the study of climate modelling. The mixing layer heights at the site are found to be located ~0.577 ± 0.1 and 0.457 ± 0.05 km above ground level during day-time and night-time respectively.
(4) Observations of trace gases (ozone, CO, NO–NO_y, CH_4 and SO_2) show that the photochemical ozone production is generally not significant over the CGH region. Despite higher CO and NO_y concentrations, ozone levels in this region are nearly similar to those at other global high-altitude sites.
(5) Modelling of the observations of ozone vertical distribution and meteorological parameters suggests that in the CGH region regional photochemistry and biomass burning processes play a controlling role in the lower troposphere, while the middle–upper tropospheric variations are driven by dynamical processes, including advection and stratospheric intrusion.

The main objective of the existing and upcoming observational facilities is to provide *in situ* measurements of scientifically useful parameters of gases and aerosols so that detailed study of the physical, chemical and dynamical processes in the lower atmosphere region of the CGH can be carried out using modelling. Presently, there are four scientists and four research scholars in atmospheric science group at ARIES. Over 50 papers have been published so far in peer-reviewed journals. This group has successfully contributed to the award of five Ph D theses (including one collaborated). Atmospheric scientists at ARIES are also playing a major role in the installation of the 206.5 MHz ST radar and a host of other instruments to measure trace gases and aerosol properties in the area of atmospheric sciences. Apart from DST, other national and international organizations have taken note of the strategic location of this high-altitude atmospheric science laboratory, which is well located for studies on the regional climate change issues. The atmospheric science group would, therefore, like to expand its ongoing collaborations with universities and research institutions of the country and abroad.

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