

Article

Spatiotemporal Distribution Patterns of Negative Air Ions in Forest Ecosystems of Zhejiang Province: Results from 6 Years of Long-Term Field Monitoring

Jiejie Jiao ^{1,2}, Yaowen Xu ^{1,2}, Chuping Wu ^{1,2}, Bo Jiang ^{1,2} and Xiaodong Jiang ^{3,*}

¹ Zhejiang Academy of Forestry, Hangzhou 310023, China

² Zhejiang Hangzhou Urban Ecosystem Research Station, Hangzhou 310023, China

³ Ecological and Environmental Science and Research Institute of Zhejiang Province, Hangzhou 310007, China

* Correspondence: jiangxiaodong7@126.com

Abstract

Negative air ions (NAIs) are key ecological indicators of atmospheric cleanliness and forest ecosystem service functions, particularly in the context of forest wellness and ecotourism. However, long-term, high-frequency observations of NAIs across broad spatial scales remain scarce, limiting our understanding of its regional spatiotemporal dynamics and environmental controls. Here, we present a six-year (2018–2023) continuous, hourly monitoring dataset of NAI concentrations from 60 fixed forest sites across Zhejiang Province, a typical subtropical humid region in southeastern China. The provincial mean NAI concentration over the study period was $1672 \text{ ions} \cdot \text{cm}^{-3}$, with a pronounced “high around the periphery, low in the center” spatial pattern, with the mountainous southwestern areas consistently showing the highest concentrations and the central Jinqu Basin the lowest. On diurnal scales, NAIs exhibited a bimodal pattern with primary peaks at 7:00 and secondary peaks at 16:00, rather than a simple daytime–nighttime dichotomy. Seasonal dynamics showed significantly higher NAI in summer than in autumn and winter; however, the summer–winter difference was only ~25%, much smaller than the ratios reported for temperate regions. Interannually, NAI concentrations increased from 2018 to 2023 (average annual increase of $158 \text{ ions} \cdot \text{cm}^{-3}$), peaking during the 2020–2022 period, when anthropogenic emissions were substantially reduced. Using linear mixed-effects models, we identified relative humidity as the dominant positive driver of NAI variability, followed by wind speed as a negative modulator, and precipitation playing a minor role. These findings reveal the multi-scale spatiotemporal dynamics of NAIs in subtropical forests and underscore the overriding control of humidity over ion persistence. Our study provides a robust regional benchmark for background NAI levels in humid subtropical climates and offers direct scientific support for forest-based health resource planning and air quality assessment.



Academic Editors: Anže Japelj and
Silvija Krajter Ostoić

Received: 18 May 2026

Revised: 20 June 2026

Accepted: 24 June 2026

Published: 27 June 2026

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Keywords: negative air ion; subtropical forest ecosystems; spatiotemporal patterns; environmental drivers; long-term monitoring; Zhejiang Province

1. Introduction

Negative air ions (NAIs) are clusters of negatively charged ions in the atmosphere, typically formed when oxygen molecules capture free electrons, and are especially abundant in forest environments [1]. NAIs mainly originate from the ionization phenomenon in nature, including the ionization of gas molecules caused by cosmic rays, ultraviolet

rays, radioactive substances in the atmosphere, and the charge separation effect resulting from the collision and dissociation of water molecules during phenomena such as waterfalls, ocean waves, and thunderstorms. Beyond these well-recognized sources, natural terrestrial radioactivity plays a fundamental role in sustaining background ionization. The decay of radon (^{222}Rn) exhaled from soils, along with gamma radiation from primordial radionuclides such as ^{40}K , ^{238}U , and ^{232}Th in rocks and soils, continuously generates free electrons and small ions in the near-surface atmosphere. In forest ecosystems, high soil porosity and organic matter content often enhance radon exhalation, providing a persistent in situ ionization source that is particularly important under stable meteorological conditions when turbulent mixing is weak. Simultaneously, artificial corona discharge and the Lerner effect are important pathways for their generation [1–4]. As an important ecological indicator of atmospheric cleanliness and ecosystem service functions, NAI plays multiple roles, including the deposition of fine particulate matter, suppression of harmful microorganisms, regulation of plant physiological metabolism, and improvement of human neurological and cardiovascular functions [2–6]. In recent years, with the rise of concepts such as “forest wellness” and “ecotourism,” the concentration of NAI in forest ecosystems has become a key criterion for evaluating forest environmental quality, planning wellness bases, and conducting forest therapy [7,8]. Therefore, systematically elucidating the long-term spatiotemporal patterns of NAI within forest ecosystems and identifying their key environmental regulatory factors hold significant scientific and practical value for the assessment of forest ecosystem services, forest management, and early warning of regional ecological health.

Currently, research on NAI in forests mainly focuses on short-term field monitoring and laboratory simulations [9]. Common monitoring methods include mobile surveys within specific landscape units or intermittent observations at a few fixed sites, with monitoring periods typically ranging from several weeks to one year [10]. The temporal resolution is most often daily averages or several instantaneous values per day. These studies have preliminarily revealed differences in NAI concentrations among different underlying surface types, as well as correlations with meteorological factors such as temperature, humidity, wind speed, solar radiation, and aerosol indicators such as $\text{PM}_{2.5}$ and PM_{10} [11]. However, NAI are characterized by low concentrations, short lifespans (generally from several seconds to several minutes), and high susceptibility to pronounced disturbances from local microclimates and source–sink processes [12]. Short-term, low-frequency monitoring strategies with limited site coverage are insufficient for effectively capturing interannual fluctuations in NAI and cannot disentangle the effects of incidental meteorological events from those of systematic environmental changes on ion concentrations [13]. More importantly, the relationships between NAI and various environmental factors are not constant but may undergo nonlinear transformations with changes in season, year, or regional background. For example, high temperatures typically promote negative ion production indirectly by enhancing photochemical reactions [14]; however, strong turbulent dilution effects that accompany extreme heat may cause localized concentration decreases. Increased relative humidity favors ion hydration and stable persistence, but excessively high humidity is often associated with prolonged overcast and rainy conditions, and precipitation can indirectly increase negative air ion concentrations through the wet removal of $\text{PM}_{2.5}$, in addition to the direct generation of NAI via the Lenard effect during rainfall events [15–17]. These complex interactive effects can only be effectively disentangled and quantified with the support of long-term, high-temporal-resolution, and multifactor synchronous observation datasets. Unfortunately, large-scale monitoring networks for NAI in forests, including continuous observations for over a year, covering extensive regions, and synchronously recording major environmental variables, are currently extremely limited. Consequently,

there is still a lack of systematic understanding of the historical regional evolution patterns and driving mechanisms of this important ecological indicator.

Zhejiang Province is located on the southeast coast of China and has a land area of approximately 105,500 km². Its terrain is complex and diverse, and it has a typical subtropical monsoon humid climate, characterized by distinct seasons and abundant precipitation. Meanwhile, Zhejiang's forest coverage rate has long been above 61%. This high degree of heterogeneity in natural geography and underlying surfaces provides an ideal natural experimental platform for studying the spatiotemporal distribution patterns of regional-scale NAIs and their responses to various environmental factors. We established 60 fixed monitoring sites across the province, each equipped with a high-precision online NAI concentration monitor, PM_{2.5} laser sensor, and temperature and humidity probes, among others, for continuous, synchronous, and automatic hourly monitoring from January 2018 to December 2023. This monitoring system significantly surpasses the vast majority of existing similar studies in spatial scale (60 sites covering the entire province), temporal span (6 years), and data-sampling frequency (once per hour), thus providing a robust data foundation for revealing the multi-scale spatiotemporal characteristics of NAI in typical subtropical forests and their relationships with other environmental factors.

Based on the above long-term, high-frequency, and multifactor integrated dataset, this study aims to systematically explore the following three interrelated core scientific questions: (1) What are the patterns of variation in NAI concentrations in forests in Zhejiang Province across different temporal scales? Do these concentrations exhibit stable “higher during the day and lower at night” or “higher in summer and lower in winter” patterns? (2) What are the spatial differences and gradient characteristics of atmospheric negative ion concentrations in forests at the provincial scale? (3) How do key environmental factors, such as PM_{2.5} concentration, air temperature, and relative humidity, affect the atmospheric negative ion concentrations? We further emphasize the necessity of explaining these effects through physical mechanisms, including ion generation, attachment loss, and recombination processes. By systematically addressing these questions, this study not only provides a set of 6-year benchmark data on the background characteristics of NAI in forests at the regional scale in a subtropical humid climate zone, but also offers a direct scientific basis for the comprehensive assessment of air quality and the development of forest-based health and wellness tourism resources in the region.

2. Materials and Methods

2.1. Study Area

Zhejiang Province is located on the southeastern coast of China, on the southern wing of the Yangtze River Delta, between 118°01′–123°10′ E and 27°02′–31°11′ N. The land area is approximately 105,500 square kilometers, and the topography includes mountains, hills, basins, and plains, which slope in a stepped manner from southwest to northeast. Zhejiang Province has a typical subtropical monsoon humid climate with four distinct seasons and coinciding periods of rainfall and warmth. The province's multi-year average precipitation is 1100–2000 mm, and the annual mean temperature is 15.0–18.5 °C. In 2017, 60 fixed monitoring stations for negative air ions in forest ecosystems were established in 11 cities across the province (Figure 1). These stations are representative of typical subtropical evergreen broad-leaved forests, evergreen and deciduous broad-leaved mixed forests, coniferous and broad-leaved mixed forests, and planted coniferous forests. The dominant species include *Cyclobalanopsis glauca*, *Castanopsis eyrei*, and *Castanopsis sclerophylla* of the Fagaceae family, *Cinnamomum camphora* and *Phoebe bournei* of the Lauraceae family, and *Pinus massoniana* and *Cunninghamia lanceolata*. All monitoring sites are located within forest interiors, with distances to the nearest urban settlement or major anthropogenic emission

source typically exceeding 1 km, and most sites located more than 5 km away, thereby minimizing direct local human interference.

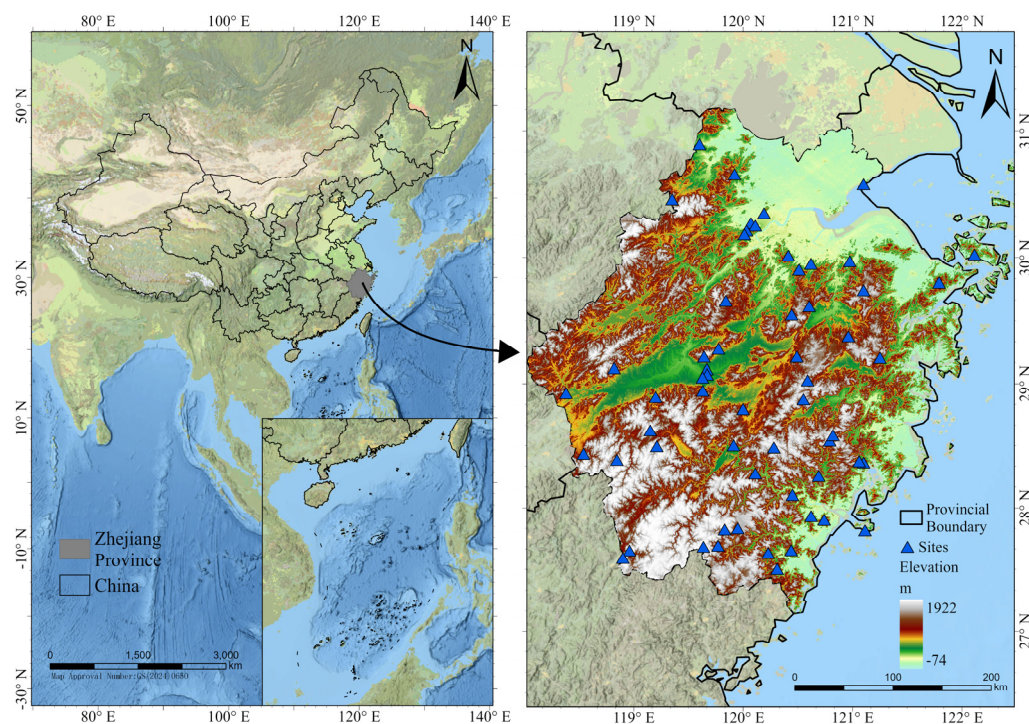


Figure 1. The location of the study area and 60 fixed monitoring stations.

2.2. Research Methods

The RR-9411A automatic meteorological monitoring system (Beijing Yugen Technology Co., Ltd., Beijing, China) was used to synchronously monitor the NAI concentration, PM_{2.5}, wind speed, temperature, atmospheric pressure, relative humidity, wind direction, and O₃ concentration for 24 h on each day. The NAI sensor was model RR-AON1000 (Beijing Yugen Technology Co., Ltd., China; <https://www.rainroot.com.cn>, accessed on 10 June 2025), with a measurement range of $0\text{--}1.2 \times 10^7 \text{ ions}\cdot\text{cm}^{-3}$, mobility $\geq 0.4 \text{ cm}^2\cdot\text{V}^{-1}\cdot\text{s}^{-1}$, and measurement accuracy $\leq \pm 10\%$ [17]. The sensor operates on the principle of the aspiration-type capacitance method: a built-in fan draws ambient air at a constant flow rate ($750 \text{ cm}^3\cdot\text{s}^{-1}$) through a coaxial double-cylinder ion collector, where negatively charged ions impinge on the collection electrode and induce a weak current; the current is then amplified and converted by an algorithm into ion concentration. The sensor incorporates a patented air-path design to enhance measurement stability and accuracy. We acknowledge that high humidity (>90%) can occasionally cause minor leakage currents, but internal dew point compensation algorithms mitigate this. Periods with relative humidity > 95% and instrument fault alerts were systematically excluded as outliers. All 60 units were factory calibrated before deployment. Annual inter-comparison using a portable reference ion counter (same model) was conducted at each site. The temperature and humidity sensors were model HMP60 (Vaisala, Finland), with a temperature measurement range of $-40\text{--}60^\circ\text{C}$, accuracy $\leq \pm 0.5^\circ\text{C}$, humidity measurement range of 0–100%, and accuracy $\leq \pm 3\%$. The wind speed sensor was a model RR-30WS (Beijing Yugen Technology Co., Ltd., China), with a measurement range of $0\text{--}60 \text{ m}\cdot\text{s}^{-1}$ and an accuracy of $\pm 0.5 \text{ m}\cdot\text{s}^{-1}$. The PM_{2.5} sensor was a model RR-9421 (Beijing Yugen Technology Co., Ltd., China), with a measurement range of $1\text{--}1000 \mu\text{g}\cdot\text{m}^{-3}$ and an accuracy of $\pm 1\%$. The acquisition frequency was 1 min, and the data were averaged and recorded every 1 h. The instrument was equipped with a built-in GPRS remote transmission module to facilitate data transfer. The monitoring probe

was placed at a height of 1.8 m above-ground, with no obstacles covering the area around the device, and was at least 2 m from the nearest tree trunk. The monitoring period was from January 2018 to December 2023.

2.3. Data Processing and Analysis

Owing to the wide variation in NAI concentration data, the following cases were defined as outliers, and the corresponding data were excluded: (1) data with an NAI concentration of 0; (2) data where each value was compared to its preceding and following values and found to be more than three times greater or less than 1/3 of these values; and (3) six or more consecutive identical data values. Approximately 31,536,000 complete data points were collected during the study period. After removing the outliers, approximately 31,200,000 valid data points remained for the analysis. According to the climatological classification of seasons, monitoring data from March to May were used as spring data for analysis, data from June to August as summer data, data from September to November as autumn data, and data from December to February of the following year as winter data.

A one-way analysis of variance (ANOVA) was conducted to compare NAI concentrations across different months, seasons, and years at a significance level of $p < 0.05$. The relationship between the NAI and environmental variables was determined using Pearson's correlation analysis. A linear mixed-effects model was used to analyze the effects of environmental factors on NAI concentrations, with PM_{2.5}, temperature, relative humidity, wind speed, O₃, and precipitation set as fixed effects, and monitoring sites set as random effects to eliminate the influence of site heterogeneity (such as altitude, forest type, and equipment differences). A model selection procedure (stepwise AIC-based backward elimination) was used to identify the most parsimonious linear mixed-effects model. The final model retained only relative humidity, wind speed, and precipitation, because PM_{2.5}, temperature, O₃, and atmospheric pressure had $p > 0.05$. Statistical analyses were performed using SPSS (version 23.0; IBM, Armonk, New York, USA) and R (version 4.0.2; <https://www.r-project.org/>; accessed on 4 April 2026).

3. Results

3.1. Daily Dynamics of NAI Concentration

From January 2018 to December 2023, the average NAI concentration in Zhejiang Province over the 72-month period was 1672 ions·cm⁻³, displaying considerable variation over time. Diurnal dynamics showed that the NAI concentration peaked at approximately 7:00 (1722 ions·cm⁻³), with a secondary peak at 16:00 (1677 ions·cm⁻³); the lowest value was observed at 20:00 (1643 ions·cm⁻³), with a secondary trough at 12:00 (1644 ions·cm⁻³) (Figure 2). There were differences in diurnal dynamics by month: 11 months exhibited a multimodal pattern, whereas the month of October exhibited a unimodal pattern. Peaks were commonly observed at 7:00, with some months showing peaks at 16:00 h. Troughs were more dispersed, mainly occurring between 12:00 and 13:00 and between 17:00 and 22:00 (Figure 3).

3.2. Monthly, Quarterly, and Annual Dynamics of NAI Concentration

As shown in Figure 4, the NAI concentration in Zhejiang Province fluctuated during the monthly variation process, showing a clear pattern of monthly dynamics. The average NAI concentration was highest in August (1921 ions·cm⁻³) and lowest in October (1425 ions·cm⁻³), with the former being 1.3 times greater than that of the latter.

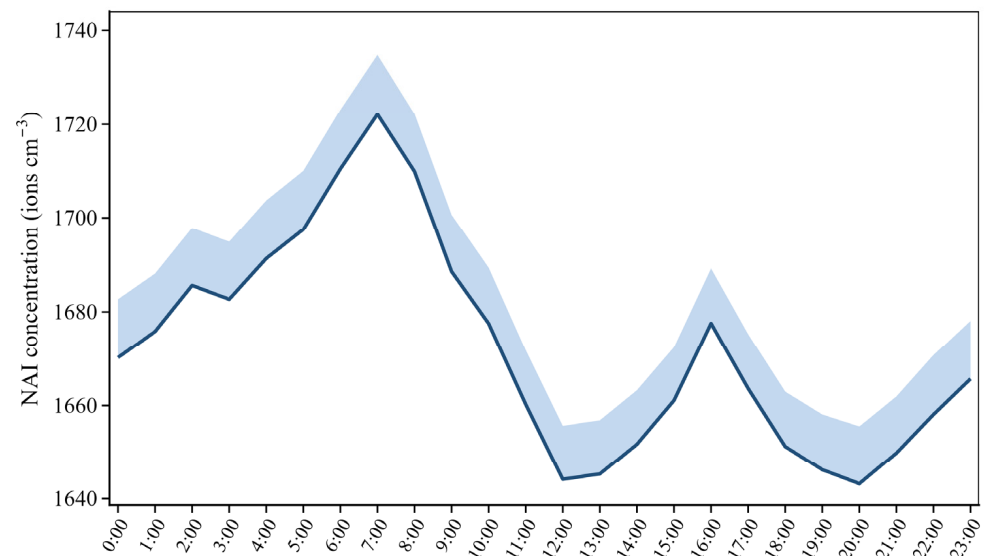


Figure 2. Daily variations in NAI concentration throughout the year. The solid line now represents the arithmetic mean, and the shaded area represents the standard error, the same as below.

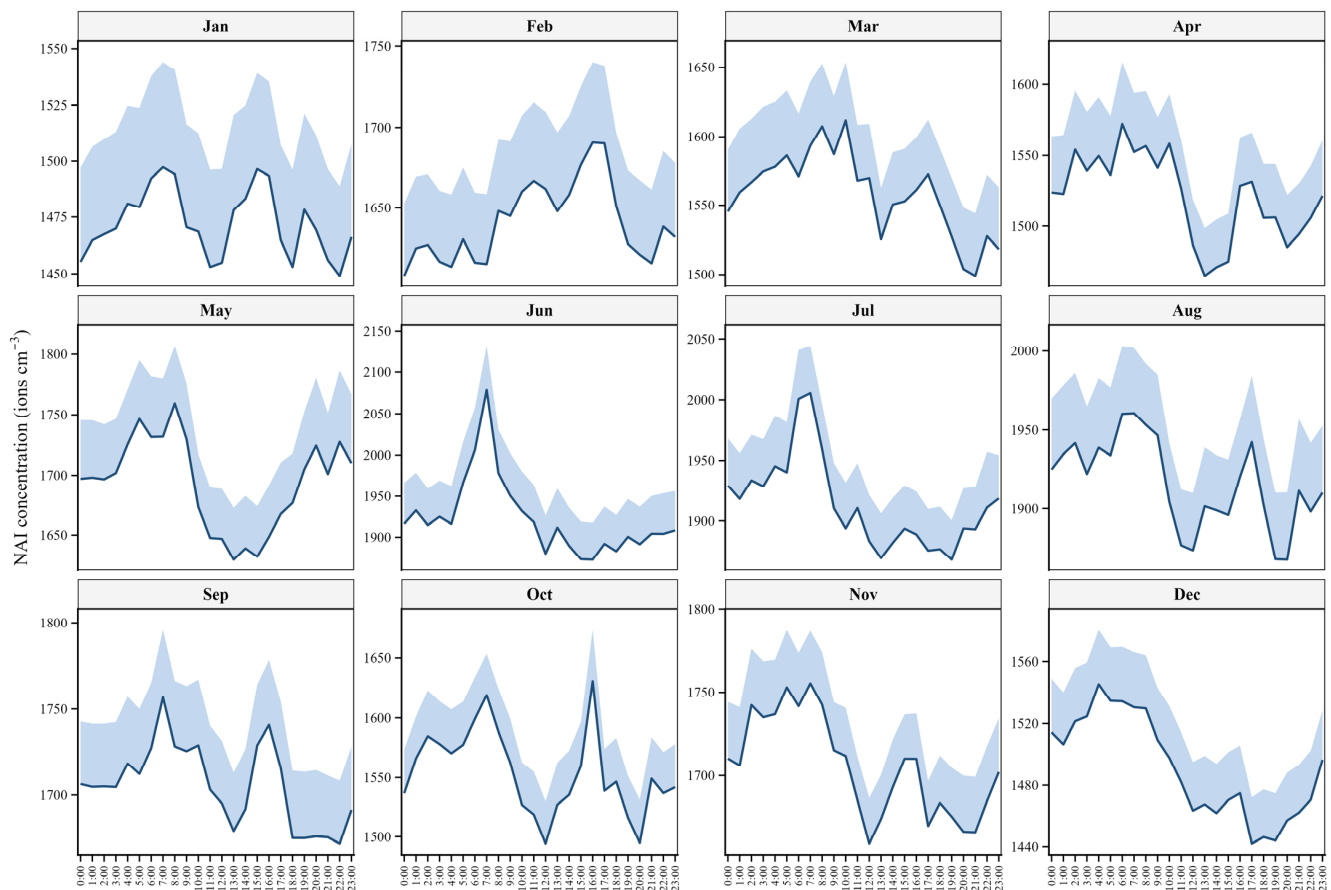


Figure 3. Daily variations in NAI concentration in each month.

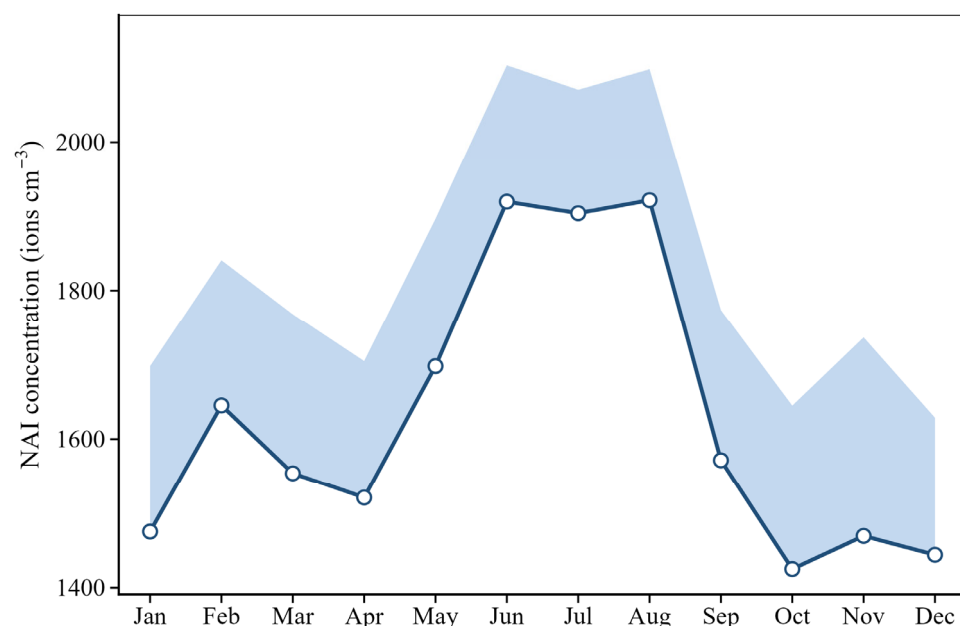


Figure 4. Monthly dynamics of NAI concentration.

The average NAI concentration in spring, summer, autumn, and winter were 1526 ions·cm⁻³, 1915 ions·cm⁻³, 1502 ions·cm⁻³, and 1526 ions·cm⁻³, respectively (Figure 5). The NAI concentration in summer was 20.6% higher than that in spring. Analysis of variance indicated that the concentration in summer was significantly higher than that in autumn and winter ($p < 0.05$). No significant differences were observed between spring, autumn, and winter ($p > 0.05$).

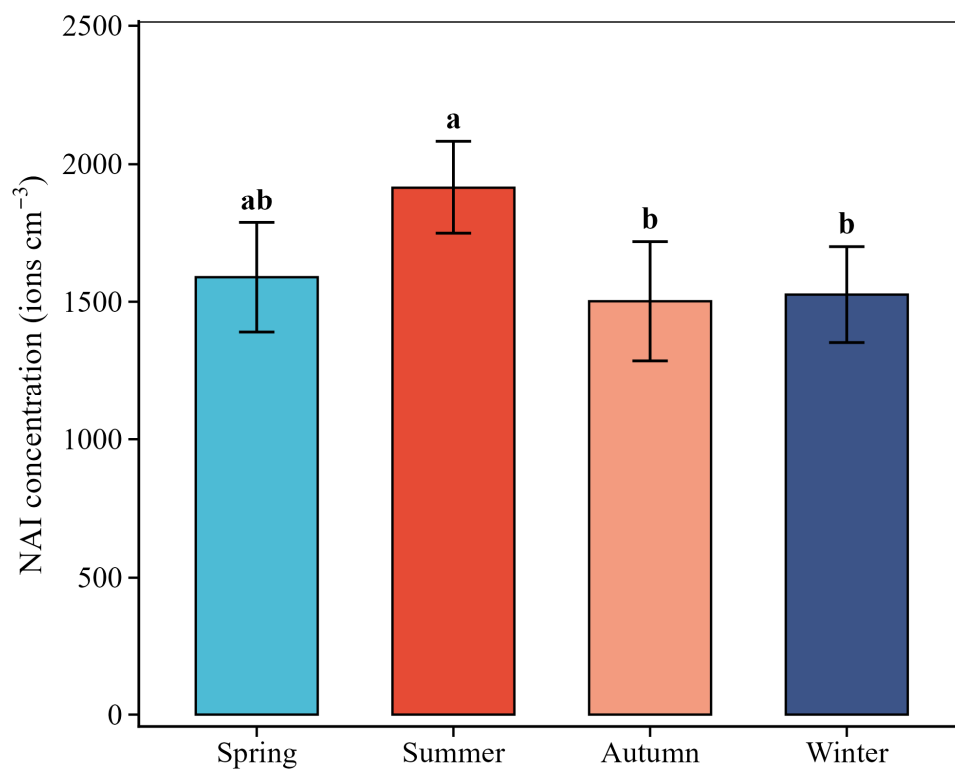


Figure 5. Quarterly dynamics of NAI concentration. The error bars represent the standard error of the mean, bars sharing the same letter are not significantly different ($p > 0.05$).

The annual pattern of NAI concentrations in Zhejiang Province exhibited marked fluctuations and an overall increasing trend (Figure 6). Between 2018 and 2023, the average NAI concentration peaked in 2021 at 2029 ions·cm⁻³. NAI concentrations in 2021 and 2022 were relatively high, with no significant differences ($p > 0.05$). The 2019 NAI concentration was significantly lower than that in 2021 and 2022 ($p < 0.05$), and 2018 was significantly lower than that in 2019–2023 ($p < 0.05$).

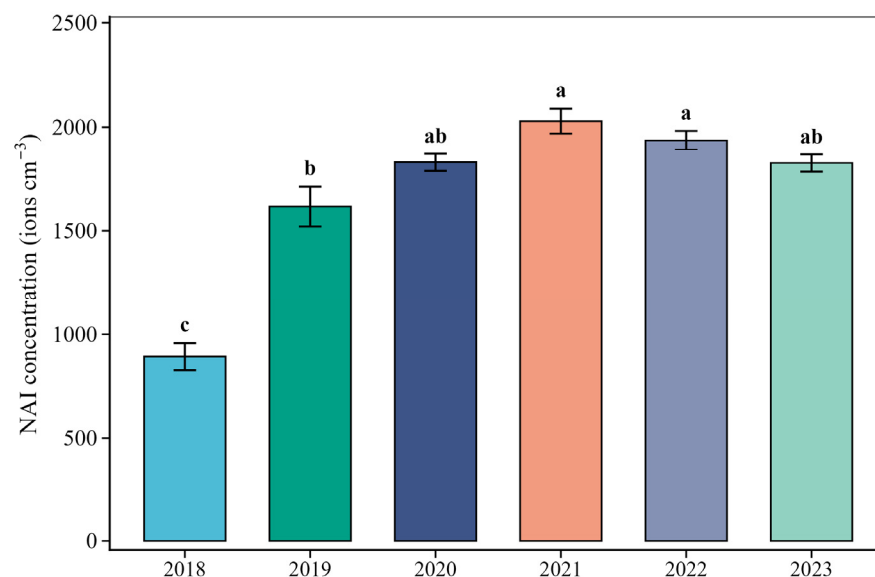


Figure 6. Annual dynamics of NAI concentration. The error bars represent the standard error of the mean, bars sharing the same letter are not significantly different ($p > 0.05$).

3.3. Spatiotemporal Distribution Patterns of NAI Concentration in Zhejiang Province

During 2018–2023, the NAI concentration in Zhejiang Province consistently exhibited a spatial distribution pattern of “high around the periphery and low in the center” (Figure 7). The Jinqu Basin in central Zhejiang is a lowland area with a relatively low NAI concentration, whereas the southwestern mountainous area has consistently been the region with the highest negative oxygen ion concentration. There were also significant differences in the absolute concentrations of negative oxygen ions in different years. The overall NAI concentration in Zhejiang Province showed an increasing trend from 2018 to 2023, with an average annual increase of 158 ions·cm⁻³ (Figure 7).

3.4. Environmental Factor Effects on NAI Concentration

Correlation analysis indicated that NAI concentration was significantly positively correlated with temperature, relative humidity, wind speed, wind direction, and precipitation, and significantly negatively correlated with PM_{2.5} and atmospheric pressure (Figure 8). While a statistically significant ($p < 0.001$) negative correlation was detected with O₃, the correlation coefficient was negligible ($R = -0.01$), indicating no practically meaningful relationship (Figure 8). This example highlights the need to distinguish between statistical significance (inflated by large sample size) and effect size in large studies. The results from the linear mixed-effects model showed that relative humidity was the primary meteorological factor affecting NAI concentration (relative contribution, 84.78%), followed by wind speed and precipitation (relative contributions of 13.04% and 2.17%, respectively) (Table 1).

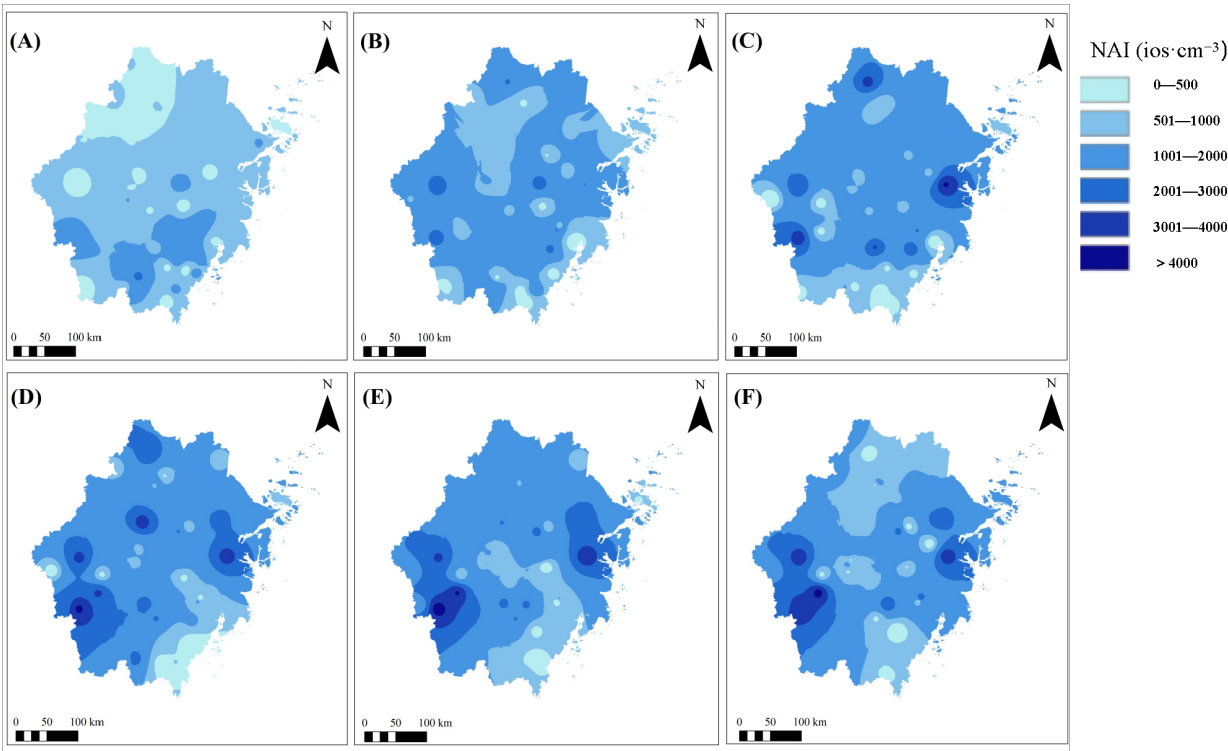


Figure 7. Spatial distribution patterns of NAI concentration in Zhejiang Province in 2018 (A), 2019 (B), 2020 (C), 2021 (D), 2022 (E), 2023 (F).

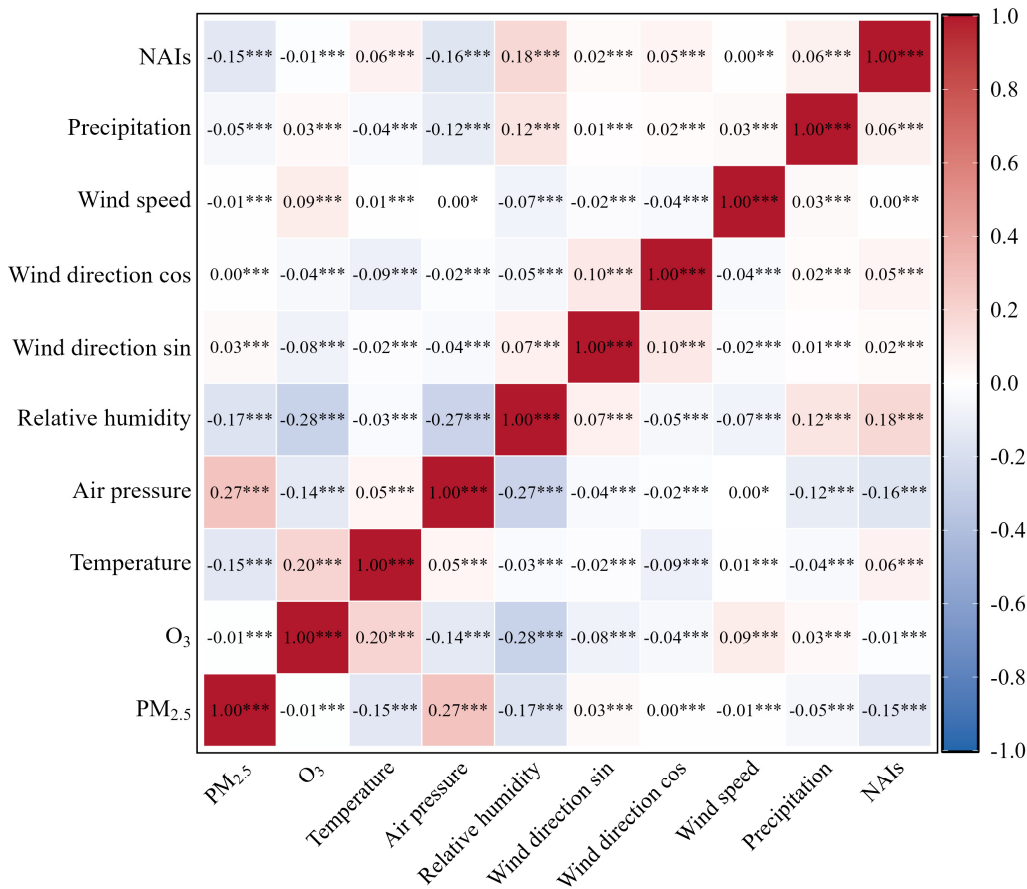


Figure 8. Correlation between NAI and environmental factors. Blue and red in the square represent negative and positive correlations, respectively. * Correlation is significant at the 0.05 level; ** correlation is significant at the 0.01 level; *** correlation is significant at the 0.001 level.

Table 1. Linear mixed-effects model of NAI and environmental factors.

Environmental Factor	Effect Estimate	Standard Error	t Value	p Value	Relative Contribution (%)
Relative humidity	6.250	0.438	14.283	<0.001	84.78
Wind speed	−30.10	4.633	−6.496	<0.001	13.04
Precipitation	0.152	0.113	1.342	<0.05	2.17

Note: only variables with significant effects ($p < 0.05$) after stepwise selection are shown.

4. Discussion

4.1. Temporal of NAI Concentration

Based on 6 years of on-site monitoring, we found that the average concentration of forest NAI in Zhejiang Province reached $1672 \text{ ions}\cdot\text{cm}^{-3}$, indicating that Zhejiang's forest ecosystems, dominated by subtropical evergreen broad-leaved and mixed coniferous–broad-leaved forests, possess an exceptionally strong air purification and health-promoting service function. This value is notably higher than those reported for other forest types. For instance, in the warm temperate Songshan National Nature Reserve in Beijing, seasonal mean NAI concentrations ranged from $632 \text{ ions}\cdot\text{cm}^{-3}$ in spring to $833 \text{ ions}\cdot\text{cm}^{-3}$ in summer [18]. In contrast, comparable background concentrations have only been reported in a few less-disturbed forest ecosystems [19–21]. Such a high background concentration likely arises from a combination of mechanisms rather than from a single factor. First, natural ionization sources continuously supply free electrons and primary ions in the near-surface atmosphere [4]. Second, the low aerosol-particle concentrations reduce the ion-aerosol attachment sink, thereby prolonging the atmospheric lifetime of NAI. Third, the persistently high relative humidity (annual mean $> 75\%$) in this humid subtropical region promotes ion hydration and the growth of small ions into larger, more stable cluster ions with lower recombination coefficients, effectively preserving the ion population. Fourth, extensive forest cover (over 61%) and abundant vegetation may emit biogenic volatile organic compounds that participate in ion-induced nucleation, potentially contributing to the generation of charged clusters [19]. Collectively, these coexisting processes, rather than any single driver, explain the elevated NAI levels observed in this region.

At the diurnal scale, NAI concentration exhibits a “bimodal pattern with early morning and evening peaks and a secondary trough in the afternoon,” rather than the simpler “daytime high, nighttime low” pattern. The first peak is at 7:00. This finding coincides with previous findings in subtropical forests and is likely driven by the following factors: nighttime temperature inversions suppress vertical mixing, allowing NAI to accumulate in the near-surface layer by reducing turbulent dilution; meanwhile, such stable conditions also promote the accumulation of soil-exhaled radon near the ground, and the subsequent radioactive decay of radon and its short-lived progeny provides a sustained in situ ionization source, substantially increasing ion pair production [19]. Additionally, relatively low nighttime temperatures slow down ion–aerosol recombination rates as recombination coefficients decrease with temperature, and high relative humidity (often exceeding 80% at night) enhances ion hydration, thereby prolonging NAI lifetime by forming larger hydrated clusters with lower attachment coefficients [21,22]. Together, these factors lead to a prominent morning peak around 7:00, before solar heating breaks the inversion and re-intensifies turbulent mixing. In addition, sunrise-induced activation of photosynthesis rapidly releasing large amounts of volatile organic compounds (VOCs), and persistently high relative humidity, providing abundant reaction precursors and a stable hydrated environment for NAI [18]. The secondary peak at approximately 16:00 is attributed to a rebound in photochemical ion production as solar radiation, while diminished from its midday peak, is

still sufficient for photoionization, combined with a relaxation of turbulent dilution as wind speeds typically decrease in the late afternoon. Additionally, plant transpiration elevates local humidity, favoring ion hydration. Although turbulent dilution is strongest at midday, in the afternoon—as solar radiation weakens and turbulence decreases—the efficiency of free electrons combining with oxygen molecules via photochemistry rebounds [19]. In addition, plant transpiration elevates local humidity, leading to a modest rebound in NAI concentration. Notably, the trough at 12:00 was not the result of decreased emissions but was more likely controlled by the combined dilution effect of strong vertical mixing and horizontal advection due to turbulence. Interestingly, the trough around 20:00 has seldom been reported in previous studies. We speculate that the stabilization of the boundary layer after sunset was not yet fully established, while anthropogenic activities (such as evening return traffic and residential cooking) maintained a certain level of aerosol concentration. These aerosols can efficiently adsorb and deplete NAI, resulting in the lowest daily values.

On monthly and seasonal scales, although the summer mean was the highest, it surpassed that of winter by only approximately 25%—much lower than the typical “higher in summer, lower in winter” ratio (e.g., 2–3 times) reported for temperate regions. We propose several possible explanations for this phenomenon: (1) in Zhejiang province, average monthly temperatures in winter remain above 5 °C, so evergreen broad-leaved forests do not completely enter dormancy, and the decrease in VOCs release is limited; (2) winter relative humidity is often higher than in summer (post-meiyu season tends to be drier), mitigating the negative impact of low temperature on NAI; and (3) winter also sees reduced anthropogenic activity and lower PM_{2.5} concentrations, resulting in less NAI consumption. The combined influence of these factors led to only minor seasonal differences in the NAI concentrations. This result is consistent with observations from forests in subtropical Taiwan and some reports from Japan, but is distinctly different from findings in temperate forests in northern China and Europe [23]. This suggests that the ecological service assessment of NAI must account for differences in climate zones.

Regarding interannual dynamics, the NAI concentration showed a marked upward trend with fluctuations from 2018 to 2023. The highest values were recorded during the 2020–2022 COVID-19 pandemic, with a slight decline after lifting the pandemic controls in 2023. This time series closely matches the downward trend in PM_{2.5} concentrations in Zhejiang Province (according to publicly available provincial environmental data) and the patterns of human activity. Although this study did not directly quantify human activity indices, there is ample evidence that the pandemic period saw a dramatic reduction in traffic and industrial emissions, sharply lowering aerosol concentrations and thus reducing the NAI sink [23]. Notably, even if the pandemic years are excluded, NAI concentrations in 2019 and 2023 remained higher than those in 2018, which may be related to the long-term “Forest Zhejiang” initiatives and sustained improvements in air quality at the policy level. Therefore, the interannual increase in NAI was not merely a short-term effect of the pandemic but more broadly reflected the integrative results of regional ecological management.

4.2. Spatiotemporal Dynamics of NAI Concentration

The NAI concentration in Zhejiang Province exhibited a stable spatial pattern of “higher on the periphery and lower in the center,” with the mountainous areas in the southwest consistently serving as a high-concentration region, while the Jinqiu Basin in the central region constituted a low-concentration region. This distribution pattern may be closely correlated with elevation, forest cover, and the intensity of human activities. The southwestern mountainous area mostly consists of mid–low mountains at elevations above 500 m, with forest coverage exceeding 80%, low population density, and minimal industrial

aerosol emissions. Local circulation caused by mountainous terrain also facilitates the local accumulation of NAI: at night, mountain winds confine high NAI concentrations within valley bottoms, and during the day, valley winds transport NAI precursors released by vegetation uphill to monitoring sites, forming a positive feedback [24]. Additionally, the atmospheric background aerosol concentration is naturally lower at higher altitudes, resulting in an extended NAI lifespan.

In contrast, the Jinqu Basin is the main population agglomeration and agricultural/light industrial hub of Zhejiang Province, characterized by flat terrain and poor atmospheric dispersion, with $\text{PM}_{2.5}$ concentrations often being the highest in this province. High aerosol concentrations strongly deplete NAI through adsorption and recombination, leading to significantly lower NAI concentrations in this region than in the surrounding mountainous areas. Notably, the basin's low NAI level does not indicate an absolute low concentration, but rather a relative decrease compared to other regions in Zhejiang Province, indicating that even under anthropogenic influence, the baseline maintained by forest coverage still sustains a certain NAI level. This spatial gradient is similar to the “urban low, suburban high” pattern observed in other studies, which provides direct guidance for the macro-scale siting of forest-based wellness centers in the future [25,26].

This study also found that during 2018–2023, the provincial average NAI concentration increased by approximately $158 \text{ ions} \cdot \text{cm}^{-3}$ per year, and the spatial heterogeneity of this increase did not alter the fundamental “higher on the periphery, lower in the center” pattern of the NAI. This indicates that NAI enhancement occurred province-wide, likely driven by the large-scale meteorological background and regional air quality improvements [27]. Combining future high-resolution land-use data may further quantify the independent contributions of local factors, such as stand type, elevation, and distance from roads, to the spatial differentiation of NAI.

4.3. Influence of Environmental Factors on NAI

Linear mixed-effects modeling revealed that humidity was the most significant factor affecting NAI concentration, with a relative contribution as high as 84.78%, and it exerted a significant positive effect. NAIs are polar ion clusters whose survival times strongly depend on the hydration shell formed by water molecules. Under high humidity, the hydration layer is more complete, reducing the probability of recombination between ions and aerosols and inhibiting the diffusion loss of ions from the surfaces. In humid climate regions, such as Zhejiang Province, where the relative humidity exceeds 60% for most of the year, humidity is the primary limiting factor for NAI concentration.

The linear mixed-effects model, which controls for confounding factors, revealed a significant negative effect of wind speed (relative contribution 13.04%), indicating that turbulent dilution dominates when other variables are held constant. This seems contrary to the common notion that “ventilation improves air quality,”; however, it is important to note that NAIs are short-lived reactive species and not inert pollutants. Increased wind speed reduces local NAI concentration mainly through two mechanisms: first, enhanced turbulent mixing accelerates the transport of near-surface NAI to higher atmospheric layers, where there is a lack of sustained in situ generation sources (plant VOCs are mainly emitted near the surface); second, it facilitates the horizontal advection of air masses, bringing background air parcels with lower NAI concentrations to forest monitoring sites. This explanation is supported by micrometeorological studies. However, some studies have observed a positive correlation between wind speed and NAI under low wind speeds; the negative effect in this study may indicate that the mean wind speed at the forest sites in Zhejiang exceeds a certain threshold, entering the “dilution-dominated” stage [28]. Future

studies should conduct piecewise regression across wind speed intervals to clarify this threshold value.

The relative contribution of precipitation to the NAI was only 2.17%. This result was not unexpected because precipitation has dual and opposite effects on NAI: on the one hand, raindrop wet scavenging reduces PM_{2.5} levels, lowering the aerosol sink and favoring NAI increase [21]; on the other hand, while wet scavenging of PM_{2.5} can increase NAI, prolonged heavy precipitation can also temporarily reduce the exhalation of radon from the soil by filling soil pores with water, thereby potentially reducing a key source of atmospheric ionization near the ground. Moreover, increased soil moisture may limit gaseous diffusion of radon through the soil matrix [9]. The relative strength of these effects varied with precipitation intensity and duration, resulting in a minor overall contribution of precipitation to NAI.

5. Conclusions

Based on high-frequency observational data spanning six consecutive years from 60 forest sites in Zhejiang Province, this study found that the annual mean concentration of forest NAI in the subtropical humid climate zone reached 1672 ions·cm^{−3}, with concentrations in summer significantly higher than those in autumn and winter. On an interannual scale, NAI concentrations peaked from 2020 to 2022, coinciding with a decrease in human activity intensity during the same period. Spatially, the NAI showed a stable “high at the periphery, low in the center” pattern. Humidity was identified as the primary driver of the spatiotemporal variability of NAI, with wind speed as a secondary negative driver. Mechanistically, high humidity prolongs NAI lifetime by stabilizing hydration shells, while increased wind speed reduces local NAI through turbulent dilution rather than by suppressing sources. The pronounced morning NAI peak is further enhanced by nighttime temperature inversions that trap NAI near the surface. These findings reveal the temporal dynamic patterns and dominant environmental controls of NAI in subtropical forests, thereby providing a direct scientific basis for the comprehensive assessment of regional air quality and the development of forest-based health and wellness tourism resources in the future.

Author Contributions: Conceptualization, Investigation, Formal analysis, J.J.; software, B.J.; Review, Y.X.; Review, C.W.; Funding acquisition, Validation, Project administration, X.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Leading Goose Project of the Science Technology Department of Zhejiang Province (grant number 2024C03227) and Zhejiang Forestry Fresh Air (Negative air ion) Monitoring and Fixed-Point Observation (grant number 01202603).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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