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Designating Airsheds in India for Urban and Regional Air Quality Management

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Abstract: Air pollution knows no boundaries, which means for a city or a region to attain clean air standards, we must not only look at the emission sources within its own administrative boundary but also at sources in the immediate vicinity and those originating from long-range transport. And there is a limit to how much area can be explored to evaluate, govern, and manage designated airsheds for cities and larger regions. This paper discusses the need for an official airshed framework for India's air quality management and urban airsheds designated for India's 131 non-attainment cities under the national clean air program, and proposes climatically and geographically appropriate regional airsheds to support long-term planning. Between 28 states, eight union territories, 36 meteorological sub-regional divisions, and six regional meteorological departments, establishing the proposed 15 regional airsheds for integrated and collaborative air quality management across India is a unique opportunity.

Keywords: India; NCAP; air quality management; airsheds; regional air quality; urban air quality

1. Introduction

How much of a city or a region's air pollution is locally generated and how much is from long-range transport are important questions for air quality management (AQM). The first step to AQM is setting a non-administrative boundary for the region, followed by a series of analytical works to determine these contributions. This is accomplished via emissions and chemical transport modeling, and the results are used to prepare a clean air action plan to not only address the local sources but also find ways to coordinate with the long-range contributors to reduce their emissions [1,2]. The area covered within this study boundary is referred to as an "airshed" and, in general terms, a "study domain".

Khan et al. (2024) [3] reviewed air quality studies conducted across the globe using the airshed concept. While confusing, there is no set definition for how big or small an airshed can be. If an emission or pollution analysis is conducted for an area, then the boundary of the grids covering that area is the defined airshed. Often, its size is determined by the objective of the study. For example, (1) to study how air pollution travels between continents, the airshed was as big as the Pacific Ocean to understand the contributions and the evolution of pollutants originating from Asia and reaching the west coast of North America [4]; (2) to study emission intensities and enforce regulations at the state(s) level or multiple provincial level, the establishment of the California Air Resources Board in the United States and the Beijing–Tianjin–Hebei region airshed in China are examples of assessments of resource allocations and knowledge-sharing mechanisms among multiple stakeholders crossing administrative boundaries [5,6]; (3) to study the impact of local emissions and evaluate the boundary contributions via chemical transport modeling, urban airsheds were defined for 20 Indian cities [7]; (4) Singapore, a country and a city, has to work in a nested airshed environment—a smaller airshed to study the contributions of the local emission sources at great detail and a larger airshed covering the neighboring countries Malaysia and Indonesia, which account for a large portion of Singapore's pollution during

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Citation: Guttikunda, S.K. Designating Airsheds in India for Urban and Regional Air Quality Management. *Air* **2024**, *2*, 247–257. https://doi.org/10.3390/air2030015

Academic Editor: Joseph Pinto

Received: 27 May 2024
Revised: 1 July 2024
Accepted: 3 July 2024
Published: 12 July 2024

the open fire season [8]. In all the examples, the airshed concept is utilized over varying degrees of spatial, temporal, and judicial scales.

While the concepts of defining airsheds and conducting air pollution analysis are officially in practice in the United States and the European Union to support long-term air quality management plans, the concept is still in its nascent stage for low- and middle-income countries (LMICs) [3]. To date, most air quality management studies in LMICs are limited to the administrative boundaries, such as ambient monitoring campaigns. This limitation is primarily because of the difficulty in officially estimating the contribution of pollution from one region to the other and using that information to drive policy dialogs. This stage also involves navigating the blame-game negotiations. This effort is beyond just defining an airshed and requires a centrally coordinated effort to build a reliable emission inventory at representative spatial and temporal scales and conduct chemical transport modeling in a multi-pollutant environment [1,2].

Indian cities continue to top the rankings of the most polluted cities in the world (https://iqair.com—accessed on 1 May 2024). In 2023, more than 80 cities were listed in the top 100, and Delhi was again ranked the most polluted capital city in the world. In 2019, India announced the National Clean Air Programme (NCAP) and designated 131 cities as non-attainment, based on the past records of $PM_{2.5}$ and PM_{10} (particulate matter with aerodynamic diameters less than 2.5 µm and 10 µm, respectively) pollution levels [9]. These cities are required to reduce PM_{10} pollution by at least 40% by 2026, compared to the averages recorded in 2017. Under NCAP, these cities are required to document pollution trends, emission inventories, and source contributions, and prepare an action plan to target the most contributing sources. One missing component is the official designation of the city airshed sizes to address sources inside and in the immediate vicinity and regional airshed sizes to coordinate between the cities, districts, and states to address the long-range contributions.

This paper is an attempt to designate a regional airshed framework for all of India, using examples from other sectors, and to present an analysis of the air quality data for the proposed framework for a way forward. The discussions are limited to arriving at a feasible regional airshed framework for India and do not include any notes on the operational and legal aspects of such a framework. While the discussion is focused on supporting an Indian audience, the guidelines and the methodologies are equally applicable to other regions.

2. Methods and Materials

The primary objective of designating an airshed is to aid the framework for emissions and pollution management. While the initial calculations are conducted at the administrative boundary scales (for governance purposes), the eventual emissions and pollution modeling will require the air quality managers and the practitioners to set the airshed beyond the administrative boundaries (for source apportionment purposes). In LMICs, the final call on the airshed size often depends on the computational and technical capacity of the professional teams. Conversely, the capacity can be scaled to the required levels.

The urban airshed discussion is based on the material presented in [10] using geographical maps, meteorological records, and emission inventory information for the cities. For regional airsheds, the decision on the size is based on the governance feasibility between the engaging districts, states, and stakeholders. Examples from administrative, power generation and transmission, meteorology, and agricultural sectors are used to arrive at a framework for regional airsheds. All the geospatial information (GIS) databases used are open-access fields, included in the Supplementary.

3. Results and Discussion

3.1. Designating Urban Airsheds

Airsheds were designated for 131 cities under NCAP to determine the area with influential emission sources that can immediately affect the urban air quality [10]. Given the proximity of some cities in the densely populated regions of the Indo-Gangetic Plain (IGP), the total number of airsheds was reduced to 104. The two guidelines utilized in defining the urban airsheds are as follows: (1) An airshed must include any of the surroundings that influence the city's air quality—large settlements like satellite cities, large point sources like power plants, cement plants, brick kiln clusters, etc. A clear understanding of the city's geography and the emission strengths (via an inventory) of various sources inside and outside the city limits is necessary. (2) The airshed size must be kept to a mathematically manageable number for final emissions and pollution modeling. For urban-scale studies, the typical grid size is 1 km (approximately 0.01° near the Equator) and the typical airshed size is 30 × 30 grids for small cities (Tier 3 and Tier 4 cities far from the main urban centers) to 80 × 80 grids for big cities (grids in the north–south and east–west directions). It is good practice to set a rounded number of grids to support parallel processing and other state-of-the-art computational configurations.

Airshed examples in Figure 1 are from two small airsheds—Kurnool and Meerut—and two large airsheds—Delhi and Indore. Following the guidelines, urban airsheds were determined using the geographical and commercial activity information for the cities. Of the 104 airsheds, 73 contain only one city, 18 contain two cities, and nine contain three cities. Four airsheds—Delhi, Mumbai, Indore, and Chandigarh—contain 10, 8, 5, and 5 cities, respectively. An additional 33 cities, not on the NCAP list, are also part of these 104 airsheds.

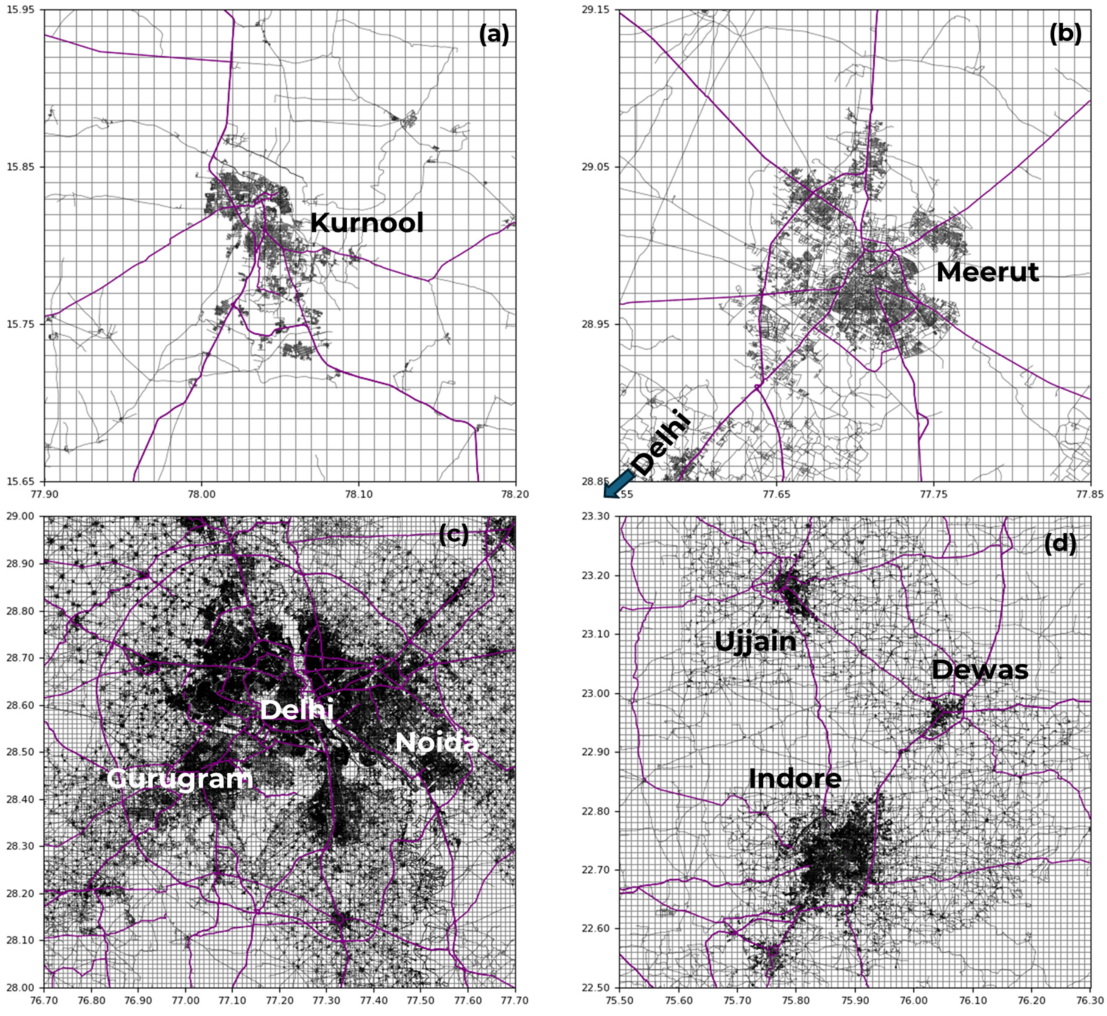

Figure 1. Four example urban airsheds: (**a**) Kurnool in South India; (**b**,**c**) Meerut and Delhi in North India; (**d**) Indore in Central India. The black lines represent the total road network and purple lines represent the major roads, extracted from the OpenStreetMap database.

For smaller Tier 2 and Tier 3 cities, with no large settlements in the immediate vicinity of the administrative boundary, decision-making for an airshed is fast. For both Kurnool (in South India, 15.8° N, 78.0° E) and Meerut (in North India, 29.0° N, 77.7° E), an airshed size of 30 × 30 grids was finalized (Figure 1a,b). Any of the contributions from outside these limits can be accounted for via boundary conditions in the chemical transport modeling. Given the proximity of Meerut city to Delhi (80 km), a question remains if this should be included in Delhi's airshed.

For Tier 1 cities, the presence of satellite cities in the immediate vicinity makes it difficult to limit the airshed sizes to their administrative boundaries. Among the 104 designated airsheds, Delhi is the largest with 100 × 100 grids and includes nine other cities, all with active sharing of transport and commercial amenities (Figure 1c). In this case, increasing the size further north to also include Meerut poses a mathematical and computational problem. Any increase in the number of grids increases the computing and storage needs exponentially, especially for chemical transport modeling at the fine resolution of 0.01°. A line is drawn to account for any outside perturbations in the boundary conditions. For Meerut, it is expected that the boundary contributions will be higher, compared to an airshed like Kurnool, and this is the case for most of the cities on the IGP. Delhi's case is like Singapore's case study, which can also use a nested airshed concept with a smaller domain over the extended main city and a larger domain with lower resolution to account for contributions from more satellite cities. This also reduces computational burden and can be explored as a solution following validation of the modeling outputs from both setups.

In the case of Indore (Figure 1d), also a large airshed with 80 × 80 grids, the three cities could be designated as smaller airsheds, especially Indore. However, since the passenger and commercial freight movement activity between the three cities is co-dependent, a combined airshed was finalized.

3.2. Designating Regional Airsheds

The airshed concept in India is not new in sectors other than air quality. For example, watershed and river basin management is a common practice. However, a similar framework was never formalized for air quality management where large regions, or a conglomerate of states, make joint decisions to manage urban and regional air quality problems. Only in the case of Delhi, the National Capital Region (NCR) exists with its own regional pollution control board to address the air pollution problems of Delhi and its surrounding states (the NCR was not formed to manage air pollution). Despite this central effort, most of the management and regulatory decisions were left to the local bodies or the respective state authorities. It is important to note that unlike an urban airshed, where most of the analytical work is conducted at a local scale, for regional airsheds, centrally coordinated national-level analytical works are key for furthering inter-state, inter-regional, and inter-airshed assessments and cooperation.

Examples of airshed-like frameworks relevant to the discussion and proposal include the following:

1. State administrative boundaries: There are 28 states and eight union territories (UTs) in India (Figure 2a), covering a total of 755 districts (as of December 2023). The district boundaries are not considered in this discussion as it becomes cumbersome to govern so many airsheds. All the states operate a pollution control board (PCB), and union territories operate a pollution control committee under a central governing body—the Central Pollution Control Board (CPCB, New Delhi, India). If there is no need to revamp the coordination program, each of the states can be an airshed, capable of monitoring, auditing, and evaluating the air pollution trends and formulating clean air action plans. In this case, the states can prepare individual implementation plans (SIPs) including not only the emission intensities within the state administrative boundary but also the contributions of the neighboring states. Excluding the UTs, which are small and can be absorbed into the neighboring states, this framework will result in 28 regional airsheds under the existing governing setup.

2. Power load dispatch centers: At the end of FY 2023–2024, India's installed power generation capacity is 440 GW and split between fossil and renewables at 55% and 45%, respectively. Data on fuel use, power generation, and power transmission from all the power plants are recorded and uploaded to the national power portal (https://npp.gov.in—accessed on 1 May 2024). The data on the transmissions are also maintained at sub-grid and sub-regional levels by five load dispatch centers (LDCs) (Figure 2b)—Northern, Northeastern, Eastern, Western, and Southern. This is a good example of seamless regional coordination for data collation from power plants and consumer grids, which is an important barrier for air quality management. However, only having five divisions to share the workload across the country to coordinate big states and large emission producers is daunting.
3. Meteorological sub-regional and regional divisions: This is an ideal framework for air quality management since the sub-regional divisions are based on long-term weather patterns, and the system comes with an operational modeling framework for meteorology for all of India, extending to the Indian Subcontinent. The meteorological systems, under the auspices of the Indian Meteorological Department (IMD), can be further extended to also include air quality modeling systems at various spatial and temporal scales. The framework includes 36 sub-regional divisions and 6 regional divisions (Figure 2c). A major barrier to this merger is likely the seamless integration of independent departments under two different ministries—PCBs under the Ministry of Environment, Forests, and Climate Change and IMD under the Ministry of Earth Science. Like LDCs, only six regional airsheds is a smaller number, and 36 is larger than the number of states to coordinate.
4. Agro-climatic zones: These zones are based on soil types, rainfall intensity, temperature variations, and ground and rain-fed water availability for agriculture. This is the most ideal framework, in terms of the number of regional airsheds, the size of the individual airsheds, geographical commonality in the airsheds, and weather patterns. More on this is discussed in the following section.
5. Other example frameworks include ten biogeographic zones, 20 water basins, and 24 land-use categories. The last category is too fragmented to define clear airsheds.

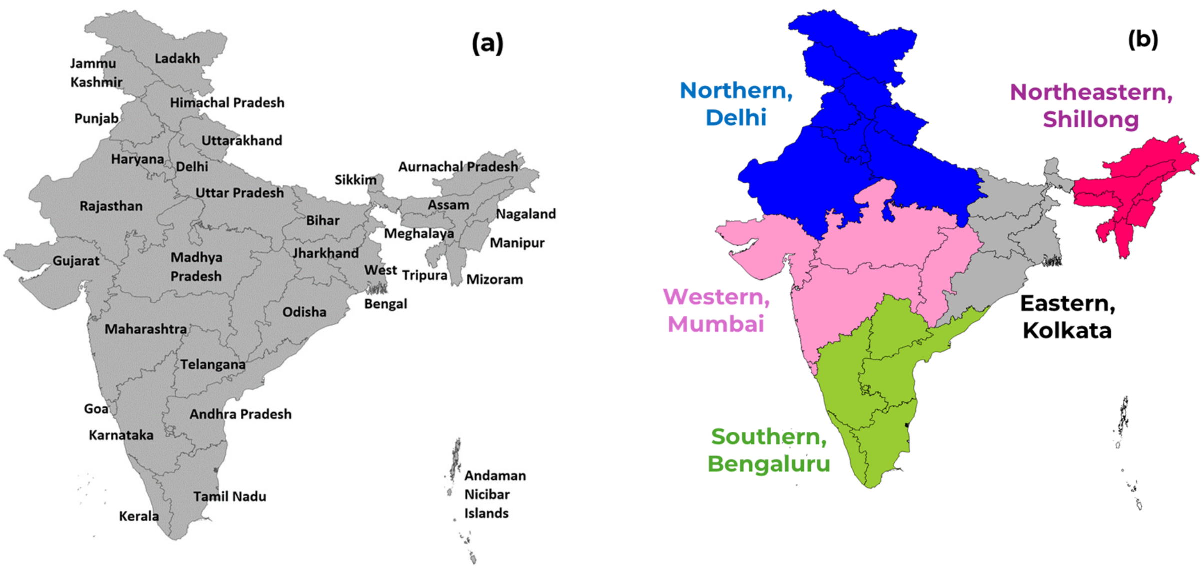

Figure 2. *Cont.*

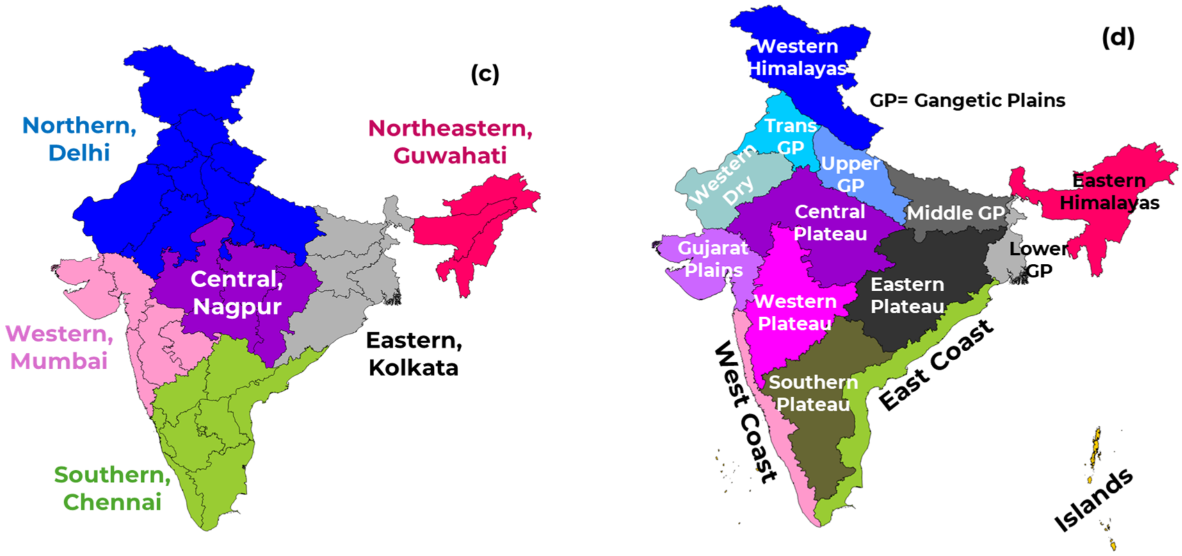

Figure 2. Examples of airshed-like operational frameworks from other sectors in India: (**a**) state administrative boundary—28 pollution control boards; (**b**) power load dispatch centers—5 regional centers (along with location of the regional headquarters); (**c**) meteorology data assimilation centers—36 sub-regional divisions and 6 regional centers (along with location of the regional headquarters); (**d**) agro-climatic zones—15 divisions.

3.3. Proposed Regional Airshed Framework for India

The proposed 15 regional airshed framework is an ideal setup for air quality management in India. These airsheds are unique not only because of their climatological conditions, but also in pollution characteristics, summarized in Table 1. A representation of $PM_{2.5}$ pollution levels in 1998 and 2022 from the global reanalysis fields [11] is shown in Figure 3 with an overlay of these airsheds. As large land fractions, there are six blocks—the Himalayas (two airsheds), Gangetic plain (four airsheds), Plateau (four airsheds), Arid/Desert land (one airshed), coast plans (three airsheds), and the islands. Within the blocks, the airsheds share approximately equal sizes (presented as shares to total India's landmass). The largest block is the Plateaus, covering approximately 40% of the landmass and hosting 36% of the total population. The IGP occupies 16% of the landmass and hosts 41% of the total population.

Table 1. Characteristics of the proposed 15 regional airsheds (Figure 2d) to support air quality management in India. Population totals are from the gridded database from the landscan program [12]. Annual average $PM_{2.5}$ concentrations are from global reanalysis fields [11,13].

Airshed	Airshed	Major	Percent	Percent	$PM_{2.5}$ Average (μg/m^3)		
Code	**Name**	**Urban Center**	**Landmass**	**Pop 2021**	**1998**	**2022**	**% Increase**
1	Western Himalayas	Dehradun	11.0%	2.9%	12.3	16.6	35%
2	Eastern Himalayas	Guwahati	9.1%	4.9%	17.9	22.1	24%
3	Trans Gangetic Plain	Delhi	4.0%	7.3%	42.3	63.8	51%
4	Upper Gangetic Plain	Kanpur	4.1%	10.0%	56.1	75.8	35%
5	Middle Gangetic Plain	Patna	5.5%	15.7%	46.4	68.5	48%
6	Lower Gangetic Plain	Kolkata	2.4%	7.5%	32.9	51.0	55%
7	Central Plateau	Indore	11.3%	10.0%	33.6	47.9	42%
8	Western Plateau	Nagpur	9.1%	7.7%	21.4	40.0	87%
9	Eastern Plateau	Raipur	11.3%	9.2%	27.2	43.0	58%
10	Southern Plateau	Bengaluru	10.0%	9.6%	16.4	27.5	68%
11	Arid Desert	Jaipur	5.2%	2.9%	45.5	57.0	25%
12	Gujarat Coast and Plains	Ahmedabad	5.6%	5.4%	31.0	42.2	36%
13	West Coast	Mumbai	3.8%	4.2%	13.0	23.7	83%
14	East Coast	Chennai	6.8%	2.9%	17.2	26.4	53%
15	Islands	--	0.7%	0.001%	8.3	9.1	9%

A detailed analysis of the evolution of $PM_{2.5}$ pollution between 1998 and 2020, along with fuel consumption patterns, energy demand, and emission trends at the state level. is provided in [14]. The reanalysis fields summarized for the proposed airsheds in Table 1 are updated to 2022, extracted from a global modeling system which combines ground-level $PM_{2.5}$ measurements and Aerosol Optical Depth (AOD) retrievals from NASA and ESA's instruments with the GEOS-Chem chemical transport model using gridded emission inventories [11,13]. In 1998, there were four airsheds with an annual average of more than 40 $\mu g/m^3$—India's annual ambient standard—and in 2022, excluding the islands, only four airsheds complied with this standard. Of the 15, 11 airsheds are crucial for overall air quality management in India and require deeper and coordinated assessments.

- The Gangetic Plains continue to be the most polluted. The IGP is the most populated region of India (and the Indian Subcontinent), also representing a large emission footprint from residential cooking and heating (especially during the winter months), power plants, and other large point sources, a large cluster of brick kilns (to meet the growing construction demand), open waste burning, dust, and vehicles supporting passenger and freight movement.
- The Plateau region between the Eastern and the Western Ghats (mountain ranges), the second most populated block in India, experienced the largest increase in the annual $PM_{2.5}$ pollution averages. This is an indication of the growing urbanization and delated demand for transport, industrial, and commercial amenities.
- The Coastal block is crucial for industrial economy and an increase in the annual averages here, despite the benefits of land–sea breeze, is an indication of growing shipping emissions and overall growth in the emissions and pollution levels at most of the coastal cities—Mundra, Surat, Mumbai, Goa, Mangalore, Kochi, Thiruvananthapuram, Chennai, Visakhapatnam, Paradip, and Haldia.
- The Arid/Desert region's high annual averages for PM pollution are due to wind erosion, a natural emission zone.
- The Himalayan block and islands are the cleanest, compared to the national standard, only as an average. The urban settlements like Jammu, Dehradun, Guwahati, and other state capital cities experience averages above the standards.

The summary of $PM_{2.5}$ source apportionment results in Figure 3 for the proposed airsheds highlights distinct emission characteristics. It is important to note that these results are averaged over all the grids, covering the airsheds and extracted from a global model, which inherently masks some urban features because of the model grid resolution. Possible regional centers for these can be housed in major cities. Some of the highlights include the following: (1) The highest share of the power generation is present in the Eastern Plateau (airshed 9), which includes a large cluster of coal-fired thermal power plants of Chhattisgarh, Northern Madhya Pradesh, and Odisha. (2) Residential cooking and heating, power generation, and all other industries together are responsible for 40–60% of the $PM_{2.5}$ pollution in all the airsheds, and approximately 80% of the pollution comes from fossil fuel burning sources. (3) The windblown dust share is the highest in airsheds 11 and 12, which are natural desert dust regions. (4) On an annual scale, biomass burning activities, including post-harvest crop residue burning activities, contribute less than 3%. The same on a seasonal basis will present a different share. (5) All transport contribution is consistently between 5 and 10% in all the airsheds. The same from a modeling system at a higher resolution and focused on urban airsheds will yield a different share. Overall, the size of the proposed airsheds can capture the source and seasonal trends representative of the regional emission sources and their intensities. Combined with nesting simulations for urban airsheds, the results can aid clean air action plans.

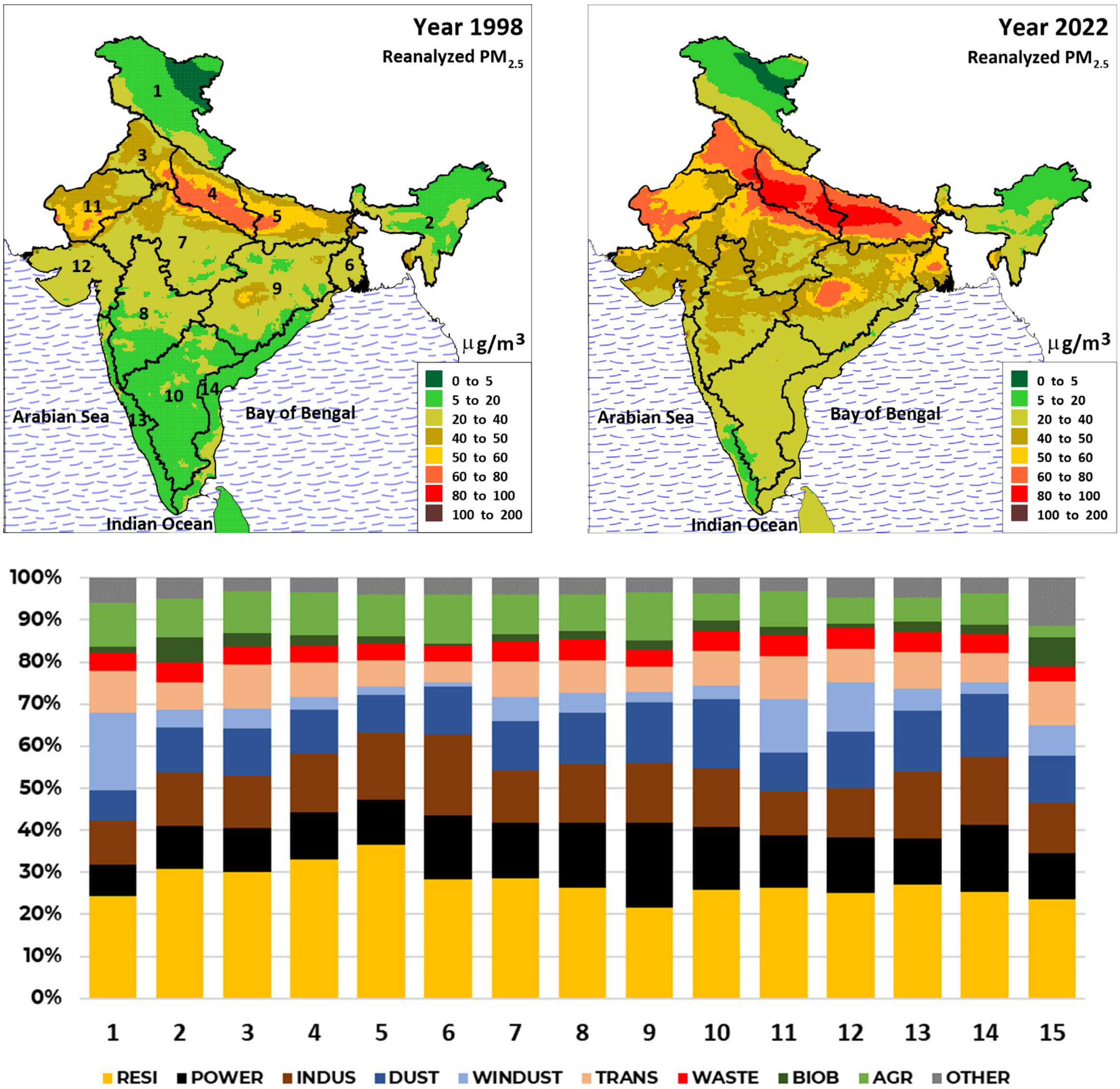

Figure 3. Reanalyzed $PM_{2.5}$ concentrations for the years 1998 and 2022 with a map of the proposed 15 regional airsheds [11]. Source contributions averaged for all the grids covering the airsheds, estimated from the same global reanalysis system [15,16]. Aggregated source definitions are DUST = anthropogenic dust; WINDUST = wind erosion (dust storms); WASTE = waste burning; RESI = all commercial and residential cooking, lighting, and heating; TRANS = all transport (excluding aviation and shipping); POWER = energy generation; INDUS = all industries and product use (including solvents); BIOB = biomass burning, including forest fires and agricultural waste burning; AGR = agricultural activities (excluding agricultural waste burning); OTHER = all others. The numbers on the map and stack graph represent the 15 proposed regional airsheds described in Table 1.

4. Conclusions

Designating airsheds for the cities or for all of India is only the first step towards AQM. Between 28 states, eight UTs, 36 meteorological sub-regional divisions, and six regional meteorological departments, establishing the 13 regional airsheds for integrating AQM efforts across India is a unique opportunity (excluding the Arid/Desert land and the islands, clubbed into one of the neighboring airsheds). The regional centers can be housed in one of the major cities in each of the airsheds (example list in Table 1). While there is strong seasonality in the air pollution patterns within the airsheds and between the airsheds, the designation (delineation) of the airsheds does not change with seasons, and the sole purpose of this exercise remains to support long-term air quality management in the cities and the regions.

4.1. Need for a Centralized National-Scale Assessment System

The urban or regional airsheds are defined to account for the contributions of various sectors or regions and be in a decision-making position to hold the sectors or the regions accountable. To achieve this, irrespective of the number of urban or regional airsheds, a centralized national-scale assessment system is a must, which will unify independent urban and regional emission inventories, chemical transport modeling systems, source apportionment assessments, and evaluation methods under one umbrella. An example framework is the United States Environmental Protection Agency (US EPA), which designated the US states and territories into 10 operational regional airsheds (Figure 4). This allowed for streamlining the modeling and analytical efforts within an airshed by the regional offices and between the airsheds collectively at the federal level. The regional offices are responsible for coordinating with their states to implement the US EPA programs, except for those programs that are specifically delegated to states, and the US EPA remains the federal agency for all statutory purposes. In the US example and the proposed airsheds for India, the focus is on the assessment of regional contributions to each other and regional coordination within the country.

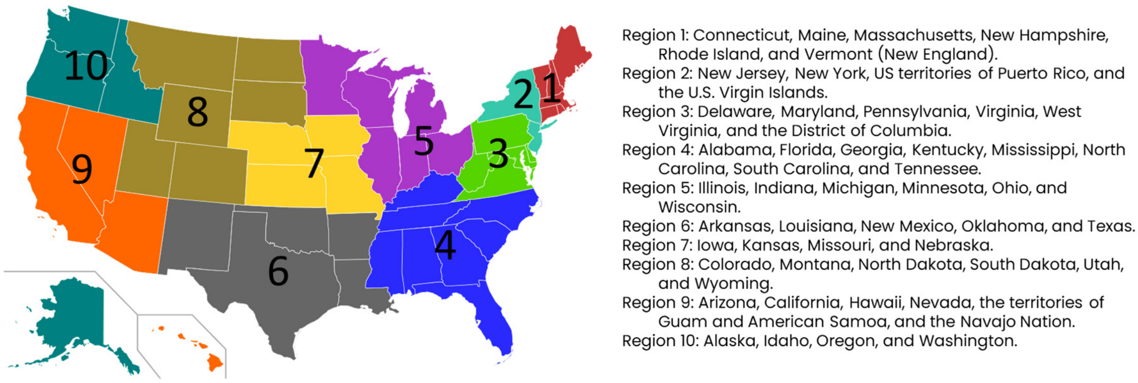

Figure 4. Designated regional airsheds under the United States Environmental Protection Agency.

4.2. Who Is Involved in Managing Urban and Regional Airsheds?

In an urban airshed, covering the main city administrative boundary and the neighboring satellite cities, most of the jurisdictional authority to act against the emission sources will be with the urban local bodies (ULBs), local ministries, some state authorities, and local operators. For example, if open waste burning is a major contributor, the ULBs can be held accountable; if there is a decision to aggressively promote bus usage against cars and motorcycles, the local transport authorities can take immediate charge. This makes coordination between the acting members easier and always confined by geography and regulations.

In a regional airshed, the participating members are from a broader institutional setup like states and sectoral ministries, and most of the analytical work will be at a macro level (a resolution lower than urban analytical works). The main advantage here is the option to coordinate regionally and address the issue of long-range transport of pollution at a more granular level. For example, the proposed Eastern Plateau airshed hosts a large portion of the coal-fired thermal power plants, and these emissions have the tendency to travel distances farther than the airshed size [17]. These contributions can also be evaluated and officially notified at regional scales, with a higher chance of regional coordination. Within the regional airsheds, further analysis can distribute these contributions to urban airsheds for local actions.

4.3. What Is the Target Pollutant?

The spatial extent of the airshed and the grid sizes are also determined by the target pollutant. For example, if PM is the main pollutant of concern, a pollutant which often exceeds the ambient standard in Indian cities, conducting analyses at urban scales is recommended. When all the cities control $PM_{2.5}$ pollution, either by addressing the local contributors or coordinating efforts with sources outside the city limits, the overall reductions in PM pollution can also be accounted for at the regional and national level. Often, the outside contribution (also referred to as long-range transport) is dominated by secondary $PM_{2.5}$ in the form of sulfate and nitrate aerosols from the chemical conversion of sulfur dioxide and nitrogen-oxide gases. However, if the pollutant of concern is CO or ozone, both regional pollutants with more uniformity in the spatial patterns over long distances, conducting emissions and pollution analysis at the regional scale is recommended. A holistic approach to clean air will eventually include a multi-pollutant strategy to benefit urban and regional air quality.

4.4. Modeling Airshed Contributions

An important outcome of urban- and regional-scale airshed management is the information on the contribution of sources within and outside the designated airsheds. The sources can be a sector (like industries, road transport, and residential) or zones within an urban airshed or larger areas (like the 15 proposed regional airsheds). In the urban-scale assessments, this source contribution information is crucial for the local stakeholders, which will help prioritize the actions necessary to reach their clean air targets. Similarly, in the regional-scale assessments, this information will help distribute emission control responsibilities to the contributing regions. In both cases, the source contribution information is an estimate using a combination of tools to develop emission inventories and to conduct chemical transport modeling at the desired spatial resolutions. This effort is computationally demanding and data-intensive, but it is the necessary next step in airshed-level air quality management and can be achieved using established state-of-the-art modeling systems at various complexities. These modeling systems must evolve collaboratively among all the participating authorities with mutual consensus, taking into consideration the technical and institutional capacities to oversee the efforts, and the final decision-making process, including the delineation of regional airsheds, will take time. In this paper, the scope of the discussion is limited to a proposal for designating the airshed boundaries for air quality management within India. The necessary efforts, resources, and challenges in modeling urban and regional air quality will be further explored and are documented as part of an operational air quality forecasting platform @ https://indiaairquality.info (accessed on 1 May 2024).

4.5. Need for Indian Subcontinent-Scale Assessment System

Since India is not alone in the fight against air pollution, a future system will have to include the neighboring countries and make it a Subcontinent-level effort with Bangladesh, Bhutan, Nepal, Pakistan, and Sri Lanka to support intergovernmental efforts to evaluate contributions and share knowledge. This challenging step is beyond the proposed 15 inter-regional airsheds for India, and this evolution will require extensive analyses of institutional, jurisdictional, legal, and informational understandings of the problem.

Supplementary Materials: All the GIS and pollution databases discussed in this manuscript are available for open use at https://doi.org/10.5281/zenodo.11332107 (accessed on 1 May 2024). This resource includes (a) ESRI shapefiles for Indian states, districts, meteorological sub-divisions, agro-climatic zones, and 0.1-degree resolution mesh; (b) $PM_{2.5}$ annual and monthly average concentrations at 0.1-degree resolution from a global reanalysis model for 1998 to 2022; (c) population density at 0.1-degree resolution for 2021.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: See Supplementary Materials.

Acknowledgments: The analysis and conclusions presented herein are exclusively those of the author and do not represent the supporting organizations or the educational departments. The author thanks the anonymous reviewers for their timely and constructive comments and suggestions.

Conflicts of Interest: The author declares no conflicts of interest.

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