Analysis and Control Strategies for Ningbo's Atmospheric Environment Based on Urban Climatic Maps: Postprint

Authors: Liu Lele, Zhao Xiaofeng, Zhao Yanchuang, Deng Junjun

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Abstract

Burgeoning urbanization has transformed urban climate and environment, giving rise to numerous climate and environmental issues that require effective urban climate-environment information and mitigation strategies to address and alleviate. Urban environmental climate maps provide crucial guidance for the planning and regulation of urban climate and environment. Building upon traditional urban climate maps, this study proposes a construction methodology for urban environmental climate maps that integrates multi-seasonal and multi-environmental-element approaches. Based on this methodology, taking Ningbo city—which features complex underlying surfaces and pronounced seasonal climate characteristics—as a case study, we comprehensively employ technical approaches including remote sensing retrieval, GIS spatial analysis, and mesoscale numerical simulation to conduct multi-seasonal analysis and assessment of urban heat load, air pollution, ventilation potential, wind fields, and the overall urban climate environment. The results indicate that regarding the primary elements shaping the urban climate environment, both urban heat load and air pollutant distribution exhibit significant seasonal and spatial variations. Ningbo is affected by both heat load and air pollution in spring and summer, by air pollution alone in winter, and minimally by both factors in autumn. The spatial patterns of ventilation potential demonstrate high similarity across seasons. The wind environment is complex and variable, displaying pronounced seasonal and spatial heterogeneity. Holistic analysis of the urban climate environment reveals that high-value and medium-value areas are primarily distributed across forested mountains, farmland, and water bodies. High-risk areas are situated in the coastal heavy chemical industry belt of Beilun, Zhenhai, and the southern bank of Hangzhou Bay. Medium-risk areas are distributed in the eastern part of Jiangbei District, the east and west wings of Yinzhou urban area, Cixi urban area, and the northeastern part of Fenghua urban area, where factory buildings are dense. Furthermore, building upon the aforementioned analysis, we propose an urban ventilation corridor planning scheme and climate-environment regulation strategies, including 2 primary ventilation corridors, 5 secondary ventilation corridors, 3 tertiary bidirectional ventilation corridors influenced by sea-land breezes, 12 tertiary unidirectional ventilation corridors influenced by sea-land breezes, 13 tertiary unidirectional ventilation corridors influenced by valley breezes, and seven categories of urban climate-environment regulation strategies. The proposed multi-seasonal, multi-environmental-element integrated construction methodology for urban environmental climate maps is applicable to the analysis and assessment of complex climate environments in monsoon climate regions. It can enhance the comprehensiveness and accuracy of urban climate-environment analysis, and through the formulation and implementation of ventilation corridor planning and related regulation strategies, improve urban heat load conditions and air quality, mitigate urban climate-environment issues across seasons, provide vital decision-making support for urban environmental protection, meteorological, planning, and other departments, thereby fostering sustainable urban development and eco-city construction.

Full Text

Preamble

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Ningbo Atmospheric Environment Analysis and Regulating Countermeasure Based on Urban Climatic Map

Liu L L, Zhao X F*, Zhao Y C, Deng J J*
Key Laboratory of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China*
Ningbo Urban Environment Observation and Research Station, Chinese Academy of Sciences, Ningbo 315800, China
University of Chinese Academy of Sciences, Beijing 100049, China

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Received: 2015-07-09; **Online Publication:** 2016-06-13
Corresponding Author: E-mail: xfzhao@iue.ac.cn

Abstract

Rapid urbanization has profoundly altered urban climate and environment, generating numerous climatic and environmental problems that require valid analysis and regulating countermeasures. Urban climatic maps provide crucial guidance for urban climate environment planning and regulation. This research proposes a novel method for constructing urban climatic maps that integrates multiple seasons and environmental elements, building upon traditional urban climatic mapping approaches. Using Ningbo City—a region with complex underlying surfaces and pronounced seasonal climate characteristics—as a case study, we conducted multi-seasonal analysis and evaluation of urban thermal load, air pollution, ventilation potential, wind fields, and overall urban climate environment through remote sensing inversion, mesoscale numerical simulation, and GIS spatial analysis.

The results reveal significant seasonal and spatial variations in the key elements shaping urban climate environment. Ningbo experiences both thermal load and air pollution impacts in spring and summer, pollution-only impacts in winter, and relatively minor effects from both factors in autumn. Ventilation potential patterns show high seasonal similarity, while wind environments are complex and variable with remarkable seasonal and spatial differences. High and medium-value urban climate environment areas are primarily distributed in forested mountains, croplands, and water bodies. High-risk zones are located in heavy chemical industrial zones along the coast of Beilun, Zhenhai, and the southern Hangzhou Bay shore. Medium-risk areas occur in regions with dense industrial factory clusters, such as eastern Jiangbei District, the eastern and western wings of Yinzhou urban area, Cixi urban area, and northeastern Fenghua urban area.

Based on these analyses, we propose an urban ventilation channel planning scheme comprising two first-class channels, five second-class channels, three third-class bidirectional channels influenced by sea-land breezes, twelve third-class unidirectional channels influenced by sea-land breezes, and thirteen third-class unidirectional channels influenced by mountain-valley breezes, plus seven categories of urban climate environment regulation countermeasures. The proposed multi-season, multi-element urban climatic mapping method is applicable to complex climate environment analysis and evaluation in monsoon climate regions, enhancing comprehensiveness and accuracy. Through ventilation channel planning and implementation of relevant regulation measures, this approach can improve urban thermal load conditions and atmospheric environmental quality, alleviating seasonal urban climate environment problems and providing critical decision support for urban environmental protection and planning departments, thereby promoting sustainable urban development and ecological city construction.

Keywords: Ningbo City; urban climate; thermal load; wind environment; urban planning; ventilation channel; regulation countermeasure

1. Introduction

Rapid urbanization in China, accompanied by swift industrialization, has exacerbated urban environmental issues. Urban heat islands [1-2] and haze pollution [3-4] have attracted widespread attention in major cities. According to China' s Environmental Status Bulletin, the national average number of haze days reached 35.9 days in 2013, the highest on record [5]. Since pollutant emission reduction cannot continue indefinitely, improving pollutant dispersion conditions through urban planning has become a critical research focus in atmospheric environmental regulation.

Urban Climatic Map (UCMap) is an emerging information assessment tool that integrates urban climate-environment factors with urban planning and construction considerations. It uses two-dimensional spatial representation to display urban climate phenomena and existing problems, combining land use information to provide scientific assessments that guide urban construction and planning practice [6]. Since Knoche first proposed developing a series of climate maps at different scales in the 1950s [7], and Stuttgart climatologists pioneered UCMap research to mitigate climate pollution in low-wind environments [8], this tool has been widely applied to create healthy and comfortable living environments [9-13]. Cities like Tokyo and Sakai have developed their own research systems [10-11], while Hong Kong built upon German and Japanese experiences using geographic information data and wind tunnel simulations to enhance accuracy [14-15].

However, previous UCMap studies have several limitations. In environmental element assessment, most focused primarily on urban heat islands, rarely considering recently prominent issues like haze pollution. Studies by He Xiaodong et al. on Beijing [12] and Lin Yaoyu et al. on Shenzhen [13] analyzed only thermal load issues. In data acquisition, most relied on ground station monitoring data without incorporating multi-source remote sensing information, such as the Hong Kong and Kaohsiung studies by Ng et al. [14-15]. Regarding assessment seasons, most research considered only summer or winter-summer seasons, lacking comprehensive year-round analysis—examples include Hong Kong studies [15] and Beijing summer analyses [16]. In monsoon climate zones, complex natural environments and rapid urbanization create distinctly seasonal urban climate characteristics, making single-season or single-issue studies inadequate for current urban planning needs.

Addressing these gaps, this study uses Ningbo urban area as the research zone, employing remote sensing inversion information and spatiotemporal data to propose a multi-season, multi-element UCMap construction method suitable for complex climate environment analysis in monsoon climate regions.

2. Study Area

Ningbo City is located along the central coast of China at 120°55 E–122°16 E, 28°51 N–30°33 N, characterized by a subtropical monsoon climate with distinct seasonal alternation. The multi-year average temperature is 16.4°C, with July (28.0°C) and January (4.7°C) being the hottest and coldest months, respectively. The terrain is high in the southwest and low in the northeast. Considering the influence of surrounding environments on Ningbo urban area, the study area was defined as Ningbo City proper and its surrounding regions.

Rapid urbanization in Ningbo has increased building density and height, altered natural landforms, and expanded population, making urban underlying surfaces rougher and reducing internal wind speeds, leading to high-temperature weather and frequent extreme events [17-18]. The annual average temperature shows an overall fluctuating upward trend, while annual average wind speed displays a fluctuating downward trend [19]. Urban heat island effects occur year-round, with stronger intensity in summer than winter, and both heat island area and quantity increase significantly with urbanization [18]. Haze events have caused rapid deterioration of atmospheric quality, with multiple sustained pollution episodes in 2013, reaching historically severe levels [20]. Air pollution shows obvious seasonal variation, concentrated in spring and summer, with significantly higher pollution levels in urban areas than suburbs.

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3. Methods

3.1 Data Collection

Based on research objectives and image quality, Landsat-8 images were selected for representative months from 2013-2014. MODIS data were chosen for periods with higher air pollution concentrations in each season. Meteorological data included wind speed and direction observations from 118/39 meteorological stations and 1°×1° reanalysis data. Population data used township-level resident statistics from the 2010 Sixth National Census. Additional data included 30m×30m resolution digital elevation data and other auxiliary information. All images used the GCS_WGS_1984 projection coordinate system. Software used included ArcGIS 10.1, ENVI 5.0, and WRF 2.2.

Table 1 Remote sensing images and meteorological data used in this study

Data Type	Date	Resolution/Path	Remarks
Landsat-8 OLI/TIRS	2014-04-10, 2013-08-29, 2013-11-17, 2013-12-03	30m×30m, Path 118/Row 39	Representative months
MODIS	2014-03-10, 2013-07-02, 2013-10-28, 2013-12-06	1km×1km, H28V06	High pollution periods
Meteorological	2014-04-01–30, 2013-07-01–31, 2013-10-01–31, 2014-01-01–31	Station data + 1°×1° reanalysis	Wind speed/direction, 6 basic elements

3.2 Land Cover Information Extraction

Landsat-8 OLI images were resampled and band-composited. Based on Normalized Difference Vegetation Index (NDVI) thresholds (NDVI $>$ 0.65 for vegetation, NDVI $<$ 0 for water, 0 NDVI 0.65 for construction land), unsupervised classification divided the data into land cover types, with results refined using threshold segmentation.

3.3 Surface Temperature Retrieval

Land surface temperature was retrieved from Landsat-8 thermal infrared bands [21]. Following Landsat-8 band characteristics, the thermal infrared band (10.6-11.19 m) was selected. Pixel gray values were converted to top-of-atmosphere radiance, followed by atmospheric correction and emissivity correction. Atmospheric parameters (upward/downward radiance, transmittance) were obtained from NASA’ s atmospheric parameter query website [22]. Based on land cover classification, lookup tables were used to convert top-of-atmosphere radiance to surface radiance, then to land surface temperature with emissivity assignments.

3.4 Aerosol Optical Depth Retrieval

Aerosol Optical Depth (AOD) retrieval employed the dark pixel algorithm. The radiative transfer model calculated relationships between AOD and atmospheric parameters under different observation conditions to establish AOD lookup tables. MODIS band data were preprocessed to extract dark pixels at 2.1 m. Solar and sensor zenith/azimuth angles were used to remove apparent reflectance from red bands based on linear relationships between visible and shortwave infrared bands. Linear interpolation in the lookup table yielded AOD values [23].

3.5 Mesoscale Numerical Forecast Model

The Weather Research and Forecasting (WRF) model was used with four nested grids covering 120.55°–122.64°E, 28.98°–30.49°N at 66×54 grid points. Coarse and fine grids used 3 km resolution. Parameterization schemes included: Monin-Obukhov for surface layer, Dudhia for shortwave radiation, RRTM for longwave radiation, Ferrier for microphysics, Betts-Miller-Janjic for cumulus (coarse grid only), and YSU for boundary layer, coupled with an urban canopy model [24-25]. Simulated average wind speed and direction for representative months showed high consistency with observations.

3.6 Population Density Visualization

Mountain-valley breezes formed by topographic thermal effects promote atmospheric circulation. Vegetated mountainous areas serve as important fresh air sources for urban areas [12]. Slope values were calculated from DEM data and overlaid with land cover classification. Areas with Slope 40% and vegetation cover were identified as mountain forest areas using ArcGIS 10.1 buffer analysis. Population density negatively impacts thermal load and reflects building height/density, which also reduces ventilation potential. Township-level census data were spatially visualized by linking population statistics with administrative vector data to calculate population density.

3.7 Urban Thermal Load Analysis

Urban thermal load is the primary cause of urban temperature increase. To characterize spatial differences, a Heat Contribution Index (H) was calculated from land surface temperature data: $H = (Ti - T)/T$, where Ti is the temperature at pixel i and T is the regional average temperature [26]. Based on the histogram distribution of H values, threshold segmentation was applied (Table 2).

Table 2 Thresholds used in thermal load level segmentation

Thermal Load Level	Threshold Values	Classification Values
High cooling load	-0.25	-
Moderate cooling load	-0.25 to -0.15	-

Thermal Load Level	Threshold Values	Classification Values
Low cooling load	-0.15 to -0.05	-
Neutral	-0.05 to 0.05	-
Low thermal load	0.05 to 0.15	-
Moderate thermal load	0.15 to 0.25	-
High thermal load	0.25	-

3.8 Urban Air Pollution Analysis

Aerosol Optical Depth is a key physical parameter indicating atmospheric turbidity and pollution degree [23]. AOD values were segmented into pollution levels based on magnitude (Table 3).

Table 3 Thresholds used in air pollution level segmentation

Air Pollution Level	Threshold Values	Classification Values
Slight pollution	0–0.5	-
Mild pollution	0.5–0.75	-
Moderate pollution	0.75–1.0	-
Severe pollution	> 1.0	-

3.9 Urban Ventilation Potential Analysis

Natural surface aerodynamic characteristics show that construction land with high surface roughness has weaker ventilation potential, while surfaces with low roughness have higher potential. Ventilation potential analysis results were obtained by overlaying land cover components (forest, mountain forest, construction land, water) with classification rules (Table 4).

Table 4 Thresholds used in ventilation potential level segmentation

Component	Classification Rules	Classification Values
Forest distribution	Non-forested areas	-
Mountain forest distribution	Vegetated with slope 40%	-
Construction land distribution	Non-construction land	-
	Construction land 2000 m from water, 1.5 km	-
	Construction land 2000 m from water, 1.5–3 km	-
	Construction land > 3 km from water	-
Water distribution	Inland water and buffer 30 m	-

3.10 Urban Wind Environment Analysis

Urban wind environment is a complex system. WRF-simulated monthly average wind direction and speed data for representative months were georeferenced and corrected to produce wind environment analysis results using ArcGIS 10.1.

3.11 Urban Climate Environment Analysis and Planning Recommendations

Urban climate environment analysis evaluates conditions based on input climate data and land cover information [6]. Using ArcGIS 10.1 spatial analysis tools, thermal load, air pollution, and ventilation potential results for representative months were overlaid and reclassified, then combined with wind environment analysis to produce monthly climate environment assessments. Based on distribution characteristics and planning objectives, areas were classified as high-value, medium-value, low-value, transitional, low-risk, medium-risk, and high-risk climate environment zones.

Planning recommendations propose ventilation channel strategies and urban design guidelines at city and regional scales to mitigate climate issues. Ventilation channel planning uses water bodies, green spaces, and street canyons as pathways for cool air flow, with high-value areas as upstream sources and high-risk areas as downstream destinations, aiming to improve local microclimate and protect existing favorable climate environments [26].

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4. Results and Analysis

4.1 Seasonal Urban Climate Environment Analysis and Assessment

Thermal Load: Ningbo's thermal load distribution shows distinct seasonal and spatial patterns (Fig. 4). Built-up areas exhibit significantly higher thermal load than surrounding agricultural land. Spring and summer have more extensive thermal load distribution, with stronger effects than autumn and winter. Winter thermal load concentrates in coastal industrial zones. Overall, thermal load 主要分布在城镇中心区及其外围郊区, particularly in coastal industrial belts like Beilun and Yuyao. Cooling load areas that mitigate thermal effects are distributed in high-altitude mountainous regions, vegetated slopes, and water bodies.

Air Pollution: Aerosol optical thickness distribution shows significant seasonal and spatial variation (Fig. 5). Areas reaching severe pollution levels in spring, summer, and winter cover 706 km^2, 684 km^2, and 500 km^2 respectively, with spring and winter having the most extensive distribution (approximately 70% of study area). Pollution distribution is concentrated, with severe zones mainly in coastal industrial belts and central urban areas, moderate zones around towns, and light zones in high-altitude mountains.

Ventilation Potential: Distribution shows notable spatial differences but high seasonal similarity (Fig. 6). High ventilation potential occurs in water bodies, croplands, and forested mountains. Moderate potential is found in forested areas, while low potential concentrates in high-density built-up areas like the Sanjiangkou main urban zone and Beilun coastal industrial belt, primarily due to high population and building density with closely arranged low-rise buildings that reduce wind permeability.

Wind Environment: Ningbo' s wind environment is complex with significant seasonal and spatial variation (Fig. 7). Spring has east-southeast dominant winds with average built-up wind speeds ~0.5 m/s (poor ventilation). Summer has northeast winds with speeds ~1.5 m/s. Autumn shows significant mountain-valley breezes. Winter has north-northwest winds with speeds ~4 m/s. Low wind speeds reduce pollutant dispersion capacity [13].

Figure 4 [**Figure 4: see original paper**] Analysis and evaluation on thermal load in four seasons of Ningbo City
Figure 5 [**Figure 5: see original paper**] Analysis and evaluation on air pollution in four seasons of Ningbo City
Figure 6 [**Figure 6: see original paper**] Analysis and evaluation on ventilation potential in four seasons of Ningbo City
Figure 7 [**Figure 7: see original paper**] Analysis and evaluation on wind environment in four seasons of Ningbo City

4.2 Urban Climate Environment Synthesis

The integrated urban climate environment analysis (Fig. 8) reveals:

- **High-value and medium-value zones** have good climate quality with low thermal load, minimal pollution, and good ventilation, distributed in mountains, croplands, and water bodies—the origins of fresh air.
- **Low-value and transitional zones** have moderate quality with mild thermal load and pollution, and relatively lower ventilation, mainly in peri-urban farmland.
- **High-risk zones** suffer strong thermal load and severe pollution, typically located in coastal heavy chemical industrial belts of Beilun, Zhenhai, and southern Hangzhou Bay.
- **Medium-risk zones** experience moderate thermal load and pollution with low ventilation, distributed in factory-dense areas like eastern Jiangbei, Yinzhou' s east-west wings, Cixi urban area, and northeastern Fenghua.
- **Low-risk zones** are mainly medium-low density built-up areas.

Figure 8 [**Figure 8: see original paper**] Analysis and evaluation on climate environment of Ningbo City

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5. Urban Climate Environment Planning and Regulation Measures

Based on comprehensive analysis, a ventilation channel plan was developed (Fig. 9):

- **Two first-class channels** along the Yong River estuary-Xiangshan Harbor line and Xiangshan Harbor west coast-Yan River estuary, utilizing cooling water bodies and seasonal prevailing winds to deliver fresh air to Beilun-Zhenhai industrial zones and urban risk areas. These require strict protection and appropriate widening.

- **Five second-class channels** along Sanjiangkou Park-Moushan Lake line and Tingxia Reservoir line, connecting major water bodies and green spaces to guide airflow, using first-class channels to improve local microclimate.
- **Three third-class bidirectional channels** influenced by sea-land breezes.
- **Twelve third-class unidirectional channels** influenced by sea-land breezes.
- **Thirteen third-class unidirectional channels** influenced by mountain-valley breezes.

Seven regulation countermeasure types: 1. Protect and widen channels in high/medium-value zones; avoid development. 2. Preserve and improve existing environments in low-value/transitional zones. 3. Prevent medium-risk zones from merging with high-risk zones; expand green/blue spaces. 4. In low-risk zones, create channels by widening streets and opening green spaces. 5. In high-risk zones, avoid large buildings causing wind-blocking effects, control population density, increase green/blue areas, and optimize building layout. 6. Reduce artificial heat release and improve energy structure. 7. Orient buildings toward prevailing winds and channels.

Figure 9 [**Figure 9: see original paper**] Adjustment measures on climate environment of Ningbo City
Figure 10 [**Figure 10: see original paper**] Adjustment measures on urban climate environment of Ningbo City

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6. Conclusions and Discussion

This study conducted multi-seasonal, multi-element comprehensive analysis and evaluation of Ningbo’ s urban climate environment, yielding three main conclusions:

1. **Seasonal and spatial variations:** Ningbo’ s thermal load and air pollution exhibit significant seasonal and spatial differences—summer affected by both, winter by pollution only, autumn minimally affected. Ventilation potential shows spatial variation but high seasonal similarity. Wind environments are complex with marked seasonal/spatial differences.

2. **Spatial distribution patterns:** High/medium-value climate zones are in mountains, croplands, and water bodies. High-risk zones are in coastal heavy industry belts. Medium-risk zones are in factory-dense areas. Low-risk zones are in medium-low density built-up areas.

3. **Planning solutions:** The proposed ventilation channel system includes

2 first-class, 5 second-class, and 28 third-class channels oriented to address seasonal climate problems, plus seven categories of regulation measures.

This research improves existing UCMap methods by integrating multi-seasonal, multi-element analysis applicable to complex monsoon climate regions. It enhances analysis comprehensiveness and accuracy, and can improve thermal load and air quality through ventilation planning. Compared with international studies that typically focus only on summer (occasionally winter) and thermal islands alone, this study incorporates air pollution using high-resolution remote sensing AOD data instead of limited ground stations, providing refined spatial pollution distribution.

Limitations and future work: Current limitations include insufficiently high-resolution land use and population data, reducing evaluation precision. Future improvements will use higher-resolution remote sensing for detailed land use information and extend analysis to neighborhood scales for multi-scale assessment.

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Note: Figure translations are in progress. See original paper for figures.