CHAPTER 1

INTRODUCTION

1 INTRODUCTION

Analysis of spatio-temporal variation in PM2.5 (particulate matter <2.5 µm aerodynamic diameter), AOD 550 nm (Aerosol Optical Depth at 550 nm) and meteorological forcing variables [air temperature (AT), surface pressure (Ps), relative humidity (RH), wind speed (WS)] and PM2.5-meteorology PM2.5-AOD relationships; diurnal analysis of planetary boundary layer height (PBLH) and PM2.5, and the nature and strength of their (PM2.5-PBLH) relationship; estimation of PM10 surface concentration using Geographic Weighted Regression (GWR) model over Brahmaputra valley (BV), at the valley-site scale forms the core of investigations of this research work.

PM2.5 and PM10 (particulate matter <10 µm aerodynamic diameter) surface concentration are critical parameters for air quality monitoring. AOD 550 nm represents columnar aerosol loading, and is an important parameter for aerosol characterization. PBLH, a fundamental parameter of boundary layer determines many tropospheric processes critical to air pollution within the boundary layer. PM2.5 and PM10 surface concentration and AOD 550 nm are inherently connected with meteorological variables as well as PBLH through several mechanisms.

Aerosols are ubiquitous specks of matter suspended in the air in the form of small solid and liquid particles, having an atmospheric lifetime of at least 1 hour. These tiny particles play a critical role in the earth's radiation budget (by scattering and absorbing incoming solar radiation), cloud formation, and poor air quality. Aerosols have a short atmospheric lifetime of about a week or less [1] and can be transported to long-range distances by wind during their lifetime. Discrete natural and anthropogenic origin of aerosols, sinks, long-range transportation processes along with meteorological conditions causes heterogeneity in aerosol distribution and optical properties [1,2] over a region. Local meteorological forcing variables AT, Ps, WS and RH have a large influence on PM2.5 and PM10 variability over space and time via several atmospheric processes [3-8] (the feedback mechanism are discussed in details in Table 2.2 Chapter 2).

PBLH is another key atmospheric variable highly responsible for the aerosol variation. PBLH plays a dominant role in dictating the dispersion of aerosols by turbulence mixing (mechanical and thermal), vertical diffusion, convective transport and entrainment of aerosols [9-13]. It also determines many tropospheric processes critical to aerosols' vertical distribution and deposition, e.g., a high convective boundary layer (CBL) during day-time increases vertical diffusion of aerosols, and a shallow stable boundary layer (SBL) during night-time reduces vertical diffusion of aerosols (details of Aerosol-PBLH interaction processes are discussed in Section 3.1, Chapter 3).

Aerosol, meteorology and PBLH vary dramatically over a complex terrain compared to that over a homogeneous surface. The mesoscale circulation systems (mountain and valley winds), mechanical turbulence (eddies), frictional drag, heat transfer, terrain-induced flow modification and ground inversion are common phenomena over a hilly terrain [14]. These processes not only regulate the local meteorological conditions and boundary layer dynamics over complex terrain but also affects the atmospheric transport and vertical mixing of aerosols at a wide range of temporal and spatial scales.

The unique geographical orientation, terrain complexity, local meteorological conditions, boundary layer dynamics modified by terrain complexity, an abundance of local aerosols sources (particularly biogenic aerosols), entrapment of long-range transported aerosols, and the extant state of air quality, make BV significant to aerosol studies [2, 15-17]. (The significance and necessity of aerosol study over the valley are discussed chapter-wise.)

Data availability at a high spatial and temporal scale for a study aiming at aerosol analysis is a basic necessity. Unavailability of data at a higher temporal scale as well as the inadequate number and disproportionate distribution of ground-based stations over BV has been a limiting factor for BV. The inadequacy of ground-based data (which is widely acknowledged for its accuracy) can be complemented efficiently by the integration of satellite and reanalysis data. Satellite remote sensing and reanalysis have emerged as the most reliable alternative data sources, supplementing surface observations, for aerosol research over any ecosystem. MERRA-2 (Modern-Era Retrospective Analysis for Research and Application version-2) and ERA5 ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis provide accurate information of aerosol major components, PBLH and meteorological variables respectively, at high spatial and temporal resolutions. MODIS (Moderate Resolution Imaging Spectroradiometer) onboard Terra and Aqua provide AOD retrievals at 10 x 10 km resolution on daily scale. Because of these advantages, remote sensing data have been widely used by researchers for aerosol research across the globe [18-28]. MERRA-2 aerosol products have also proven their efficacy as an alternative source for PM2.5 (particulate matter $\leq$ 2.5 in atmospheric diameter) surface concentration across India [29]. Furthermore, MODIS AOD 550 nm retrievals coupled with reanalysis derived meteorological products have been extensively used in GWR models for estimation of PM2.5 [30-32] and PM10 surface concentration over a large geographic area in recent years.

Most of the aerosol studies over BV focus on chemical characterization, source inventory, the radiative impact of aerosols, aerosol type, seasonal heterogeneity and physical characteristics of different PM (PM2.5 and PM10) fractions [2, 17, 33-41]. Moreover, in terms of spatial coverage, the studies do not cover the entire valley as the studies are mostly confined to select sites. There is a dearth of studies on the analysis of spatial heterogeneity and temporal variability of PM2.5 and PM10 surface concentration, AOD 550 nm and meteorological parameters AT, RH, WS and Ps, as well as understanding PM2.5-Meteorological and PM2.5-AOD 550 nm relationships over BV at the valley-site scale. Similarly, diurnal variability of PBLH and its influence on PM2.5 and PM10 surface concentration, PBLH-PM2.5 and PBLH-PM10 relationship is virtually non-existent at the valley-site scale. GWR, known for its efficiency in capturing spatial heterogeneity in relations and estimation, and widely applied for varieties of geography, terrains and climatic zones, has not been applied yet for the complex terrain of BV. As mentioned earlier, the scarcity of ground-based data is a limiting factor for aerosol studies over BV. Studies show satellite and reanalysis data sources are been effectively utilised as alternative data sources., These data sources, however, are not been explored extensively over BV.

1.2 OBJECTIVES

The objectives are:

1. Analysis of the spatio-temporal variation in PM2.5, AOD 550 nm and meteorological parameters, and their relation over the BV at the valley-site scale.
2. Analysis of the boundary layer height variation and its interaction with PM2.5 surface concentration at diurnal and seasonal scale over BV at the valley-site scale.
3. Estimation of PM10 surface concentration using Geographic Weighted Regression model by integrative assimilation of surface PM10, AOD 550 nm, and meteorological variables.

The unavailability of data at a high temporal scale as well as the inadequate number and disproportionate distribution of ground-based stations over BV is a limitation in aerosol studies. In this context, the present study in its scope includes extraction of AOD 550 nm, AT, Ps, WS, RH and major aerosol components data from MODIS Terra and Aqua, ERA5 ECMWF reanalysis and MERRA-2 respectively, validation of satellite and reanalysis data with reference to ground-based data, data pre-processing, data integration, estimation of PBLH using eight atmospheric fields from radiosonde data, GWR model fitting, validation and performance evaluation. This study is a step in bridging the extant gap in aerosol studies and overcoming the data limitations over BV.

1.3 DESCRIPTION OF THE STUDY AREA

BV, one of the largest river valleys in India, is surrounded by the mountains of the Eastern Himalayan in the north and Garo-Khasi-Jayantia and North Cachar hills in the south and southeast (Figure 1.1). The unique terrain provides access to the Indo-Gangetic plain (IGP) in the west, the Bay of Bengal (BoB) and the seasonal south-west trade winds in the southwest. These westerly winds carry aerosols from west Asia across the Indian landmass to Northeast India [2, 33]. A complex matrix of pollutants is generated over the valley from biogenic aerosols emitted by the forest cover (~66%), carbonaceous aerosols derived from fossil and biofuel combustion, and the sea salt and dust particles transported from the BoB [2, 16]. In addition, the complex topography of BV generates micro-meteorological conditions supporting locally generated and transported aerosol accumulation resulting in a thick layer of surface aerosols, dependent on the boundary layer effect [17].

The distinct climatic profile of BV is an outcome of its unique location and orography, the predominant maritime tropical air masses from BoB and the Southern Indian Ocean, and the local mountain and valley winds [42]. BV is experiencing an increase in surface temperature [43], an increase in average precipitation rate, highly anomalous summer monsoon patterns and prolonged dry weather conditions resulting in unusual dust outbreaks over the region [44]. The wind pattern is dominated by the

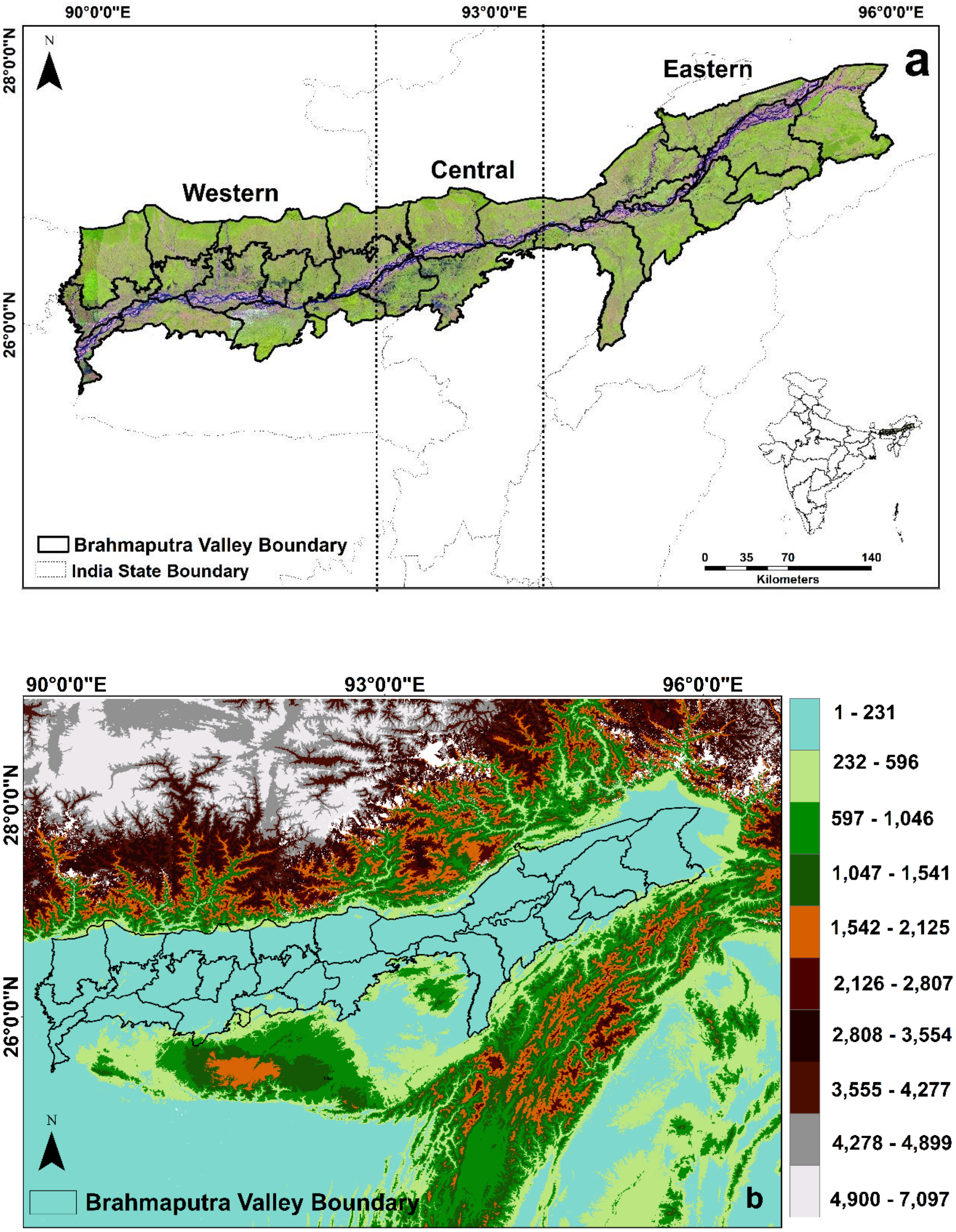

Figure 1.1 Map showing (a) the boundary of the Brahmaputra valley and (b) the elevation of the Brahmaputra valley and the surrounding areas.

Southwest monsoon and Northeast monsoon wind systems- a part of the great monsoon wind system of Asia locally modulated by the hilly tracts of Northeast India. Northeast India where BV is located has four distinct seasons: pre-monsoon season (March-May), monsoon (June-September), post-monsoon season (October-December) and winter (January-February).

Guwahati, the largest city in the BV, experiences elevated concentrations of PM2.5 and PM10 comparable to or higher in magnitude than those found in other Indian megacities during dry seasons [2, 17]. It also receives high loading of carbonaceous aerosols from open burning of solid waste disposal, rapid urbanization and poor environmental quality control [45].

About 3% of the population of Assam (the Indian state BV is located in) suffer from asthma above the national mean [46]. PM2.5 and PM10 surface mass concentrations of Guwahati city exceeded two to four times the annual average air quality standards stipulated by the National Ambient Air Quality Standards (NAAQS) [17].

For ease of reference, BV has been divided into three sections: the western part, the central and the eastern part (Figure 1.1).

1.4 THESIS ORGANIZATION

This thesis is organized into the following five chapters:

Chapter 1 Introduction: Based on analytical appraisal and synthesis of the relevant research literature, this chapter introduces the topic, highlights the importance of the study, identifies the research gap, and outlines the objectives and the scopes. This chapter sets the framework for the work.

Chapter 2 Variation and relationship of PM2.5, AOD 550 nm and meteorological parameters over Brahmaputra valley at the valley-site scale: summarizes the relevant literature related to PM2.5, AOD 550 nm and meteorology feedback mechanism and interaction, aerosol studies over BV, recognizes the research gap and significance of the study. Specifications of the data used, and the details of methodology. appreciation of results and conclusion.

Chapter 3 Boundary layer dynamism and PM2.5-PBLH interaction over Brahmaputra valley at the valley-site scale: synthesizes the studies related to PBLH and PM2.5, recognizes the research gaps and the importance of the work over BV; technical details of the data used and the methodology applied; analysis, results and discussion, and conclusion.

Chapter 4 Estimation of PM10 over Brahmaputra valley using Geographic Weighted Regression model: appraises the literature related to the studies on GWR model and its performance for PM10 estimation; data specification, model fitting, validation and performance evaluation; analysis, results and discussion, and conclusion.

Chapter 5 Conclusion: summarizes the major findings of the work and future scope.

1.5 REFERENCE

[1] Kaufman, Y. J., Tanré, D., and Boucher, O. A satellite view of aerosols in the climate system. *Nature*, 419(6903):215-223, 2002.

[2] Pathak, B., Borgohain, A., Bhuyan, P. K., Kundu, S. S., Sudhakar, S., Gogoi, M. M., and Takemura, T. Spatial heterogeneity in near surface aerosol characteristics across the Brahmaputra valley. *Journal of Earth System Science*, 123(4):651-663, 2014.

[3] Hien, P. D., Bac, V. T., Tham, H. C., Nhan, D. D., and Vinh, L. D. Influence of meteorological conditions on $PM_{2.5}$ and $PM_{2.5-10}$ concentrations during the monsoon season in Hanoi, Vietnam. *Atmospheric Environment*, 36(21):3473-3484, 2002.

[4] DeGaetano, A. T. and Doherty, O. M. Temporal, spatial and meteorological variations in hourly $PM_{2.5}$ concentration extremes in New York City. *Atmospheric Environment*, 38(11):1547-1558, 2004.

[5] Wise, E. K. and Comrie, A. C. Meteorologically adjusted urban air quality trends in the Southwestern United States. *Atmospheric Environment*, 39(16):2969-2980, 2005.

[6] Seinfeld, J. H. and Pandis, S. N. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change.* John Wiley & Sons, New York, 2nd Edition, 2006.

[7] Jacob, D. J. and Winner, D. A. Effect of climate change on air quality. *Atmospheric Environment*, 43(1):51-63, 2009.

[8] Porter, W. C., Heald, C. L., Cooley, D., and Russell, B. Investigating the observed sensitivities of air-quality extremes to meteorological drivers via quantile regression. *Atmospheric Chemistry and Physics*, 15(18):10349-10366, 2015.

[9] Stull, R. B. *An introduction to boundary layer meteorology.* Springer Science & Business Media, 1988.

[10] Garratt, J. R. The atmospheric boundary layer. *Earth-Science Reviews*, 37(1-2):89-134, 1994.

[11] Arya, S. P. *Air pollution meteorology and dispersion.* New York: Oxford University Press, 1999.

[12] Oke, T. R. *Boundary layer climates.* Routledge, 2nd edition, 2002.

[13] Liu, S. and Liang, X. Z. Observed diurnal cycle climatology of planetary boundary layer height. *Journal of Climate*, 23(21):5790-5809, 2010.

[14] Finnigan, J. J. Boundary Layer (Atmospheric) and Air Pollution Complex Terrain. In *Encyclopedia of Atmospheric Sciences*, 2nd Edition, Volume 1, pages 242-249. Elsevier, 2015.

[15] Gogoi, M. M., Krishna Moorthy, K., Babu, S. S., and Bhuyan, P. K. Climatology of columnar aerosol properties and the influence of synoptic conditions: First-time results from the northeastern region of India. *Journal of Geophysical Research: Atmospheres*, 114(D8), 2009.

[16] Pathak, B., Kalita, G., Bhuyan, K., Bhuyan, P. K. and Moorthy, K. K. Aerosol temporal characteristics and its impact on shortwave radiative forcing at a location in the Northeast of India. *Journal of Geophysical Research: Atmospheres*, 115(D19), 2010.

[17] Tiwari, S., Dumka, U. C., Gautam, A. S., Kaskaoutis, D. G., Srivastava, A. K., Bisht, D. S., Chakrabarty, R. K., Sumlin, B. J. and Solmon, F. Assessment of $PM_{2.5}$ and PM_{10} over Guwahati in Brahmaputra River Valley: Temporal evolution, source apportionment and meteorological dependence. *Atmospheric Pollution Research*, 8(1):13-28, 2017.

[18] Tanré, D., Kaufman, Y. J., Herman, M., and Mattoo, S. Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances. *Journal of Geophysical Research: Atmospheres*, 102(D14):16971-16988, 1997.

[19] Wang, J. and Christopher, S. A. Intercomparison between satellite-derived aerosol optical thickness and $PM_{2.5}$ mass: Implications for air quality studies. *Geophysical Research Letters*, 30(21), 2003.

[20] Engel-Cox, J. A., Hoff, R. M., and Haymet, A. D. J. Recommendations on the use of satellite remote-sensing data for urban air quality. *Journal of the Air & Waste Management Association*, 54(11):1360-1371, 2004.

[21] Al-Saadi, J., Szykman, J., Pierce, R. B., Kittaka, C., Neil, D., Chu, D. A., Remer, L., Gumley, L., Prins, E., Weinstock, L., and MacDonald, C. Improving national air quality forecasts with satellite aerosol observations. *Bulletin of the American Meteorological Society*, 86(9):1249-1262, 2005.

[22] van Donkelaar, A., Martin, R. V., and Park, R. J. Estimating ground-level $PM_{2.5}$ using Aerosol Optical Depth determined from satellite remote sensing. *Journal of Geophysical Research: Atmospheres*, 111(D21), 2006.

[23] Di Nicolantonio, W., Cacciari, A., Bolzacchini, F., Ferrero, L., Volta, M., and Pisoni, E. MODIS aerosol optical properties over North Italy for estimating surface-level $PM_{2.5}$. In *Proceedings of Envisat Symposium*, 636, 2007.

[24] Gupta, P. and Christopher, S. A. Seven year particulate matter air quality assessment from surface and satellite measurements. *Atmospheric Chemistry and Physics*, 8(12):3311-3324, 2008.

[25] Gupta, P. and Christopher, S.A. Particulate matter air quality assessment using integrated surface, satellite, and meteorological products: Multiple regression approach. *Journal of Geophysical Research: Atmospheres*, 114(D14), 2009.

[26] Di Nicolantonio, W. and Cacciari, A. MODIS multiannual observations in support of air quality monitoring in Northern Italy. *Italian Journal of Remote Sensing*, 43(3), 2011.

[27] Carmona, J. M., Gupta, P., Lozano-García, D. F., Vanoye, A. Y., Yépez, F. D., and Mendoza, A. Spatial and temporal distribution of $PM_{2.5}$ pollution over Northeastern Mexico: Application of MERRA-2 reanalysis datasets. *Remote Sensing*, 12(14):2286, 2020.

[28] Si, Y., Lu, Q., Zhang, X., Hu, X., Wang, F., Li, L., and Gu, S. A review of advances in the retrieval of aerosol properties by remote sensing multi-angle technology. *Atmospheric Environment*, 244:117928, 2021.

[29] Bali, K., Dey, S., and Ganguly, D. Diurnal patterns in ambient $PM_{2.5}$ exposure over India using MERRA-2 reanalysis data. *Atmospheric Environment*, 248:118180, 2021.

[30] van Donkelaar, A., Martin, R. V., Spurr, R. J., and Burnett, R. T. High-resolution satellite-derived $PM_{2.5}$ from optimal estimation and geographically weighted regression over North America. *Environmental Science & Technology*, 49(17):10482-10491, 2015.

[31] Unnithan, S. K. and Gnanappazham, L. Spatiotemporal mixed effects modeling for the estimation of $PM_{2.5}$ from MODIS AOD over the Indian subcontinent. *GIScience & Remote Sensing*, 57(2):159-173, 2020.

[32] Yang, J., Liu, S., Geng, Q., Chen, G., and Wang, Y. Estimation of $PM_{2.5}$ concentration considering meteorological factors, policy, and interregional atmospheric transport. *International Journal of Environmental Science and Technology*, 1-12, 2021.

[33] Gogoi, M. M., Pathak, B., Moorthy, K. K., Bhuyan, P. K., Babu, S. S., Bhuyan, K., and Kalita, G. Multi-year investigations of near surface and columnar aerosols over Dibrugarh, northeastern location of India: Heterogeneity in source impacts. *Atmospheric Environment*, 45(9):1714-1724, 2011.

[34] Chakrabarty, R. K., Garro, M. A., Wilcox, E. M., and Moosmüller, H. Strong radiative heating due to wintertime black carbon aerosols in the Brahmaputra River Valley. *Geophysical Research Letters*, 39(9), 2012.

[35] Pathak, B., Bhuyan, P. K., Gogoi, M., and Bhuyan, K. Seasonal heterogeneity in aerosol types over Dibrugarh-North-Eastern India. *Atmospheric Environment*, 47:307-315, 2012.

[36] Kumar, A. Variability of aerosol optical depth and cloud parameters over North Eastern regions of India retrieved from MODIS satellite data. *Journal of Atmospheric and Solar-Terrestrial Physics*, 100:34-49, 2013

[37] Pathak, B., Subba, T., Dahutia, P., Bhuyan, P. K., Moorthy, K. K., Gogoi, M. M., Babu, S. S., Chutia, L., Ajay, P., Biswas, J., and Bharali, C. Aerosol characteristics in north-east India using ARFINET spectral optical depth measurements. *Atmospheric Environment*, 125:461-473, 2016.

[38] Biswas, J., Pathak, B., Patadia, F., Bhuyan, P. K., Gogoi, M. M., and Babu, S. S. Satellite-retrieved direct radiative forcing of aerosols over North-East India and adjoining areas: climatology and impact assessment. *International Journal of Climatology*, 37:298-317, 2017.

[39] Bhuyan, P., Deka, P., Prakash, A., Balachandran, S., and Hoque, R. R. Chemical characterization and source apportionment of aerosol over mid Brahmaputra valley, India. *Environmental Pollution*, 234:997-1010, 2018.

[40] Barman, N. and Gokhale, S. Urban black carbon-source apportionment, emissions and long-range transport over the Brahmaputra River Valley. *Science of the Total Environment*, 693:133577, 2019.

[41] Rabha, S., Saikia, B. K., Singh, G. K., and Gupta, T. Meteorological Influence and Chemical Compositions of Atmospheric Particulate Matters in an Indian Urban Area. *ACS Earth and Space Chemistry*, 5(7):1686-1694, 2021.

[42] Barthakur, M. Weather and climate. In *The Brahmaputra Basin Water Resources*, Springer Dordrecht, 1st edition, 2004.

[43] Song, M., Ma, Y., Zhang, Y., Li, M., Ma, W., and Sun, F. Climate change features along the Brahmaputra valley in the past 26 years and possible causes. *Climatic Change*, 106(4):649-660, 2011.

[44] Sharma, A. R., Kharol, S. K., and Badarinath, K. V. S. Satellite observations of unusual dust event over North-East India and its relation with meteorological conditions. *Journal of Atmospheric and Solar-Terrestrial Physics*, 71(17-18):2032-2039, 2009.

[45] TERI. Risk *Assessment and Review of Prevailing Laws, Standards, Policies and Programmes to Climate Proof Cities*. Synthesis Report for Guwahati, 2013.

[46] Assam Science Technology and Environment Council (ASTEC). *Recommendation of State of Assam's Strategy and Action Plan on climate change*, Guwahati India, 2011.