

## Postprint of Comprehensive Climate and Environmental Observation and Scientific Research from the Boundary Layer to the Middle and Upper Atmosphere

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### Abstract

Over the past 50 years, the Xianghe Climate and Environment Comprehensive Field Scientific Observation and Research Station of the Institute of Atmospheric Physics, Chinese Academy of Sciences (hereinafter referred to as “Xianghe Station”) has established comprehensive detection capabilities for climate and environment extending from the boundary layer to the middle and upper atmosphere. Having joined multiple domestic and international atmospheric observation networks, it stands as a rare comprehensive atmospheric field scientific test station internationally. Since the 21st century, Xianghe Station has conducted numerous large-scale international comprehensive observation experiments. Based on long-term continuous observation data, it has carried out fundamental and applied research on energy propagation and material exchange in the middle and upper atmosphere, atmospheric physicochemistry and air quality in the boundary layer, and solar energy monitoring and forecasting, achieving a series of prominent research outcomes. Building on past achievements and forging ahead, Xianghe Station will intensify efforts in the development and upgrading of advanced detection instruments and equipment, enhance detection capabilities for thermodynamic processes in the middle and upper atmosphere and physicochemical processes in the boundary layer, and establish a comprehensive field atmospheric detection base integrating observation, experimentation, and research. This will enhance scientific understanding of fundamental processes in the middle atmosphere, exchange processes and mechanisms between upper and lower atmospheric layers, and the weather-climate and environmental effects of pollution reduction, thereby providing scientific and technological support for China to gain discourse power on global climate and environmental

issues and for national security.

## Full Text

### Preamble

#### **Integrated Observation and Research on Climate and Environment from Boundary Layer to Middle and Upper Levels of Atmosphere**

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### Abstract

After more than 50 years of development, the Xianghe station (XH) of the Institute of Atmospheric Physics, Chinese Academy of Sciences, has established comprehensive detection capabilities spanning from the boundary layer to the middle and upper atmosphere. As one of the few integrated atmospheric field scientific test stations worldwide, XH has joined numerous domestic and international atmospheric observation networks. Since the 21st century, XH has conducted multiple large-scale international comprehensive observation campaigns. Based on long-term continuous observation data, the station has carried out fundamental and applied research on energy propagation and mass exchange in the middle and upper atmosphere, boundary layer atmospheric physics and chemistry and air quality, and solar energy monitoring and forecasting, achieving a series of prominent results. Looking forward, XH will continue to focus on the development and upgrading of advanced detection instruments, enhancing capabilities for thermodynamic detection of the middle and upper atmosphere and physical-chemical process detection in the boundary layer. The station aims to build a comprehensive atmospheric detection base integrating observation, experimentation, and research to advance scientific understanding of fundamental middle atmospheric processes, exchange mechanisms between atmospheric layers, and the weather-climate-environmental effects of pollution reduction, thereby providing scientific and technological support for China's voice in global climate and environmental issues and for national security.

**Keywords:** ozone, MST radar, aerosol-cloud-radiation interaction, air pollution, carbon monitoring

## 1. MST Radar Continuous Observations: New Insights into Inertial Gravity Wave and Turbulence Parameter Characteristics and Distribution

The MST radar at Xianghe station represents one of the major core facilities supported by the national major scientific infrastructure “Meridian Project.” By utilizing scattering of electromagnetic waves by atmospheric refractive index irregularities caused by turbulence and other atmospheric activities, the radar achieves all-day, high spatiotemporal resolution (vertical resolution 150 m; temporal resolution 30 min) continuous detection of horizontal wind, vertical velocity, and turbulence in the troposphere-lower stratosphere (3–25 km) and mesosphere-lower thermosphere (60–90 km and above), providing a unique and important means for investigating multi-scale dynamic characteristics, processes, and atmospheric coupling across the entire atmospheric column.

Since 2011, the MST radar has provided high-quality continuous observation data for the Meridian Project and the CAS Solar-Terrestrial Space Environment Observation Network, supporting multiple aerospace missions and earning numerous individual and collective honors. Through validation against radiosonde and meteor radar data, the radar’s detection capabilities and reliability of horizontal wind data in both the troposphere-lower stratosphere and mesosphere-lower thermosphere have been confirmed [1,2]. Comparisons with the HWM07 model and ERA-Interim reanalysis data demonstrate that the MST radar exhibits excellent detection capability for atmospheric horizontal winds at 3–25 km and 65–100 km altitudes [Figure 1: see original paper], enabling investigation of dynamic coupling between upper and lower atmospheric layers.

The research team developed two power spectrum data inversion algorithms that effectively remove aircraft clutter interference, significantly improving retrieval accuracy for vertical velocity and spectral width [3]. This work resulted in one authorized patent [4], with the developed algorithms being applicable to wind profilers based on the same detection principle. An accurate method for extracting gravity wave parameters at each sampling height was developed, yielding new insights into inertial gravity wave characteristics and wave sources in the troposphere-lower stratosphere. This method decomposes meridional perturbations observed by MST radar into upward and downward propagating wave components, making research results more rigorous and accurate [Figure 2: see original paper]. Based on improved spectral width data, the team evaluated the applicability of three internationally common turbulence parameter calculation models for the first time [5] and obtained the first high spatiotemporal resolution turbulence dissipation rates and vertical turbulent diffusion coefficients over mainland China in the troposphere-lower stratosphere [6], with temporal-altitude profiles shown in [Figure 3: see original paper], providing important measured parameters for models.

Scientific questions refined from these atmospheric dynamic studies have provided valuable references for the optimal design and data application of

the Tibetan Plateau subsystem of Meridian Project Phase II at Yangbajing. The Xianghe station research team integrates scientific research with advanced detection technology, ensuring systematic overall planning and long-term advancement across multiple chains and levels from scientific objectives, detection modes, signal data processing to application research. Future prospects include multi-MST radar network observations to provide important data for fundamental frontier and applied problem research.

## 2. Ozone Observations Reveal Interannual and Decadal Variation Characteristics of Ozone in the Northern Hemisphere Mid-Latitudes

Atmospheric ozone content is a key focus in global climate and atmospheric environment research. Approximately 10% of ozone exists in the troposphere, serving as an important greenhouse and pollutant gas, while about 90% resides in the stratosphere, absorbing solar ultraviolet radiation to protect Earth's ecosystems and directly influencing stratospheric temperature structure, atmospheric circulation, and global climate. Changes in tropospheric and stratospheric ozone caused by natural processes and human activities have attracted widespread attention.

Dobson total ozone observations at Xianghe station show that sulfate aerosols from the 1984 El Chichón eruption and 1991 Pinatubo eruption affected mid-latitude stratospheric ozone concentrations through chemical processes. Emissions of anthropogenic precursors such as freons led to ozone depletion in mid-latitudes [7]. Since then, total ozone at Xianghe has generally shown an upward trend, while the overall level has declined since 2010 [Figure 4: see original paper].

The research team independently developed single-cell and double-cell ozonesondes [8] and conducted observations for over 20 years [9], obtaining the only long-term ozone profile dataset in mainland China. Comparison with Dobson measurements validated the reliability of ozonesonde measurements [Figure 5: see original paper]. Based on long-term ozone profile observations combined with numerical modeling, the study revealed trends in tropospheric ozone changes at Xianghe and quantified the relative contributions of human activities and natural processes. From 2002–2010, tropospheric ozone at Xianghe showed a significant upward trend, particularly pronounced in summer, mainly due to tropospheric photochemical production with dynamics playing a secondary role [10]. After implementing major pollutant total emission control measures in 2013, tropospheric ozone at Xianghe showed a slow but non-significant upward trend.

### 3. Research on Initiation Mechanisms of Upward Lightning from Tall Structures and Upper Atmospheric Transient Luminous Events

With urban development and clean energy utilization, tall structures such as urban high-rise buildings, communication towers, and wind turbines have increased, drawing attention to naturally occurring upward lightning. Since 2008, Xianghe station has deployed lightning location instruments that, through multi-station networking, enable real-time lightning location in the Beijing area and three-dimensional lightning channel mapping [11,12]. Research shows upward lightning is typically triggered by nearby lightning activity, predominantly induced by positive cloud-to-ground flashes, though it can also self-initiate under special conditions [13,14]. Initiation also depends on the intra-cloud leader structure of positive cloud-to-ground flashes, where the “positive-above-negative-below” structure of flashes initiated as intracloud discharges favors upward lightning initiation. When the horizontally developing negative leader at lower levels passes tall structures, upward lightning is easily triggered [Figure 6: see original paper] [15].

Tropospheric thunderstorms produce not only intracloud flashes and cloud-to-ground flashes but also transient luminous events (TLEs) above thunderstorm clouds. TLEs appear between thunderstorm tops and the lower ionosphere, can develop upward from thunderstorm tops to the lower ionosphere across several atmospheric layers, and significantly influence material and energy exchange between atmospheric layers, representing an important frontier in atmospheric and space physics research. Investigation of upper atmospheric TLEs is crucial for environmental protection and utilization of the near-space region.

The morphologies of upper atmospheric TLEs (called “red sprites”) over mainland China mainly include carrot-like and columnar shapes, extending spatially between 40–90 km with durations typically of tens of milliseconds [16,17]. Most red sprites are produced by tropospheric positive cloud-to-ground flashes that transfer positive charge from thunderstorm clouds to ground, while those produced by negative cloud-to-ground flashes are rare. Research has found that not only large peak current negative flashes (>90 kA, mostly exceeding 100 kA) can produce red sprites, but small peak current negative flashes can also produce them under suitable conditions [18]. Comparative studies show no obvious relationship between the abundance of red sprites and the phase and vertical distribution of thunderstorm particles, with no special characteristics found associated with red sprites. However, red sprite occurrence is accompanied by decreased lightning frequency [19,20].

#### 4. Systematic Assessment of Aerosol and Cloud Radiation Effects: Revealing Radiative Effects of North China Atmospheric Environmental Control Measures

Aerosols are the primary parameter affecting clear-sky surface radiation. Based on long-term continuous high-quality aerosol, cloud, and radiation observation data combined with radiative transfer modeling, the Xianghe research team first analyzed aerosol direct radiative effects in China [Figure 7: see original paper], establishing a radiative effect parameterization scheme that considers not only aerosol effects on total solar radiation but also systematically accounts for aerosol effects on diffuse radiation at an early stage internationally [21,22].

Clouds are important parameters affecting surface radiation energy budget, with cloud radiative effects (CRE) closely related to cloud macro- and microphysical properties. Using high-temporal-resolution radiation measurements at Xianghe station combined with all-sky imager observations, the team investigated parameter relationships between cloud fraction (CF) and surface solar radiation under both sun-obscured and sun-unobscured conditions. The annual mean CF at Xianghe is 0.50, with cumulus clouds dominating in summer (32%), occurring at frequencies approximately equal to the sum of stratiform and cirrus cloud frequencies. The annual mean CRE is  $-29.5 \text{ W} \cdot \text{m}^{-2}$ , with summer CRE at  $-78.2 \text{ W} \cdot \text{m}^{-2}$ . Under sun-unobscured conditions, CF variation primarily affects diffuse radiation, showing a linear relationship with CRE. Under sun-obscured conditions, CF variation affects both direct and diffuse radiation, resulting in a non-linear relationship between CF and CRE, with the slope decreasing as CF increases [23].

Analysis of solar total, direct, and diffuse radiation trends at Xianghe station over the past decade shows increases in total and direct radiation but decreases in diffuse radiation, indicating declining aerosol concentrations with reduced aerosol absorption being the main factor causing diffuse radiation decreases [24]. Since the implementation of China's Air Pollution Prevention and Control Action Plan in 2013, the research team found that surface solar radiation in central and eastern China has increased at  $0.70\text{--}1.16 \text{ W} \cdot \text{m}^{-2}$  per year, with rapidly declining aerosol radiative effects being the primary cause of significant surface solar radiation increases [25], while cloud changes contributed little to the solar surface radiation trend. Air pollution control plays an important role in regulating surface solar radiation, thereby significantly impacting terrestrial ecosystems and photovoltaic power generation.

#### 5. Establishment of North China Solar Energy Resource Assessment and Short-term Forecasting System

Under carbon neutrality goals, China will significantly increase the proportion of new energy sources such as photovoltaics in its energy structure. The intermittency and instability of photovoltaic solar energy represent major challenges for grid integration. In addition to developing new energy storage technologies,

advancing solar energy short-term forecasting technology is an economically effective approach to improving solar energy utilization efficiency. The launch of China's new generation geostationary meteorological satellite Fengyun-4 (FY-4) provides new observational capabilities for solar energy nowcasting (<3 h).

Based on high-quality radiation observation data from Xianghe station and utilizing FY-4A multi-channel reflectance data, a surface solar irradiance estimation and short-term forecasting system has been established [26]. The solar irradiance estimation method employs a hybrid approach combining physical clear-sky models and empirical cloudy-sky models. The core of the short-term forecasting model derives cloud motion vectors based on FY-4 cloud indices to predict surface solar radiation within the next 3 hours. The system simultaneously estimates and forecasts both horizontal total radiation and normal direct radiation. Research demonstrates FY-4's broad application prospects in surface solar radiation short-term forecasting, which will significantly promote the development and utilization of photovoltaic energy in China. The system exhibits good performance in North China, with future improvements focusing on calibrating surface solar irradiance estimation models and expanding their application.

## 6. Analysis of Air Pollution Sources in North China: Supporting National Major Events

The Xianghe research team has conducted comprehensive atmospheric environment observations in North China since 2004, organizing multiple international cooperative observation programs to serve air pollution control. Addressing core scientific questions regarding the entire process of heavy pollution occurrence-evolution-dissipation, the team established a closed research system for heavy pollution processes along the southeast airflow direction in Beijing using the Xianghe atmospheric supersite. Synchronous observations of boundary layer meteorology and atmospheric chemistry captured key parameters including meteorological elements, atmospheric pollution chemical composition, and boundary layer physicochemical structure, revealing evolution patterns of boundary layer meteorology and atmospheric pollution from multiple perspectives and providing refined datasets for in-depth investigation of heavy pollution formation mechanisms in autumn and winter [27,28], offering technical support for air quality assessment.

Results show that since the implementation of the "coal-to-gas" policy, organic carbon (OC) and elemental carbon (EC) concentrations in rural areas of the Beijing-Tianjin-Hebei region have significantly decreased, with corresponding reductions in diurnal variation amplitude. Concentration decreases of total carbon (OC+EC) and PM<sub>2.5</sub> in coal-ban areas were significantly higher than in non-ban areas. Relative to the 2016/2017 winter, meteorological conditions and emission reductions contributed 26% and 45% to EC concentration decreases in the 2017/2018 and 2018/2019 winters, respectively, while their contributions to PM<sub>2.5</sub> concentration decreases were 50% and 33%, and 66% and 57% for

primary OC and PM<sub>2.5</sub> concentration decreases, respectively. Clean energy utilization has played an important role in continuous air quality improvement [29].

## 7. Conclusion and Outlook

Through accumulation of long-term continuous high-quality detection data at Xianghe station and focusing on core scientific questions regarding middle and upper atmospheric processes and their weather-climate effects, we have enhanced understanding of fundamental middle atmospheric processes, exchange mechanisms between atmospheric layers, ozone layer changes and climate effects. Future development will focus on four main aspects:

1. **Enhanced middle atmospheric thermodynamic detection:** Establish a three-dimensional integrated detection system centered on VHF/MST radar, multi-wavelength lidar, and GPS digital ozonesondes, building Xianghe into a comprehensive detection platform focusing on middle atmospheric sounding with boundary layer physicochemical process detection.
2. **Strengthened aerosol-cloud-radiation observations:** Improve the North China aerosol-cloud-radiation observation platform, enhance atmospheric parameter and aerosol profile detection capabilities, strengthen hydrometeor profile detection, develop atmospheric and surface parameter remote sensing validation methods, and conduct in-depth research on aerosol-cloud-radiation-precipitation interactions and their impacts on regional and global climate change.
3. **International network integration:** Actively join international observation networks, become a representative Chinese site in international carbon satellite ground validation networks, support China's carbon neutrality goals, and provide scientific support for China's position in global climate and environmental negotiations.
4. **Integrated observation-experiment-research base:** Continue developing and upgrading advanced detection instruments and equipment to build a field base integrating observation, experimentation, and research.

As an important national scientific and technological innovation base and a key component of the national innovation system, Xianghe station has constructed a comprehensive climate and environmental observation system from the near-surface to the middle and upper atmosphere through generations of effort. The station has conducted extensive field observations, obtained valuable datasets including China's longest ozone total column and profile records, aerosol optical and radiation data, and long-term atmospheric wind field profiles from the lower atmosphere to 90 km altitude. These high-quality, long-term, continuous, and systematic comprehensive atmospheric key element datasets have played important roles in fundamental scientific research on major global environmental and

climate issues.

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