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Review

Interplay Between Meteorology and Seasonality in Urban Air Pollution Across Selected Cities in East, South, and Southeast Asia: A Comparative Review

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Highlights

- Significant variation in air pollution levels was observed across seasons.
- Meteorological conditions in Asia significantly influence Asian air pollution.
- Higher concentrations of PM_{10} and $PM_{2.5}$ were reported during the winter season.
- Increased vehicular emissions and coal burning drive higher pollution levels.

Abstract

Air pollution is a growing environmental issue in rapidly urbanizing Asian cities, where meteorological conditions and seasonal variability strongly influence pollutant concentrations. This review synthesizes published evidence on the interactions between meteorology, seasonality, and urban air pollution across selected cities in East Asia, South Asia, and Southeast Asia. The literature was collected from major scientific databases and organized according to meteorological drivers, seasonal characteristics, and dominant emission sources. Particular emphasis was placed on particulate matter ($PM_{2.5}$ and PM_{10}), SO_2, NO_2, NO_x, CO, and O_3. The reviewed studies indicate that wind speed and direction, precipitation, temperature, atmospheric stability, and monsoon circulation strongly influence pollutant transport, dispersion, and removal. Pollutant concentrations generally reach their highest in winter due to stagnant conditions and higher human emissions. In contrast, the summer and monsoon seasons tend to have lower PM levels due to better atmospheric mixing and wet deposition. Regional differences in dominant sources were also observed, including coal combustion and heating in East Asia, traffic and biomass burning in South Asia, and biomass burning and transboundary transport in Southeast Asia. These findings highlight the importance of seasonally adaptive and region-specific air quality management strategies in Asian cities.

Keywords: air quality; atmospheric dispersion; emission; seasonal variation

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1. Introduction

Air pollution is a major global concern, especially in cities across Asian countries, where various sources, including automobiles, industrial emissions, open burning of

municipal solid waste, and the burning of fossil fuels and biomass, cause numerous problems [1–4]. Zeng and Zhang reported that air pollution in any region is characterized by decreased atmospheric visibility, deteriorating air quality, and increased atmospheric oxidizing capacity [5]. In recent years, regional air pollution has become a growing threat to major cities globally, causing serious health issues, economic challenges, damaging crop production, and jeopardizing environmental sustainability, surpassing weather-related concerns [4,6,7]. In Asian countries, air pollution is recognized as a significant environmental issue that has caused more harm to human health and the environment than any other kind of pollution [8]. It is reported that air pollution can significantly affect the climate, the environment, transportation, and human health [9,10]. Urban air pollution has been attracting increasing attention recently, as a large share of the world's growing population now lives in cities. This situation is similar in Asian countries, where air pollution is rising due to expanding industrial activity, motor vehicle use, and unprecedented population growth. For instance, Begum et al. reported high average annual concentrations of PM_{10} (42.8 and 41.1 $\mu g/m^3$, respectively) in two different cities of Bangladesh (Dhaka and Rajshahi) during 2001–2002 [11], while in Bandung and Lembang, Indonesia, the mean annual concentrations of PM_{10} and $PM_{2.5}$ were 17.6 $\pm$ 9.4 and 7.1 $\pm$ 7 $\mu g/m^3$, respectively, and 14.03 $\pm$ 6.86 and 11.88 $\pm$ 6.60 $\mu g/m^3$, respectively, during 2002–2004 [12]. These findings align with recent studies [13–16], indicating that air pollution remains a significant environmental issue in many Asian cities. For instance, a review of Asian megacities found that urban air pollution is now a major environmental issue in the region. This is mainly due to rapid urban growth, industrial activity, rising vehicle emissions, and complex weather patterns [14]. Similarly, Zhou et al. noted that rapid urbanization has led to higher $PM_{2.5}$ levels worldwide, with many Asian cities facing ongoing particulate pollution [13]. In South Asia, land-use changes and urban expansion have worsened air quality, especially in rapidly growing cities in Bangladesh [15]. Although some East Asian cities have seen improvements in air quality, many urban centers in South and Southeast Asia still have particulate matter levels above WHO guidelines, which significantly endanger public health and sustainable urban development [14,16]. However, variation in pollutant concentrations across locations could be due to meteorological conditions and seasonal variations [9,17,18].

Studies [19–21] reported that various meteorological parameters, including temperature, wind speed, wind direction, and relative humidity, influence the concentrations of air pollutants in ambient air. Additionally, pollutant concentrations can vary depending on the source and local topographic conditions [8,22]. Meteorological conditions play a crucial role in affecting atmospheric pollutant levels by influencing their dispersion, transport, chemical stability, and deposition [8,23–25]. Air pollution is influenced by both the regional and local-scale meteorology in numerous ways. The mixing scale of different air pollutants and the formation of secondary air pollutants are greatly influenced by large-scale weather patterns, which govern stable atmospheric conditions, large-scale circulations, temperature advection, humidity, and cloud formation [26]. Studies reveal that the concentration of atmospheric particulate matter (PM) of various sizes is mainly affected by meteorological parameters, including wind speed and direction, precipitation, relative humidity, and solar radiation [27,28].

Air pollution levels are also greatly affected by seasonal variation. Many factors influence seasonal variations in air pollutants, including synoptic wind patterns, prevailing air mass type, growth and decay of the convective boundary layer, large-scale air circulation, the southwest monsoon system, and variations in solar radiation [29]. Several studies have shown that air pollutant concentrations tend to be higher in winter than in other seasons [22,25–27,30–34]. The main reasons include low wind speeds and a lower mixing

height, which lead to longer residence times for PM in the atmosphere and, consequently, higher pollution levels compared to seasons such as summer or monsoon [35,36].

While numerous studies [18,25,27,31,32,34,37–44] have examined the relationships between meteorology and air pollution across various Asian cities, most prior research has focused on specific countries, pollutants, or short-term data. Existing review studies have typically either emphasized atmospheric processes or regional air quality concerns without offering a comparative synthesis across different Asian subregions. Consequently, there is an ongoing necessity for an integrated review that compares shared meteorological mechanisms, delineates region-specific differences, and summarizes the prevailing seasonal drivers across East Asia, South Asia, and Southeast Asia. This review addresses the gap by synthesizing existing evidence on how meteorological conditions and seasonal variability influence urban air pollution in selected Asian cities. The selected cities represent diverse climatic conditions, monsoon regimes, topographical settings, and emission characteristics, and were chosen for their status as national capital cities or major urban centers/megacities, along with sufficient peer-reviewed literature to enable meaningful comparisons. The review examines major pollutants, including $PM_{2.5}$, PM_{10}, SO_2, NO_2, NO_x, CO, and O_3, to uncover shared mechanisms and regional variations that can inform future strategies for air quality management and climate adaptation.

2. Methodology

This study was conducted to collect information from trusted, authoritative sources and synthesize existing knowledge on how meteorological conditions and seasonal variability influence urban air pollution across selected cities in East Asia, South Asia, and Southeast Asia, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This structured approach ensures transparent and thorough reporting of the methods and findings in a systematic review [45,46]. This method provides access to a broad range of scholarly publications and detailed reports, enabling a thorough review of existing knowledge on the topic.

A thorough literature review was carried out using leading scientific databases and scholarly platforms, including Scopus, SpringerLink, Web of Science, ScienceDirect, Google Scholar, PubMed, ResearchGate, and reports from institutional and government sources. The literature searches were conducted from May to August, 2025. The references were managed with Zotero software (version 7.0), and Boolean operators were used to enhance clarity and reproducibility. Sample search strings included: (“air pollution” OR “air quality”) AND (“seasonal variation” OR “monsoon”) AND (“meteorology” OR “meteorological factors”) AND Asia; (“$PM_{2.5}$” OR “PM_{10}”) AND (“temperature” OR “precipitation” OR “wind speed”) AND (“Asian cities”); and (“urban air pollution”) AND (“meteorological drivers”) AND (“seasonality”) AND (“East Asia” OR “Southeast Asia”). Additional targeted searches with city names and pollutant-specific terms were also performed to ensure comprehensive coverage.

For this review, studies were considered eligible if published in peer-reviewed journals or authoritative institutional reports, written in English, focused on urban air pollution in East Asia, South Asia, or Southeast Asia, and examined meteorological conditions, seasonal variability, and atmospheric pollutants. The review focused on studies reporting at least one pollutant, including $PM_{2.5}$, PM_{10}, SO_2, NO_2, NO_x, CO, and O_3. Also, the citation lists of included papers were examined. Exclusions included studies unrelated to atmospheric pollution or indoor air quality, those lacking methodological details, conference abstracts, editorials, and duplicates. All retrieved records were screened based on titles, abstracts, and full texts. Although duplicate checks were performed, no duplicates were identified. Initially, 155 records were found through database searches. After screening and eligibility

assessment, 34 records were excluded for not meeting the criteria, leaving 121 studies included in the final review. The papers finally included can be divided by source as follows: Scopus (45), Web of Science (25), PubMed (12), Google Scholar (20), ScienceDirect (10), SpringerLink (05), ResearchGate (04). Although each paper was found in multiple sources, the list is organized by the first identified source. Two reviewers independently conducted study screening and data extraction, resolving any disagreements through discussion and consensus.

The relevant details from each study, such as location, study period, pollutant type, concentrations, meteorological variables, emission sources, seasonal patterns, key findings, and limitations, were collected. This information was then sorted into East Asia, South Asia, and Southeast Asia to explore shared mechanisms and regional differences in how meteorology and seasonality influence urban air pollution. The quality of the selected studies was assessed based on the clarity of their research objectives, the adequacy of meteorological variables and pollutants measurements considered, and the consistency of their reported findings. Relevant information was extracted from the selected studies and organized into thematic sub-topics. However, studies that lacked sufficient methodological details or were not relevant to this review's objectives were excluded during screening. The entire process of literature identification, screening, eligibility assessment, and final study selection is outlined in Figure 1.

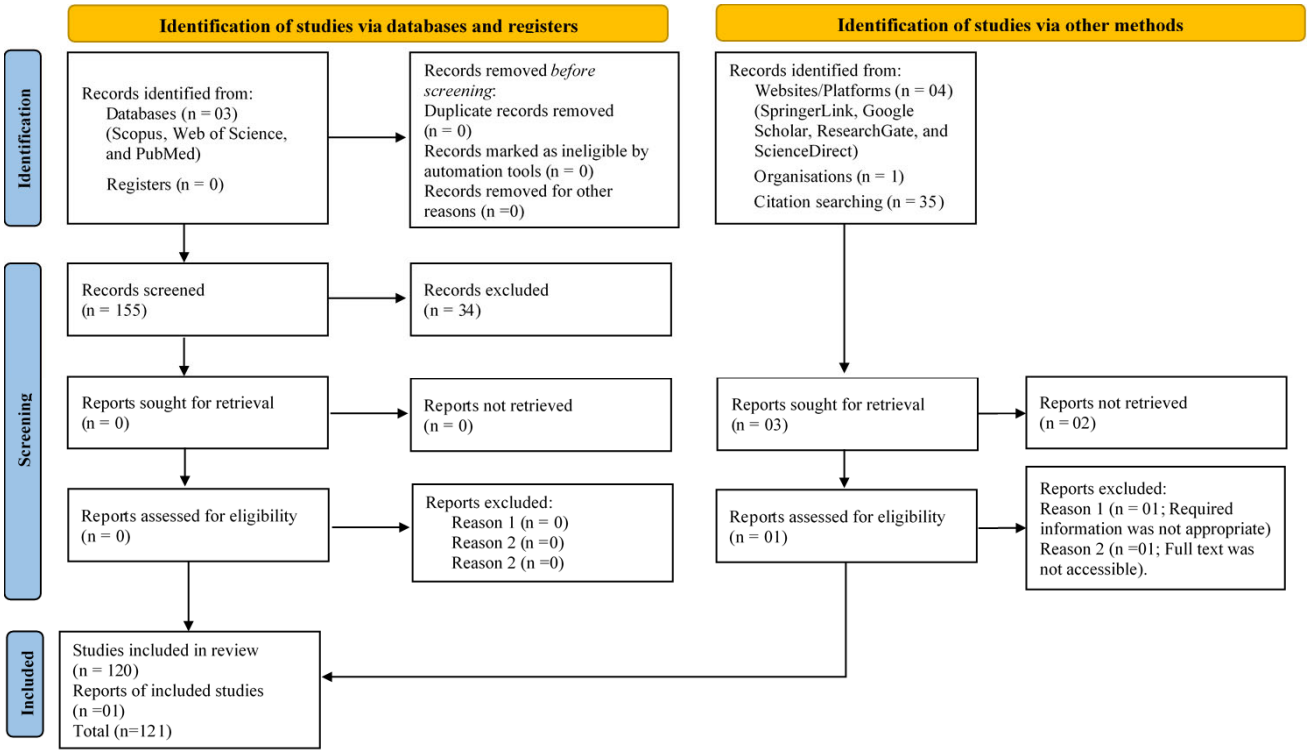


Figure 1. Illustrating the identification, screening, eligibility assessment, and final selection of studies included in this review. https://www.prisma-statement.org/prisma-2020-flow-diagram (accessed on 28 June 2026).

3. Results and Discussion

3.1. Key Features and Processes Influencing Air Pollution Meteorology and Atmospheric Dispersion

Generally, pollutants released into the atmosphere undergo various key processes, including transportation, dispersion, transformation, and removal. Studies indicate that dispersion, the process by which pollutants spread through the air to form a plume covering a large area and decreasing their concentrations, results from atmospheric turbulence,

which causes pollutants to scatter in various directions [47–51]. Essentially, pollutants move as the air circulates in the atmosphere. Airflow transports and disperses different pollutants (gaseous or particulate) originating from natural or anthropogenic sources into the atmosphere. Dispersion in the atmosphere is a key factor in determining air quality and pollutant distribution. Air pollutants disperse via mass transport and dilution driven by atmospheric turbulence and eddies, influenced by factors such as wind speed, temperature gradients, and terrain characteristics. The structure of the boundary layer, influenced by stability, convective conditions, and mechanical mixing, significantly affects pollutant dispersion. Urban heat islands (UHIs), for example, can promote turbulence and vertical mixing, while complex terrain, such as valleys, may allow pollutants to accumulate beneath stable atmospheric conditions [52–57].

Air pollution meteorology focuses on the fate of various air pollutants after they are released from natural or anthropogenic sources. Different gaseous and particulate pollutants are generally dispersed by atmospheric air movement, which transports them from emission sources and gradually diffuses them into larger air volumes through turbulence. This dispersion and dilution can vary depending on pollutant concentration, atmospheric density, and the Earth's complex terrain and buildings [58–60]. For instance, generally, the concentration of PM decreases as wind speed increases [28,61]. However, studies have shown that pollution levels may sometimes increase with rising wind speed, likely due to regional topographic features. For instance, the average PM_{10} concentration in Kathmandu Valley, Nepal, is reported to increase with wind speed, suggesting that, rather than dispersing pollutants, the wind facilitates their entry into the valley [27]. This could be due to mountain breezes that carry pollutants back into Kathmandu Valley at night. This observation strongly supports Ghim et al., who stated that topographic features could act as barriers that impede the transfer of air pollutants between regions [62].

Once atmospheric pollutants are emitted from any specific source, such as point sources (e.g., power plants or industrial chimneys), mobile sources (e.g., road transportation, shipping, airplanes), or area sources (e.g., biomass burning, households, construction sites), their dispersion is affected by various factors, including wind speed and direction, terrain types, heating effects, and others. Topography is a crucial factor influencing air pollution research, especially in pollutant dispersion. For example, pollution dispersion in an area with flat terrain can differ significantly from that in an area with an orographic structure, as supported by other studies [34,63], which state that in urban areas with an orographic nature, the dispersion of pollutants from the lower atmosphere is reduced. In flat topographical regions, this situation differs because uniform, horizontal winds can help restrict pollutant accumulation. Besides these factors, building geometry, such as building height and the distance between buildings, also plays a significant role in the transport and dispersion of pollutants in cities. Bhaskar and Mehta reported that in Ahmedabad (India), pollutant transport and dispersion are influenced by the ratio of building height to width (the distance between buildings) [34]. They observed that pollution concentrations increase with narrower widths and taller buildings. This discussion reflects that dispersion greatly influences how pollutants are distributed.

Wind speed and direction are among the most important factors influencing pollutant dispersion and levels. High wind speeds help dilute and spread pollutants, reducing their concentrations at the surface, while stagnant conditions with low wind speeds cause pollutants to accumulate in the lower troposphere, worsening pollution [53,64–66]. Heating effects (e.g., from UHIs) enhance convective mixing during the day and help dilute pollutants. In contrast, night-time cooling creates stable atmospheric stratification, preventing vertical mixing and trapping pollution near the surface. Significantly, seasonal variations

also influence air quality, as inversions that trap pollutants occur more frequently at lower temperatures in winter [52,54,65,67].

3.2. Relationship Between Meteorology and Air Pollution: An Overview

Meteorology and air pollution are closely interconnected. Pollutant dispersion, transport, and the stability of chemical species are strongly influenced by various meteorological factors, which affect atmospheric pollutant levels. Meteorological conditions also determine the transport of air pollutants from their sources to receptors. The movement of air particles in the atmosphere is primarily influenced by meteorology [68]. For example, PM becomes airborne due to atmospheric turbulence and is then strongly influenced by prevailing weather conditions [27]. Different meteorological conditions dictate how pollutants disperse in the atmosphere, especially in the troposphere, which contains 95% of the Earth's air mass and extends up to 12 km above the surface. Various atmospheric conditions significantly affect the concentrations of different air pollutants (both gaseous and particulate) [22]. Bhaskar and Mehta highlighted the importance of various meteorological parameters for the transport and dispersion of pollutants [34], while other studies reported that wind speed and precipitation are crucial in determining atmospheric pollution levels [69,70].

Polluted air results from emissions from multiple sources, while meteorological conditions govern the transport and dispersion of pollutants [49,56,71–73]. Wind, as a key meteorological parameter, plays a predominant role in the movement of pollutants in the atmosphere. The dispersion of pollutants strongly depends on wind velocity. Light winds lead to poor dispersion, whereas strong winds enhance it. Grundstrom et al. reported that atmospheric air pollutant concentrations are significantly influenced by wind speed [74]. Furthermore, conditions that favor poor dispersion include stable atmospheric conditions, large differences between daytime and night-time temperatures, fog that limits incoming solar radiation and prevents surface warming, and minimal lateral wind movement across the prevailing wind direction [49,75–78].

Precipitation is another key meteorological parameter closely linked to air pollution, as it removes atmospheric pollutants through various mechanisms. For example, studies identified two methods by which air pollutants are removed from the atmosphere: the "Rainout" (in-cloud) and "Washout" (below-cloud) processes [49,79]. In the "Rainout" process, tiny pollutant particles become nuclei for rain droplets and fall as precipitation. Conversely, in the "Washout" process, pollutants are entrained in falling raindrops or dissolved within them. An example of SO_2 removal from the atmosphere in Great Britain illustrates the vital connection between meteorology and air pollution. In that study, Peirce et al. reported that 15% of SO_2 was removed by precipitation, 25% was blown to Norway and Sweden, and the remaining 60% estimated as the surface sink. Stable atmospheric conditions are a key meteorological factor closely linked to air pollution because they tend to block vertical air movement and suppress turbulence [49]. Conversely, unstable conditions promote vertical mixing, which helps disperse pollutants. These conditions significantly influence how pollution spreads in the atmosphere [80–82]. For example, it has been observed that pollutant levels, such as NO_x and particulate matter, are generally higher under stable atmospheric conditions [74]. Some studies [49,83,84] also reported that pollution dispersion is poor in high-stability weather patterns, such as anticyclones, which are considered precursors to air pollution in a region. However, Lazaridis explained that stable atmospheric conditions occur when the air remains relatively stationary, with only slight shifts due to external forces [68]. This occurs when external forces move the air to its current location before it has a chance to change position. In contrast, unstable conditions happen when external forces push the air away from its original location. The atmosphere's ability to mix and spread air pollutants, which depends on the vertical temperature profile

and the surrounding air's humidity, is crucial in determining whether conditions are stable or unstable.

3.3. Influence of Meteorological Parameters on Air Pollution

Air pollution is a growing concern worldwide and significantly impacts the global climate, environmental systems, and public health. Meteorology greatly influences the distribution of air pollution across any geographical area. This section explains how meteorological factors such as wind speed and direction, sea breezes, precipitation, and temperature affect air pollution in various Asian cities.

3.3.1. Influence of Wind Speed and Wind Direction

Wind speed and wind direction are crucial meteorological factors affecting air pollution levels. Typically, wind direction indicates the path of pollutant movement, while wind speed influences how pollutants disperse. Giri et al. emphasized that understanding wind speed and direction is vital for linking pollution sources to pollutant concentrations and for tracking pollutant transport within an area [27]. For instance, in Beijing during winter and spring, prevailing northern and north-western winds carry dust from the Gobi Desert, resulting in reduced visibility and elevated PM_{10} levels [85]. Gaseous pollutant levels are also heavily impacted by wind direction. In Wuqing (located between Beijing and Tianjin), hourly CO concentrations remained below 1 ppm when winds originated from the south with speeds over 4 m/s [26]. Similarly, it is reported that in Shanghai, summer winds from the southeast to southwest brought cleaner air from the East China Sea at an average speed of 3.1 m/s. Conversely, in winter, northeast winds from the Yellow Sea and northwest winds transported more polluted air masses from Jiangsu Province [85].

Several studies show that low wind speeds are usually responsible for heavy air pollution, as pollutants tend to accumulate when the wind is weak. In contrast, at high wind speeds, pollutants are carried over long distances, which reduces pollution levels. Xu et al. noted that low wind speeds significantly contribute to increased air pollution in large cities like Beijing [26]. Wang et al. found a negative relationship between wind speed and $PM_{2.5}$ levels in Beijing, reporting that the average $PM_{2.5}$ concentration at mild wind speeds was 100 $\mu g/m^3$. This level decreased when wind speed exceeded 2 m/s [61]. Therefore, low winds are not ideal for dispersing $PM_{2.5}$. Xu et al. also studied NO_x concentrations in Wuqing and observed higher NO_x levels at wind speeds below 2 m/s [26]. Wind speed is a crucial meteorological parameter for removing fine particulate matter ($PM_{2.5}$) from the atmosphere, as it helps explain differences in atmospheric particulate concentrations [86]. In a study of meteorological effects on PM_{10} and NO_2 across three Malaysian stations, Dominick et al. observed a negative correlation between wind speed and both NO_2 and PM_{10} [8]. Similarly, Bhaskar and Mehta found in Ahmedabad, India, that higher wind speeds are associated with lower NO_2 levels [34].

3.3.2. Influence of Sea Breeze

The sea breeze primarily results from temperature differences between the land surface and the sea. It also plays a crucial role in dispersing and transporting air pollutants from various sources, making it an important meteorological phenomenon, especially in coastal areas. Klemm et al. observed that a sea breeze is more effective during weak synoptic flow. On sunny days, the maximum land air temperature is higher than the sea surface temperature, and these temperature differences drive the sea breeze circulation from the sea to the land, changing the land's air temperature [87]. This circulation significantly affects air pollution levels in coastal urban regions, as supported by another study [88], which explains that when a sea breeze is combined with low wind speeds, it can increase pollutant concentrations in coastal cities by causing air stagnation. Recent studies indicate

that sea-breeze systems can significantly influence the distribution of air pollutants both spatially and temporally, including NO_2, O_3, and $PM_{2.5}$, by transporting emissions inland and promoting pollutant accumulation during stagnant conditions [89,90]. Additionally, low wind speeds associated with sea-breeze circulation can worsen air stagnation and pollutant recirculation, resulting in higher pollution levels in coastal cities [91,92].

3.3.3. Influence of Precipitation

Precipitation plays a crucial role in removing air pollutants, mainly particulate matter of different sizes (such as PM_{10} and $PM_{2.5}$), more so than other meteorological factors. In many countries across South, Southeast, and East Asia, including China, India, Bangladesh, and Vietnam, air pollution levels are strongly influenced by precipitation and the monsoon. During the monsoon, substantial moisture gathers over the Indian Ocean, leading to heavy rainfall in South and Southeast Asia, which, in turn, affects pollution levels [34]. Figure 2 illustrates how precipitation affects air pollution in most Asian cities. Hien et al. stated that among various meteorological factors, precipitation greatly influences the daily variations in $PM_{2.5}$ and PM_{10} by removing atmospheric particles of different sizes and reducing soil dust resuspension through increased soil humidity [86]. A significant negative correlation between PM_{10} and rainfall in Ahmedabad, India, has been reported by Bhaskar and Mehta [34]. Giri et al. studied Kathmandu Valley, Nepal, and confirmed that regional precipitation strongly affects atmospheric PM levels. For example, the daily average PM_{10} was 146.79 $\mu g/m^3$ without rain in Kathmandu Valley, decreasing with increasing rainfall, to 81.88 $\mu g/m^3$ at 10–20 mm and 67.23 $\mu g/m^3$ at 30–40 mm [27]. Begum et al. reported that during winter in Dhaka, Bangladesh, when rainfall was minimal, PM_{10} and $PM_{2.5}$ concentrations were high, averaging 223 $\pm$ 82.3 $\mu g/m^3$ and 73.4 $\pm$ 41.9 $\mu g/m^3$, respectively. With heavy rain, these levels dropped significantly to 40.6 $\pm$ 14.1 $\mu g/m^3$ and 14.2 $\pm$ 3.8 $\mu g/m^3$, respectively [93].

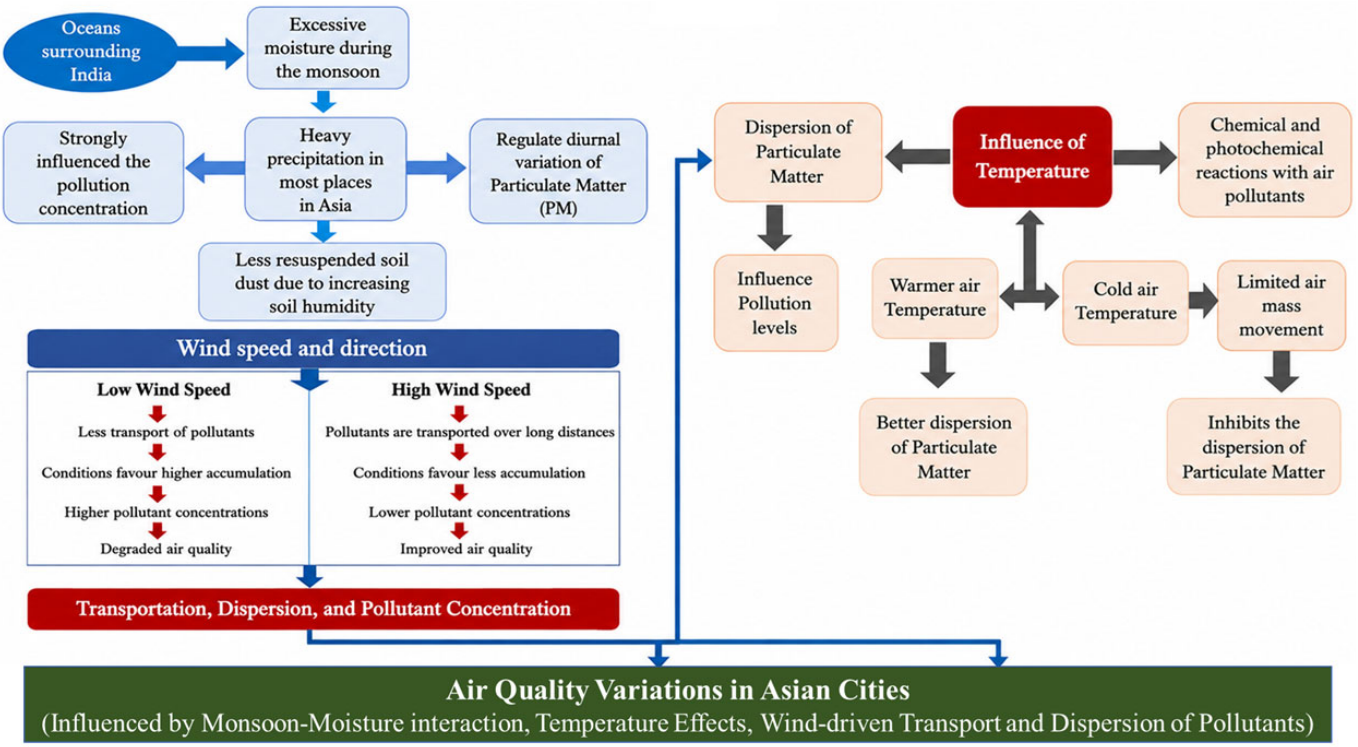


Figure 2. Schematic illustration of the effects of monsoonal moisture, wind speed and direction, and temperature on pollutant transport, dispersion, atmospheric accumulation, photochemical reactions, and seasonal air quality in Asian cities.

3.3.4. Influence of Temperature

Like other meteorological factors, temperature significantly affects pollution levels and their atmospheric dispersion (Figure 2). Zeng and Zhang explain that lower air temperatures reduce air mass movements, thereby hindering pollutant dispersion [5]. Variations in the vertical temperature profile are influenced by factors such as seasons, day length, and geographical location, all of which substantially affect pollution concentrations [22]. Studies reported that temperature influences chemical and photochemical reactions involving air pollutants and notably affects particulate dispersion [27,86]. During winter, $PM_{2.5}$ and PM_{10} are more strongly regulated by temperature, with better dispersion observed under warmer conditions than in cold weather. However, Dominick et al. identified positive correlations between temperature and PM_{10} at three stations in Malaysia [8]. A similar finding has also been reported by Azmi et al. (2010), indicating a positive relationship between temperature and PM_{10} in Klang Valley, Malaysia [94], which is due to the summer monsoon (Southwest monsoon) in Malaysia, characterized by drier and clearer weather.

3.4. Seasonal Variation in Air Pollution with Identified Emission Sources: An Overview

Variations in different seasons (i.e., duration) across different geographical regions in East, South, and Southeast Asia are closely linked to seasonal changes in air pollution levels. The concentration of pollutants varies across months, influenced by climate patterns, atmospheric conditions, and weather changes on specific days. It is stated that these factors could lead to fluctuations in pollutant levels in any area [95]. During winter, pollution levels remain high, mainly due to poor dispersion. Zeng and Zhang explained that sunlight diminishes and daylight hours shorten in winter, leading to lower temperatures and stable temperature inversions that hinder vertical dispersion of pollutants [5]. Oanh et al. studied six Asian cities, including Bandung, Bangkok, Beijing, Chennai, Manila, and Hanoi, between 2001 and 2004 and observed higher $PM_{2.5}$ and PM_{10} concentrations, especially during the dry season. For example, during the dry season, daily average concentrations ranged from 44 to 168 $\mu g/m^3$, and during the wet season, they ranged from 18 to 104 $\mu g/m^3$ and from 33 to 180 $\mu g/m^3$, respectively [30]. Air pollution in cities like Beijing, Shanghai, Hong Kong, Hanoi, Dhaka, and Ahmedabad stems from both local and regional or transboundary sources [31,34,44,86,93,96]. The primary sources of increased winter pollution in these Asian cities are shown in Figure 3. Local sources include coal burning from industry and heating, vehicle emissions, and biomass burning. Non-local sources mainly involve long-range or regional transport of pollutants and dust storms. For instance, in Hong Kong, regional pollution from Mainland China significantly affects local air quality, along with local emissions [97].

In most Asian countries, the pre-monsoon period typically features high wind speeds and low humidity, while the monsoon season is marked by heavy rainfall, elevated temperatures, and increased humidity. During the monsoon, pollutant levels in the atmosphere tend to be lower due to high precipitation and humidity, which affect pollutant dispersion. For example, concentrations of particles like PM_{10} and $PM_{2.5}$ are significantly reduced during this time, influenced by wind speed and direction, as illustrated in Figure 4. Rain facilitates the removal of atmospheric PM through "washout," and soil dust levels decrease as soil humidity rises [24]. Conversely, the post-monsoon season is characterized by low wind speeds and humidity, resulting in higher pollutant concentrations. During this period, particulate matter accumulates and disperses slowly due to reduced boundary layer height and humidity [98].

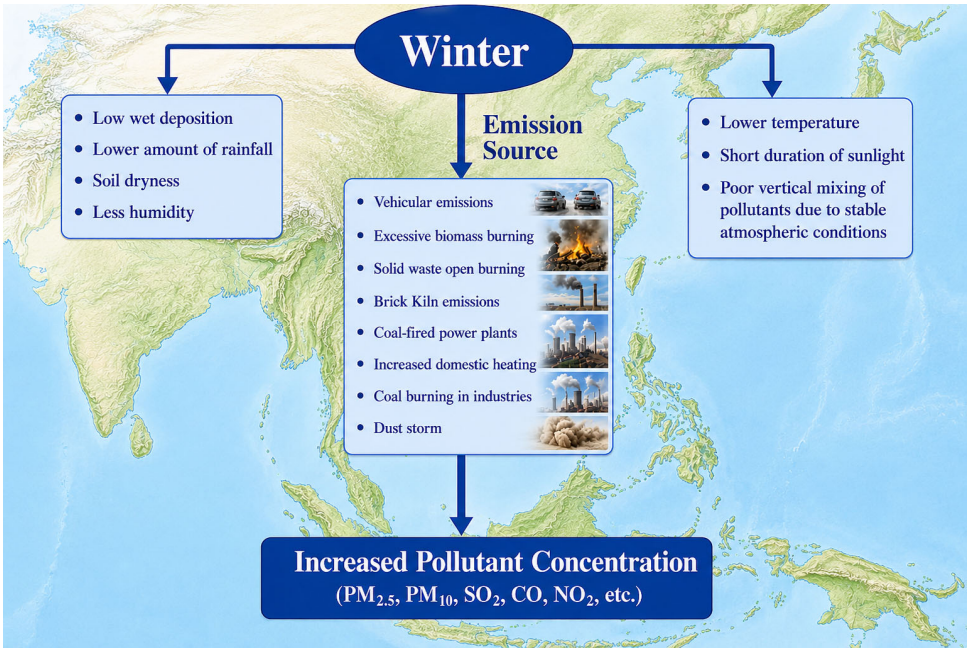


Figure 3. Schematic diagram of air pollution status in winter with primary emission sources.

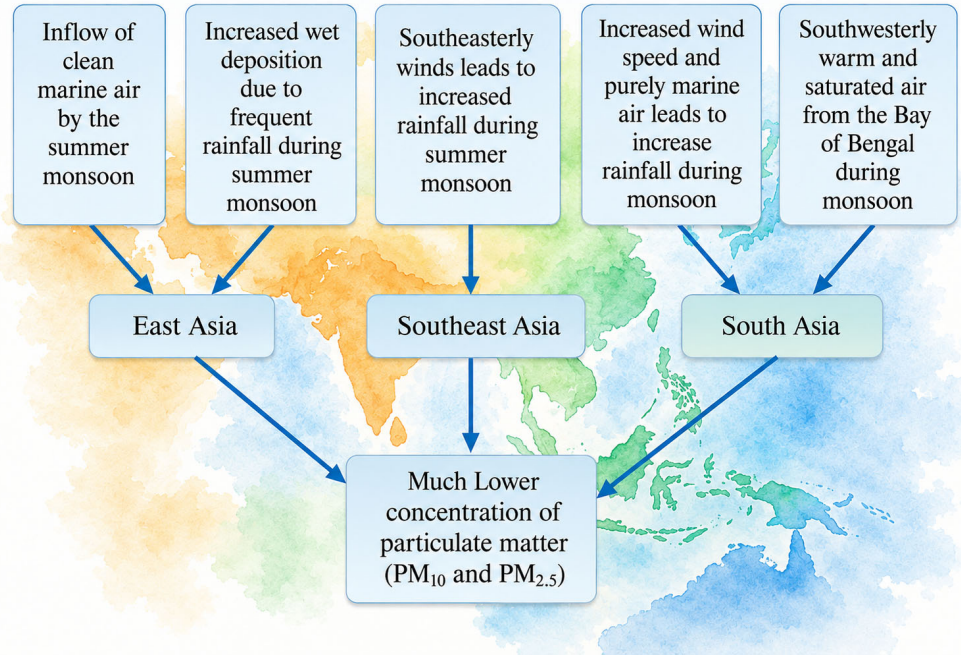


Figure 4. Schematic diagram of factors impacting air pollution in the monsoon.

During summer, atmospheric pollution levels are generally lower compared to winter due to enhanced dispersion and wet deposition caused by higher wind speeds and increased rainfall. Figure 5 illustrates the factors contributing to this seasonal reduction in air pollution in Asian countries. Meteorological factors may contribute to increased air pollution during the summer monsoon in the Asian region (e.g., Malaysia, where low-level southwesterly winds are common. Studies reported that elevated temperatures promote photochemical reactions that increase ozone levels, while humidity influences particle formation. Some cities, such as Shanghai and Guangzhou, report higher ozone concentrations in summer than in winter, attributed to increased solar radiation and stagnant atmospheric conditions during the colder months [52,64,65,67].

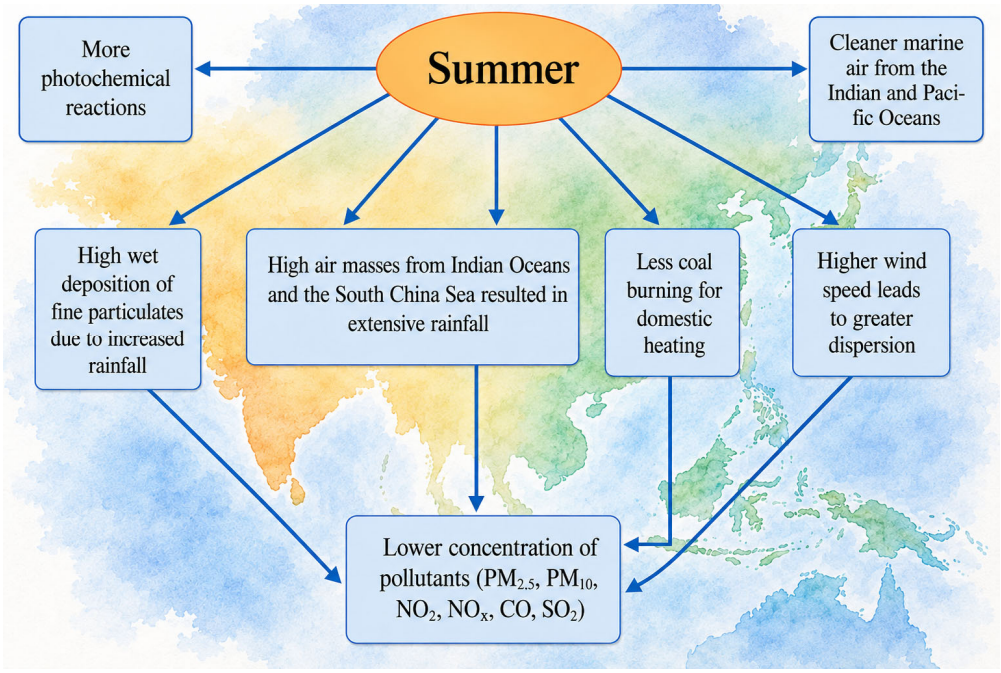


Figure 5. Schematic diagram of air pollution status in summer in Asia.

The summer monsoon affects air quality by altering wind patterns and increasing wet deposition. However, variability in monsoon rainfall can lead to uneven aerosol washout, resulting in local pollution spikes. For example, the summer monsoon reduces $PM_{2.5}$ levels through enhanced wet deposition, but localized emissions can still trigger episodic pollution events [54,67,96]. Additionally, higher energy consumption for cooling during hot months leads to increased emissions, further contributing to air pollution [52,65]. The following sections explore how air pollution levels change with seasonal influences in winter, summer, and the monsoon across various cities in East Asia, South Asia, and Southeast Asia.

3.5. Air Pollution in the Major Cities of East Asia

3.5.1. Air Pollution in East Asian Cities During Winter

In East Asian cities, air pollution tends to peak in winter due to increased heating along with stagnant meteorological conditions leading to higher concentrations of pollutants like $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO. Louie et al. in their study of seasonal patterns and regional transport of $PM_{2.5}$ in Hong Kong, observed the highest annual average concentration (33–69 $\mu g/m^3$) during winter, attributed to the influence of East Asian anticyclones [31]. Similarly, elevated PM levels in Beijing were recorded during winter, often associated with East Asian anticyclones [33]. A separate study across three Chinese megacities (Beijing, Shanghai, and Guangzhou) found that winter had the highest average $PM_{2.5}$ and PM_{10} concentrations, with levels decreasing in other seasons [25]. This increase is believed to stem from higher emissions from power generation and heating, combined with winter meteorological conditions that limit pollutant dispersion. Additionally, concentrations of CO, NO_2, and SO_2 in these cities were also elevated in winter.

Yan et al. identified $PM_{2.5}$ and O_3 as the main air pollutants in Shanghai. The most severe air pollution occurred during winter, driven by increased industrial energy use and residential heating. Shanghai experienced moderate pollution in winter, with a trend of winter > spring > autumn > summer, and the $PM_{2.5}/PM_{10}$ ratio followed a similar pattern. Both $PM_{2.5}$ and PM_{10} showed a significant linear relationship and tended to remain in the air during cold winter weather, leading to reduced sedimentation [99]. In winter,

$PM_{2.5}$ remained the main pollutant when analyzing Shanghai's temporal air quality, even though overall air quality improved. This is largely because coal burning for winter heating elevates $PM_{2.5}$ levels in the city [100]. In another study, Wang et al. reported that the daily average SO_2 concentration in Beijing was significantly higher in winter (163.7 ppb) than in summer (14.8 ppb) during 2001–2003 [101]. This rise is mainly due to increased coal burning for industry and domestic heating in winter. Similarly, it is reported that residential coal-burning from November to February contributes more to winter air pollution in Southeastern China [97]. Jo et al. studied two Korean cities, Seoul and Taegu, and observed higher concentrations of CO, SO_2, and NO_2 during winter. For example, in Seoul, January levels were about 9 ppm for CO, 90 ppb for SO_2, and 50 ppb for NO_2, driven by increased vehicle use and fuel consumption amid rapid urbanization and industrial growth [38].

Allabakash et al. examined PM levels in South Korea from 2015 to 2020 using multivariable linear regression models. They observed that $PM_{2.5}$ concentrations tend to peak in December and January and are negatively associated with meteorological factors like temperature, relative humidity, and precipitation [102]. In Wuqing, China, haze days occur more frequently during winter, leading to elevated levels of NO_x, CO, and SO_2 [26]. This increased pollution is likely caused by the dominance of cold high-pressure systems and low surface wind speeds, which create conditions conducive to haze or fog formation.

3.5.2. Air Pollution in East Asian Cities During Summer and Spring

Studies across East Asian cities consistently reveal significant seasonal fluctuations in air pollutants, influenced by weather and emission patterns. In Beijing, the average $PM_{2.5}$ levels are substantially lower in summer (93.2 $\mu g/m^3$) than in winter (214.2 $\mu g/m^3$) [101]. This decrease in summer is mainly attributed to frequent rainfall, which facilitates wet deposition and removes fine particles from the atmosphere. Similarly, multiple studies in Shanghai show seasonal differences between particulate matter and ozone (O_3). Gao et al. reported a 67% rise in O_3 levels from 2006 to 2015 at an urban site, with O_3 becoming the dominant summer pollutant [103]. However, O_3 formation is strongly affected by locally emitted NO_x and volatile organic compounds (VOCs), with a marked inverse relationship between O_3 and NO_x. For instance, higher NO_x levels tend to inhibit O_3 formation. Chen et al. confirmed that O_3 is the primary summer pollutant in Shanghai, while $PM_{2.5}$ dominates in winter. Meteorological factors, such as higher temperatures, are positively associated with O_3 levels. Conversely, concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO decline during summer in Asia [100], as sunlight accelerates oxidation of SO_2, NO_2, and CO, forming secondary products, and thus removing these pollutants from the gas phase, as well as due to the effects caused by rainfall. Nonetheless, these same conditions promote photochemical reactions that increase O_3 pollution, making summer the most severe season for O_3 formation. In addition, natural processes also contribute to seasonal air pollution events. Liu et al. reported severe sandstorms accompanied by haze pollution in Beijing during spring, which were associated with regional transport and secondary formation of PM. For instance, air masses from Mongolia brought crustal materials and bioaerosols, raising organic carbon levels in $PM_{2.5}$ [104].

Similar seasonal patterns have been observed in other Asian cities. In Seoul, lower NO_2 levels were recorded during summer, with monthly averages around 40 ppb in July compared to 50 ppb in January [38]. This decrease was linked to reduced fuel use and increased photochemical activity. In Hong Kong, the lowest annual $PM_{2.5}$ level (14.8 $\mu g/m^3$) was recorded in summer [31], driven by south-easterly winds, heavy rainfall, and an influx of cleaner marine air. Nevertheless, long-range transport also affects air quality. For instance, volcanic emissions from Taal volcano in the Philippines led to significant increases in SO_2 and sulfate in $PM_{2.5}$ in Hong Kong [105], illustrating the impact of transboundary

pollution. Seasonal declines in gaseous pollutants are also seen in northern China. Xu et al. observed lower summer levels of CO, SO_2, and NO_2 in Wuqing, mainly due to higher mixing layer heights, less coal burning for heating, and stronger photochemical reactions. For instance, the hourly average SO_2 in summer (5.7 ± 6.3 ppb) was much lower than in winter (28.5 ± 6.3 ppb). Similarly, NO_x levels in Shangdianzi were lower in summer (20.4 ± 12.2 ppb) than in winter (80.8 ± 65.5 ppb), largely due to decreased coal use and improved atmospheric dispersion [26]. These results underscore the combined roles of emissions, weather conditions, and atmospheric chemistry in shaping seasonal air pollution patterns across East Asia.

3.5.3. Air Pollution in East Asian Cities During the Summer Monsoon and Winter Monsoon

In East Asia, the winter monsoon is associated with anticyclonic weather patterns and cold surges from the Siberian High, leading to dry atmospheric conditions and, eventually, a favorable environment for pollutant accumulation. In contrast, the summer monsoon brings moist air from the Pacific and Indian Oceans to this region of Asia, leading to heavy rainfall (Figure 6a,b).

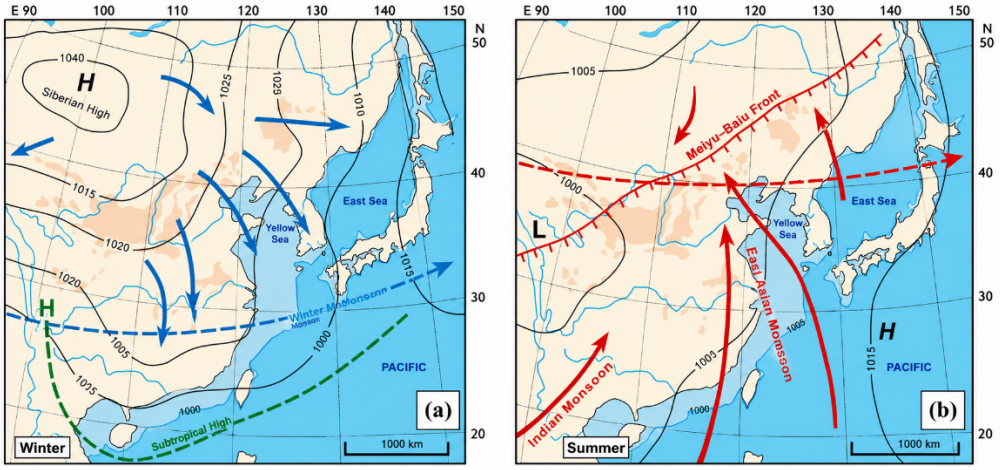


Figure 6. (**a**) East Asian winter and (**b**) summer monsoon system (Source: [106]).

Atmospheric circulation is crucial in distributing pollutants across regions. For example, the East Asian summer monsoon significantly influences air mass movement and rainfall, affecting pollutant levels over large parts of China [107]. During summer, pollutant levels tend to be low, rising during the winter monsoon in East Asian countries. This low level during the summer is due to the monsoon's heavy rainfall. Specifically, in southeast China, heavy rainfall from mid-May to mid-June, driven by the monsoon, greatly reduces pollution. For instance, CO levels in the lower troposphere of southeast China drop by about 25%, from 160 ppb in May to 120 ppb in June and July [107], likely due to the influx of clean marine air during the summer monsoon. Similarly, in Hong Kong, frequent summer monsoon rains decrease air pollution through wet deposition [97]. Chan and Yao observed that Shanghai experiences regular rainfall due to its subtropical monsoon climate, which removes particulate matter from the air [85]. In Beijing, the summer monsoon brings more precipitation than the winter monsoon, leading to lower concentrations of pollutants such as SO_2 and $PM_{2.5}$ [101]. A summary of air pollution status in major East Asian cities across different seasons (winter, summer, pre-monsoon, monsoon, and post-monsoon) is presented in Table 1, highlighting pollution concentrations and identified major sources and the linkage between pollution concentrations and meteorological parameters.

Table 1. Status of air pollution in relation to meteorological influences in East Asian cities.

City and Region	Key Previous Studies	Study Period	Major Findings	Identified Reasons/ Major Source	Season	Linkage Between Air Pollution and Meteorology
Beijing, China	Wang et al. [101]	2001–2003	The highest mean concentration (214.2 $\mu g/m^3$) of $PM_{2.5}$ and a much higher concentration (163.7 ppb) of SO_2 were observed	Due to the increased coal burning for industrial purposes and domestic heating	Winter	Low temperatures, weak winds, a shallow boundary layer, and stable atmospheric conditions contribute to pollutant accumulation and limit dispersion
Beijing, China	Wang et al. [101]	2001–2003	Observed much lower average concentration (93.2 $\mu g/m^3$) of $PM_{2.5}$	High wet deposition of fine PM due to increased rainfall.	Summer	Frequent rainfall improved the wet scavenging process, aiding in the removal of particulate matter (PM)
Beijing, China	Wang et al. [101]	2001–2003	Much lower SO_2 concentration (14.8 ppb) was observed	Less coal burning for domestic heating	Summer	Strong atmospheric mixing, coupled with improved ventilation, effectively dilutes pollutants
Wuqing, China	Xu et al. [26]	2009–2010	The average SO_2 concentration was found to be significantly lower (5.7 $\pm$ 6.3 ppb)	Less coal burning for residential heating	Summer	Increased atmospheric instability and precipitation enhanced the dispersion and washout of pollutants
Wuqing, China	Xu et al. [26]	2009–2010	Higher NO_x (>96 ppb), CO (>4 ppb), and SO_2 (>66 ppb) concentrations	Dominance of a cold high-pressure system and low surface wind; excessive coal burning in winter	Winter	High-pressure systems combined with weak winds led to stagnant conditions, hindering the dispersion of pollutants
Hong Kong	Louie et al. [31]	2000–2001	Observed the highest $PM_{2.5}$ concentration (33–69 $\mu g/m^3$)	Influence of the East Asian anticyclones weather pattern.	Winter	Anticyclonic conditions led to stable atmospheric conditions, stagnation, and regional transport of pollutants
Hong Kong	Louie et al. [31]	2000–2001	Observed the lowest concentration of $PM_{2.5}$ (14.8 $\mu g/m^3$)	Due to south-easterly winds with intense rainfall and cleaner marine air.	Summer	Marine airflow and precipitation help dilute and remove pollutants from the atmosphere
Seoul, Korea	Jo et al. [38]	1989–1996	Higher CO, SO_2, and NO_2 concentrations (9 ppm, 90 ppb, and 50 ppb, respectively) in January	Increased vehicular emissions and fuel consumption due to rapid urbanization and industrial development	Winter	Low temperatures and shallow mixing layers increase pollutant accumulation near the surface
Seoul, Korea	Jo et al. [38]	1989–1996	Comparatively lower concentration of NO_2 (40 ppb) was observed	May result from less fuel consumption and more photochemical reactions	Summer	High solar radiation combined with vertical mixing led to decreased NO_2 levels
Shanghai, China	Zhang et al. [25]	2013–2014	Higher average $PM_{2.5}$ (56.1 ppb) and PM_{10} (79.9 ppb) concentrations	Increased emissions from heating sources and meteorological influence in winter, which hinders pollutant dispersion	Winter	A stable atmosphere, a low boundary-layer height, and weak winds limited the dispersion of pollutants
Shangdianzi (north of Beijing)	Xu et al. [26]	2009–2010	During July–August, a lower NO_x concentration (20.4 $\pm$ 12.2 ppb) was observed	Less coal combustion in summer and a strong photochemical reaction that removes primary pollutants from the atmosphere more quickly	Summer	Improved photochemical oxidation and increased atmospheric mixing reduced NO_x levels
Beijing, China	Wang et al. [101]	2001–2003	Lower concentrations of SO_2, $PM_{2.5}$	Relatively more precipitation in the summer monsoon period	Summer monsoon	Monsoonal rainfall and increased airflow improved pollutant removal and ventilation

Table 1. *Cont.*

City and Region	Key Previous Studies	Study Period	Major Findings	Identified Reasons/ Major Source	Season	Linkage Between Air Pollution and Meteorology
Shanghai, China	Chan and Yao [85]	2008	Lower concentration of particulate matter	Due to a subtropical monsoon climate, which leads to frequent rainfall	Summer monsoon	Increased rainfall led to more wet deposition, reducing PM concentrations
Shanghai, China	Gao et al. [103]	2006–2015	O_3 increased 67% from 2006 to 2015	High local emissions of ozone precursors (such as VOC_s and NO_x) in urban areas	Summer	High temperatures and strong solar radiation hasten the photochemical formation of ozone
Shanghai, China	Yan et al. [99]	2013–2017	$PM_{2.5}$ and O_3 (average $PM_{2.5}/PM_{10}$ = 0.68) were considered as Shanghai's primary pollutants	Industrial energy use and residential heating	Winter	Winter stagnation promoted the accumulation of $PM_{2.5}$, whereas meteorological conditions affected the variability of O_3
Shanghai, China	Chen et al. [100]	2015–2018	Observed $PM_{2.5}$ in winter and O_3 in summer as major air pollutants	Vehicle and coal combustion emissions	Winter and Summer	Winter stability enhances $PM_{2.5}$ accumulation, while summer heat and solar radiation boost O_3 formation.
Seoul, Korea	Allabakash et al. [102]	2015–2020	$PM_{2.5}$ and PM_{10} showed a downward trend from 2015 to 2020, except in 2019	Dust storm in 2019, traffic volume, and population density	Winter	PM concentrations were influenced by long-range dust transport and seasonal weather patterns
Beijing, China	Liu et al. [104]	2021	Extreme hourly maximum PM_{10} (5267.7 $\mu g/m^3$) and $PM_{2.5}$ (963.9 $\mu g/m^3$) concentration along with high organic carbon in $PM_{2.5}$	Haze mixed with sandstorms and bioaerosols	Spring	Sandstorms, regional transport, and stagnant conditions led to severe episodes of PM pollution
Hong Kong	Lin et al. [105]	2024	Maximum SO_4^{2-} concentration (35.2 ppb) within $PM_{2.5}$ in peak hours	Volcanic emission from Taal volcano, Philippines	Spring	Volcanic aerosols were transported to Hong Kong through favorable wind circulation and long-range atmospheric movement

3.6. Air Pollution in the Major Cities of South Asia

3.6.1. Air Pollution in South Asian Cities During Winter

In South Asian cities, winter typically brings heightened air pollution due to both meteorological and anthropogenic factors. In Dhaka, Bangladesh, high winter levels of PM_{10} and $PM_{2.5}$ (223 ± 82.3 $\mu g/m^3$ and 73.4 ± 41.9 $\mu g/m^3$, respectively) were observed, attributed to low wet deposition, dry soil conditions, limited rainfall, and prevailing north-westerly winds [93,108]. Urban expansion contributes to further pollution through vehicle emissions, biomass combustion, brick kilns, industrial processes, and cross-border pollution. For instance, more than 60% of $PM_{2.5}$ in Dhaka comes from biomass burning, vehicles, and brick kilns.

Fattah et al. studied urban areas in South Asia and found the poorest air quality in Delhi, Lahore, Dhaka, and Kolkata during winter, with monsoon rains helping to improve conditions. In Lahore, Dhaka, and Kolkata, $PM_{2.5}$ levels were negatively correlated with temperature due to enhanced atmospheric mixing, whereas in Delhi, a weak positive correlation led to greater accumulation at temperatures below 20 °C [39]. In Delhi, a weak positive correlation is due to widespread vehicular, industrial, and construction activities, which can result in higher temperatures that accelerate the rapid formation and accumulation of $PM_{2.5}$ from numerous active pollution sources. Faisal et al. observed increasing $PM_{2.5}$ levels in Dhaka from 2019 to 2021, attributed to construction and brick-kiln operations. Peak winter levels reached 211.23 $\mu g/m^3$ in March 2021, while summer and

monsoon periods exhibited greater variability [109]. Kathmandu Valley, Nepal, exhibits similar winter patterns. For instance, PM_{10} levels of 167.7 $\mu g/m^3$ were reported during cold temperatures (−1 °C to 15 °C) that hinder pollutant dispersion [27], and key pollution sources included industrial activities, domestic heating, vehicles, and transboundary pollution. The valley's topography worsens winter pollution peaks by trapping pollutants.

Studies reported that winter $PM_{2.5}$ levels are highest across multiple cities in India. Singh et al. reported a winter-average $PM_{2.5}$ of 74.1 ± 14.4 $\mu g/m^3$ in Chennai, primarily due to diesel exhaust, biomass burning, and marine aerosols. Similarly, Ahmedabad and Hyderabad exhibited high winter $PM_{2.5}$ levels, primarily due to biomass burning, vehicle emissions, and coal-fired power plants [1]. Ravindiran et al. reported that Chennai's AQI peaks in January, driven by industrial and urban emissions [110]. Bhaskar and Mehta documented an average winter PM_{10} level of 140 $\mu g/m^3$ in Ahmedabad, attributed to its semi-arid, dusty environment [34]. Overall, winter pollution in South Asian cities worsens due to low rainfall, stagnant air, cold weather, fog, and high levels of human-made emissions. Seasonal weather patterns and geographic features amplify pollutant build-up, often causing $PM_{2.5}$ and PM_{10} levels to exceed safe thresholds, underscoring the importance of implementing targeted mitigation measures.

3.6.2. Air Pollution in South Asian Cities During Summer

Seasonal fluctuations in PM_{10} levels in Ahmedabad, India, from 2005 to 2008 were reported by Bhaskar and Mehta [34]. During summer, the average PM_{10} concentrations were 117, 131, 115, and 106 $\mu g/m^3$, whereas in the monsoon season, the average was significantly lower at 87, 94, 105, and 92 $\mu g/m^3$ [34]. Summer winds originate from the arid and semi-arid western regions of India, transporting PM to Ahmedabad. Similarly, in Chennai, the average $PM_{2.5}$ levels in summer (67.3 ± 20.1 $\mu g/m^3$) were lower than in winter (74.1 ± 14.4 $\mu g/m^3$) [1]. The lower summer $PM_{2.5}$ in Chennai is attributed to higher wind speeds, which promote greater dispersion of pollutants.

3.6.3. Air Pollution in South Asian Cities During Pre-Monsoon, Monsoon, and Post-Monsoon

The South Asian monsoon system significantly impacts regional air quality by affecting how pollutants are transported, dispersed, and deposited. During summer, strong south-westerly winds and frequent rains can carry pollutants from urban and industrial areas to nearby plains and coastal or marine environments. A key process during this season is wet deposition, which removes particulate and gaseous pollutants from the atmosphere [52,65,67]. In some Indian coastal regions, the retreating monsoon with northeast winds may cause pollutants to recirculate and temporarily build up, illustrating the complex influence of monsoon dynamics on seasonal air quality patterns [19,54,67].

Seasonal variations in air pollutants linked to monsoon circulation have been observed in various South Asian cities. Shelton et al. examined seasonal changes in particulate matter, SO_2, O_3, NO_2, and CO in Colombo and Kandy, Sri Lanka, from 2018 to 2021. They found that Colombo experienced peak daily pollutant levels during the northeast monsoon and between monsoon seasons, whereas the Kandy valley in Sri Lanka showed the opposite pattern [41]. Higher pollution in Colombo during the northeast monsoon was partly due to stronger winds that transported emissions from nearby power plants and industries to monitoring sites. In Colombo, particulate matter, NO_2, and CO levels tended to be higher at night, whereas O_3 and SO_2 concentrations increased during the day, with solar radiation and photochemistry mainly driving the daytime O_3 spike. Conversely, Kandy valley experienced increased O_3, NO_2, $PM_{2.5}$, and PM_{10} during the first inter-monsoon period, whereas CO and SO_2 peaked in the southwest monsoon. Most pollutants showed

higher daytime levels than at night, partly because Kandy's valley topography promotes pollutants to accumulate near the valley floor [41].

Studies across South Asia also highlight how monsoon-related weather patterns affect pollutant levels. In Ahmedabad, lower average PM_{10} levels were recorded during the monsoon than during the post-monsoon period. For instance, in 2008, the mean PM_{10} was 92 $\mu g/m^3$ during the monsoon season and increased to 104 $\mu g/m^3$ afterward [34]. Similar trends were observed in the Kathmandu Valley, where a much lower daily average PM_{10} (78.1 $\mu g/m^3$) during the monsoon than in the pre-monsoon period (178.3 $\mu g/m^3$) was reported [27]. This decline was linked to stronger winds, warmer temperatures, and heavy rainfall driven by the southwest monsoon from the Bay of Bengal and Indian Ocean (Figure 7a).

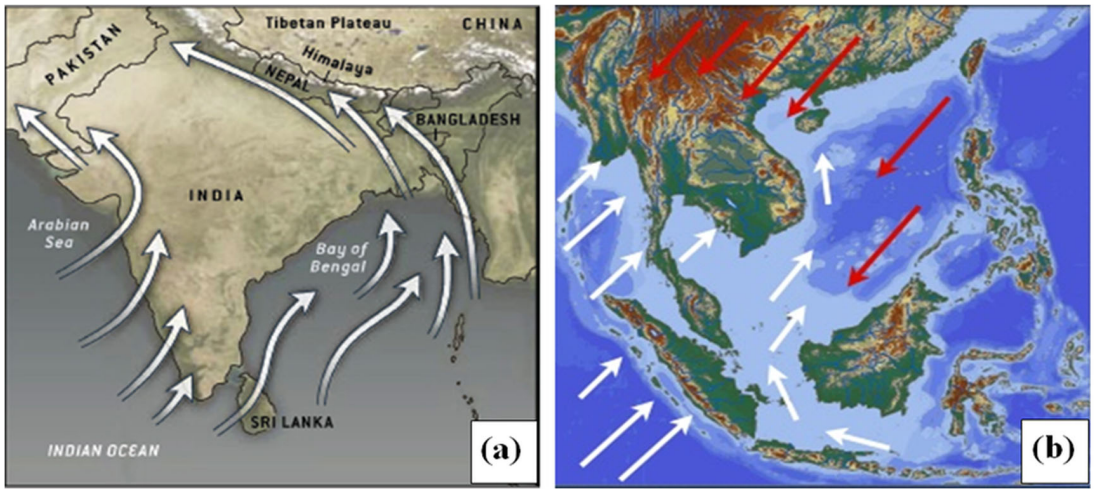


Figure 7. (**a**). Warm, saturated air from the Indian Ocean and the Bay of Bengal results in the summer monsoon in South Asia (Source: [111]); (**b**). Southeast Asian monsoon system where the red arrows indicate winds from the north-east during the winter monsoon and white arrows indicate winds from the South-west during the summer monsoon (Source: [112]).

Stable atmospheric conditions and lower mixing heights during the post-monsoon season can prolong the residence time of pollutants in the air, leading to higher concentrations of gases such as SO_2 and NO_2. In Burdwan, India, the hourly average concentrations of SO_2 and NO_2 during the post-monsoon period (8.5 $\pm$ 7.1 ppb and 162.8 $\pm$ 184.8 ppb, respectively) were greater than during the pre-monsoon season (5.1 $\pm$ 6.2 ppb and 92.5 $\pm$ 64.7 ppb, respectively) [113]. Similarly, much lower levels of PM_{10} and $PM_{2.5}$ in Dhaka during the monsoon season than during the pre-monsoon and post-monsoon periods were reported [40]. In Bangladesh, the monsoon brings stronger winds and marine air masses, which help disperse pollutants. Conversely, the pre-monsoon period sees increasing wind speeds and relative humidity associated with south-westerly marine air, while the post-monsoon season is characterized by decreasing rainfall and humidity, allowing particulate matter to accumulate in the atmosphere. A summary of air pollution status in major South Asian cities across different seasons (winter, summer, pre-monsoon, monsoon, and post-monsoon) is presented in Table 2, highlighting pollution concentrations and major sources.

Table 2. Status of air pollution in relation to meteorological influences in South Asian cities.

City and Region	Key Previous Studies	Study Period	Major Findings	Identified Reasons/ Major Source	Season	Linkage Between Air Pollution and Meteorology
Dhaka, Bangladesh	Begum et al. [93]	2005–2006	Higher concentrations of PM_{10} and $PM_{2.5}$ (223 ± 82.3 and 73.4 ± 41.9 μg/m^3)	Low wet deposition, soil dryness, low humidity	Winter	Low humidity, limited rainfall, and stable winter atmospheric conditions decreased pollutant dispersion and promoted PM accumulation
Dhaka, Bangladesh	Begum et al. [108]	2010–2012	Higher concentrations of $PM_{2.5}$ (63.9 μg/m^3)	Excessive biomass burning, vehicular emissions, and brick kiln operations	Winter	Weak winds, a shallow boundary layer, and reduced atmospheric mixing increased $PM_{2.5}$ accumulation near the surface
Dhaka, Bangladesh	Begum et al. [40]	2000–2005	Much lower PM_{10} concentrations during the monsoon compared to the pre-monsoon and post-monsoon	Due to increased wind speed and purely marine air	Monsoon	Strong monsoonal winds, marine air intrusions, and frequent rainfall contributed to improved pollutant dispersion and increased wet deposition
Kathmandu Valley, Nepal	Giri et al. [27]	2003–2005	Higher concentration of PM_{10} (167.7 μg/m^3)	Valley topography, very low rainfall	Winter	Temperature inversions, inadequate ventilation, and the enclosed valley terrain trapped pollutants and restricted their dispersion
Kathmandu Valley, Nepal	Giri et al. [27]	2003–2005	Lower average PM_{10} concentration (78.1 μg/m^3)	Due to the Indian summer monsoon rainfall, which resulted from the South-westerly warm and saturated air from the Bay of Bengal.	Monsoon	Heavy monsoon rainfall enhanced particulate removal, leading to better atmospheric cleansing
Chennai, India	Singh et al. [1]	2007–2016	Highest $PM_{2.5}$ (74.1 ± 14.4 μg/m^3) concentration	Excessive biomass burning and diesel exhaust	Winter	Limited atmospheric mixing and lower boundary-layer heights promoted the accumulation of pollutants
Chennai, India	Singh et al. [1]	2007–2016	Relatively low $PM_{2.5}$ (67.3 ± 20.1 μg/m^3)	Higher wind speed leads to greater dispersion of pollutants.	Summer	Stronger winds increased horizontal dispersion and lowered pollutant concentrations
Ahmedabad, India	Bhaskar and Mehta [34]	2005–2008	Higher concentration of PM_{10} (140 μg/m^3)	Semi-arid region, dry climate, most of the open places are covered with sand	Winter	Dry conditions and low rainfall promoted dust suspension and led to decreased atmospheric cleansing
Ahmedabad, India	Bhaskar and Mehta [34]	2005–2008	PM_{10} were reported as 117, 131, 115, and 106 μg/m^3 (from 2005–2008)	Wind direction (blows from the arid and semi-arid regions of western India), bringing particulate matter into Ahmedabad.	Summer	Regional wind transport carried dust particles into the city, raising PM_{10} levels
Ahmedabad, India	Bhaskar and Mehta [34]	2005–2008	PM_{10} were reported as 87, 94, 105, and 92 μg/m^3 (from 2005–2008)	Higher wind speed and marine air lead to increased rainfall	Monsoon	Enhanced rainfall and stronger winds facilitated the removal of PM via wet deposition and dispersion
Delhi, India	Fattah et al. [39]	2016–2021	Worst air quality in case of $PM_{2.5}$ (195.46 ± 79.24 μg/m^3) (2016–2021)	Transportation and industrial sectors are responsible for the worst air quality	Winter	Low temperatures, gentle winds, and frequent inversion conditions limited the dispersion of pollutants

Table 2. *Cont.*

City and Region	Key Previous Studies	Study Period	Major Findings	Identified Reasons/ Major Source	Season	Linkage Between Air Pollution and Meteorology
Lahore, Pakistan	Fattah et al. [39]	2016–2021	$PM_{2.5}$ was recoded as 171.30 ± 104.32 μg/m^3 (2016–2021)	Transportation and industrial sectors are responsible for the worst air quality	Winter	Persistent fog, temperature inversions, and low wind speeds contributed to increased $PM_{2.5}$ accumulation
Dhaka, Bangladesh	Faisal et al. [109]	2019–2021	The worst concentration of $PM_{2.5}$ was observed (152.65 μg/m^3)	Brick kilns	Winter	Dry conditions, a low boundary-layer height, and limited ventilation contributed to the significant accumulation of $PM_{2.5}$
Dhaka, Bangladesh	Fattah et al. [39]	2016–2021	$PM_{2.5}$ was reported as 155.39 ± 56.40 μg/m^3 (2016–2021)	Brick kilns and construction projects increased pollution rates	Winter	Stable winter atmospheric conditions and low rainfall levels limited the dispersion and deposition of pollutants
Colombo, Sri Lanka	Shelton et al. [41]	2018–2021	Higher $PM_{2.5}$ (29.5 μg/m^3), PM_{10} (48.8 μg/m^3), CO (690.5 ppb), and NO_2 (18.6 ppb) at night-time than daytime (2019–2021)	Lower atmosphere and stagnant wind conditions with increased pollutants due to traffic congestion	North-eastern monsoon	Night-time atmospheric stability combined with weaker winds limited dispersion, leading to higher pollutant levels
Kandy, Sri Lanka	Shelton et al. [41]	2018–2021	Daytime CO (763.6 ppb), SO_2 (1.8 ppb), O_3 (21.1 ppb), NO_2 (16.4 ppb), $PM_{2.5}$ (21.9 μg/m^3), and PM_{10} (51.1 μg/m^3) concentrations were much higher than at night-time (2019–2021)	Traffic jam, wind speed, and its direction	Monsoon	Daytime solar radiation increased photochemical activity, and local wind patterns affected pollutant transport and accumulation
Kolkata, India	Fattah et al. [39]	2016–2021	Very unhealthy $PM_{2.5}$ (152.84 ± 60.71 μg/m^3) observed (2016–2021)	Transportation and industrial sectors	Winter	Low wind speeds, shallow mixing layers, and winter inversions contributed to $PM_{2.5}$ accumulation and degraded air quality

3.7. Air Pollution in the Major Cities of Southeast Asia

3.7.1. Air Pollution in Southeast Asian Cities During the Winter

Multiple studies highlight significant seasonal fluctuations in air pollution levels in Southeast Asian cities, especially in winter, driven by changes in atmospheric circulation, temperature, and pollutant transport. Hien et al. found that levels of PM_{10}, SO_2, NO_2, and CO in Hanoi, Vietnam, drop considerably during summer (May–September) and increase sharply in winter (October–March) [32]. This seasonal variation is mainly driven by cold continental air masses from the East Asian anticyclone. In winter, air from Siberia carries colder temperatures and stable conditions, limiting vertical mixing and encouraging pollutant accumulation. Consequently, winter PM_{10} concentrations in Hanoi nearly double the national annual safety threshold of 50 μg/m^3 [32].

Additionally, long-range transport significantly impacts winter air pollution in northern Vietnam. Phung-Ngoc et al. studied winter pollution in Hanoi from 2006 to 2020 and found that about 30% of $PM_{2.5}$ levels increased due to long-distance transport from China during cold surge events. Meanwhile, approximately 40% of the increases were due to local pollutant stagnation during those periods [44]. Beyond atmospheric transport, changes in emission sources have also driven increases in pollution, as biomass burning is gradually

being replaced by expanding industrial activities. The northeast monsoon circulation is vital in moving pollutants from eastern China and the Red River Delta's industrial areas to Hanoi. Satellite data on sulfate aerosol optical depth (AOD) confirmed that pollutant plumes from coal-based industrial zones in eastern China were carried toward northern Vietnam during winters from 2011/12 to 2019/20.

Secondary aerosol formation plays a significant role in winter pollution episodes. Dat et al. found that secondary inorganic aerosols (SIAs) are a major part of $PM_{2.5}$ and ultrafine $PM_{0.1}$ during dry winter periods in Hanoi. Their research indicated that SIA levels rise notably during pollution events compared to normal conditions [114]. Key sources, such as long-range transport, biomass burning, and traffic emissions, influence $PM_{2.5}$ and SIA concentrations, and wind speed is crucial for pollutant dispersion. The SIA portion of $PM_{0.1}$ also strongly correlates with meteorological factors, including relative humidity, temperature, atmospheric pressure, and solar radiation. Similarly, much higher $PM_{2.5}$ levels were recorded in Hanoi during winter than in summer, with positive correlations with CO and NO_2 emissions and negative correlations with temperature [115]. In many instances, $PM_{2.5}$ concentrations exceeded the WHO guideline of 15 $\mu g/m^3$ by nearly ten times.

Seasonal variations in air pollution have been observed in Bangkok, Thailand. Sahu et al. noted significant seasonal changes in CO levels, mainly due to long-range transport from China and biomass burning in South and Southeast Asia [116]. Uttamang et al. reported that CO, SO_2, and NO_2 levels in the Bangkok Metropolitan Region generally remained within permissible limits in both summer and winter, though O_3 occasionally exceeded normal levels [117]. During O_3 episodes, contributions from both local and regional sources nearly doubled, with mobile sources accounting for the majority of precursor pollutants. In Asian cities, winter haze conditions further emphasize the impact of local emissions and atmospheric stability. Choomanee et al. found that black carbon (BC) levels relative to $PM_{2.5}$ were more than three times higher (i.e., 2.82 to 9.09 $\mu g/m^3$) during haze periods compared to non-haze times. The highest $PM_{2.5}$ levels were recorded in January 2021 and remained fairly stable across various altitudes. In contrast, BC concentrations declined with altitude, pointing to strong local sources like traffic emissions, combined with stable atmospheric conditions that limit vertical mixing during winter [42].

3.7.2. Air Pollution in Southeast Asian Cities During the Summer

Air pollution levels in Southeast Asian cities show significant seasonal changes driven by weather and emission sources. In summer, more rainfall, better atmospheric mixing, and the arrival of cleaner marine air usually lower pollutant levels. Nevertheless, regional biomass burning and human activities, such as traffic and industry, continue to contribute to air pollution in certain urban areas. For instance, in Hanoi, PM levels were found to be lowest during summer (July–August), which aligns with extended rainfall driven by moist air from the Indian Ocean and the South China Sea. Their findings showed that average summer concentrations of $PM_{2.5}$ and PM_{10} (18.9 and 27.6 $\mu g/m^3$) were more than twice as low as winter levels (51.5 and 69.8 $\mu g/m^3$) [86]. These increased levels are driven by major sources of emissions in Hanoi, including vehicle traffic, industrial manufacturing, and large-scale construction activities, all fuelled by rapid economic growth over the past few decades. Similarly, Sahu et al. observed significant seasonal variation in CO levels in Bangkok, primarily driven by biomass burning across South and Southeast Asia during the dry season [116]. Despite this, CO concentrations during summer remained relatively moderate because of dilution by cleaner marine air masses from the Indian and Pacific Oceans.

3.7.3. Air Pollution in Southeast Asia During the Monsoon

Seasonal changes in wind patterns and precipitation linked to the Southeast Asian monsoon system influence air quality. During the summer monsoon, prevailing southwest winds bring marine air masses that reduce pollutant levels in coastal areas. However, these same winds can carry urban and industrial emissions from nearby regions into rural and mountainous areas, thereby affecting air quality [53,54,65]. In the dry season, when winds mainly come from the northeast, dispersion is limited, and weak winds result in higher pollution concentrations in urban areas. At the same time, biomass burning during this period worsens air quality across many Southeast Asian countries by contributing to transboundary haze episodes [52,53,65,67].

The Southeast Asian monsoon system is typically divided into the summer and winter monsoons, both of which greatly influence air pollution levels across the region. Figure 7b shows the monsoon circulation and wind patterns in Southeast Asia that play a key role in pollutant distribution. In many Southeast Asian countries, $PM_{2.5}$ and PM_{10} are recognized as primary air pollutants, with significant contributions from biomass burning and regional transport. Juneng et al. reported relatively high PM_{10} levels (>50 $\mu g/m^3$) in the Klang Valley, Malaysia, during the summer monsoon (Southwest monsoon), which is characterized as the dry season (May to September) [118]. The high PM levels during this period are mainly due to pollutants transported from biomass burning, as Malaysia's Southwest monsoon typically brings drier, clearer weather than other parts of Southeast Asia, which often experience heavy summer rains. Conversely, lower PM_{10} levels (around 45 $\mu g/m^3$) were recorded during the rainy season [118] associated with the northeast monsoon, when northeasterly winds and higher rainfall help remove pollutants.

Rahman et al. examined a five-year dataset (2007–2011) of PM_{10}, CO, NO_2, and O_3 in the Klang Valley, finding that PM_{10} levels frequently exceeded 100 $\mu g/m^3$. Principal component analysis (PCA) identified CO and NO_2 as the leading pollutants, followed by PM_{10} and O_3. In 2009 and 2011, numerous days recorded PM_{10} concentrations nearing 150 $\mu g/m^3$ throughout Klang Valley [119]. These high levels were mainly attributed to traffic congestion, hot weather, and severe haze episodes. The southwest monsoon was associated with increased PM_{10} levels, while the northeast monsoon was associated with higher CO concentrations. Additionally, NO_2 and O_3 levels were higher during the first inter-monsoon period. Similar seasonal patterns have been observed in Thailand, with lower CO levels during the wet season [116], attributed to cleaner marine air masses and less biomass burning. In Thailand, besides vehicle emissions, biomass burning is a key source of pollution, especially in February and March, when agricultural fires are frequent. Similar conditions prevail in Indonesia and Malaysia, where biomass burning significantly impacts regional air quality. Sahu et al. estimated that biomass burning in Southeast Asia, including Indonesia and Malaysia, emits around 118 Tg of CO annually [116], making it a major contributor to regional atmospheric pollution. A summary of air pollution levels in major Southeast Asian cities across different seasons is presented in Table 3, highlighting pollution levels and main pollution sources.

Table 3. Status of air pollution in relation to meteorological influences in Southeast Asian cities.

City and Region	Key Previous Studies	Study Period	Major Findings	Identified Reasons/ Major Source	Season	Linkage Between Air Pollution and Meteorology
Hanoi, Vietnam	Hien et al. [86]	1998	Much lower concentrations of $PM_{2.5}$ and $PM_{2.5–10}$ (18.9 and 27.6 $\mu g/m^3$) compared to winter	High air masses from the Indian Ocean and the South China Sea caused an extended period of rainfall.	Summer	Persistent rain and humid maritime air masses increased wet deposition and atmospheric cleansing, leading to lower PM levels
Hanoi, Vietnam	Hien et al. [86]	1998	Higher average concentrations of $PM_{2.5}$ and $PM_{2.5–10}$ (51.5 and 69.8 $\mu g/m^3$)	Continental air from Siberia lowers temperatures and increases atmospheric stability, favoring pollutant accumulation.	Winter	Low temperatures, stable atmospheric conditions, and limited vertical mixing contributed to the accumulation of pollutants near the surface
Hanoi, Vietnam	Hien et al. [32]	2003–2004	PM_{10} levels were observed to be twice the annual average national standard of 50 $\mu g/m^3$	Invasion of cold air from the East Asian anticyclone affects	Winter	Anticyclonic conditions increased atmospheric stability and decreased dispersion, leading to higher PM_{10} levels
Hanoi, Vietnam	Phung-Ngoc et al. [44]	2006–2020	40% of the $PM_{2.5}$ level increased	Regional pollution caused by the Northeast monsoon impact	Winter	The northeast monsoon circulation enabled the long-range transport and accumulation of PM
Hanoi, Vietnam	Hoang et al. [115]	2023	Very high $PM_{2.5}$ (150.4 $\mu g/m^3$) concentration	Industrial activities, agricultural waste burning, traffic, etc.	Winter	Winter atmospheric stagnation, a low boundary-layer height, and weak winds contributed to increased $PM_{2.5}$ accumulation
Hanoi, Vietnam	Dat et al. [114]	2020	Secondary inorganic aerosol (SIA) contributed more to $PM_{2.5}$ and $PM_{0.1}$ in episodes than in non-episode periods	Long-range transportation from the upper areas	Winter	Dry conditions and regional transport favored secondary aerosol formation and accumulation
Bangkok, Thailand	Sahu et al. [116]	2005–2006	Observed a strong seasonal variation in CO concentration	Extensive biomass burning occurs in South and Southeast Asian countries, especially during the dry season.	Winter	Dry-season weather conditions and limited rainfall promoted the persistence and regional movement of pollutants

Table 3. *Cont.*

City and Region	Key Previous Studies	Study Period	Major Findings	Identified Reasons/ Major Source	Season	Linkage Between Air Pollution and Meteorology
Bangkok, Thailand	Sahu et al. [116]	2005–2006	Moderate concentrations of CO were observed	Dilution of CO was due to cleaner marine air from the Indian and Pacific Oceans.	Summer	Marine airflow and increased atmospheric ventilation reduced CO concentrations
Bangkok, Thailand	Uttamang et al. [117]	2010–2014	Concentrations of O_3 (hourly maximum concentration of O_3 ranged from 68–190 20 ppb) exceeded the standard of NAAQs of Thailand	Mobile sources	Summer and Winter	High temperatures combined with intense solar radiation increased photochemical ozone formation on sunny days
Bangkok, Thailand	Sangkham et al. [120]	2020	Higher concentration of CO (660.21 $\mu g/m^3$), NO_2 (29.07 $\mu g/m^3$), SO_2 (3.81 $\mu g/m^3$), PM_{10} (51.70 $\mu g/m^3$), and $PM_{2.5}$ (32.19 $\mu g/m^3$) was observed	Natural and anthropogenic sources	Winter	Stable atmospheric conditions, reduced mixing heights, and weaker winds limited the dispersion of pollutants
Bangkok, Thailand	Choomanee et al. [42]	2020–2021	Increased black carbon (BC) aerosol mass concentration within $PM_{2.5}$ in the haze period	Heavy traffic, local human activities, stable atmospheric conditions, and low levels of mixing during the HP	Winter	Stable atmospheric conditions combined with limited vertical mixing led to the accumulation of black carbon and fine PM
Klang Valley, Malaysia	Juneng et al. [118]	2003–2006	Relatively higher concentration of PM_{10} (>50 $\mu g/m^3$)	Regional transport of pollutants from biomass burning	Summer monsoon (dry season)	Dry-season conditions and regional airflow promoted the transboundary movement and accumulation of PM
Malaysia	Juneng et al. [118]	2000–2006	Lower PM_{10} concentration (45 $\mu g/m^3$) was observed	Mainly because of north-easterly winds.	Northeast monsoon (rainy season)	Higher rainfall and intensified monsoonal winds improved pollutant dispersion and facilitated wet deposition
Klang Valley, Malaysia	Rahman et al. [119]	2007–2011	PM_{10} exceeded the MAAQG standard (>150 $\mu g/m^3$) from 2007 to 2011	Traffic congestion, hot weather, and haze period	South-west monsoon	Elevated PM_{10} levels resulted from high temperatures, dry conditions, and regional haze transport
Malaysia	Abdullah et al. [121]	2020	$PM_{2.5}$ concentrations reduced up to 58.4%	2020 Malaysia Movement Control Order (MCO)	Spring	Spring ventilation and mixing probably enhanced pollutant dispersion and lowered emissions.

4. Conclusions

This review provides a comparative synthesis of how meteorological conditions and seasonal changes impact urban air pollution in selected cities across East Asia, South Asia, and Southeast Asia. Despite differing primary emission sources across these regions, this study highlights that meteorological processes consistently influence the timing, intensity, and duration of pollution events. Common meteorological factors include low wind speeds, shallow planetary boundary layers, stable atmospheric conditions, and high relative humidity, which were identified as the primary meteorological drivers of PM and gaseous pollutant (NO_2, SO_2, CO, and NO_x) accumulation. Conversely, strong winds, enhanced boundary layer, and precipitation tend to disperse pollutants and promote wet deposition, reducing pollution levels. Regional variations are also notable. For instance, East Asian cities experience severe winter haze linked to heating emissions and stagnant weather, along with increased summer ozone formation due to high temperatures and solar radiation. In South Asia, the southwest monsoon generally clears pollutants, but winter inversions, biomass burning, and rapid urban growth exacerbate pollution episodes. Southeast Asia's air quality is mainly affected by biomass burning, transboundary haze, and monsoon-driven transport, which influence seasonal pollution patterns.

These results show that meteorological effects on air pollution involve both shared physical processes and unique regional traits, suggesting that air quality policies should be customized to local climate conditions rather than relying on a uniform mitigation approach. Incorporating meteorological forecasts, seasonal emission controls, and chemical transport models into air quality strategies can significantly enhance pollution mitigation and safeguard public health. Additionally, climate change is likely to affect temperature, rainfall, atmospheric stability, boundary-layer dynamics, and monsoon circulation, potentially influencing future pollution events across Asia. Consequently, future research should focus on long-term, integrated observations, studying how specific pollutants respond meteorologically, exploring climate–air-quality interactions, and developing coupled emission, meteorology, and chemistry models. Enhancing regional monitoring networks and fostering international cooperation will also be vital for managing transboundary pollution and creating evidence-based policies for sustainable urban air quality.

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